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SUPER — AGN Feedback at Cosmic Noon: a Multi-phase and Multi-scale Challenge

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Theoretical models of galaxy evolution suggest that galaxy-wide outflows driven by active galactic nuclei (AGN), one of the so-called AGN-feedback mechanisms, are a fundamental process affecting the bulk of the baryons in the Universe. While the presence of such outflows out to kpc scales is now undisputed, their impact on the star formation, gas content and kinematics of the host galaxy is hotly debated. Here we report on the results from our Large Programme SUPER, which used the Spectrograph for INtegral Field Observations in the Near INfrared (SINFONI) on the Very Large Telescope (VLT) to carry out the first statistically sound high-spatial-resolution investigation of AGN outflows at $z \sim 2$, covering four orders of magnitude in AGN bolometric luminosity.

The role of AGN in galaxy evolution

The cosmic evolution of galaxies has been one of the key research topics in

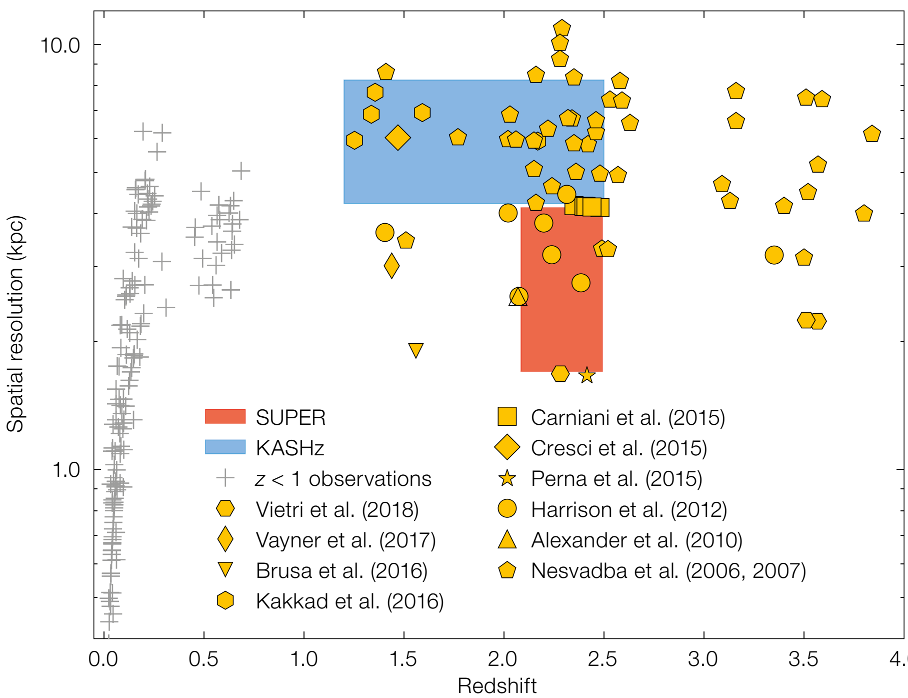


Figure 1. Summary of integral field spectroscopic observations from the literature characterising ionised outflows through the [O III] 5007 Å emission line in AGN host galaxies (adapted from Circosta et al., 2018). SUPER observations have an unprecedented spatial resolution (~ 1.7–4 kpc) for a sizeable sample of 39 AGN.

astrophysics during the last half century and is fundamental to understanding how the Universe evolved into its current form. Theoretical arguments (for example, Silk & Rees, 1998) suggest that the energy released by the black hole at the centre of most galaxies may shape the properties of the interstellar medium (ISM), itself the fuel of star formation, and consequently the growth of galaxies. AGN-feedback may therefore be a physical phenomenon that is key to regulating the evolution of galaxies. One promising mechanism to link the growth of the AGN and the evolution of its host galaxy involves fast winds launched from the accretion disc surrounding the supermassive black hole (SMBH) (for example, King & Pounds, 2003; Begelman, 2003; Menci et al., 2008; Zubovas & King, 2012; Faucher-Giguère & Quataert, 2012). These winds shock against the surrounding gas and drive outflows which propagate out to large distances from the AGN, heat the ISM and potentially eject large amount of gas out of the system (for example, Zubovas & King, 2012). Observationally, outflows have been detected in AGN at both low and high redshift. Very fast outflows have been revealed by X-ray and ultraviolet emission and absorption line studies on pc scales (with velocities up to 30% the speed of light) and via high-resolution infrared and millimetre spectroscopic observations at kpc scales (with velocities up to a few thousand km s^{-1}). But past observational studies of AGN-driven outflows were plagued by two major limitations. First, to maximise the chances of detection, observational campaigns have been conducted on AGN preselected to feature an outflow by the use of selection criteria such as broad [O III] lines or colour selection techniques. Second, most previous studies were not able to link the properties of such outflows with those of the central SMBH for a statistically significant sample, mostly owing to the lack of the necessary multiwavelength data or sufficient spatial resolution. The SUPER project was conceived to overcome these two main limitations.

The SUPER project

The SINFONI Survey for Unveiling the Physics and the Effect of Radiative feedback (SUPER[1]), is an ESO Large Programme (196.A-0377) which was awarded 280 hours of SINFONI time and which is aimed at providing the first unbiased investigation of the ionised gas in AGN at $z \sim 2$. The survey strategy, presented in Circosta et al. (2018), was to conduct a blind search of AGN-driven outflows, without preselecting the targets in a way that would maximise the chances of detecting an outflow. Our targets have been selected from deep and wide-area X-ray surveys (CDFS, COSMOS-Legacy, XMM XXL, Stripe 82X); each target has a secure spectroscopic redshift in the range z = 2.0–2.5, which ensures sampling of the Hβ and [O III] lines in the H band and the Hα and [S II] lines in the K band. It is crucial to study AGN outflows at those redshifts, since their impact depends critically on the ambient conditions and, because of the high gas content, the ISM conditions in star-forming galaxies at $z \sim 2$ are different from what is observed in local analogues (for example, Kewley et al., 2013; Steidel et al., 2014; Coil et al., 2015). Furthermore, since $z \sim$ 2–3 is the peak of star-formation and AGN activity we may expect that if AGN-feedback has a substantial role in galaxy evolution this is the right cosmic time to verify it.

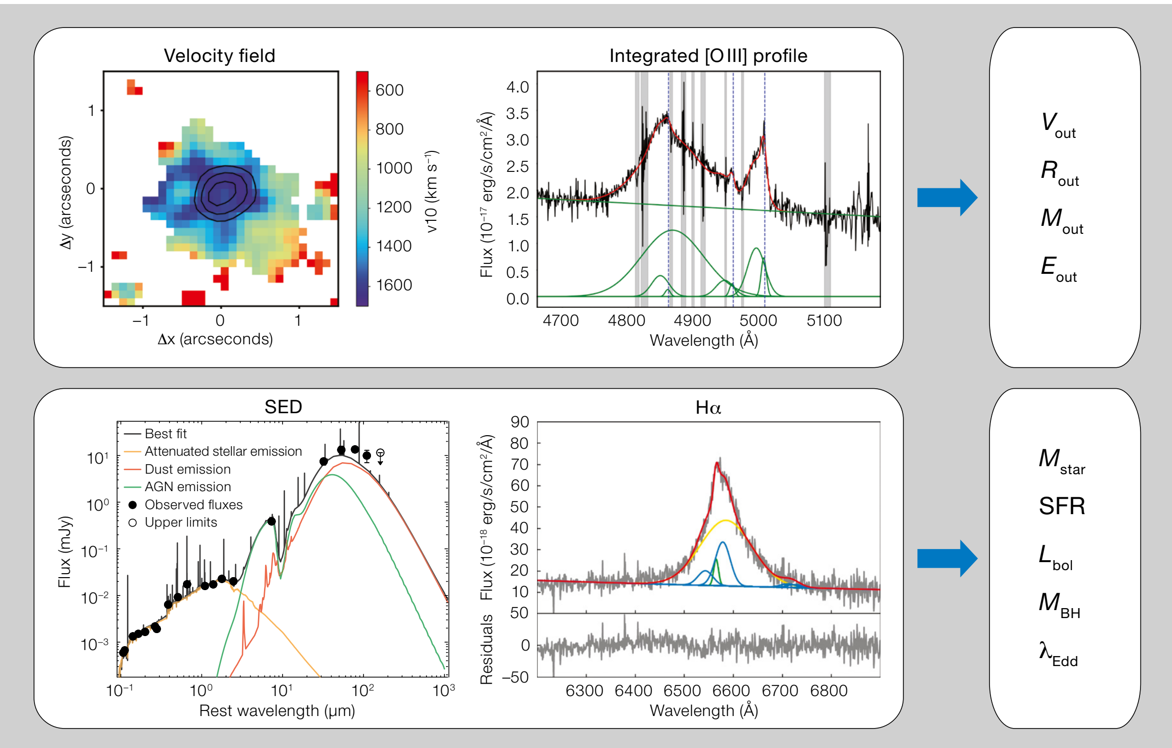
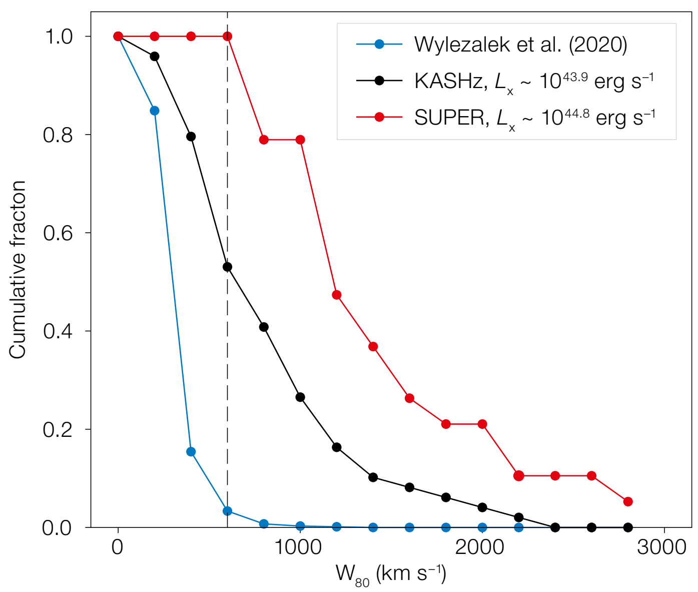


Figure 2. Upper panel: example of the [O III] velocity field reconstructed from the SINFONI observations and the extracted 1D spectra which we use to determine the velocity V_{out}, extension R_{out}, mass outflow rate M_{out} and kinetic energy E_{out} of the ionised gas outflows. Lower panel left: multi-component SED fitting from the ultraviolet to the far-infrared to characterise the properties of the host galaxy (stellar mass M_{star} and star formation rate, SFR) and the bolometric luminosity L_{bol} of the AGN. Lower panel right: line fitting of the Hα line to determine the black hole mass.



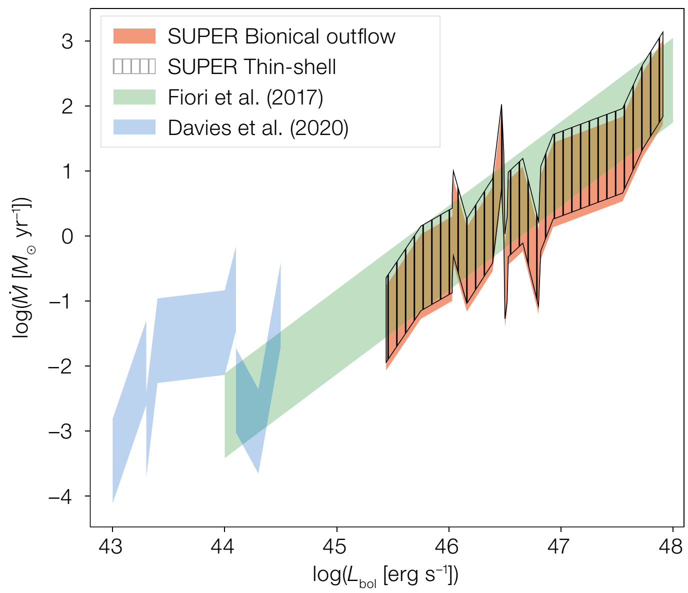


Figure 3. The inverse cumulative W80 distribution for the Type-1 AGN in the SUPER survey (red; Kakkad et al., 2020), the KASHz survey matched in redshift (black; Harrison et al., 2016), a mass-matched low-redshift star-forming sample (blue; Wylezalek et al., 2020). The dashed black-line at 600 km s^{-1} corresponds to the W80 value used to define that a target hosts an AGN-driven outflow (well justified from the fact that almost all star-forming galaxies have W80 values below this cut). Based on the above W80 criteria, all the Type-1 targets in SUPER show the presence of outflows, and ~ 52% of the redshift matched targets in the KASHz survey show outflows. The difference between the W80 distributions for SUPER and KASHz surveys is due to the different luminosity range of the AGN sampled by these surveys.

Figure 4. Ionised gas [O III] mass outflow rate vs. the bolometric luminosity of the AGN in the SUPER Type-1 sample (from Kakkad et al., 2020). The red shaded area and the black hatched area show the mass outflow rates for the SUPER targets assuming a bi-conical outflow model and a thin shell model, respectively. The green shaded area shows the outflow rates for ionised gas from literature data compiled in Fiore et al. (2017) and the blue shaded region shows the outflow rates for a low redshift X-ray AGN sample from Davies et al. (2020). The shaded regions all correspond to mass outflow rates assuming an electron density of 500–10 000 cm^{-3}.

The final sample consists of 39 AGN (Circosta et al., 2018) for which we have superb multi-wavelength ancillary data that allow us to properly characterise the central SMBH and its host galaxy: stellar masses (4×10^9 – 2×10^{11} $M_\odot$), star formation rates (25–680 $M_\odot$ yr^{-1}) and AGN bolometric luminosities (2×10^{44} – 8×10^{47} erg s^{-1}). Of the 39 targets, 22 are classified as Type-1 (56%) and the remaining 17 as Type-2 (44%), based on the presence or absence of broad emission lines such as Mg II or C IV in the rest-frame ultraviolet spectra.

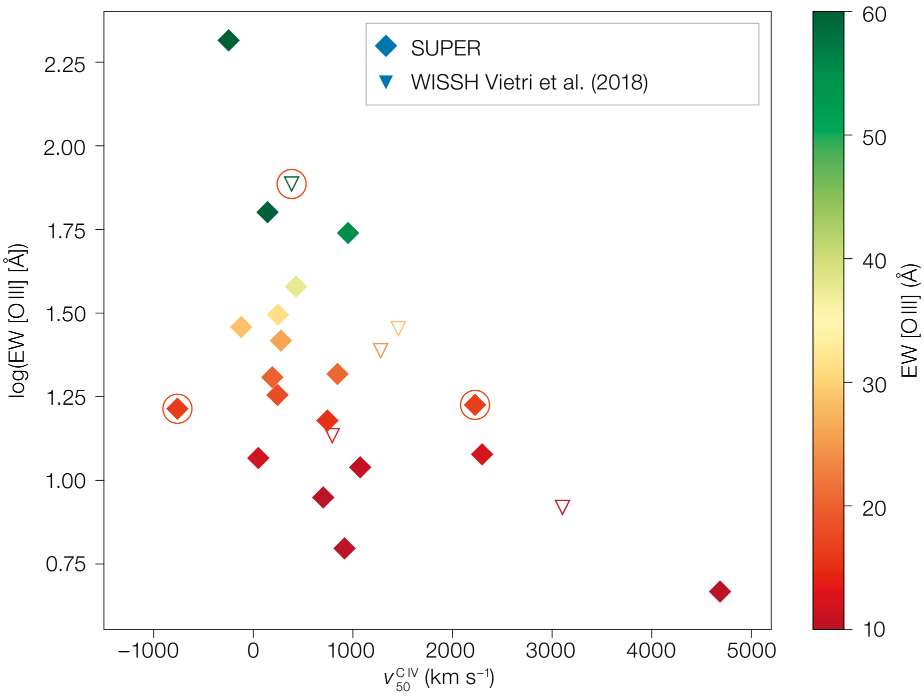
The SINFONI adaptive optics (AO) observations were performed in Laser Guide Star Seeing Enhancer (LGS-SE) mode, which has demonstrated the capability to achieve a point spread function (PSF) full width half maximum (FWHM) of 0.2–0.3 arcseconds. This allows us to spatially resolve any outflows with sizes larger than ~ 2 kpc. This is a key feature of the survey that allows us to resolve the kinematics of the ionised gas at a finer spatial scale than seeing-limited observations (see Figure 1), and consequently decreases significantly the uncertainties in the derived physical properties of the detected outflows. We set our observational strategy to be able to properly trace the PSF using directly the light distribution of the broad Hβ components for Type-1 AGN and dedicated observations of PSF reference stars that we performed close to the science observations of Type-2 AGN. Curve-of-growth analysis and more sophisticated methodologies have been used to take into account any beam-smearing effect in the data cubes and thereby to retrieve the best estimates of the outflowing gas properties (for example, extension and velocity; Kakkad et al., 2020).

AGN outflow demography and scaling relations

One of the main goals of SUPER is to perform a demographic study of the incidence of AGN-driven outflows at z ~ 2.

In Kakkad et al. (2020) we present the results obtained for the Type-1 AGN in the SUPER sample and find that all of them feature a galaxy-wide outflow (Figure 3). The parameter adopted to identify outflows is the velocity width of the [O III] line containing 80% of the flux (i.e., W80). A value of W80 larger than 600 km s^{-1} is considered a clear signature of an AGN-driven outflow, based on the W80 distributions of large galaxy samples at z ~ 2 (see Kakkad et al., 2020). We therefore show that AGN-driven outflows are common in a blind-selected sample of AGN at z ~ 2, which obviously further supports the hypothesis that AGN-feedback plays an important role in galaxy evolution. A detailed comparison of the PSF and the [O III] radial profile shows that the [O III] emission is spatially resolved for ~ 35% of the Type-1 sample and the outflows show an extension up to ~ 6 kpc.

Another main goal of SUPER was to link the properties of the observed outflows with the properties of the central SMBH (for example, its bolometric luminosity).



Theoretical models of AGN outflows predict that fast winds originating from the accretion disc impact on the ISM, resulting in a forward shock that expands within the host galaxy. This would naturally predict positive correlations between outflow properties (for example, velocity and mass outflow rate) and AGN properties (see, for example, King & Pounds, 2015). In Kakkad et al. (2020), we explore a range of plausible assumptions about the physical properties of the outflow (its geometry, velocity and radius) and of the outflowing gas (its electron density) and report the range of derived mass outflow rates for each target. The mass outflow rates for the Type-1 sample are in the range ~ 0.01–1000 $M_\odot$ yr^{-1}. After factoring in the systematic uncertainties in the outflow models, these outflow rates seem to correlate with the bolometric luminosity of the AGN (see Figure 4), as expected on the basis of the above theoretical arguments.

Tracing AGN winds from pc to kpc scales

Several theoretical models have been proposed to describe how the energy released by the central SMBH couples to the surrounding medium and generates the outflows observed on galaxy scales. With SUPER we have the remarkable opportunity to constrain the different models, since we are able to trace the winds from scales smaller than 1 pc out to several kpc. In Vietri et al. (2020), we use ancillary data to study the high-ionisation C IV 1549 Å line originating from the broad line region (BLR) surrounding the central SMBH. We confirm the well-known fact that the C IV line width does not correlate with the Balmer lines and the peak of the line profile is blueshifted with respect to the [O III]-based systemic redshift. These findings support the idea that the C IV line is tracing outflowing gas in the BLR, for which we estimated velocities up to ~ 4700 km s^{-1}. We inferred BLR mass outflow rates in the range 0.005–3 $M_\odot$ yr^{-1}, showing a correlation with the bolometric luminosity consistent with that observed for ionised winds in the narrow line region (NLR) and X-ray winds detected in local AGN. Finally, we found an anti-correlation between the equivalent width of the [O III] line and the C IV velocity shift (see Figure 5), and a positive correlation with the [O III] outflow velocity. These findings, for the first time in an unbiased sample of AGN at z ~ 2, support a scenario in which BLR winds are connected to galaxy-scale detected outflows and are therefore actually capable of affecting the gas in the NLR located at kpc scales (Vietri et al., 2020).

Figure 5. [O III] equivalent width as a function of the velocity shift of the C IV emission line for the SUPER sample (diamonds), colour-coded according to the [O III] equivalent width. Additionally, the WISE/SDSS Selected Hyperluminous quasars (WISSH; Bischetti et al., 2017) sample with reliable [O III] measurements are also reported (empty triangles). A clear anti-correlation is present, which supports the idea that the BLR winds traced by the C IV are connected with the winds on kpc scales detected in the NLR using the [O III] line (Vietri et al., 2020).

Ongoing work, data releases and outlook

At the time of writing all the data for the Large Programme have been acquired, and a first set of results has been already published. The SUPER first data release is accessible via the ESO Science Archive Facility (SAF)[2] and consists of flux-calibrated data cubes for half of the sample. Next year we plan to have a second and final data release for the whole SUPER sample.

The team is working on a series of additional studies, combining the SINFONI data with follow-up data obtained in recent years. These include:

– A systematic study of the molecular gas reservoir, as traced by ALMA CO(3-2) observations, in the SUPER AGN host galaxies, to assess the impact that the AGN may have on them (Circosta et al., 2021).
– The dust properties of our targets, as traced by ALMA Band-7 continuum observations at high resolution, compared with the spatial location of the outflow and of the unobscured star formation as traced by the SINFONI Hα emission (Lamperti et al., in preparation).
– The outflow properties of the full SUPER sample, and the dependence on the host galaxy properties, for example stellar mass and star formation rate (Perna et al., in preparation).

SUPER has already fulfilled its ambition and represents a major advancement in the systematic studies of AGN-driven outflows at a crucial cosmic epoch corresponding to the peak of volume-averaged star formation and supermassive black hole accretion in the Universe. It further represents the ideal sample for follow-up studies with current and future facilities. The hot ionised gas kinematics need to be complemented with a significant investment of ALMA time to trace the cold molecular phase of the outflows (for example, Cicone et al., 2018). The launch of the JWST will enable the study of the H_2 rotational emission lines in the mid-infrared which could be used as an alternative means to trace the molecular phase of these outflows. Finally, the next generation of integral field units at the forthcoming extremely large telescopes (for example, the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph [HARMONI] at ESO's Extremely Large Telescope) will have the necessary sensitivity and spatial resolution to trace the dependency of the mass outflow rate as a function of radius inside the galaxy, which is very much needed to provide strong constraints on the different theoretical models. Finally, these observational efforts should be complemented by the investment of substantial resources in the modelling of the multi-phase outflows, in particular with detailed simulations able to trace the cold molecular gas.

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Links

[1] SUPER website: www.super-survey.org
[2] SUPER first data release access via the ESO SAF: https://archive.eso.org/scienceportal/home?data_collection=SUPER&publ_date=2020-09-29

ESO/P. Horálek

As the Sun sets, ESO's Very Large Telescope (VLT) springs into action to begin its nightly mission. Consisting of four 8.2-metre Unit Telescopes (UTs) — named Antu, Kueyen, Melipal, and Yepun — and four smaller 1.8-metre Auxiliary Telescopes (ATs), the VLT is one of the most advanced telescope facilities in the world. All eight telescopes can be seen in this image, the smaller and rounder ATs scattered amongst the larger and more angular UTs.