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The Close AGN Reference Survey (CARS): Data Release 1 and Beyond

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Accretion of matter onto the supermassive black holes that live at the heart of most galaxies is one of the most energetic processes in the Universe. These active galactic nuclei (AGN), and the energy they expel, are believed to play a critical role in how galaxies evolve. Despite this, our understanding of how the energy emitted from the active nucleus couples to the rest of the galaxy is limited. The goal of the Close AGN Reference Survey (CARS) has been to construct a dataset that is tailored to answering this question. We have observed the brightest unobscured AGN at redshifts $0.01 < z < 0.06$ with the best astronomical observatories in the world, including the Multi Unit Spectroscopic Explorer (MUSE) at ESO's Very Large Telescope, the Atacama Large Millimeter/submillimeter Array (ALMA), the Very Large Array (VLA), the Hubble Space Telescope, and the Chandra X-ray Observatory. In this article we highlight the ongoing work of the CARS team, along with the recent data release and accompanying papers, before discussing what comes next for the survey.

The coupling of energy emitted from the accretion region within active galactic nuclei (AGN) to the host galaxies in which they reside is called AGN feedback. It is often invoked to explain the discrepancy between the luminosity of the observed galaxy population and what is predicted by simulations of the Universe. In particular, without some mechanism to regulate star formation in massive galaxies, simulations massively overpredict the number of bright galaxies. AGN feedback is thought to work in two primary ways. In the first case, when the AGN luminosity is larger than ~ 1/100 of the Eddington luminosity, the radiation pressure from the active nucleus propels gas from the host galaxy in galactic-scale outflows (Nesvadba et al., 2007; Liu et al., 2013a; Cicone et al., 2018) in what is termed quasar or radiative-mode feedback. In the second case, for low-luminosity AGN, mechanical energy from radio jets heats the surrounding environment and prevents the gas cooling to the temperatures required for star formation (see Nulsen et al., 2005; Cavagnolo et al., 2010; Wagner, Bicknell & Umemura, 2012; Gaspari et al., 2020 for a review). This is known as kinetic or radio-mode feedback. Each mode provides a mechanism that regulates star formation and cooling flows. This can be implemented to curtail galaxy growth in simulations, allowing us to more accurately model the observed population of galaxies.

Despite the enormous importance of AGN feedback in galaxy evolution, nailing down the exact mechanisms and effects has been notoriously difficult. This is due to a multitude of factors, including the difficulty of estimating star formation rates in AGN, the lack of multi-wavelength data, and poor spatial resolution. Concurrently, numerical simulations have a tough time resolving the full spatial/temporal scales of AGN feeding and feedback, involving over nine orders of magnitude in dynamical range. This is why we undertook the Close AGN Reference Survey[1] (CARS). The CARS sample contains the most luminous unobscured AGN in the nearby Universe (Husemann et al., 2022) surveyed across the electromagnetic spectrum at high spatial resolution. In other words, if we are going to be able to see AGN feedback at work anywhere, it should be in these data. The questions we aim the survey to answer are:

- How common are and what are the properties of multi-phase gas outflows?
- What is the relative role of radiative pressure vs. radio jet-driven outflows?
- Do we see evidence of suppression or enhancement of star formation?
- What is the timescale of AGN accretion and outflows?
- Are the effects of AGN feedback confined to the centres of galaxies or more global?
- Can we see signatures of AGN fueling on host galaxy scales?

So far the survey has produced 11 refereed papers, with two approaching submission (and various others in preparation). These have included serendipitous discoveries of changing-look AGN (McElroy et al., 2016; Husemann et al., 2016; Krumpe et al., 2017), detailed multi-wavelength analyses of AGN-driven outflows (Powell et al., 2018; Husemann et al., 2019), and several studies of star formation using multiple tracers (Busch et al., 2018; Neumann et al., 2019; Smirnova-Pinchukova et al., 2019). In this article we focus on three key papers, dealing with: (1) the integral field unit (IFU) sample and using black hole mass as a tracer of the mean AGN lifetime (Husemann et al., 2022); (2) characterising the spatial extent of AGN-driven ionised outflows (Singha et al., 2022); and (3) a systematic star formation rate estimation and exploration of the effect of positive and negative AGN feedback (Smirnova-Pinchukova et al., 2022).

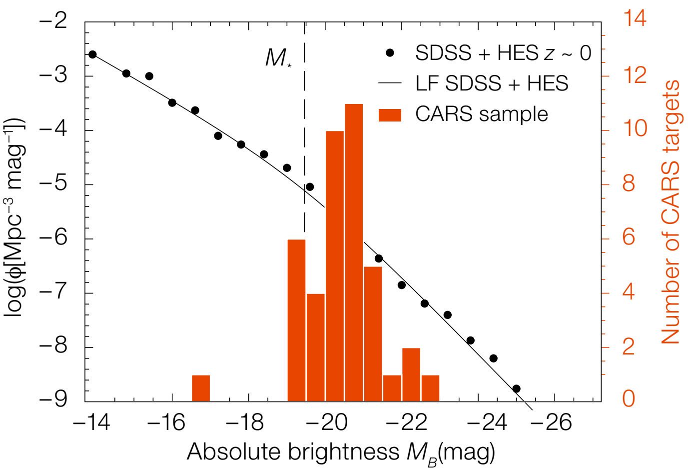


Figure 1. Histogram of the absolute magnitude of the chosen sample and the $z = 0$ type-1 AGN luminosity function (LF) derived from the Sloan Digital Sky Survey (SDSS) and the Hamburg/ESO Survey (HES).

The IFU sample and data release paper

CARS contains only unobscured AGN. In these galaxies the central engine is visible, meaning that the emission from the accretion disc and surrounding fast-moving clouds in the broad line region (BLR) can be observed directly. This is advantageous for two reasons. The first is that it allows for the masses of the central black holes and their accretion rates to be estimated from their central spectra. Secondly, it implies that the contribution of the AGN to the observations can be easily characterised as a point-source, as its sub-parsec size is completely unresolved in these observations. This means we can decompose the observations into AGN and host galaxy components, greatly aiding our further analysis.

The sample was selected from the Hamburg/ESO Survey (Wisotzki et al., 2000), which is a catalogue of ultraviolet-bright AGN. We applied a redshift limit of $z < 0.06$ to guarantee a minimum spatial resolution of 1 kpc, both to allow us to accurately decompose the host galaxy from the AGN and to reveal sufficient detail to achieve our science goals. The distribution of the targets is shown in Figure 1, where we see how the CARS galaxies compare to the overall unobscured AGN luminosity distribution.

Our integral field spectroscopic data — from instruments such as the Multi Unit Spectroscopic Explorer (MUSE) at ESO's Very Large Telescope (VLT) — provide spectra from across the entire spatial extent of the galaxies. To deblend the AGN from their host galaxies, we characterised the wavelength-dependent point spread function (PSF) by mapping the flux intensity of three prominent broad lines from the unresolved BLR using QDeblend3D[2]. We interpolated the PSF between the wavelengths of these lines and scaled to the central AGN spectrum to form an AGN datacube. An iterative algorithm was used to clean residual host galaxy light from the AGN spectrum before subtracting the AGN data cube. The process converges quickly and typically leads to a robust separation into an AGN and a host galaxy IFU datacube.

By examining images of the galaxies, the team classified the sample into disc-dominated, bulge-dominated, and irregular galaxies. Additionally, we noted whether galaxies displayed evidence of a bar or not. This analysis showed that 74% of the galaxies are discs, while only 14% are bulge-dominated. 12% of the sample was classed as irregular (meaning they were neither disc nor bulge dominated), but 40% show some signs of an interaction. We find that 50% of the overall sample have bars, and most of the disc galaxies do.

We used PyParadise[3] (see Walcher et al., 2015; Weaver et al., 2018; Husemann et al., 2019) to model the integral field data of the sample. This analysis is performed after the AGN emission has been removed, which allows us to look at the remaining gas and stellar emission from the host galaxy. PyParadise models the stellar absorption and gas emission features across the datacubes, allowing us to construct spatially resolved maps of these properties across the galaxies. We were able to take these measures one step further to classify the dominant ionising source in each spectrum using BPT diagrams (Baldwin, Phillips & Terlevich, 1981; Kewley et al., 2006), enabling us to see how far AGN ionisation extends and where star formation is the dominant ionising source.

We found a wide range of measured extended narrow line region (ENLR) sizes — from several hundred parsecs up to

Figure 2. Maximum ENLR size as a function of black hole mass, with a linear best-fit relation shown (in red). The right axis shows the AGN lifetime; our inferred AGN lifetime relation is shown as the blue line.

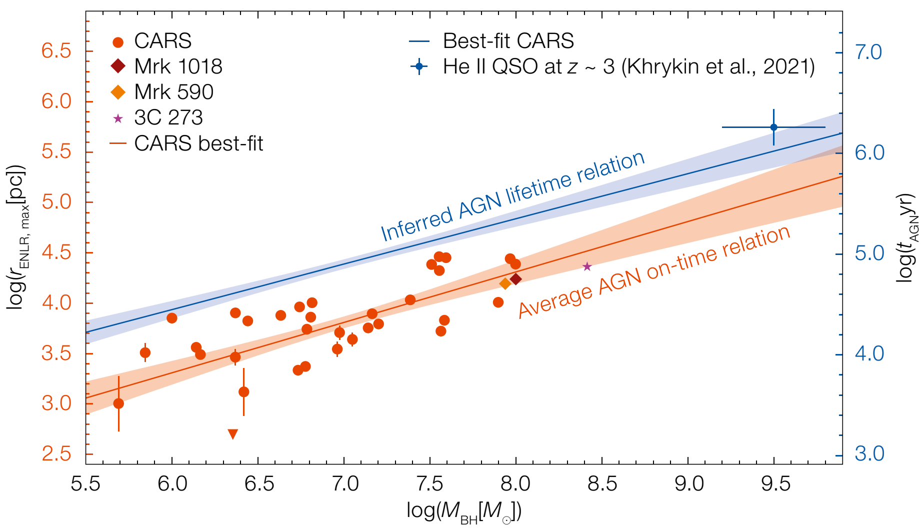
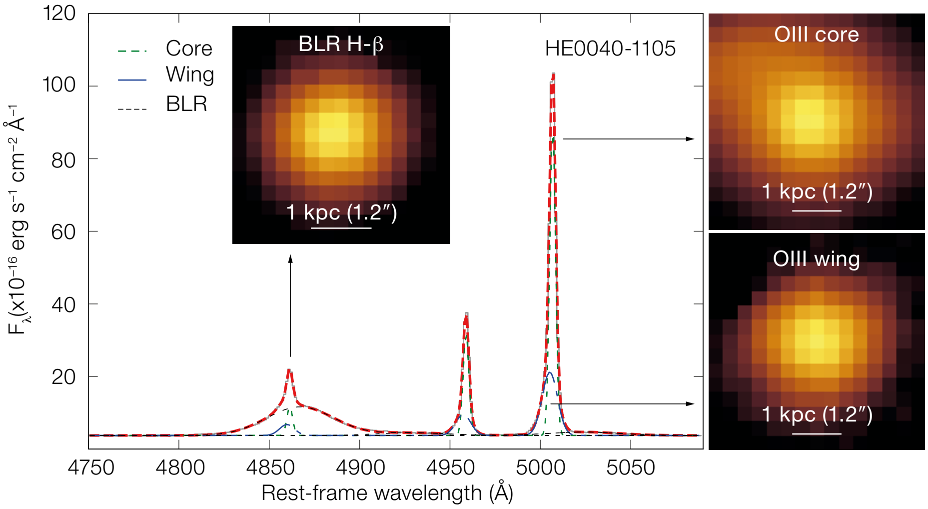


Figure 3. The central figure shows the spectrum from the centre of this AGN (in black), the fit to the data (in red) and the fit split up into the core of the emission (green dashed) and broad emission from in the wings of the [OIII] line. The three images show intensity maps of the inner 3 arcseconds (2.5 kpc) of the three emission lines in the spectrum, as indicated by the arrows. The [O III] wing originates from a region only ~ 100 pc away from the unresolved BLR emission. The [O III] core component extends ~ 2.5 kpc away from the nucleus and leaves a clearly different light profile.



tens of kiloparsecs — and tested whether these are correlated with the luminosity of the AGN. However, we found that the ENLR-size–luminosity correlation is weak in the CARS sample. Surprisingly the strongest correlation was found between the maximum ENLR size and the mass of the black hole (shown in Figure 2), despite lacking an obvious direct connection. The simplest interpretation is that the maximum ENLR size is related to the timescale of the current AGN lifetime (t_{AGN}) — through the light travel time of ionising photons — which is correlated with black hole mass, M_{BH}. Hence, more massive black holes would statistically show longer periods of high accretion phases. We find a relationship of the form $t_{AGN} \sim M_{BH}^{0.5}$ using a Bayesian model, which agrees with the independent measurements for AGN lifetimes at higher redshifts which involve significantly more massive black holes. If such a relationship is confirmed, it implies that the released energy for AGN feedback will depend not solely on the luminosities of the AGN, but also on their actual time life that appears to scale with black hole mass.

Tracing the outflows

Spatially resolved spectroscopy across the entire galaxy provides ideal data from which to understand outflows, a key feature of our current model for AGN feedback. In Singha et al. (2022) we make use of the MUSE observations of the CARS galaxies to look for and characterise outflows driven by the active nucleus.

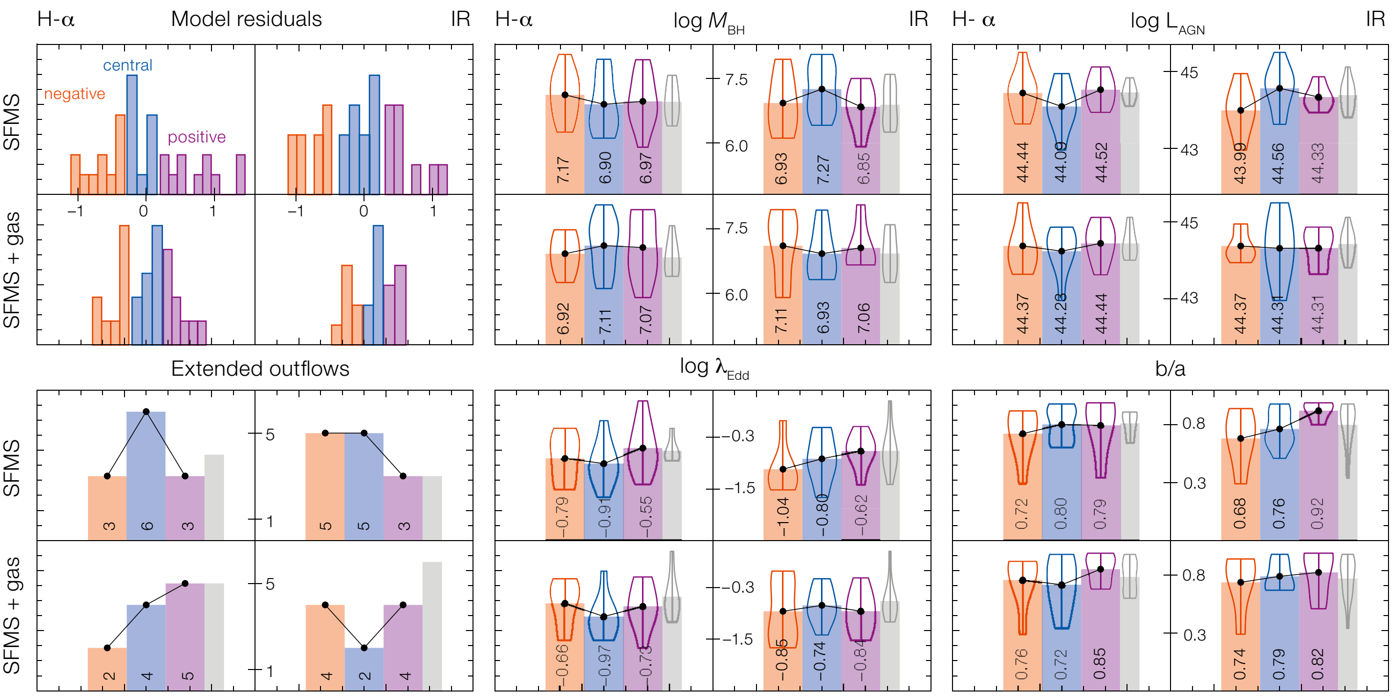
We used a method called spectro-astrometry (Bailey, 1998) which allows us to determine the location of any astronomical signature using spectroscopy. The unresolved BLR provides an excellent opportunity to model the PSF. The bright [O III] emission line in the optical regime is amongst the best signatures of outflows from AGN. Although ionised by the AGN, this gas is further away from the black hole, and as a result the resulting [OIII] emission line is usually narrow, unless an outflow is present. By modelling the asymmetry of broad underlying features in this line one can find evidence of outflowing gas, as shown in Figure 3. Where such signatures are present, we can determine whether the outflow is compact or extended. If the surface brightness profile of the [O III] wing is properly described by the PSF, we find the outflow to be compact, if not then it is extended. 23 out of the 36 AGN exhibit outflows which are unresolved by the IFU and are therefore compact, whereas for the other 13 sources, the outflows are resolved and therefore possibly extended on galactic scales (> 1 kpc).

This demonstrates that in an unbiased sample of nearby luminous AGN, compact (< 1 kpc) and extended (~ several kpc) outflows are both likely to occur. Our results are significant as they settle the long-standing debate in the AGN community about the spatial extent of outflows. Previous IFU studies focusing on the AGN-driven warm, ionised gas outflows (for example, Liu et al., 2013a; Harrison et al., 2014; Kang & Woo, 2018; and Wylezalek et al., 2020) found that kiloparsec-scale outflows are prevalent amongst luminous AGN. However, these studies did not account for PSF effects which cause centrally concentrated emission to be 'smeared' across the galaxy and appear as if it was spatially extended (Husemann et al., 2016).

The spectro-astrometric analysis further sheds light on the launching mechanism of these outflows. We find that the distributions of the BLR H-β luminosities, an indicator of the bolometric luminosity of the compact and the extended outflowing AGN, are almost identical. Our findings strongly indicate that the extensions of the AGN-driven outflows are not related to the AGN accretion properties. 1D spectroscopic analyses (such as Zakamska & Greene, 2014; Woo et al., 2016; Rakshit & Woo, 2018) and IFU observations (Liu et al. 2013b; Kang & Woo, 2018) suggested that the accretion properties of the AGN are related to the outflows and that outflows are mainly driven by AGN winds. Not only do our results show that the AGN accretion properties do not relate to the outflows, but also that they are launched from a region less than 100 pc from the nucleus, which is about a few orders of magnitude higher than the size of the AGN accretion disc (~ 10^{-5} pc). These findings imply that other parameters such as AGN lifetime or the radio properties of the AGN could be related to the outflows.

Star formation and AGN feedback

In Smirnova-Pinchukova et al. (2022), we present a complete census of the integrated star-forming properties of the galaxies in the survey. In order to



understand how AGN affect star formation we first need to quantify the number of stars being formed, both now and in the past. To do this we combined the CARS MUSE data with dedicated observations from the James Clerk Maxwell Telescope, the Panoramic Near-Infrared Camera (PANIC) at Calar Alto observatory, the Dark Energy Camera (DECam), and the Stratospheric Observatory For Infrared Astronomy (SOFIA), in addition to archival broadband photometry to construct panchromatic spectral energy distributions (SEDs) from the far infrared to ultraviolet wavelengths. We then used AGNFitter (Calistro Rivera et al., 2016) to model the SEDs and predict the star formation rates and stellar masses. The spatially resolved spectroscopic data also allow us to use the H-α line as a measure of star formation, after the contribution from the AGN has been removed.

A control sample of inactive galaxies was used to probe the impact of AGN on star formation. We found no evidence that star formation is systematically lower in the AGN sample, and that there is no trend between star formation rate and luminosity of the AGN.

By using two different methods of measuring star formation we probe two different timescales. The far-infrared tells us the star formation rates on timescales of ~100 Myr while the H-α emission probes much more recent star formation (~5 Myr). These two measures allow us to determine whether star formation is increasing (meaning the H-α star formation rate is higher than the infrared one) or decreasing (vice versa). We find that declining star formation rates seem to be associated with the presence of an outflow, implying that feedback has an impact on star formation. Increasing star formation seems to be correlated with an ongoing interaction or a younger AGN phase.

Additionally, we find some evidence that the orientation of the central engine of the AGN with respect to the global axis of the host galaxy may impact the efficiency of feedback. Somewhat lower star formation rates are correlated with inclination (b/a) as shown in the bottom right panel of Figure 4. When the inclination is higher (meaning the galaxy is more edge-on) AGN radiation from the ionisation cone will encounter a larger cross section of the galactic disc, resulting in a greater feedback effect. This result is tentative and requires further investigation with larger samples.

Figure 4. We compare the star formation rate residuals from the star forming main sequence (SFMS) and SFMS+gas models to AGN parameters using the H-α and infrared data (left and right of each panel). The top-left histogram shows the residuals, with negative in red and positive in purple. The rest of the panels compare the AGN parameters: logarithm of black hole mass, logarithm of AGN bolometric luminosity, number of galaxies with extended outflows, logarithm of Eddington ratio, and inclination (b/a).

Future directions

In this article we have focused on the optical IFU data from MUSE used in our three DR1 papers, but the interplay between AGN and their host galaxies cannot be disentangled using this alone. Recent work, such as that by Harrison et al. (2015) and Jarvis et al. (2019), has demonstrated the importance of radio-mode AGN feedback even in radio-quiet AGN. To investigate this, we will add very long baseline interferometry (VLBI) data to our arsenal. We also have yet to delve into the impact of feedback on the cold interstellar medium. We will leverage our ALMA observations here to reveal the impact of our AGN on both the diffuse and dense molecular gas.

Furthermore, to fully understand how AGN feedback begins on the smallest scales we need to zoom into the central (< 500 pc) region around the black hole to see how the energy released from the AGN couples with the surrounding medium. In the next phase of the survey, we will obtain high-angular-resolution observations with ESO's upgraded MUSE in its narrow-field mode, observations with the adaptive-optics-assisted Near-infrared Integral Field Spectrograph at Gemini North, and near-ultraviolet Hubble Space Telescope imaging to provide an unprecedented view of the very heart of the central engine of active galaxies. We hope that this and future data releases from the CARS team will serve as a legacy sample for AGN for years to come.

DR1 data access

The data release includes a query page[4], where the user can harness the power of the various datasets via customized SQL queries. The data are fully Virtual Observatory-compliant and can be accessed via the various table protocols of the Virtual Observatory. There you can find:

- 3D IFU observations along with higher-level data products from MUSE, the VIsible Multi-Object Spectrograph (VIMOS) at ESO's VLT and the Potsdam MultiAperture Spectrophotometer at Calar Alto Observatory;
- AGN spectral parameters;
- SED modelling;
- Characterisation of the warm, ionised outflows;
- Host galaxy parameters.

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Links

[1] CARS survey: www.cars-survey.org
[2] QDeblend3D: http://www.bhusemann-astro.org/?q=qdeblend3d
[3] PyParadise: https://github.com/brandherd/PyParadise
[4] CARS query page: https://cars.aip.de/

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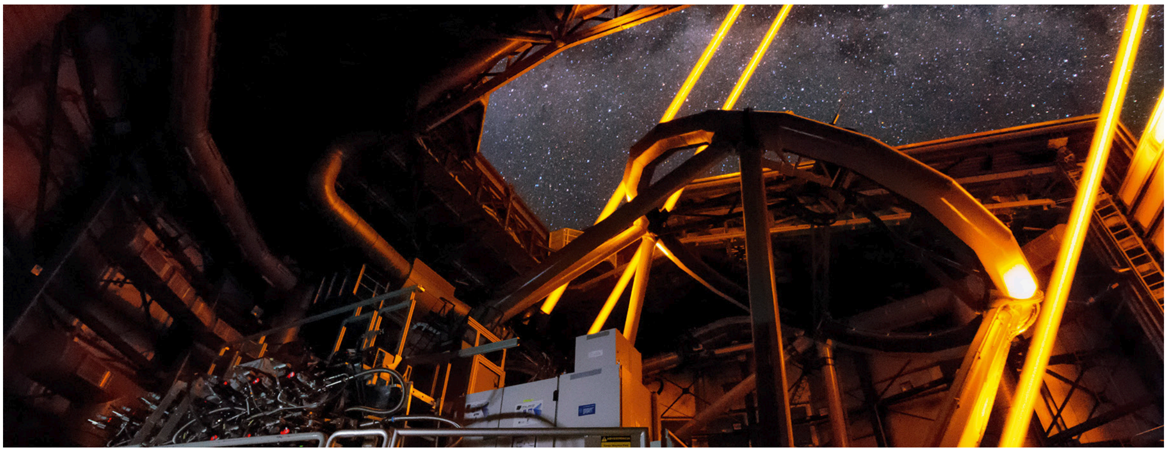

Inside Unit Telescope 4 of the Very Large Telescope, the four lasers of the Laser Guide Star Facility — part of the Adaptive Optic Facility (AOF) — points to the skies during the first observations using the MUSE instrument. The sharpness and dynamic range of images using the AOF-equipped MUSE instrument will dramatically improve future observations.