AGN Feedback Across All Scales and Time

ESO Workshop
6–10 July 2026
Garching near Munich

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Invited Speakers

Manuela Bischetti (INAF)
Michaela Hirschmann (EPFL)
Julie Hlavacek-Larrondo (Université de Montréal)
Sebastian Hönig (University of Sothampton)
Sophie Koudmani (University of Hertfordshire)
Dipanjan Mukherjee (IUCAA)
Michele Perna (CAB)
Mateusz Ruszkowski (University of Michigan)

Abstract deadline: 15 January 2026
Registration deadline: 15 April 2026

https://www.eso.org/sci/meetings/2026/AGN-FAAST.html
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Background image: Artist's impress of the quasar ULAS J1120+0641 (ESO/M. Kornmesser)

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Radio emission in star-forming galaxies: connection to restarted or relic AGN activity

Marco Albán
Max Planck Institut for Radio Astronomy

Galaxies with weak or ambiguous AGN signatures attribute their radio emission to star formation, while others propose AGN-driven winds or weak, unresolved jets as the dominant mechanism. To investigate this connection, we take a step back and analyze a sample of star-forming (SF) galaxies with no clear current AGN signatures. Using low-(LOFAR, 144MHz) and high-frequency (FIRST, 1.4GHz) surveys, combined with spatially resolved spectroscopy from the MaNGA survey, we compare SF galaxies with 144 MHz detections that either do or do not have GHz detections. Despite being matched in stellar mass, redshift, and radio (MHz) luminosity, GHz-detected SF galaxies systematically differ from their non-GHz-detected counterparts. The former display enhanced ionized gas-emission line widths, higher central outflow fractions, redder colors, increased central obscuration, and offset emission-line ratios that shift towards (or closer to) the AGN regime (in the [NII] BPT diagram). Furthermore, the non-GHz galaxies are likely undetected due to their extended radio morphologies, while the GHz-detected ones are significantly more radio compact. Most of the properties from the GHz-detected (compared to non-detected) remarkably resemble the behavior found in many studies of radio-detected AGNs. This suggests that the underlying physical mechanisms shaping GHz-detected SF galaxies properties are fundamentally similar. This raises intriguing questions about whether some compact SF galaxies represent a precursor phase of AGN evolution or a form of low-power AGN. The radio compact characteristic sizes of GHz-detected SF galaxies also suggest a connection between AGN and old starburst galaxies.

Radio Emission as a Tracer of AGN Feedback Across Cosmic Time

Elisa Amenta
University of Bologna - IRA-INAF

AGN feedback is a key ingredient in models of galaxy evolution, regulating star formation and driving the observed correlations between supermassive black holes and their host galaxies. In this context, the role of radio-quiet AGN, much more common than their jet-dominated radio-loud counterpart, has become progressively more recognised. The radio emission in these sources can arise from coronal activity, star-formation activity, winds and weak jets, providing a unique window into feedback processes. In particular, understanding the impact of low-power radio jets and winds on the host galaxy and their

relation with outflows in different gas phases is now urgent for our comprehension of AGN feedback and galaxy evolution. In this talk I will emphasise the value of both single-object and statistical studies on the origin of the radio emission in radio-quiet AGN. I will show key results from the X-ray-selected radio-quiet AGN of SUBWAYS (z ~0.1–0.5, Lbol~10^(45–46)), where ultra-fast outflows have been detected in the X-rays. Radio follow-up observations hint at a connection between the latter and outflows traced by the extended radio emission. I will also present some preliminary results on XID2028, an obscured quasar at z=1.59, where the combination of VLA, MIRI, NIRspec and ALMA data provides stronger constraints on the nature of the outflows, and their impact on the host galaxy. These results confirm that low-power jets or winds can play a relevant role in AGN feedback.

The eROSITA view on AGN feedback: Linking [O III] outflow kinematics to accretion and obscuration in X-ray AGN

Carolina Andonie
Max Planck Institute for Extraterrestrial Physics

Powerful outflows from active galactic nuclei (AGN) are a direct manifestation of black hole feedback in galaxies, yet the processes that drive these outflows are not fully understood. In this study, we analyze nearly 3,000 X-ray AGN identified by eROSITA with high-quality SDSS optical spectra out to z~0.8. By modeling both the X-ray and optical spectra, we quantify AGN obscuration, measure the Eddington ratio (lambda_Edd), and characterize large-scale outflow kinematics using the [O III] emission line. We find that roughly 40% of AGN in our sample host [O III] outflows with velocities exceeding 600 km/s, with the incidence of outflows strongly increasing with AGN luminosity. We also find that the outflow incidence systematically increases with the Eddington ratio, and at the same time, the AGN obscuration traced by the NH systematically decreases with the Eddington ratio. In fact, AGN accreting above \log lambda_Edd >~-1.7 are found to be two times less obscured and to launch twice more outflows compared to lower-accreting systems. These results suggest that AGN radiative feedback efficiently expels circumnuclear material, decreasing obscuration and driving powerful outflows that can reach the host galaxy. I will discuss the implications of these findings for our understanding of how black holes regulate their growth and that of their host galaxies, and how future facilities such us 4MOST will allow to extend this research to much optically fainter (and obscured) AGN.

Ionization echoes of past AGN in Green Bean galaxies

Arina Arshinova
The Special Astrophysical Observatory of the Russian Academy of Sciences

Green Bean galaxies represent a short-lived AGN phase, during which extended emission-line structures trace the large-scale responses of the surrounding gas to past active AGN episodes in galaxies at redshifts 0.2-0.6. We present spatially resolved spectroscopic observations of a sample of Green Bean galaxies obtained with long-slit and 3D spectroscopy at the 6-m BTA telescope. Across the sample, we detect a clear spatial decoupling between the current nuclear activity and the extended ionized gas at the distances of ~20-80 kpc, together with a spatial misalignment between radio and ionized gas structures. The central regions typically show weak or low-ionization signatures, while the large-scale gas requires a much higher ionizing output. Our results demonstrate that radiative AGN feedback leaves long-lived, galaxy-scale imprints in the circumgalactic medium that can be detected long after the nucleus has faded. The consistency of these features across multiple objects suggests that extended ionization structures on scales of tens of kiloparsecs provide key constraints on AGN duty cycles and feedback timescales.

An HIPER view of AGN feedback on the gas reservoirs at cosmic noon

Elena Bertola
INAF OA Arcetri

Active galactic nuclei (AGN) are thought to play a key role in shaping the buildup of galaxies. AGN-driven outflows could be responsible for efficient gas removal or heating and are now routinely detected at any redshift. At the same time, if AGN influence galaxy growth, then they will reasonably impact the molecular gas reservoir first, and star formation as a consequence. While convincing evidence that AGN hosts at cosmic noon (z~1-3) harbor reduced amounts of molecular gas mass compared to their non-AGN analogs is growing, we still have to pinpoint how such a reduction is set into place. The ERIS GTO program HIPER (High resolution Investigation of Feedback Processes with ERis; PI: G. Cresci) specifically aims at probing whether the level of molecular gas depletion is related to the properties, such as strength and velocity, of AGN-driven winds. I will present our most recent efforts in investigating causes and effects of AGN feedback on galaxies at cosmic noon, from gas depletion in AGN hosts to the properties of AGN-driven outflows as traced with new-generation instruments as JWST/NIRspec and VLT/ERIS.

A roadmap to next-generation baryonic feedback models in cosmological simulations

Leah Bigwood
Institute of Astronomy, University of Cambridge

Recent observational evidence suggests that baryonic feedback, how energy from active galactic nuclei (AGN) and supernovae redistributes gas within and beyond halos, may be more extreme than commonly assumed in current cosmological hydrodynamical simulations. Whether such extreme feedback is physically plausible, which astrophysical mechanisms could drive feedback on these scales, and how simulation models must be updated to capture these processes remain open questions. In this talk, I will outline a path forward that combines new, publicly available multi-wavelength survey data with next-generation hydrodynamical simulations to transform our understanding of baryonic feedback. I will first present a roadmap for comparing simulations to kinetic Sunyaev–Zel'dovich (kSZ) measurements, showing that most state-of-the-art simulations under-predict gas ejection from haloes, underscoring the need for stronger or qualitatively different feedback models. I will then introduce a new suite of hydrodynamical simulations

exploring AGN feedback, providing insight into the mechanisms required to reconcile recent observational evidence of large-scale gas redistribution, whilst maintaining consistency with key galaxy, group and cluster properties.

Manuela Bischetti
INAF Osservatorio Astronomico di Trieste

Studying HI recombination within the inner kiloparsec: simulations of AGN jet-triggered shock–cloud interactions

Santiago Javier Bonanad Hurtado
Universitat de València

Observations of young radio sources hosting relativistic jets reveal fast atomic and molecular outflows, with line widths implying outward velocities of 100-1000 km/s. Numerical simulations of relativistic jets show that their bow shocks strongly ionise and drive turbulence in the ISM; however, explaining the presence of such lines requires that the shocked ISM gas undergo rapid recombination. This is hard to reconcile with the physical conditions seen in previous simulations of powerful jets. We study the production of AGN-driven outflows in realistic multiphase media through hydrodynamical simulations. By zooming in on the interaction between a planar shock front and a cold atomic cloud within the inner kiloparsec, we ensure adequate spatial resolution for the cloud structure. We include a simple chemical network tracking protons, electrons and atomic HI for the first time to our knowledge in this kind of simulations. The parameter space we explore is motivated by both numerical simulations and analytical models of jet propagation (e.g. Perucho 2024), which link the local physical conditions to the properties of the underlying AGN jet that triggered the shock wave. We find that mid-to-high-power jets fully ionise the cloud, whereas low-power jets allow significant HI survival. A multiphase outflow emerges, with the velocities of the cold phase showing good agreement with observations. These values provide a proxy for jet power in systems where AGN feedback is relevant.

How turbulence affects accretion onto supermassive black holes

Olga Borodina
Center for Astrophysics | Harvard & Smithsonian

General-relativistic magnetohydrodynamic simulations resolve accretion and jet launching near supermassive black holes (SMBHs), but cosmological simulations lack the resolution to model these processes self-consistently. We use idealized simulations of low-power AGN jets to bridge this gap and study how interstellar medium (ISM) properties and jet-launching parameters regulate accretion and jet propagation. We find that turbulence in the ISM is essential for both jet launching and propagation. Without turbulence, cold gas cannot reach the Bondi radius, limiting jet power to 10^39 erg/s for a 10^6 solar mass SMBH. A turbulent, multiphase medium sustains higher accretion rates and enables jets to propagate to distances of 400 pc. Self-regulation of accretion is not achieved in turbulent environments unless the accretion efficiency is sufficiently high. Jet power depends on the gas density near the black hole, while the global ISM density has little effect on the maximum jet extent. Instead, the ISM Mach number plays a key role: supersonic turbulence produces dense filaments that intermittently boost jet power and low-density cavities that facilitate extended propagation, whereas subsonic or uniform media confine jets more efficiently despite relatively steady but low power. Finally, low accretion efficiencies do not lead to self-regulation, while increasing the jet opening angle promotes it without fully suppressing accretion.

Discovery of ultra-fast outflows with vout > 0.3c in local, bright AGN

Laura Borrelli
Univerity of Bologna

Ultra-fast outflows are highly ionized thick winds with characteristic absorption features (FeXXV and FeXXVI at 6.67-6.97 keV rest-frame) in the hard X-ray band, strongly blue-shifted by the extreme outflow velocities. These quasi-relativistic winds are thought to be the most promising mechanism powering AGN feedback, influencing the SMBH/host galaxy co-evolution. Assessing the relation between UFO velocity and AGN power, and the maximum velocity achievable by UFOs, is crucial to determine the launching mechanism of nuclear winds (i.e., radiation vs. magnetic driving). While few high-z luminous QSOs do show UFOs with velocities up to 0.4-0.6c, in the local Universe we have been limited so far by the background noise, shaping the canonical band limit of 10 keV, corresponding to a maximum velocity detectable of ~0.2c. We will present the first systematic XMM study on 33 bright sources to search for UFOs in the 7-12 keV band. Particular care has been dedicated to assessing the impact of the background with three different techniques employed. Our extension to E>10 keV in the search for UFOs has led to the detection of four previously unknown UFOs with very high velocities (v>0.3c), confirming that local Seyferts do show such high velocity UFOs. Discovering high-energy UFOs at low redshift and luminosity will influence our current knowledge on the linear correlation between bolometric luminosity of AGN and the outflow velocity of the winds.

A tale of emission and absorption: Decoding early quasar feedback with multiple outflow tracers

Matilde Brazzini
University of Trieste

Outflows from active galactic nuclei are invoked as the principal feedback process regulating the co-evolution of supermassive black holes and their host galaxies. Their complex, multi-phase and multi-scale nature demands a comprehensive, multi-tracer approach to fully characterize their physical properties. In this talk, I will focus on the z=5-7 redshift range, and investigate the early feedback mechanisms shaping the (post-)Reionization Universe, where these processes are expected to be particularly intense and efficient. I will analyze state-of-the-art samples of quasar spectra from these early cosmic epochs, using observations from X-Shooter/VLT. For these objects, I will provide a complete characterization of nuclear and galaxy-scale outflows by exploiting the combined power of diverse emission and absorption diagnostics. These include narrow and broad blue-shifted UV absorption lines, the presence of blue-shifted wings in CIV emission, and velocity shifts in CIV and MgII profiles. I will explore the mutual interplay of these different tracers, along with their driving mechanisms and their impact on interstellar and circumgalactic media of the host galaxy. Special attention will be given to the connection between nuclear winds, revealed by asymmetric and blueshifted emission, and strong absorption features, either broad and narrow, that appear to be ubiquitous in high-z quasar spectra. This work offers new insights into AGN feedback and its role in shaping galaxies, from distant and remote cosmic epochs to the cosmos as we observe today.

The Evolution of AGN Feedback in SZ-Selected Galaxy Clusters Over the Last 10 Gyr

Michael Calzadilla
CfA

For years we have grappled with the “cooling flow problem” in galaxy clusters, where the massive reserves of hot (10^7 K) gas in the intracluster medium (ICM) have been universally observed to form stars with an efficiency of only 1-10%. Feedback from accreting active galactic nuclei (AGN) has been identified as the likely heating source capable of suppressing runaway cooling by up to two orders of magnitude. Numerous studies have by now established the link between excess cooling of the ICM and corresponding levels of AGN feedback. However, until recently most of these studies have been limited to nearby, low-redshift systems. In this work, we build on these previous studies by assembling a large (N = 95) sample of brightest cluster galaxies (BCGs) from Sunyaev-Zel’dovich detected South Pole Telescope clusters, spanning a large redshift range (0.3 <z< 1.7) corresponding to 10 Gyr in evolution. This unique dataset is complete with multi-wavelength follow up from Chandra, Magellan, ATCA, and others, giving us the unique opportunity to study the evolution of BCG growth channels, feedback effectiveness over time, and the conditions for ICM cooling as a function of redshift. In this talk, we will focus in particular on whether the observed ICM entropy threshold below which runaway cooling triggers star formation and AGN feedback at low redshifts persists to higher redshifts or has evolved with time. We will also discuss how the efficiency of AGN feedback in regulating ICM cooling and star formation in BCGs in the early universe compares to the present day.

Unveiling the role of multi-phase AGN outflows with MIR-ACLE

Matteo Ceci
University of Florence

I will present results from the MIRACLE (Mid-IR Activity of Circumnuclear Line Emission) program, combining JWST/MIRI, ALMA, and MUSE integral-field spectroscopy for 7 nearby Seyfert galaxies to investigate AGN feedback across spatial scales and gas phases. The addition of JWST data enables us to probe the physical conditions of atomic and molecular gas in the dusty circumnuclear medium, revealing the impact of AGN activity on host galaxy evolution. The rich set of mid-IR emission lines also provides a unique benchmark for photoionization models and diagnostics. Focusing on NGC 1365 and NGC 1068, I will present an unprecedented multi-phase view of AGN-driven outflows from tens of pc to kpc scales. We trace low- and high-ionization gas together with cold and warm molecular components, quantifying their relative contribution to outflow energetics and mass. Using mid-IR line-ratio diagnostics and advanced photoionization and kinematic modeling (HOMERUN + MOKA3D), we derive a fully self-consistent characterization of the ionized outflows, reproducing more than 50 emission lines between optical to mid-IR band. This approach decouples AGN- and SF-driven components and provides robust estimates of ionization, density, extinction, and outflow mass. We show that classical methods can underestimate outflow masses by up to an order of magnitude, highlighting the need for physically grounded multiphase modeling to compare observations and simulations of AGN feedback.

The role of AGN feedback in forming early massive quenched galaxies in COLIBRE

Ángel Chandro-Gómez
ICRAR/UWA

JWST has revealed a substantial population of massive ($M_\star$10^10$M_\odot$) quenched galaxies (MQGs) at z2, whose short quenching timescales strongly suggest that active galactic nucleus (AGN) feedback is the dominant quenching mechanism. In this talk, we use the new COLIBRE cosmological hydrodynamical simulations to investigate how AGN feedback drives the formation and evolution of MQGs. Our fiducial COLIBRE simulation, which adopts a single thermal AGN feedback model, reproduces the observed MQG number densities and stellar mass functions in broad agreement with JWST constraints. In contrast, simulations employing a hybrid AGN feedback model, combining thermal and kinetic (BH-spin-regulated jet) modes, produce significantly lower MQG number densities at high redshift, due to less efficient early black hole (BH) growth. Despite these differences, AGN feedback remains the dominant quenching mechanism in early MQGs across all models. Compared to massive star-forming galaxies, MQGs host more massive BHs and experience enhanced BH accretion prior to quenching, leading to more efficient energy injection into the surrounding gas, driven by their overdense environments. Consequently, MQGs exhibit dust and molecular gas fractions more than an order of magnitude lower than their star-forming counterparts, while retaining similar sizes and kinematics. Finally, we find that $\sim$55% of MQGs undergo rejuvenation episodes, highlighting the often temporary impact of AGN feedback at high redshift.

The Luminosity Function of UV-Selected Unobscured Quasars at z≈5: A Deep Learning Selection with Gemini/GMOS Confirmation

Yunyi Choi
Seoul National University

The number density of quasars during the epoch of reionization shows significant discrepancies across different wavelength regimes, leaving key uncertainties in our understanding of early supermassive black hole growth and the role of AGN feedback. Recent JWST observations have intensified this tension by revealing up to two orders of magnitude more faint AGN than predicted from extrapolations of UV-based quasar luminosity functions, commonly referred to as Luminous Red Dots (LRDs). In this talk, I present a quasar sample at z≈5 constructed from the Subaru/HSC Deep and UltraDeep surveys, extending down to $M_{1450} \approx -22$ AB, where the bright end of X-ray–based constraints begins to overlap. Instead of traditional color-selection techniques, we employ a deep neural network–based classification approach while minimizing the use of photometric flags to maximize the effective survey area. This strategy enables a search over a total area of 30.65 deg^2, approximately twice as large as in previous studies at similar depths. As a result, we identify 76 quasar candidates in the redshift range z=4.5-5.5. Follow-up Gemini/GMOS spectroscopy totaling 31 hours confirms the validity of our selection method and reveals 10 high-redshift quasars spanning z = 4.42–5.81 with a wide range of Lyα luminosities. These results provide a robust UV-based determination of the luminosity function for faint, unobscured AGN during the epoch of reionization and establish a critical observational bridge to test the connection between UV-selected quasars and the LRD population discovered by JWST through future near-infrared observations.

Rapid emergence of overmassive BHs and LRD-like systems in the early universe

Sunmyon Chon
MPA

High-redshift AGN pose a persistent challenge for models of supermassive black hole (SMBH) growth. Recent JWST surveys have uncovered a surprisingly abundant population of overmassive BHs at redshifts of roughly 4–6, with BH masses lying far above local BH–galaxy scaling relations. Explaining how such systems form and grow so rapidly inside young galaxies is now a key problem. In this talk, I will present new fully cosmological radiation-hydrodynamic simulations that, for the first time, self-consistently capture the birth of massive BH seeds, their early accretion-driven growth, and the observable signatures they produce in dense proto-cluster environments. We find that heavy BH seeds with characteristic masses of 10^6 Msun form naturally at z~13, exceeding theoretical expectations by an order of magnitude. Shortly after formation, these seeds build dense, optically thick accretion disks; electron scattering in the surrounding gas generates broad hydrogen-alpha emission with properties similar to the JWST "little red dots." Sustained super-Eddington accretion then enables rapid growth to roughly thirty million solar masses by z~8. These results outline a unified scenario in which little red dots represent a brief, enshrouded phase of heavy-seed formation that naturally evolves into the overmassive quasars detected by JWST, providing a viable pathway toward the SMBHs powering AGN across cosmic time.

Spatially-resolving the molecular gas reservoir in nearby galaxies to unveil the impact of AGN feedback on the ISM

Chiara Circosta
IRAM

AGN feedback is one of the mechanisms responsible for quenching star formation in galaxies. Yet, proving its role observationally remains a challenge. A key way to assess the impact of AGN activity on future star formation is to compare the molecular gas content of AGN hosts and non-AGN galaxies. In the local Universe, AGN exhibit equal (or even higher) molecular gas reservoirs on galaxy-wide scales than non-AGN galaxies with similar properties. However, recent studies investigating AGN feedback on (sub-)kpc scales find first indications that AGN activity may deplete the molecular gas in the center of galaxies, although statistical and homogeneous samples are still missing. In this talk, I will present new results from KILOGAS, an ALMA program aimed at mapping the molecular gas reservoir through CO(2-1) observations at 1 kpc resolution in ~500 nearby galaxies. The KILOGAS sample is representative of the galaxy population, includes several tens of AGN and hundreds of AGN-dominated spaxels, as well as a robust control sample of non-AGN galaxies and stellar/star formation (SF) maps from optical IFS data. I will compare the molecular gas fractions of AGN-dominated and SF-dominated regions and examine their location on the resolved molecular gas main sequence. These results provide new constraints on the imprint of AGN feedback on the ISM at kpc scales.

Unveiling AGN feedback via PAH emission at Cosmic Noon with JWST

Camilla Di Giusto
University of Hertfordshire

Active galactic nuclei (AGN) at the centre of most massive galaxies are believed to regulate star formation in their host galaxies. This feedback manifests in the form of jet or radiation-pressure driven winds that can extend out to kpc scales. Feedback from AGN and/or star formation is expected to be greatest at Cosmic Noon ($1 < z < 3$), where the volume-averaged SFR and BH growth rate peaks in the universe. One of the ways to test its presence is by searching for connections between multi-phase outflows and star-forming properties of the host galaxy. Emission from polycyclic aromatic hydrocarbons (PAHs) are reliable tracers of star formation, as they are likely excited by UV light from massive stars. However, PAH emission can also be destroyed due to radiation from the AGN. In this study, we present JWST/MIRI-MRS observations of PAH emission in AGN host galaxies at $z \sim 2$. In most targets, the PAH emission is weak or absent in the central regions, but stronger in off-nuclear regions, suggesting that the AGN may have destroyed PAH molecules in the centre. Only one target displays a strong detection both in the centre as well as in the galaxy outskirts, out to tens of kpc scales. This suggests that AGN may suppress star formation in the central regions, leaving the outer regions of the galaxy less affected. Our results show that PAH emission at Cosmic Noon can therefore give us a hint on the ongoing star formation in AGN, especially where other tracers, like Hα, can be strongly affected by dust obscuration.

Variable fuelling of AGN jets: implications for jet power estimates and jet morphology up to 50 kpc

Emma Elley
University of Oxford

In AGN, chaotic cold accretion predicts pink noise "flickering" variability in the fuelling rate as cold clouds of material fall chaotically inwards towards the central accretion disk. We present high-resolution relativistic hydrodynamic simulations of jets with flickering jet power using the PLUTO code. We simulate the expected radio emission using a Lagrangian particle approach, capturing the effects of shock-heating together with synchrotron and adiabatic cooling. We present simulated radio emission maps, helping to bridge the gap between simulation and observation. We show that moderate rises in jet power can result in short-lived large increases in the radiative efficiency of the jet hotspot. We discuss the mechanism behind this hotspot brightening – namely the interaction of travelling shocks with a pre-existing forward and reverse shock structure at the jet head, which we term the "interacting shocks" mechanism. We present semi-analytical estimates for the expected level of hotspot brightening. Furthermore, we present a new relativistic magnetohydrodynamic simulation of a flickering jet, which we use to investigate interactions between the interacting shocks mechanism and magnetic field structures in the jet. Overall, we find that flickering can profoundly impact the dynamics, morphology and radiative efficiency of astrophysical jets, with significant implications for jet power estimates.

Connecting the dust, radio, and outflow properties in quasars

Vicky Fawcett
ESO

The most rapid SMBH growth in the Universe has occurred in luminous quasi-stellar objects (QSOs), making them the perfect laboratories for observing galaxy–SMBH evolution. When we have an unobscured view of the accretion disc, which peaks in the UV, QSOs display very blue UV–optical colours. However, there exists an important population of QSOs, obscured by dust, which are typically uncharacterised by optical spectroscopic surveys. These dusty QSOs could represent an important short-lived transitional phase in the evolution of galaxies (a "blow-out" phase). Utilising data from DESI we can now, for the first time, explore a statistically significant sample of these reddened QSOs. Combining DESI spectra with radio data from the LoTSS DR2, we find a striking positive relationship between the amount of dust extinction and the radio detection fraction in DESI QSOs. This demonstrates an intrinsic connection between opacity and the production of radio emission in QSOs which may be due to outflow-driven shocks. In our latest work, we test this scenario by exploring the radio spectral slopes and ionised outflow properties of dusty QSOs, finding evidence that dusty QSOs might reside in a short-lived blow-out phase.

Footprints in the Wind: Probing X-ray Outflows in NGC 7469 using Near-Infrared Emission Lines

Léa Feuillet
The Catholic University of America

AGN winds play an important role in the co-evolution of supermassive black holes and their host galaxies, yet their driving mechanisms and impact on star formation remain subjects of active investigation. Critically, the lack of X-ray Integral Field Units currently limits our ability to acquire spatially resolved velocity information in the X-ray regime. However, instead, this can be achieved using the James Webb Space Telescope. As part of an ongoing investigation of the nuclear feedback processes in the nearby luminous AGN NGC 7469, we present an analysis of the kinematics of the X-ray emitting outflows using near-infrared footprint lines. These high-ionization emission lines are associated with the same gas analyzed in the X-ray, and thus can be used to probe the footprint of the X-ray wind's velocity structure and ionization state. Thanks to the wide wavelength range available with JWST we also use nebular and coronal emission lines to offer a comprehensive multi-phase view of the outflows. We present mass and kinetic energy outflow rates, and find that while the feedback processes in NGC 7469 are not efficient by theoretical benchmarks, the most massive and energetic component is the high ionization X-ray gas.

Resolving the central parsecs of AGN through cosmic time: Implications of recent GRAVITY+ observations at z=2-4 on AGN structure and feedback

Simon Flesch
Max Planck Institute for Extraterrestrial Physics

In this talk, I present recent observational insights on AGN structure and feedback at z=2-4 on parsec to sub-parsec scales, made possible by interferometric spectro-astrometry with GRAVITY and its recent upgrade, GRAVITY+. First, by spatially resolving the Broad Line Region (BLR) kinematics, we obtain the most precise direct black hole mass estimates in those epochs so far. I will compare these to masses derived from common virial estimators widely used at high redshift with JWST. Second, our studies reveal significant outflow components from the BLR, providing key insights into outflow origin and structure. I will show how this BLR outflow component varies as a function of AGN properties, and discuss the implications for this feedback driving mechanism. Further, we have for the first time successfully resolved the [OIII] emitting region interferometrically on tens-of-parsec scales at z=3.3. Combined with the kinematically resolved broad H-beta, this allows us to trace gas motion from sub-parsec scales out to its immediate surroundings. I will discuss these new insights in the context of AGN feedback and a potential connection to larger scales. Together, these novel GRAVITY+ observations provide a unique view of AGN feedback at ~parsec scales at high redshift, tracing it from its very origin. Additionally, they can serve as calibrators for larger studies and as constraints for numerical simulations.

The Duty Cycle and Variability of Active Galactic Nuclei during Galaxy Quenching

Decker French
University of Illinois

The impact of AGN feedback on galaxies is difficult to assess due to the variability of AGN, with complete duty cycles more rapid than the timescales on which we observe evolutionary trends in galaxies. However, this variability also offers opportunities to measure the duty cycle of AGN activity, particularly in galaxies undergoing quenching. I will present results using AGN variability on a range of timescales in recently-quenched, post-starburst galaxies, with implications for how AGN feedback may act during this phase. I will discuss radio variability on decades-long timescales indicative of newly-launched outflows, as well as extended emission line regions that trace AGN activity on timescales of 10,000-100,000 years. With these variability tracers, we see evidence for AGN activity that is relatively weak and intermittent, but nonetheless contains enough energy to suppress star formation, drive the low velocity outflows seen in molecular gas, and remove molecular gas in quenching galaxies.

The hottest phase of quasar winds revealed: excess intergalactic heating detected via the thermal Sunyaev-Zel'dovich effect

Kirsten Hall
Center for Astrophysics | Harvard & Smithsonian

Despite recent discoveries of qua5:sar feedback in action through outflows and jets, the amount of energy that the active nucleus is capable of injecting into the extended medium of the host galaxy remains unknown. Theory suggests that quasar winds produce very hot gas bubbles that extend through the host galaxy and into the circumgalactic medium. Because this gas component is so hot and diffuse, the only way to measure its total energy is through the thermal Sunyaev-Zel'dovich (tSZ) effect. With targeted multi-wavelength interferometric observations, I will report our recent results on the radio through sub-mm emission of radio quiet quasars and their companions/environments. We report the discovery of a dual quasar system at z=2.37 which is embedded in a bubble of hot gas as detected (at 6.4 sigma) by a tSZ flux decrement. The total thermal energy of the hot gas surrounding the galaxy is greater than that expected from the entire atmosphere of the circumgalactic medium. We further detect a large-scale tSZ "bubble" in the CGM, and take advantage of the interferometric data to measure the total tSZ effect on 500 kpc scales.

On the impact of weak shocks driven by intermediate-

power AGN jets on galaxy clusters

Kiara Hervella Seoane
Universitat de Vàlencia

Low-power radio jets dominate the AGN population, yet their main feedback mechanism and efficiency remains mysterious. In this talk, we will present our recent work focus on the impact of intermediate-power relativistic jets on the inner region of realistic intracluster mediums (ICM), focusing on the role of weak shocks on heating and the environmental coupling in regulating energy deposition. We present six three-dimensional relativistic-hydrodynamic (RHD) jet simulations with powers between Lj $\sim$ 10^44–10^45 erg/s, propagating through realistic ICM extracted from cosmological Gadget-3 runs. Each simulation tracks 20 Myr of continuous jet activity with radiative cooling included. Despite their intermediate power and midly relativistic speed at injection, these jets decelerate rapidly to trans-sonic velocities (average Mach 2.3) and generate weak bow shocks that dominate the energy transfer. Approximately, 80% of the injected kinetic power is converted into internal energy of the ambient ICM, and bremsstrahlung cooling noticeably reduces the temperature of the shocked shells as they expand. Our results demonstrate that heating of the intergalactic and intracluster medium is highly efficient even in the case of weak shocks in low power and/or FRI-like sources. This finding suggests low-power jets are a viable solution to the long-standing cooling-flow problem and likely regulate star formation across diverse galaxy cluster environments.

From Build-Up to Blow-Out: AGN Feedback as Traced by Molecular Gas in Local Seyfert AGN

Erin Hicks
University of Alaska Anchorage

Previously, the Galaxy Activity, Torus, and Outflow Survey (GATOS) identified a deficit of both cold and hot molecular gas within the circumnuclear region (r < 200 pc) of higher-luminosity Seyfert AGN compared to their lower-luminosity counterparts. A turnover in molecular gas concentration delineates two distinct regimes in the sample: an "AGN build-up" branch for sources below 10^41.5 erg/s (2–10 keV) and an "AGN feedback" branch for those above. We now extend this analysis by comparing the kinematics of cold molecular gas, traced by CO(3–2), and hot molecular gas, traced by the H2 2.12 micron ro-vibrational line. Both phases exhibit rotation-dominated velocity fields and they are found to be co-spatial. However, the hot molecular phase consistently displays higher velocity dispersions than the cold phase. Deviations from pure rotation increase with X-ray luminosity, with non-circular motions more prominent in the hot molecular gas. Using JWST/MIRI spectroscopy, we also probe the warm molecular gas phase traced by the H2 S(1)–S(8) rotational lines and find, via LTE modeling, an increase in molecular gas temperature within the circumnuclear region of local Seyferts with higher ionized mass outflow rates. In addition, we find a strong spatial correlation between regions of enhanced molecular gas temperature and [Fe II] 5.34 micron emission, a tracer of shocks, as well as higher [Fe II] 5.34 micron / [Ar II] 6.99 micron ratios in Seyferts with higher ionized outflow rates. Together, these results reinforce the interpretation that AGN-driven feedback becomes increasingly important at higher luminosities, directly influencing the distribution, temperatures, and kinematics of circumnuclear molecular gas in local Seyfert galaxies.

Michaela Hirschmann
EPFL

AGN Feedback in Clusters of Galaxies as seen by JWST

Julie Hlavacek-Larrondo
Université de Montréal

The best place to study radio-mode AGN feedback is in the hot atmospheres of galaxy clusters, which host the most massive black holes and where we can directly image their impact on the surrounding medium. At cluster centers, supermassive black holes launch powerful relativistic jets that inject vast amounts of energy through shock fronts, sound waves, turbulence, and molecular outflows. In this talk, I will present novel multi-wavelength observations that, for the first time, allow us to trace the entire radio-mode feedback cycle—from heating, to cooling, to feeding, and across scales from kiloparsecs down to parsecs. First, I will present new JWST observations of the archetypal Centaurus cluster, where NIRSpec/IFU data reveal a rotating circumnuclear disk directly connected to the surrounding filament network. This structure provides the long-sought missing link that channels gas from kiloparsec to 100-pc scales and ultimately into the central black hole, effectively closing the feedback loop. I will then place these results in a broader context using the Perseus cluster, where the combination of JWST with state-of-the-art XRISM and SITELLE/IFU observations allows us to map the full multiphase feedback cycle. In this system, I will show that the hot X-ray–emitting gas is deeply intertwined with the cold and warm nebular components, demonstrating that AGN feedback is inherently multiphase and dynamically complex. Together, these findings shed new light on the fundamental mechanisms that drive galaxy evolution, particularly supermassive black hole fueling/feedback and its intricate interplay with the host galaxy.

Determining how AGN accelerate outflows using current and next-generation surveys

Luke Holden
University of Hertfordshire

Despite playing a crucial role in feedback, it remains unclear how AGN accelerate gas outflows, particularly given that different accretion regimes have distinct energetic outputs (i.e. radiation, jets, and winds). To address this, we applied a probabilistic classification scheme to optical spectroscopy from the DESI survey and 144 MHz radio observations from the LOFAR Two-meter Sky Survey (LoTSS), thereby producing a sample of tens of thousands of high-confidence AGN, classified into HERGs, LERGs, and radio-quiet AGN — the largest sample of its kind. This has permitted us to statistically determine the roles of optical luminosity (correlated with radiation pressure) and radio luminosity (tracing shocks and jets) simultaneously in driving warm (T>10,000K), ionised outflows. For radiatively-efficient systems (HERGs and RQAGN), we

recover the result that the highest outflow velocities are found at intermediate radio luminosities, and show for the first time that this occurs only at high optical luminosities, indicating that both radiation pressure and shocks/jets are important. Moreover, within this luminosity regime, we discover a correlation between optical luminosity and outflow velocity, indicating a complex interplay between these mechanisms. In contrast, no such relations are found for radiatively-inefficient systems (LERGs), suggesting different acceleration mechanisms — this is critical for understanding how different AGN types regulate the growth of their galaxies.

Sebastian Hönig
University of Southampton

Mapping AGN Feedback on Parsec Scales with the LBTI and VLTI

Jacob Isbell
University of Arizona

The "dusty torus" around active galactic nuclei (AGN) regulates both black hole fueling and galaxy-scale feedback. It is no longer thought to be a simple torus, but rather a dynamic interface between a geometrically thin fueling disk and an outflowing wind. This dusty structure traces molecular inflows, ionized winds, and various heating mechanisms near the accretion disk. An increasing number of AGN have been imaged on scales ranging from 1-100 pc in the mid-infrared, directly measuring the morphology of the circumnuclear material. In this talk, I present new VLTI and LBTI imaging of nearby Seyfert 1 & 2 AGN at 1–10 pc resolution, with the ultimate goal of testing the Unified Model of AGN. The images reveal the expected optically thick disk and dusty winds. However, by combining these images with spatially-resolved SED fitting, I demonstrate that shock heating by the jet is far more prevalent than previously assumed. Crucially, the "polar dust" identified in the VLTI/MIDI era—thought to be radiation-driven winds—appears to be physically coupled to the radio jet, suggesting a more complex interaction than current radiative transfer models predict. Mapping these local signatures of feedback is essential for decoding the physics of distant, unresolved AGN. Furthermore, by achieving the effective resolution of a 30-meter class telescope today, the LBTI results provide a possible roadmap for future ELT METIS and MICADO observations, establishing locally the morphology and emission benchmarks necessary to distinguish and understand feedback throughout cosmic time.

A spectral and spatial decomposition of Little Red Dots with JWST NIRSpec IFU

Yuzo Ishikawa
Massachusetts Institute of Technology

Little Red Dots (LRDs) are a population of compact, faint, and extremely red sources recently identified by JWST. To-date broadband imaging and slit/grism spectroscopy have shown that LRDs have a V-shaped reddened spectral energy distribution (SED), narrow emission lines, broad Balmer emission lines, and sometimes a Balmer absorption. Although the structure and physical mechanisms of LRDs are debated, existing literature suggest that LRDs are likely associated with a reddened accreting black hole, or a dust-obscured stellar population, or some combination of both. Furthermore, whether feedback is present or if it even drives the evolution of LRDs remain unknown. To address these questions, we have obtained deep, NIRSpec IFU observations of 5 broad Ha-selected LRDs with the PRISM and G395H modes. In this study, we spatially decompose the continuum, emission line, and absorption line features. For the first time, we observe extended narrow line emission traced with [O III] and Ha around the LRDs, in contrast to a compact broad Balmer emission that is nearly co-spatial with the Balmer absorption. In addition to the line intensity maps, we also obtain velocity maps, enabling us to explore the gas dynamics around LRDs for the first time and address feedback in LRDs. The nature and impact of LRDs will likely continue to be debated, but they likely represent a key phase in early galaxy and black hole evolution, offering new insights in the early epoch of cosmic history.

Early evolution of a young AGN jet in NGC 1275: Kinematics and jet–ambient medium interactions on (sub-)parsec scales

Minchul Kam
ASIAA

NGC 1275, the central galaxy of the Perseus cluster, hosts a radio jet whose most recent activity began only about 20 years ago, providing a rare opportunity to investigate how an AGN jet propagates and interacts with the ambient medium on (sub-)parsec scales at an exceptionally early stage. We present a kinematic study of this young jet from its emergence in 2003 through its first two decades, based on the Very Long Baseline Array (VLBA) data at 43 GHz. We find that the C3 component, a bright feature located at the jet termination region, has maintained a nearly constant apparent velocity of 0.26c throughout the observing period. In addition, we detect the emergence of several new subcomponents from C3, each exhibiting apparent speeds higher than that of C3. Our analysis suggests that these features arise from interactions between the jet and the ambient medium, in which portions of the jet termination region fragment into subcomponents and propagate outward. These results provide direct observational evidence of jet-ambient medium interactions at a very early evolutionalry stage on (sub-)parsec scales.

Looking for AGN feedback signatures in radio-quiet AGN: A multi-wavelength, multi-scale study

Preeti Kharb
National Centre for Radio Astrophysics - Tata Institute of Fundamental Research (NCRA-TIFR)

I will present multi-scale observational results from our study of radio outflows in “radio-quiet”(RQ) AGN. This study utilises multiple radio observatories, including the VLA, GMRT, and the VLBA, examines the optical spectra of nearby Seyfert and LINER galaxies, and looks at their inter-relationship. Polarization imaging with the VLA and GMRT of Seyfert galaxies such as NGC3516 and NGC4151 suggests stratified radio outflows, consistent with “spine-sheath” jet structures or coexisting “jet-wind” systems. Nested biconical structures are also inferred from VLBA and SDSS emission-line data for the KISSR sample of double-peaked Seyfert and LINER galaxies, supported by MAPPINGS models invoking “shock+precursor ionization” of narrow-line region gas and the prevalence of “fast” 10 - 100 parsec-scale jets revealed by very long baseline interferometry. Several Seyfert galaxies show clear evidence for episodic jet activity; in NGC 2639, multiple relic lobes are detected, while both NGC 2639 and NGC 4051 exhibit molecular-gas cavities on parsec and kiloparsec scales. These findings imply that recurrent, multi-component radio outflows play a significant role in “local AGN feedback” in RQ AGN.

Probing the Circumnuclear Environment of NGC 7582 Through Water Ice Absorption

Khushboo Khushboo
Ludwig Maximilian University of Munich

Recent JWST mid-infrared observations of the Seyfert 2 nucleus of NGC 7582 (within the central ~50 pc) have revealed prominent ice absorption features that are not reproduced by existing AGN dust radiative transfer models. In particular, template spectra from the AGN model library of Siebenmorgen et al. (2014) fail to produce the observed ice signatures and underestimate the flux level by a factor of compared to the JWST spectrum. To address this discrepancy, we propose a new class of frosty AGN models that incorporate icy grain mantles within a clumpy dust torus. By implementing Monte Carlo radiative transfer calculations, we include both the effect of embedded ice features and the contribution of additional heating spectra from type-I quasars, thereby extending and updating the current AGN model libraries. This framework allows us to tackle several key scientific questions: At what radius in the accretion disk does the snow line emerge? Under what conditions can water freeze out onto dust particles in AGN environments? Is the ice reservoir preferentially located within the accretion disk, in clumps, or in the inner/outer torus regions? Beyond these physical insights, our work also addresses the broader puzzle of why current AGN models fail so severely in reproducing the JWST mid-infrared data. Our findings highlight the need to revise torus models to include icy dust components, which may fundamentally alter our interpretation of AGN spectral energy distributions and their role in galaxy evolution.

Cosmic evolution of jet-mode AGN feedback: new insights from LOFAR surveys

Rohit Kondapally
Durham University

Active galactic nuclei (AGN) can have a significant effect on their host galaxies by regulating their growth or suppressing star formation (known as AGN feedback). Of particular importance for massive galaxies and clusters are jet-mode AGN which display powerful radio jets and keep galaxies ‘red and dead’ once quenched. However, the cosmic evolution of these AGN remains poorly constrained at early times. The LOFAR telescope has been undertaking one of the deepest wide-field radio continuum surveys to date: this represents a novel sample to statistically study the evolution of AGN activity and feedback across cosmic time. Using this sample, I will present the first robust measurement of jet-mode AGN feedback out to z ~ 2.5. We discover a new dominant population of jet-mode AGN hosted by star-forming galaxies at high redshifts, that has not been previously observed. The bulk of the radio-mode heating output at earlier times is performed by this new population, which has interesting implications for galaxy quenching. Through comparison with various models, we find that the latest cosmological simulations are unable to match these latest observations.

Constraining AGN Feedback with Fast Radio Bursts: Forward Modeling Dispersion Measures in Cosmological Simulations

Ralf Konietzka
Harvard University

The dispersion measures (DMs) of Fast Radio Bursts (FRBs) arise predominantly from free electrons in the large-scale structure of the Universe. The increasing number of FRB observations have started to empirically constrain the distribution of cosmic baryons, providing new, stringent tests of AGN feedback models implemented in cosmological simulations. In this talk, I present a novel forward-modeling framework for measuring FRB DMs in IllustrisTNG that continuously traces rays through the simulation while reconstructing all traversed line segments within the underlying Voronoi mesh. This approach overcomes a key limitation of previous TNG-based studies, in which a sparse snapshot sampling in the path integral leads to a systematic misestimation of the variance and higher-order moments of the DM distribution by over 50%. By confronting our simulated FRB catalogs with recent observations from DSA-110, ASKAP, and CHIME, we quantify the distribution of baryons relative to the underlying matter, allowing us to place new constraints on the efficiency and large-scale impact of AGN feedback. We find that neither the momentum-driven AGN feedback model in IllustrisTNG nor the thermal bubble feedback implementation in the original Illustris simulation can reproduce the observed FRB DM signal, pointing to the need for next-generation AGN implementations capable of redistributing baryons in a manner consistent with observations. Our results add to the growing body of evidence from probes such as the kSZ effect and X-ray observations, indicating a significant tension between simulations and the observed baryon distribution, and highlight the power of FRBs as a new, independent probe of AGN feedback.

The driving mechanisms of AGN feedback

Sophie Koudmani
University of Hertfordshire

Supermassive black holes (SMBHs) reside at the centres of most massive, if not all, galaxies influencing their host galaxy's evolution through a complex feedback cycle. SMBH feeding and feedback spans a vast range of scales, from the accretion disc to the cosmic web, so that all past cosmological simulations have had to rely on simple 'subgrid' models for SMBH evolution, limiting their predictive capabilities. Recent observational breakthroughs have challenged these models as JWST has detected significantly more active SMBHs in the early Universe than had been predicted. The recent evidence for a gravitational wave background from SMBH mergers also points to the need for more efficient early SMBH growth. I will discuss the latest advancements on unravelling the driving mechanisms of active galactic nuclei (AGN) feedback from SMBHs across the scales from GR(R)MHD simulations to idealised galaxies and cosmological volumes as well as multi-wavelength observational campaigns poised to uncover the nature of AGN feedback.

Signatures of jet-ISM interaction in a high redshift radio galaxy at cosmic noon

Pranav Kukreti
Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg

High redshift radio galaxies are among the most massive galaxies in the early Universe, with powerful radio jets and quasar-level AGN activity. They are the only objects at cosmic noon, where we can study feedback from both jets and quasar in the same galaxy. The central quasar is also obscured by dust (type-2 AGN), allowing us to study the host galaxy. I will present the results for a high redshift radio galaxy at z~3.5, where we identify feedback driven by shocks and photoionisation in a spatially resolved manner using JWST NIRSpec IFU data. In addition to quasar photoionisation, we detect strong jet-ISM interaction at a distance of ~15 kpc from the quasar, allowing us to assess the impact of jets beyond the host galaxy. We find this interaction is driving shocks into the surrounding medium, as shown by their ionisation ratios. We compare this with high-resolution radio spectral index maps, which show a flattening of the radio spectra, showing a strong re-acceleration of the radio plasma in the interaction region. This study highlights the importance of jet-driven feedback even in some highly accreting AGN at cosmic noon, and allows us to assess the relative contribution of shocks and photoionisation driven feedback in the same galaxy.

Exploring Supermassive Black Hole Feedback in Novel Regimes of the IllustrisTNG Universe: Dense Environ-

ments and Early Cosmic Times

Shalini Kurinchi-Vendhan
University of California San Diego

Supermassive black holes (SMBHs) and their host galaxies evolve in tandem, with active galactic nuclei (AGN) playing a critical role in regulating galaxy growth. While the impact of AGN feedback on massive, central galaxies in the local Universe is known to be important, the relative significance of SMBHs across different galaxy environments and redshifts still lacks consensus. In two complementary studies, we leverage the state-of-the-art IllustrisTNG cosmological simulations to investigate the co-evolution of SMBHs and galaxies, focusing on massive galaxies that undergo extreme transformations in dense cosmological environments, as well as those that are quenched in the high-redshift Universe. We find that $z \approx 0$ satellite galaxies that are stripped of their gas during infall into galaxy groups and clusters exhibit elevated AGN fractions, indicating that extreme environments can enhance SMBH activity. Furthermore, our analysis of z 3 massive galaxies shows that AGN feedback is the primary mechanism suppressing their star formation: rapid SMBH growth and the early onset of kinetic feedback efficiently deplete cold gas reservoirs, with dense large-scale structures further amplifying the quenching process. Together, these results highlight the role of AGN feedback as a driver of galaxy evolution across a wide range of environments and cosmic times.

AGN feedback in a dual supermassive black hole system observed with VLT/ERIS and X-shooter

Isabella Lamperti
University of Florence

Mergers can trigger AGN activity and starburst events, making them ideal environments for studying outflows and the feedback effects of AGN and star formation. The galaxy MCG-03-34-43 is an advanced merger where recent HST and Chandra observations have revealed a dual AGN system at its center, with a separation of less than 120 pc (Trindade-Falcao et al. 2024). Using VLT/ERIS near-infrared (NIR) integral field spectroscopy, we analyzed the ionized gas kinematics in the nuclear region of this target and detected outflows originating from both nuclei. NIR emission line diagnostic diagrams indicate that AGN photoionization dominates the central region, except for the area between the two nuclei, which exhibits enhanced star formation, possibly driven by positive AGN feedback. Combining ERIS with rest-frame optical data from VLT/X-shooter, we find evidence that the outflows, traced by hydrogen recombination lines as well as by high-ionisation (coronal) lines, are dust-poor, unlike the surrounding ISM. Additionally, we estimate the mass outflow rate and assess its potential impact on star formation in the host galaxy. This system offers a unique opportunity to study the feedback effects along different directions due to the presence of the dual AGN. Studying such systems enhances our understanding of the complex interplay between AGN activity and galaxy evolution.

AGN feedback from Galaxy-Scale jets across cosmic time with LOFAR-VLBI

Giulia Lusetti
The Open University

Despite major progress in understanding AGN feedback on galaxy group and cluster scales, a fundamental question remains: how does AGN feedback operate on the scale of individual galaxies ($<$100 kpc), where jets and outflows first interact with the host-galaxy interstellar medium? In this talk, I focus on the role of galaxy-scale radio jets as a key channel through which supermassive black holes couple to the interstellar and circumgalactic medium. Using data from the first generation of the LOFAR-VLBI Deep Fields —deep, wide-area radio surveys that combine unprecedented sensitivity with sub-arcsecond resolution enabled by LOFAR's international baselines— we assemble a large ($\approx$1000 objects down to $\sim$10 kpc in size), statistically representative sample of galaxy-scale jets and their host-galaxy properties over a wide redshift range, up to $z \simeq 3$. This dataset enabled a systematic characterisation of jet sizes, morphologies and energetics. Furthermore allowed us to assess how frequently radio jets remain confined within their host galaxies, providing new observational constraints on the onset and efficiency of AGN feedback on galactic scales. The extensive multi-wavelength coverage of the LOFAR Deep Fields further allowed us to investigate how jet incidence and properties depend on host-galaxy stellar mass and accretion mode, and how these trends evolve with cosmic time through redshift-binned population studies, up to the epoch of cosmic noon z ~ 2 and beyond, the most active phase of galaxy formation, when star formation and black-hole accretion were most intensive.

Identifying heating processes from jets in a galaxy cluster

Meenakshi M
Leibniz Institute for Astrophysics

We investigate how jets heat the intracluster medium (ICM) by disentangling the contributions from different heating channels. To this end, we implement a heating estimation method based on passive entropy tracers and validate it using controlled tests and in-situ shock detection. Using these diagnostics, we simulate single high-power jet outbursts with varying jet densities in a cluster environment. Light jets inflate wider bubbles and displace more gas from the cluster core, while denser jets propagate more efficiently to larger distances with minimal core disturbance. At early times, shock heating dominates for all jets. At later stages, light jets heat the ICM mainly through turbulent dissipation, whereas denser jets continue to deposit energy primarily via shocks. Turbulent and mixing-driven heating dominates inside the cocoon, while shocks and acoustic compressions prevail outside. Light-jet shocks weaken rapidly, whereas dense jets sustain strong shocks to large radii.

Quantifying Ionized AGN Feedback: Simple Kinematics but Large Masses in Ionized Outflows

Alessandro Marconi
University of Florence

Ionized outflows are routinely observed in local active galactic nuclei and are widely regarded as a primary channel through which AGN feedback operates, yet their quantitative impact remains poorly constrained. We present new results from the analysis of a sample of nearby AGN observed with MUSE/VLT, revealing a common and unexpectedly simple kinematic structure in their ionized outflows. Despite the apparent complexity of the observed velocity fields, the outflows are consistently described by a biconical geometry with a radially varying velocity law: the radial velocity is approximately constant out to $\sim$1 kpc and then undergoes a clear acceleration, increasing by more than a factor of two. This behaviour is ubiquitous across the sample and largely independent of AGN or host-galaxy properties. These results are enabled by MOKA3D, a new forward-modelling framework that self-consistently accounts for the intrinsic clumpiness and flux distribution of the emitting gas, showing that much of the observed kinematic complexity arises from inhomogeneous emission rather than from multiple dynamical components. By combining MOKA3D with the photoionization framework HOMERUN, we obtain robust measurements of outflow masses. Applied to joint MUSE and JWST/MIRI observations of NGC 1068, this approach reveals an ionized outflow that is significantly more massive and energetic than previously inferred, with properties comparable to those of molecular outflows. These results demonstrate that ionized outflows can play a major role in AGN feedback on kiloparsec scales and highlight the need for self-consistent kinematic and physical modelling to quantify their impact.

Fueling, Winds, and Self-Regulation: SMBH Growth and Feedback from Cosmic Noon to the Local Universe with the FIRE simulations

Jonathan Mercedes Feliz
University of Connecticut

Feedback from active galactic nuclei (AGN), powered by gas accretion onto supermassive black holes (SMBHs), is widely invoked as a key regulator of star formation in massive galaxies. However, the coupling between sub-kpc fueling, time-variable accretion, and multiphase outflows is hard to isolate observationally and difficult to capture in a single theoretical framework. High-resolution FIRE cosmological hydrodynamic simulations with a multiphase interstellar medium and explicit SMBH accretion and feedback models make it possible to follow these connections in time, from the gas supply in the circumgalactic medium (CGM) to nuclear inflow and the launching and impact of winds. In this presentation, I will summarize recent results focusing on three regimes that highlight the diversity of fueling and feedback across mass scale and cosmic time, from massive galaxies at their peak activity to Seyfert galaxies in the local universe. (1) I will first present a new nuclear fueling channel driving luminous quasars at cosmic noon based on the large pileup of gas in the inner CGM produced by a global galactic outflow that later reaccretes coherently onto the galaxy, resulting in significantly higher inflow rates than pre-outflow conditions that can directly supply the nuclear region and trigger a luminous quasar phase. (2) I will then show that the resulting powerful

AGN-driven winds can carve central cavities and suppress star formation in massive galaxies at cosmic noon primarily by preventing gas accretion into the ISM rather than by ejecting the existing star-forming gas reservoir. At the same time, strong AGN wind–ISM interactions can locally compress gas and result in positive feedback, including the rapid formation of ultra-dense, off-center stellar clumps. (3) Finally, I will discuss fueling and feedback self-regulation in simulations of Seyfert-like galaxies at low redshift, where we identify recurrent cycles linking increased inflow toward the accretion disk, enhanced SMBH accretion, feedback-driven clearing of the nuclear region, and subsequent re-fueling on ~10–100 Myr timescales. Comparisons to the observed connection between AGN luminosity and nuclear gas deficit provide direct constraints on the characteristic spatial and temporal scales of SMBH self-regulation.

Evidence for depleted gas reservoirs in the most luminous unobscured quasars at cosmic noon

Stephen Molyneux
The University of Oslo

Over the last decade, ALMA observations have constrained the molecular gas content of diverse samples of AGN host galaxies in the high-z Universe. Despite this, it has been difficult to get a clear consensus as to whether AGN hosts at high-z have lower molecular gas content as a result of strong feedback and large statistical samples are still missing in the literature. However, in our recent study of 41 of the most luminous, unobscured quasars at $z \sim 2$ we find universally low gas fractions in the entire sample relative to both obscured/red quasars and SFGs of similar luminosity at the same redshift. I will present evidence for a correlation between the gas fractions and obscuration that would be consistent with an evolutionary sequence from a gas-rich, dusty quasar to a gas-poor, unobscured quasar. I will also present tentative trends linking the gas fractions and the broad-line region (BLR) properties, with quasars showing stronger BLR winds having higher gas fractions.

Impact of kpc scale relativistic jets on a galaxy’s evolution

Dipanjan Mukherjee
Inter-University Centre for Astronomy and Astrophysics

Relativistic jets from supermassive blackholes are an important driver of feedback in galaxies with an active black hole. They impact the nearby environment over different physical scales during their lifetime, with varying effects. The jets can act as an important agent of injecting energy in the host’s ISM, as confirmed both in observations of multi-phase gas, as well as in simulations. Such interactions have the potential to impact the kinematics of the gas as well its star formation. However, to what extent such feedback is efficient in impacting the large scale gas in the galaxy is still a question of debate. We have undertaken a multi-faceted approach to understand the impact of such relativistic jets and related phenomenon through a wide ranging campaign of high resolution simulations. Such simulations include new sub-grid physics such as turbulence regulated star formation and acceleration and evolution of non-thermal electrons, which provide more accurate predictions of impact of jets on the galaxy's observable prorperties. The results have been further augmented by spatially resolved observations of multi-phase gas in galaxies with such jets, to corroborate the theoretical findings. I will outline the recent results from such on-going works and future directions of research in this context.

Observational signatures of AGN outflows from the radio to the optical

Rion Nazareth
Newcastle University

Multi-wavelength observations show that bright AGN drive large-scale outflows. How these outflows interact with multiphase gas and impact galaxy evolution on cosmological timescales is still not understood. In this talk, I will discuss how we can connect theoretical models of AGN outflows to observable signatures, focusing on optical emission lines and radio emission. I will present results from recent high-resolution hydrodynamical simulations with AREPO that follow energy-driven AGN outflows expanding through a realistic multiphase interstellar medium. By resolving the cool gas phase (T<10^4.5 K) and its interaction with the outflow, the simulations allow predictions for commonly used optical tracers, including [O III] emission lines, and show how these tracers relate to the total mass, momentum, and energy of the outflow. I will also present new magnetohydrodynamic (MHD) simulations including cosmic-ray transport physics to model relativistic particles accelerated in shocks generated by these outflows. This approach is useful to find the dominant source of radio-emissions in AGN. Understanding the exact physical mechanisms behind these outflows has important implications for constraining AGN impact on host galaxies, as well as their role in galaxy evolution and the regulation of star formation.

Feedback in Cluster Cores: The Life of Multiphase Filaments

Valeria Olivares
Universidad de Santiago de Chile

Galaxy cluster cores are exceptional laboratories for probing the baryon cycle that regulates galaxy evolution and active galactic nucleus (AGN) feedback. They provide a unique window into how the intracluster medium (ICM) cools, fuels central galaxies, sustains star formation, and ultimately triggers feedback from the Universe's most massive black holes. In this talk, I present a newly identified correlation between the surface brightness of the hot and warm gas phases within filamentary structures in cluster centers, based on MUSE, SITELLE, and Chandra observations. Remarkably, this correlation closely resembles those observed in the tails of jellyfish galaxies, revealing an unexpected connection between cluster-scale filaments and ram-pressure-stripped systems. I further demonstrate that AGN feedback plays a crucial role in shaping the filaments morphology, pressure balance, and metallicity, highlighting their dynamic, multiphase nature. Finally, I present new high-resolution ALMA observations of a filament in the Perseus cluster to investigate the impact of AGN feedback on cold molecular clouds and their potential for star formation.

A first JWST view on Compton Thick AGN in the early Universe

Eleonora Parlanti
Scuola Normale Superiore

Feedback driven by Active Galactic Nuclei (AGN) is thought to play a fundamental role in shaping galaxy properties and in driving the co-evolution of galaxies and their central black holes (BHs). Obscured AGN are thought to represent a crucial phase of BH growth, in which the central BH is hidden in large amounts of gas and dust and undergoes rapid accretion. When the feedback becomes strong enough, it will eventually sweep away the gas and dust, and the obscured AGN will shine as a bright quasar. However, observational constraints on AGN feedback during these obscured phases at z>3 have remained limited so far. Thanks to the unprecedented sensitivity of JWST we can now, for the first time, detect the rest-frame optical emission of obscured AGN at high redshift. I will present the preliminary results from JWST NIRSpec/IFU observations of a sample of Compton-thick AGN at high redshift (z>3), targeting the main rest-frame optical emission lines. These observations reveal ubiquitous ionized gas outflows, indicating that strong feedback is active during these heavily obscured phases. I will describe the properties and energetics of these outflows and discuss their impact on the host galaxies. Finally, I will place these obscured AGN in the broader context of AGN populations by comparing their properties with those of unobscured AGN at similar redshifts, and with the AGN population newly discovered by JWST, providing new insights into the role of feedback during the obscured phases in the co-evolution of galaxies and supermassive black holes.

Winds of Quench: Multi-facility Constraints on AGN-driven Quenching at $z > 3$

Robert Pascalau
Kavli Institute for Cosmology, Cambridge

High-z massive quenched galaxies (MQGs) form and quench very quickly, challenging theoretical models. AGN feedback is thought to play a central role, but the dominant mechanism remains elusive. We present deep JWST/NIRSpec IFU observations of two MQGs caught at different stages of quenching. GS-9209 (z=4.7) is already quenched yet hosts a residual neutral gas outflow, while GS-10578 (z=3.1) is observed transitioning to quiescence during an intense AGN-driven outflow episode. Our IFU study enables a robust characterisation of the geometry and spatial extent of outflowing gas. Together with the observation of older stellar cores in these galaxies, we show that AGN ejective feedback is strongly linked to inside-out quenching. We also present 9 MQGs at z=2-5 observed in ALMA Cycle 11; all are depleted of cold gas (<5% cold gas mass fraction; 5 sigma). Reconstructed gas-consumption histories indicate very short depletion timescales and reveal a diversity of quenching pathways, with some galaxies requiring gas removal while others are consistent with rapid gas consumption. However, JWST spectroscopy reveals that, in targets with neutral gas outflows, the gas cannot escape the galaxy's gravity, hence the need for preventative feedback to explain long-term quiescence. Finally, we discuss the implications of an approved ACA pilot program targeting the CGM of GS-10578 to search for expelled cold gas and a thermal Sunyaev–Zel'dovich signal, providing a test of AGN feedback at high-z.

Probing Extreme Quasar Outflows through Broad Absorption Variability at High Redshift

Aromal Pathayappura
Western University

Quasar-driven outflows are key to understanding supermassive black hole growth and AGN feedback, especially at high redshifts. Broad absorption lines (BALs) in quasar spectra provide a direct way to probe these outflows, particularly high-velocity systems that can strongly affect the host galaxy. We present results from a South African Large Telescope (SALT) monitoring campaign of C IV BAL variability in 64 high-redshift quasars ($2 < z < 4$) with outflow velocities above 15,000 km/s. This is one of the largest BAL monitoring programs to date, with near-annual cadence in the observer's frame (corresponding to a few months in the rest frame) over an eight-year period (2018–present). We carried out detailed analysis on interesting variability at both long and short timescales that includes large kinematic shifts in absorption (~1000 km/s), oscillatory changes in absorption strength on short timescales, and evidence for shielding between different outflow components within the same source. Using this dataset, we explore correlations between BAL properties, their variability, and global quasar properties. We also use state-of-the-art, spectral synthesis code 'SimBAL' to investigate the physical nature of these extreme outflows that suggests a distance of several tens to hundreds of parsecs to the outflow from the central engine. Our results highlight the importance of high-velocity BAL outflows for AGN feedback and also reveal several challenges for standard accretion disk wind models.

Witnessing AGN outflows cooling and enriching CGM at Cosmic Noon

Bo Peng
Max Planck Institute for Astrophysics

Understanding the physical properties and phase interactions within galactic outflows remains a major challenge. In this talk, I will present results from a detailed study of the multi-phase outflows in the $z \sim 2.8$ submillimeter galaxy-quasar system SMM J02399-0136, a uniquely rich environment for exploring large-scale feedback. Leveraging high-resolution observations from HST, JWST, and ALMA/ACA across a suite of emission lines—including Lyα, [O III], [C II], [N II], [C I], and CO—we map a complex structure of ionized, neutral, and molecular gas extending from the QSO out to 60 kpc. These observations reveal jet-ISM interactions, collimated outflows, filamentary and enriched CGM, with evidence for periodic feedback, turbulence, strong UV/optical line cooling. I will discuss how multi-line diagnostics constrain key physical conditions—such as density, ionization state, and chemical abundance, and highlight how deep imaging enables new insights into feedback processes at galactic scales.

Michele Perna
Centro de Astrobiología (CAB)

A population-based approach to understanding radio AGN feedback with LOFAR

Jonny Pierce
University of Hertfordshire

While previous studies suggest that the total kinetic power output from radio AGN jets is sufficient to offset radiative cooling in large-scale cosmological environments, many have relied on generalised scaling relations to estimate jet power from radio luminosity, neglecting additional important information such as source size and environment. I will here present our study of a large sample of LoTSS Deep Field radio AGN, for which we have inferred the cosmic evolution of kinetic jet powers using a physically motivated semi-analytical model for the first time. Initial analysis on a sample of 619 radio AGN at z<2.5 from LoTSS and LOFAR-VLBI images of the Lockman Hole (limiting angular resolutions of 6”, 1”.8 and 0”.4) implied a population dominated by short-lived sources with lower jet powers. Incorporating this weighting towards shorter lifetimes and utilising ELAIS-N1 and Boötes LoTSS Deep Field data to expand our analysis to a sample of 5,187 objects, we derived jet kinetic luminosity functions and integrated kinetic luminosity densities for the radio AGN population out to z=2.5. We find the total power output per comoving volume to be $\sim$10^32–10^33 W Mpc^$-$3 across the full redshift range, with suggestions of moderate positive evolution from z=0 -1 and little evolution between z=1 and z=2. This broadly agrees with previous observational results and the expectations of cosmological models, strongly supporting the viability of radio AGN jet feedback across cosmic time.

Silicate emission in type-2 quasars: JWST/MIRI constraints on torus geometry and radiative feedback

Cristina Ramos Almeida
Instituto de Astrofísica de Canarias

We present new insights into the dusty environments of type-2 quasars (QSO2s) enabled by mid-infrared spectroscopy from JWST/MIRI. The mid-infrared spectra of five optically selected QSO2s at z~0.1 reveal

the presence of 9.7, 18, and 23 μm silicate features in emission in two objects, challenging the classical picture of obscured AGN showing silicate absorption. The high angular resolution of JWST/MIRI allows us to isolate the nuclear regions where directly illuminated dusty clouds produce these emission features. We focus on the QSO2 with the strongest silicate emission, fitting its nuclear mid-IR spectrum with the CLUMPY and CAT3D-WIND torus models. Both models reproduce the spectrum with intermediate torus covering factors and inclination angles, with a preference for the disk+wind geometry of CAT3D-WIND. Furthermore, four of the five QSO2s fall in the “blowout” region of the Eddington ratio–column density plane, consistent with active clearing of nuclear dust by radiation pressure in these objects. This contrasts with Seyfert 2 galaxies, which remain in “permitted” regions and typically show silicate absorption. This supports a scenario where the more luminous the AGN and the higher their Eddington ratio, the lower the torus covering factor, driven by radiation pressure on dusty gas.

The wind properties of the X-ray selected SDSS-V quasar sample: strong optical-to-UV emission is key regardless of X-ray strength

Amy Rankine
University of Edinburgh

Quasar winds are evident in rest-frame UV spectra in the form of blueshifted broad emission lines. How such winds are launched – and how such launching relates to the physical state of the accretion disc system that powers quasars – remains a key open question. SDSS-V follow-up of eROSITA sources is yielding a large quasar sample for which we have access to their wind properties and (via measurements of the X-ray, UV and optical emission) constraints on their accretion state. I will present new measurements for a sample of 3000 quasars at redshifts 1.5-3.5 that quantify how the strength of quasar accretion disc-winds (from the CIV emission line) depends on both the strength of the UV ionising continuum (probed via HeII emission) and the X-ray properties derived from the eROSITA spectra (i.e., photon index). We show that quasars with a given X-ray luminosity have a broad range of wind properties that appear to depend most strongly on the strength of the UV-bright inner accretion disc (revealed by the HeII emission line strength). A strong UV component can lead to over-ionisation of the wind such that the outflow strength is decreased. These results point to radiation-driven winds whose strength and presence are highly sensitive to the physical structure of the accretion system. The X-ray photon index and luminosity, however, do not impact the strength of the wind. With this information in hand we gain a new perspective of the wind properties of the X-ray selected quasars.

Multiphase gas reservoirs around z~3 quasars and the impact of feedback from host-galaxy to halo scales

Jelena Ritter
Max Planck Institute for Astrophysics

Extended Ly-alpha nebulae observed around quasars trace the cool gas within the circumgalactic medium and can provide key insights into the complex interplay between gas dynamics and active galactic nuclei (AGN) feedback. However, the connection between this cool phase and the cold molecular gas of the host galaxies remains largely unexplored. In this talk, I leverage ALMA CO(4–3) observations of 37 quasars at z ~ 3, all of which have been previously mapped in Ly-alpha with VLT/MUSE, to investigate the relation between the CO emission, and hence the molecular gas content, and halo properties. I show that systems with higher black hole mass and lower Eddington ratio exhibit higher CO detection rates while also demonstrating lower Ly-alpha surface brightness. This result suggest that radiative feedback regulates cold gas survival in dusty, gas-rich environments and consequently influences the reprocessed Ly-alpha emission from halo gas. I report on the incidence and properties of CO-emitting companions to quantify the quasar–galaxy clustering and to investigate the impact of the quasar environment on surrounding galaxies. Additionally, I explore a connection between the orientation of the quasar host galaxy disks and the large-scale morphology and kinematics of the Ly-alpha nebulae. This investigation aims to provide a deeper understanding of the connections between quasar activity and the multiphase gas content of quasar host galaxies and their halos.

The Largest Catalogue to Date: AGN Outflows in Dwarf Galaxies

Víctor Rodríguez Morales
Institute of Space Sciences (ICE-CSIC)

Dwarf galaxies have been historically thought to be regulated by winds from supernovae. However, in recent years, several studies have provided growing evidence for the presence of AGN outflows, and of possible AGN feedback, in dwarf galaxies. In this talk, we present a catalogue of 1242 dwarf galaxies with AGN outflows, the largest sample to date, drawn from DESI DR1 spectroscopy based on the detection of a broad component in the [OIII] emission line. We analyze the kinematic and energetic properties of these outflows, introducing a pioneering outflow velocity threshold to determine the ionization source. We find, based on the coupling efficiency and the capability of the outflow to escape the dark matter halo, that AGN feedback in dwarf galaxies may be as important as, or even more significant, than that in massive galaxies.

Unveiling the role of stellar- and AGN-driven outflows in the evolution of low-mass galaxies

Michael Romano
Max Planck Institute for Radio Astronomy

Stellar and AGN feedback shape the baryon cycle of galaxies by driving large-scale outflows that regulate star formation and redistribute gas beyond the interstellar medium. Low-mass galaxies, with their shallow gravitational potentials, are particularly sensitive to these processes, as feedback can efficiently expel material into the circumgalactic and intergalactic medium. I will present new statistical constraints on ionized gas outflows in low-mass galaxies (log($M_*/M_\odot$) < 10) at z < 0.5 from the first data release of the Dark Energy Spectroscopic Instrument (DESI). Using optical emission-line diagnostics, we identify thousands of dwarf galaxies with robust outflow signatures, including a significant population of AGN and composite systems. Typical velocities and mass-loading factors of AGN-driven outflows exceed those from star-formation–driven winds, indicating more efficient gas removal. Derived scaling relations show decreasing outflow efficiency with stellar mass and systematic offsets from cosmological simulations, highlighting the need for multi-phase observations. These results demonstrate the feasibility of statistical studies of AGN feedback in dwarfs and pave the way for synergistic follow-up with current and forthcoming facilities to fully characterize their baryon cycle.

The imprint of AGN-driven outflows on the CGM: the case of Ly-a nebulae around high-z quasars

Silvia Rueda-Vargas
ESO

AGN feedback is a multiscale process involving phenomena from sub-parsec accretion disk winds to galaxy-wide outflows which might have an effect on the Interstellar Medium (ISM), Circumgalactic Medium (CGM) and Intergalactic Medium (IGM). While AGN-driven outflows are routinely observed on ISM scales, their impact on the CGM remains unconstrained. In recent years, integral-field spectrographs such as VLT/MUSE and Keck/KCWI have revealed that luminous Lyα nebulae, extending from tens to hundreds of kiloparsecs, are ubiquitous around high-redshift quasars, providing a unique laboratory to study the impact of AGN feedback at CGM scales. Using a radiation-hydrodynamic cosmological simulation, Costa et. al (2022) predict that AGN-driven outflows can regulate the properties of the Lyα nebulae by clearing low-optical-depth paths in the host galaxy, thereby facilitating the escape and scattering of Lyα photons from the galactic nucleus into the CGM. In this talk, I present an observational test of this prediction using a sample of six quasars at z $\approx$ 2–3 surrounded by extended Lyα nebulae detected with VLT/MUSE and Keck/KCWI. We combine these data with new VLT/ERIS and Gemini/GNIRS observations targeting the [O III] λ5007 emission line to characterize the kinematics and energetics of ionized AGN-driven outflows on ISM scales. We detect ionized outflows in all sources and find a positive monotonic correlation between outflow kinetic power and both the size and luminosity of the associated Lyα nebulae. Additionally, we observe a spatial alignment between extended [O III] emission and the inner, brightest regions of the Lyα nebulae, suggesting a physical connection between ISM-scale outflows and CGM-scale emission. Our results provide tentative observational evidence of the theoretical prediction by Costa et. al (2022) that AGN-driven outflows play a key role in shaping the CGM by mediating the nuclear activity and the host galaxy environment. Our findings place new empirical constraints on feedback models and highlight the importance of jointly probing ISM and CGM scales to understand the global impact of AGN feedback across cosmic time.

How feedback processes shape the CGM and ICM

Mateusz Ruszkowski
University of Michigan

Feedback governs the thermodynamic and dynamical evolution of the circumgalactic and intracluster media, yet the physical pathways by which energy and momentum are transferred to diffuse gas remain incompletely understood. In this review, I will take a physics-centered perspective on how feedback operates via light and mass-loaded jets, microphysical transport processes in the thermal plasma, and non-thermal components including cosmic rays, magnetic fields, and turbulence. A central theme will be the multiscale character of feedback, from jets launched at the center to the formation of cold filaments traced by Hα emission and the regulation of halo-scale gas properties in massive galaxies, groups, and clusters.

A striking excess of red quasars with steep radio spectral slopes: a dusty blow-out phase revealed through AGN-driven shocks?

Ciera Sargent
Durham University

Red quasars exhibit a higher incidence of compact (< galaxy-scale) radio emission than blue quasars, arising from systems near the radio-loud/radio-quiet threshold. This excess cannot be fully explained by orientation-based unification models, instead supporting the idea that red quasars represent a distinct evolutionary phase, possibly an obscured to unobscured transition, where low-power jets and/or AGN-driven winds expel obscuring gas and dust. I will show evidence for an excess of steep-spectrum radio emission from red quasars with compact (<6”) radio morphologies over 0.14-3 GHz. This steep-spectrum excess is not seen in normal blue quasars (radio compact or extended) or red quasars with extended low-frequency radio emission, which instead display a wide range of spectral slopes consistent with a range of different physical processes. The strength of the steep-spectrum excess increases with dust extinction, alongside a rising radio-detection fraction. I argue that this emission arises from shocks between quasar-driven winds/jets and the dusty nuclear-host galaxy environment. The majority (86%) of the dustiest quasars ($E(B-V) > 0.4$) with steep spectra have radio luminosities consistent with wind-shock models assuming a wind efficiency of 7%. These results support a “dusty blow-out” scenario in which a compact jet and/or AGN-driven winds interact with a dusty ISM, causing shocks, leading to steep spectral slopes and enhanced radio detection rates.

Tracing Multiphase AGN Feedback at Cosmic Dawn: ALMA–JWST Insights into z ~ 6 Quasar Outflows.

Sowkhya Shanbhog
Scuola Normale Superiore - Pisa

Quasars at z ~ 6 host rapidly growing supermassive black holes whose energetic output is expected to drive powerful feedback capable of influencing early galaxy evolution. Galactic outflows in these systems are predicted to span multiple gas phases, ranging from cold, neutral gas to warm, ionized gas. Their spatial extent and kinematic structure provide key insights into how feedback couples to the interstellar medium. In this work, we investigate multiphase outflows in a sample of z ~ 6 quasars observed with ALMA in [C II] and JWST/NIRSpec IFU spectroscopy, which covers the rest-optical emission lines ([O III], Hβ, Hα). The ALMA [C II] data probe the cold gas that may dominate the outflow mass, while JWST probes the ionized phase. Using the JWST IFU data, we construct flux, velocity, and velocity-dispersion maps and measure the spatial extent and morphology of ionized outflows. These measurements, combined with multicomponent spectral fitting to derive ionized gas masses, outflow rates, and energetics, are compared directly to [C II]–based estimates of the cold component. By correlating velocities, momentum fluxes, and spatial extents between phases, we test whether cold and ionized outflows are co-spatial or arise from different regions of the host galaxy, quantify the relative mass loading in each phase, and investigate trends with AGN luminosity and black hole properties. This study aims to assess whether early quasars drive momentum- or energy-dominated winds, evaluate their capacity to evacuate or heat the gas reservoir on kiloparsec scales, and provide new constraints on the strength and spatial reach of AGN feedback in the first billion years of cosmic time.

Arkenstone BH: Resolving High Specific Energy Black Hole Feedback in Cosmological Simulations

James Sullivan
Columbia University

Arkenstone BH (ArkBH) is an extension of the Arkenstone framework, originally developed to resolve high specific energy stellar feedback driven outflows in cosmological simulations. ArkBH extends this approach to black hole feedback by providing a framework for launching and resolving high specific energy black hole driven outflows, particularly relevant to jet mode feedback. We demonstrate that ArkBH successfully quenches galaxies in both isolated and cosmological zoom-in simulations by counteracting gas inflow from the circumgalactic medium into the interstellar medium. Importantly, the model also avoids local self regulation of black hole accretion and feedback, a common limitation of many existing subgrid prescriptions. This sets the stage for our current work implementing the model in larger cosmological boxes. This will enable robust statistical studies of the importance of preventive feedback in galaxy evolution and allows us to better constrain the effects of varying outflow velocities, energies, and mass loadings. Lastly, these cosmological runs will allow us to compare our results against key observational constraints, including the kinematic Sunyaev-Zel'dovich effect and intracluster medium velocity dispersions.

AGN Feedback Models and AGN Demographics I: Radio-Mode AGN in EAGLE, SIMBA and TNG100 are Inconsistent with Observations

Arjun Suresh
New York University

We provide an overview of our studies examining the link between radio AGN activity and host galaxy properties, and how these trends compare between observations and simulations. This talk will summarize two published papers. The first presents an observational study that derives the most accurate constraints to date on the intrinsic relationship between radio AGN activity and host-galaxy stellar mass and specific star formation rate. The second paper uses these constraints to test AGN feedback models implemented in cosmological simulations. In the first paper, we combine MaNGA optical IFU data with the FIRST and NVSS radio catalogs to infer, for the first time, the intrinsic Eddington ratio distribution of radio AGN and its dependence on host-galaxy properties, explicitly accounting for both star formation contamination and flux-limited selection effects. We show that properly modeling these selection effects is essential for recovering unbiased relationships between AGN activity and host galaxies, and that neglecting them can lead to misleading conclusions, as in many previous studies. Consistent with earlier work, we find a strong dependence of the Eddington ratio distribution on stellar mass; however, at fixed mass, we find no dependence on host specific star formation rate (sSFR), which is a novel result. In the second paper, we compare these observational constraints with predictions from the EAGLE, SIMBA and TNG100 cosmological simulations, whose radio-mode AGN feedback models are calibrated to match the low-redshift stellar mass function but not the AGN–host relations we probe. All three simulations fail to reproduce the observed strong mass dependence and sSFR independence of radio AGN activity. Our findings highlight a pressing need to revisit the AGN feedback prescriptions in EAGLE, SIMBA, TNG100 and other similar models.

Bubbling up: AGN wind explains Fermi/eRosita bubble morphology, kinematics and X-ray emission

Matas Tartėnas
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Although Sagittarius A* is quiescent today, the Galactic Centre bears clear evidence for past, and likely episodic, activity: X-ray echoes in molecular clouds, radio lobes and bubbles (15 pc to ~100 pc scales), X-ray chimneys, and most strikingly, the ten-kiloparsec bipolar Fermi and eRosita bubbles. The origin of the Fermi and eRosita bubbles remains debated. Here we test whether Wind driven by an active Sagittarius A* can inflate bubbles consistent with their observed morphology, line-of-sight kinematics, and X-ray emission. I will present results from a set of simulations of an AGN episode in a simplified Milky Way model using Arepo and the direct AGN wind injection scheme BOLA. We vary four key parameters - AGN luminosity, episode duration, wind velocity, and halo density - to explore the range of possible outflow morphologies and kinematics. We find that a 0.4 Myr AGN episode at ~0.4 L_Edd reproduces the observed bubble properties: their height, width, X-ray luminosity, and line-of-sight kinematics. These matches are achieved 6 Myr after the AGN episode, consistent with the bubbles' inferred age. This shows that fossil outflows exist well beyond the initial outburst.

Resolving AGN feedback in the dense ISM of M51

Mallory Thorp

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AGN can have a profound impact on the interstellar medium (ISM), but characterizing the extent of AGN feedback and its ability to regulate star formation remains difficult, in part due to the variety of nuclear activity tracers but also the complexity of the cold, dense ISM where star formation occurs. To address this complexity, we use new observations from SWAN (Surveying Whirlpool at Arcseconds with NOEMA) to study how AGN feedback shapes the dense molecular ISM of M51, a nearby spiral galaxy hosting an obscured AGN. SWAN provides GMC-scale mapping of multiple dense gas tracers HCN, HCO+, HNC, and N2H+ in the central 5 kpc of M51, as well as tracers of slow shocks like HNCO that can be present near the AGN-powered molecular and ionized gas outflows. We combine this new dataset with optical integral field spectroscopy from VENGA (VIRUS-P Exploration of Nearby Galaxies) and X-ray spectroscopy from Chandra to investigate how different tracers of AGN activity impact the dense ISM. This multiwavelength approach reveals how mechanical and radiative feedback leave different imprints on the ISM over a range of scales, with shocks driven by mechanical feedback being the predominant regulator of the central gas reservoir. We further investigate which shocks clear out molecular gas in the center of M51, and which can actually lead to dense gas build up that would be missed in lower spatial resolution studies. Most importantly, we highlight which multiwavelength observations are necessary to constrain where correlations between different dense gas tracers break down, and highlight which tracers are less sensitive to AGN feedback. Altogether, this work establishes the empirical diagnostics needed to interpret dense gas observations and star formation conditions in AGN hosts, demonstrating the critical role of high-resolution, multiwavelength observations in disentangling feedback mechanisms across galactic scales.

Radiative feedback of super-Eddington accreting QSOs at high-redshift in cosmological simulations

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The discovery of gargantuan black holes (BHs) with masses in excess of a billion solar masses at $z > 6$ suggests extremely rapid BH growth and significant energy input into their host galaxies in the early Universe. As observations continue to probe these objects at higher redshifts, developing a robust theoretical framework for their formation and impact is crucial. In this work, we use high-resolution zoom-in simulations of a massive protocluster at $z \sim 6$, employing both the fiducial FABLE galaxy formation model and modifications to allow earlier seeding and super-Eddington accretion. We perform radiative transfer calculations in post-processing with a novel ray-tracing code to assess the effects of the quasar radiation field on its environment. We find that super-Eddington accretion drives strong feedback, launching powerful outflows that (i) increase the abundance of fast cold gas and (ii) strengthen the impact of the quasar radiation field, piercing far into the circumgalactic and intergalactic media.

Fast & Furious at z∼2: type-2 AGN host faster ionised winds than type-1 objects

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Although AGN-driven outflows are widely accepted to be a crucial ingredient of galaxy evolution, definitive observational evidence of their impact on the host galaxy is still missing. Cosmic noon (z∼2) is the epoch where AGN feedback is expected to be most effective, and a sweet spot for ground-based AO-assisted near-IR IFU observations, able to probe down to ∼1 kpc scales at higher spectral resolution compared to JWST. In this talk, I will present results from the SUPER survey, a completed AO VLT/SINFONI large program, aiming to investigate AGN feedback at z∼2. In particular, I will focus on the properties of the type-2 AGN subsample, for which we found evidence of spatially resolved ionised outflows, extending up to kpc scales and fast enough to reach 30-50 kpc from the galaxy centre. These type-2 AGN are all obscured systems and, interestingly, host faster ionised outflows than the type-1 AGN in SUPER of comparable bolometric luminosity. I will then discuss the main implications of these results, particularly the key role of dust in driving AGN outflows, the origin of the type-1/type-2 AGN dichotomy at high redshift, and the ejective/preventative ability of these winds. Finally, I will briefly show how the new VLT/ERIS IFU spectrograph, with performance superior to SINFONI, is now delivering a zoomed-in view of z∼2 galaxies, thus paving the way for future observations at cosmic noon with ELT/ MICADO and HARMONI.

Sub-Eddington, yet mighty: accretion and feedback of bright quasars from Reionisation to Cosmic noon’

Bartolomeo Trefoloni
Scuola Normale Superiore

The James Webb Space Telescope (JWST) has provided a transformative view of the first quasars and their host galaxies. I will present new JWST/NIRSpec integral field spectroscopy of a sample of quasars at the epoch of Reionization—the most distant quasars known to date. These data reveal powerful nuclear-scale outflows and extended [O III] emission up to ∼7 kpc, tracing large-scale ionized outflows. The associated mass outflow rates are comparable to the star formation rates, suggesting early feedback capable of quenching star formation. I will also introduce a novel, self-consistent method to determine key AGN properties (black hole mass, bolometric luminosity, and Eddington ratio), here applied for the first time on JWST data. This approach shows that super-Eddington accretion represents a short, bursty phase in AGN evolution, while black holes grow for most of their lifetime at an average Eddington ratio of ∼0.1. These results challenge current models of black hole formation and support scenarios involving massive or even primordial black hole seeds.

Can AGN Feedback Quench Star Formation in Mergers? Constraints from Multiwavelength SED Fitting and ALMA Observations of their Molecular Gas

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Major galaxy mergers trigger intense starbursts that are eventually quenched, with AGN feedback proposed as the key mechanism. The dual AGN phase at <10 kpc separations—when both SMBHs grow simultaneously—may mark the critical transition from peak activity to quenching. We present studies addressing the conditions and evidence for AGN feedback in merging systems. Multiwavelength SED analysis of 72 Swift-BAT AGN in mergers reveals that late-stage coalescence exhibits 5$\times$ enhanced star formation alongside 2.4$\times$ higher AGN luminosities and 2.8$\times$ increased obscuration, indicating peak SMBH accretion coincident with peak starburst activity. High-resolution ALMA CO observations show that molecular gas becomes concentrated within SMBH spheres of influence as separations decrease, making fuel reservoirs potentially vulnerable to feedback-driven removal. However, ALMA ACA 12CO(2–1) observations of 18 GOALS (U)LIRGs reveal no clear signatures of strong molecular outflows. Identified outflow candidates have velocities below escape velocities, suggesting gas remains gravitationally bound. Mass outflow rates and AGN contributions to bolometric luminosity support a scenario where feedback is primarily stellar-driven rather than AGN-driven. These results suggest that despite favorable conditions—concentrated gas and active SMBHs—AGN feedback may not yet dominate in these systems, raising questions about when and how AGN-driven quenching occurs.

A Wind-Driven Feedback Sequence in Luminous Type 2 Quasars

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We present new Chandra imaging spectroscopy of two luminous type 2 quasars, FIRST J120041.4+314745 and 2MASX J13003807+5454367, combined with HST [O III] imaging and kinematics, to investigate the role of hot, photoionized X-ray gas in driving AGN feedback on kiloparsec scales. Both systems host extended soft X-ray emission dominated by photoionization, yet display strikingly different feedback signatures. In FIRST J120041, the soft X-rays are clumpy and spatially coincident with high-velocity [O III] outflows, indicating strong coupling between the hot and warm ionized phases. In contrast, 2MASX J130038 shows centrally concentrated X-ray emission, largely rotational [O III] kinematics, and only tentative evidence for nascent outflow activity. We measure substantial hot-gas reservoirs (Mx-ray $\approx 10^8$ M$\odot$) in both quasars, exceeding the [O III] outflow masses, after volume normalization, by factors of ~4-16, implying that the hot phase dominates the ionized gas budget. We also report a tentative blueshifted Fe XXVI emission line in 2MASX J130038, consistent with a fast nuclear wind confined to the inner few hundred parsecs. Placing these objects in the context of a larger QSO2 sample, we propose a wind-driven evolutionary sequence in which AGN feedback emerges through the progressive clearing of circumnuclear gas, linking nuclear winds to galaxy-scale outflows.

Radio AGN as beacons of galaxy overdensities up to z~4

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Radio AGN are key tracers of BH growth and feedback, yet the role of environment across cosmic time in regulating their incidence is poorly constrained. While there is a strong correspondence between radio AGN and massive galaxies in overdense regions in the local Universe, it is still unclear if the same picture holds at high-z. In this talk, I will present our ongoing investigation on how the environment, the stellar mass, and redshift shape the occurrence of radio AGN. We exploit the incredibly rich dataset available for the COSMOS field, including the COSMOS-Web coverage with NIRCam, the deep VLA 3 GHz radio AGN catalog, and a recently released catalog of >1500 galaxy groups up to z~4. We measure the radio AGN luminosity function separately for galaxies in groups and in the field, quantifying environmental enhancement of AGN density as a function of radio power, stellar mass, and redshift. By modeling these trends, and by comparing the AGN fractions between group and field galaxies in bins of stellar mass, we disentangle the relative contributions of host galaxy mass, environment, and cosmic epoch to the triggering of radio AGN activity. Our findings suggest that large-scale (Mpc) overdensities can significantly enhance the incidence of radio AGN jets since z~4, at fixed galaxy stellar mass. These results pinpoint the primary role played by dense environments in fueling black hole growth from the local galaxy groups to the high redshift proto-groups and proto-clusters.

Quenching that shapes the first billion years

Akash Vani
Max Planck Institute for Astrophysics

Recent JWST observations of the first billion years revealed rapid quenching, structurally evolved galaxies and massive galaxies, exposing tensions with current numerical simulations. I present an upgraded semi-analytic framework called LGalaxies built on top of Gadget-4 in which we systematically tested some of the proposed solutions and introduce a self-consistent, physically motivated prescription for high-efficiency star formation and 'regulated' stellar feedback based on gas surface densities at high redshift within the ΛCDM cosmology. We also update galaxy merging and structural evolution by incorporating gas density-dependent processes and black-hole fueling channels, such as cold-gas inflows triggered by disk instabilities that are frequent at intermediate z. These mechanisms drive morphological transformation and compact galaxy sizes. The upgrades produce a boosted UV luminosity function over 10<z<13, more compact and massive quenched galaxies across 0<z<4, and, owing to already implemented advanced environmental effects, quenched satellite populations already at z>4. Across 0<z<13, from dwarfs to the most massive galaxies, the model reproduces key observables while maintaining agreement for the galaxy population at z=0. The updated mechanisms also impact black hole fueling channels as well as the growth and quenching of AGN in the early universe. Methodologically, we introduce a new calibration framework that is ~10$\times$ faster than prior implementations in the framework and a redesigned codebase that substantially improves speed and efficiency. We also describe ongoing efforts, such as a high-resolution dark-matter simulation tailored to early-universe galaxy formation, deep learning accelerated parameter exploration, and new drivers of morphological evolution relevant to high-z galaxies. Taken together, these advances, implemented within the fast, modular LGalaxies framework, offer a viable path to resolving several JWST-driven discrepancies and provide a computationally efficient platform for interpreting early galaxy formation.

GA-NIFS: The cosmic evolution of AGN outflows up to z~3-6 with JWST NIRSpec

Giacomo Venturi
Scuola Normale Superiore

The period between z~3-6 is a crucial transitional phase in galaxy evolution, leading to "cosmic noon" (z~1-3). A key actor in this phase is expected to be AGN feedback acting through energetic radiation and fast gas outflows. However, little is known so far about AGN feedback at these redshifts. I will present our study of AGN outflows at z~3-6 from GOODS-S and COSMOS fields, the largest spatially resolved sample to date (16 targets), exploiting JWST NIRSpec IFU observations from the GA-NIFS GTO survey. We found an outflow incidence of ~80%, significantly higher than in most AGN samples at lower redshifts. By mapping the rest-optical ionised gas emission lines ([OIII], Ha…) at sub-kpc scales, we inferred the outflow properties (kinematics, energetics) and probed their relations with AGN luminosity and galaxy star formation rate, and compared them with literature studies at different redshifts and AGN luminosities. We find evidence for a cosmic evolution of the outflow properties, indicating that outflows were stronger in the early Universe than at later times, and more capable of affecting their host galaxy evolution.

Connecting AGN feedback in galaxy formation simulations to recent and upcoming multi-wavelength observations

Rainer Weinberger
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Massive black holes (MBHs) play a crucial role in galaxy formation simulations, significantly impacting surrounding gas and reducing star formation through feedback effects. While cosmological galaxy formation models are effective at quenching massive galaxies and suppressing cooling flows, the detailed mechanisms of active galactic nucleus (AGN) feedback remain uncertain. This talk outlines new progress in linking AGN feedback - via jets and winds - to observed multi-wavelength signatures. Using cosmological and isolated cluster simulations with jet feedback, I will show how AGN jets influence cluster thermodynamics and turbulence as measured using X-ray data from XRISM, and discuss modelling radio emissions with a Fokker-Planck solver for non-thermal electrons to compare spectral aging and multifrequency observations, in particular low-frequency LOFAR data. Additionally, I'll share initial findings on connecting AGN activity to warm ionized and neutral gas phases traced by H-alpha, [OIII] emission and NaID absorption, and compare to recent JWST NIRSpec results.

Observational signatures of jet feedback on galaxy scales

Sophie Young
University of Tasmania

Jet kinetic feedback on galaxy scales is a key mechanism regulating galaxy evolution. Jet-environment interactions are complex. The jets drive shocks, turbulence, and outflows in the multiphase interstellar medium (ISM). Conversely, mass-loading and disruption of the jets by the ambient gas can alter the jet morphology and feedback being imparted. I will present a suite of simulations of jets propagating through a multiphase ISM and out to circumgalactic scales to explore how jet and environment properties shape observable radio signatures over time. These simulations track ionised and neutral outflows as jets burrow through the surrounding gas. Calculating free-free absorption and interplanetary scintillation signatures in post-processing, I will show how different feedback channels connect to the jets' observable properties, such as source size, broadband radio SEDs, and flux variability. Such approaches will be essential for interpreting data from large surveys, and predicting potential source populations observable with next-generation radio facilities.

Direct Evidence for AGN-Powered Turbulent Heating in the Perseus Cluster from XRISM

Congyao Zhang
Masaryk University

Radio-mode AGN feedback is one of the most plausible heating mechanisms in galaxy clusters, preventing their inner gas atmospheres from catastrophic overcooling. However, the underlying physics remains poorly understood, particularly the mechanisms by which AGN-inflated bubbles transfer their energy to the intracluster medium. In this talk, I will highlight a groundbreaking result on AGN feedback from XRISM observations of the Perseus cluster, which to date remains the only cluster target that allows us to probe a broad range of dynamical scales while simultaneously achieving sufficient spatial resolution. We have mapped the gas kinematic distribution of Perseus beyond its cool-core radius, providing direct evidence for the presence of at least two dominant gas motion drivers, with a transition occurring at a radius of ~60 kpc. These drivers are associated with AGN feedback and mergers (i.e., the cosmological environment), respectively. The inner, small-scale driver sustains a heating rate at least an order of magnitude higher than that of the outer, large-scale driver, highlighting the significant role of AGN-powered turbulence in offsetting radiative cooling losses.

Central Shocks and Metal-Enriched Outflows: A New View of AGN Feedback

Peixin Zhu
Center for Astrophysics | Harvard & Smithsonian

The growth of galaxies and their central supermassive black holes (SMBHs) is tightly linked. However, the exact impact of active galactic nuclei (AGNs) feedback on the host galaxy is still uncertain, with different observations suggesting AGNs enhance, suppress, or do not affect the host galaxy star formation rate. Resolving these controversies requires proper treatment of shocks, which are known to exist with AGN-driven outflow and yet are difficult to distinguish from AGN emission. In my talk, I will present a new theoretical three-dimensional diagram built for integral-field spectroscopy that cleanly separates star formation, AGN, and shock-dominated spaxels. Furthermore, these separation results can be combined with theoretical diagnostics to map the spatial distribution of gas-phase metallicity, ionization parameter, and gas pressure within these galaxies. After applying this new technique to 8 nearby Seyfert galaxies, we reveal that AGN and star formation coexist in the galaxy center, and fast shocks are present at the base of AGN outflows in some galaxies. We also find that outflowing gas is systematically metal-enhanced relative to adjacent star-forming rings. I will discuss how these results refine the picture of AGN feedback and the implications for nuclear enrichment and gas transport.

AGN outflows in different hosts: when does it eject or compress gas?

Kastytis Zubovas
Center for Physical Sciences and Technology

Observed AGN outflows correlate with the luminosity of the driving AGN, but show order-of-magnitude scatter around the relation. One source of the scatter is the diversity of AGN host galaxy properties: identical AGN, powered by identical SMBHs, can reside in galaxies with significantly different masses, effective radii, stellar velocity dispersions and gas fractions. We ran a suite of 50 purpose-built SPH simulations of AGN outflows propagating in spherical gaseous bulges with realistic clumpy interstellar medium properties. The simulations covered a range of SMBH masses between 10^7-3×10^8 Msun, with velocity dispersions and bulge masses spanning the observed scatter in the M-sigma and MBH-Mbulge relations. We tested the evolution of outflows and their impact on the host galaxy gas when driven by constant-luminosity AGN with Eddington ratios of 0.1-1. I will present results showing how galaxies with deeper gravitational potentials and higher gas fractions efficiently confine outflows, leading to more efficient cooling and reduced outflow energy. This produces distinct outcomes: gas compression and enhanced star formation in compact galaxies, versus gas ejection and quenching in diffuse ones. I will discuss how IFU observations of host galaxy structure and outflow kinematics can test these predictions and clarify the role of AGN feedback on star formation over multi-Myr timescales.

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