# Astro2020 Science White Paper

# Do Supermassive Black Hole Winds Impact Galaxy Evolution?

**Thematic Areas:** Formation and Evolution of Compact Objects; Galaxy Evolution; Multi-Messenger Astronomy and Astrophysics

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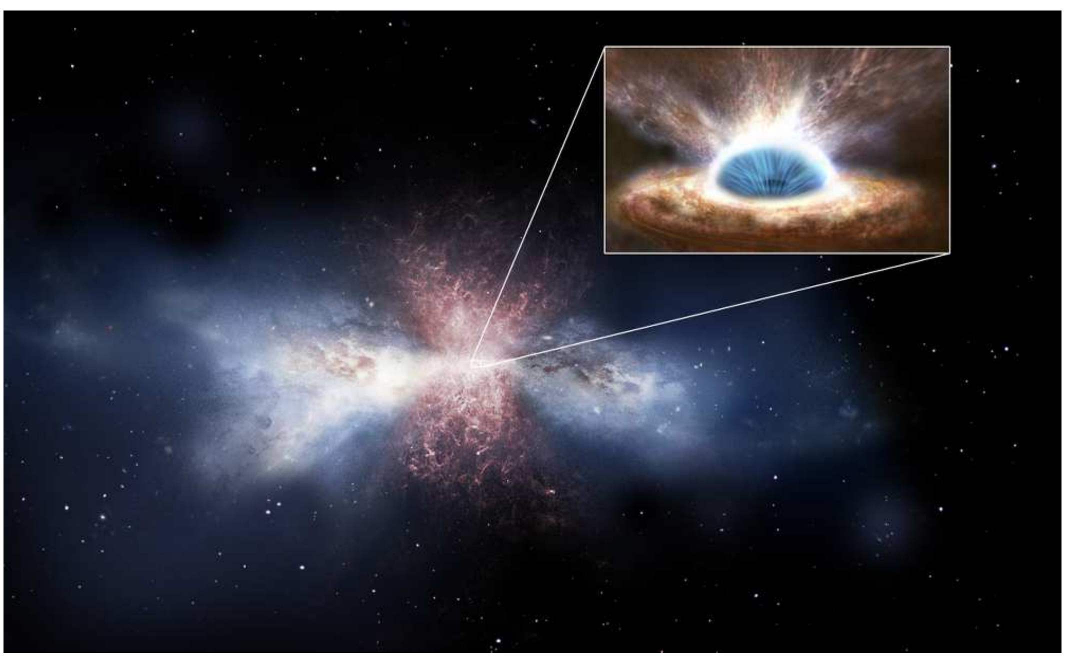

## Introduction

Virtually every galaxy in the universe hosts a supermassive black hole (SMBH) at its center, with masses that are found to correlate with galactic-scale properties (e.g., Kormendy 2016). The growth of SMBHs may be triggered by both galaxy mergers in the early universe and/or by secular processes internal to their host galaxies, mostly observed in low-redshift isolated sources (e.g., Kormendy & Kennicutt 2004). As dust and gas are gradually dispersed from the central regions, a completely obscured active galactic nucleus (AGN) evolves to a dusty phase and finally to a completely exposed quasar (e.g., Hopkins et al. 2006). Galactic winds driven by the central AGN have been invoked to play a fundamental role in this phase, quenching the growth of both the SMBH and stellar spheroidal component, and explaining the tight SMBH-spheroid mass relation (Silk & Rees 1998; King & Pounds 2003). Moreover, AGN outflows, in the form of winds and jets, are also required to prevent catastrophic cooling flows and for dispersing metals at galactic and intergalactic distances (e.g., Gaspari & Sadowski 2017a). Understanding the physics of how mass and energy flows over such enormous spatial scales is of paramount importance to understand both galaxy and SMBH evolution.

Within this context, high-velocity winds in the X-ray band are regarded as the most effective way of transporting energy from the nuclear to galactic scales (Tombesi et al. 2010, 2015; Nardini et al. 2015; King & Pounds 2015). According to models, the energy of such SMBH driven winds is deposited into the host galaxy interstellar medium (ISM), resulting into the recently observed galactic-scale molecular outflows, which are able to sweep away the galaxy's reservoir of gas and quench star formation activity (e.g., Zubovas & King 2012; Faucher-Giguere & Quataert 2012). The key questions to be addressed here are: *How do SMBHs launch winds/outflows, what is their physical geometry, and do they affect SMBH growth? How are the energy and metals transferred and deposited into the galactic and circumgalactic medium? What is the relation between SMBH feeding and feedback? How does this self-regulated cycle develops?*

X-ray observations are a unique way to address these questions because they probe the initial, highest-ionization and hottest phase of the outflow, which carries most of the kinetic energy (e.g., Tombesi et al. 2013). High throughput, high spectral and spatial resolution instruments as those proposed for *Athena*[1] (Barcons et al. 2017), *Lynx*[2] (Özel 2018), and *AXIS*[3] (Mushotzky 2018) are required to determine the acceleration and launching mechanism(s) of SMBH driven outflows and to quantify their impact on galaxy evolution.

## How do SMBHs drive winds and how much mass and power do they carry?

SMBH winds are directly observed as blue-shifted and broadened absorption lines in the X-ray spectra of at least half of AGNs (e.g., Crenshaw & Kraemer 2012; Tombesi et al. 2013). These absorption systems span a range of about six orders of magnitude of velocities and physical conditions, suggesting a continuous stream that carries kinetic energy and momentum away from sub-pc scales potentially up to the kpc-scale environment (e.g., Arav et al. 2018). Simulations of accretion disks and outflows have progressed enormously in recent decades, and show that several physical mechanisms (thermal, radiation, magnetic) are able to accelerate winds, providing a theoretical basis for understanding the observations (e.g., Blandford & Payne 1982; King &

[1]https://www.the-athena-x-ray-observatory.eu/
[2]https://wwwastro.msfc.nasa.gov/lynx/
[3]http://axis.astro.umd.edu/

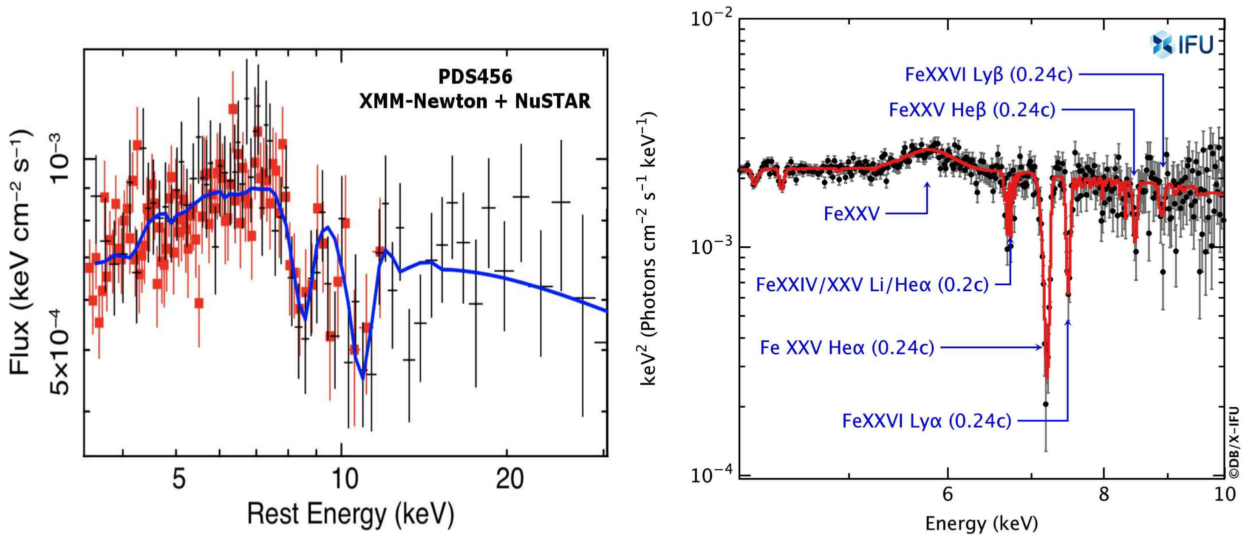


Figure 1: *Left:* Simultaneous 150 ks XMM-Newton & NuSTAR spectra of the quasar PDS 456 showing hints of a highly ionized outflow with two relativistic velocity components in absorption (Reeves et al. 2018). *Right:* Simulated 100 ks *Athena* X-IFU spectrum of the same source. A series of absorption lines from an outflow with two velocity components at $v_{out}$=0.20–0.24c and a turbulent velocity broadening of 3,000 km s$^{-1}$ would be clearly detectable thanks to the unprecedented high-energy resolution and throughput provided by the *Athena* X-IFU (Credits: X-IFU Consortium).

Pounds 2003; Proga, Stone & Kallman 2000; Fukumura et al. 2010). However, what determines the dominant mechanism is not yet understood.

Blue-shifted narrow absorption lines in the UV and soft X-rays suggest outflows with moderate velocities of hundreds to few thousands km/s. These "warm absorbers" are detected in >50% of AGN (Crenshaw & Kraemer 2012), and may have an origin in the swept-up interstellar medium (ISM) or thermally driven winds from the outer accretion disk. In the UV band, broad absorption lines are seen in ~30% of AGN, and may be present outside the line of sight in most quasars (Ganguly & Brotherton 2008). These absorbers can be outflowing with velocities as high as ~20% of the speed of light, and so they carry considerable kinetic power, defined as $E_k = (1/2)\dot{M}_{out}v_{out}^2$, where $\dot{M}$ is the mass outflow rate.

The most powerful observed outflows appear to be so highly ionized that only the bound transitions of hydrogen- and helium-like iron are left, making them detectable only at hard X-ray energies. These X-ray winds are observed in >30% of local AGN, and even in some higher redshift quasars (Chartas et al. 2002; Lanzuisi et al. 2012), with outflow velocities of up to ~30% of the speed of light (Tombesi et al. 2010). These "ultra-fast outflows" (or UFOs) have velocities that point to an origin very close to the SMBH, but the launching and acceleration mechanism(s) remain unclear.

The key to progress on this investigation is a detailed characterization of the physical properties of these winds (column density, ionization state, outflow velocity, location, geometry, covering factor, etc.). The upcoming X-ray Imaging and Spectroscopy Mission (*XRISM*) will provide high spectral resolution observations but, due to the relatively low collecting area and spatial resolution, these will be limited to the nearby brightest AGNs (e.g., Kaastra et al. 2014). Only the high-energy resolution and high throughput offered by the proposed *Athena* (e.g., Cappi et al. 2013) and *Lynx* (e.g., Özel 2018) X-ray observatories will allow the study of such outflows on a large enough sample of sources to effectively probe the prevalence and evolution of these systems from the early universe to the current epoch (e.g., Georgakakis et al. 2013). These proposed missions will provide enough S/N to utilize short time-scale ($\simeq$ hrs) variability as a tool to explore the wind launching region down to a few Schwarzschild radii (e.g., Miller et al. 2010; Waters et al. 2017).

The unprecedented data quality will allow us to seek correlations among the fundamental parameters such as density, ionization, outflow velocity, and luminosity, which will uniquely constrain predictions of radiation-driven (e.g., Proga, Stone & Kallman 2000), momentum-driven (King 2010), and magnetically-driven (Fukumura et al. 2010) accretion disk wind models. With such next generation data we will also be able to quantify the outflow efficiency (i.e., the ratio between the accretion and ejection rates), as well as the kinetic power budget of the various components in the wind to better assess their impact on the large-scale environment of the host galaxy. The feasibility of such analysis is shown in Fig. 1, where the spectrum of the quasar PDS 456 obtained simultaneously with *XMM-Newton* and *NuSTAR* showing hints of a possible two velocity component outflow (Reeves et al. 2018) is compared to simulated data from the *Athena* X-ray integral field unit (X-IFU), which will allow a full determination of the outflow kinematic and ionization structure, necessary for reliably constraining the wind energetics.

Such X-ray observations are key for determining the total column density, the highest velocities, the highest ionization, and hence the kinetic power carried by SMBH outflows, which is required to drive the ensuing galaxy-scale outflows. The proposed *Athena* and *Lynx* high spectroscopic throughput will allow for a giant leap in sensitivity to most ionization states of light elements, and to all those of iron (from neutral to hydrogen-like), hence providing a detailed characterization and understanding of the SMBH outflow.

**How do SMBH winds interact with the galaxy-scale environment?**

Understanding accretion and ejection processes is fundamental to uncover the origin of AGN feedback and the co-evolution of SMBHs and their host galaxies. Depending on the covering factors and duty cycles, the mass outflow rate from SMBH outflows may reach kinetic powers of a few per cent of the AGN bolometric luminosity, exerting a significant impact on the host galaxy, as shown by numerical simulations (Hopkins & Elvis 2010; Ostriker et al. 2010; Gaspari, Brighenti & Temi 2012; Zubovas & King 2012; Faucher-Giguere & Quataert 2012; Wagner et al. 2013; Gaspari & Sadowski 2017a). See the left panel of Fig. 2 for a schematic view.

While fast AGN outflows can carry a large amount of mechanical power from the innermost region nearest to SMBHs, how, if, and where this energy is actually released into the interstellar medium is far from understood. Although there is wide consensus that AGN feedback is likely able to quench star formation, a quantitative understanding of how this process works is still lacking. A breakthrough will come only from coordinated synergies between high-quality X-ray data (probing the first phase of the wind) and lFU observations at longer wavelengths (probing the mass and extension of the molecular and ionised outflows).

Observational evidence is mounting that AGN act on the multi-phase - molecular, atomic, ionized - ISM of their host galaxies on large scales and, through this, affect the evolution and transformation of the host galaxy (e.g., Cicone et al. 2018). For instance, kpc-scale outflows have recently been discovered in both star-forming galaxies and in powerful AGN (Veilleux et al. 2013), at millimeter and far-infrared wavelengths (with IRAM, ALMA, Herschel). The inferred mass outflow rates of up to several hundreds of solar masses per year and high kinetic power suggest that AGN activity is the driver, providing strong support to models of AGN feedback. Evidence

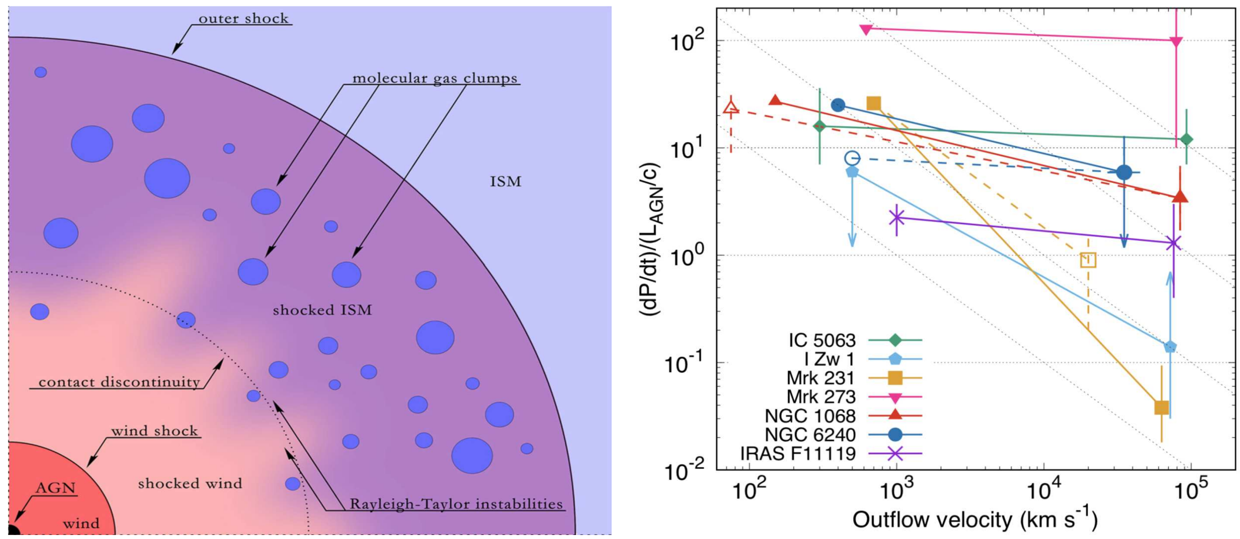


Figure 2: *Left:* Schematic view of the multi-phase AGN driven outflow launched near the central SMBH and interacting with the host galaxy interstellar medium (Zubovas & King 2014). *Right:* Momentum flux versus outflow velocity for the inner SMBH outflows (right side) and galaxy-scale molecular outflows (left side) in a small sample of seven active galaxies. The horizontal lines show the momentum-driven flows, whereas the ones ascending toward the left show the energy-driven flows (Mizumoto et al. 2018).

of powerful, massive molecular outflows has also been found in a few quasars at high redshifts (Maiolino et al. 2012).

The first evidence of a SMBH wind with a velocity of 25% of the speed of light in a late-stage galaxy merger hosting a massive molecular outflow was found comparing the X-ray and F-IR spectra of IRAS F11119+3257 (Tombesi et al. 2015). The comparison of the energetics of these outflows indicates a connection between the SMBH driven wind and the large-scale molecular outflow. This is shown for an additional six sources in the right panel of Fig. 2 from Mizumoto et al. (2018). Such a diagram provides a way to trace the SMBH wind observed in X-rays to the depletion of the "fuel" required for star formation activity, outlined by the large-scale molecular outflow observed in infrared and mm spectra (Tombesi et al. 2015; Feruglio et al. 2015, 2017; Veilleux et al. 2017). Clearly, there is an urgent need to populate the plot in the right side of Fig. 2 with a larger number of higher quality data points in order to directly compare it with theoretical models and estimate the global parameters of this crucial astrophysical process.

In nearby AGN, feedback can be directly probed by 3-D mapping of the various components which overlap spectrally or spatially. Along with spectroscopy, good spatial resolution is therefore necessary for a full characterization of the winds phenomenon. In this respect the few arcsec resolution of *Athena* is the minimum needed to start resolving the outflow patterns traced by filaments, bubbles, shells, streamers, etc. in nearby active galaxies (Wang et al. 2011; Paggi et al. 2017). This can be pushed to much higher detail and higher redshifts with the sub-arcsec resolution envisioned for *AXIS* and *Lynx*, close to the resolution achievable with *JWST* and *ALMA*.

Studies have been performed to trace the large-scale soft X-ray emission in dozens of nearby AGN, on scales ranging from a few arcsec to several tens of arcsec (Wang et al. 2011, 2012). However, to date, determining whether the extended soft X-ray emission and AGN-excited narrow line region may be related to an outflowing wind and/or shocks has been hampered by insuffi-

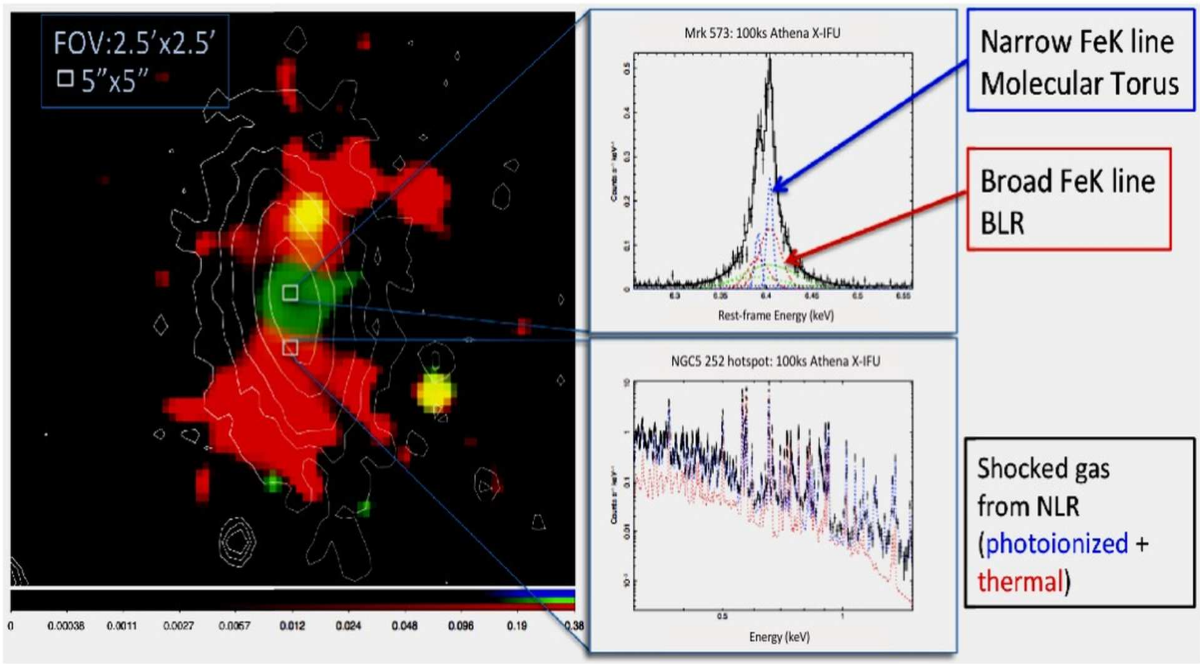


Figure 3: *Left: Athena* simulated color-coded image of the nearby Seyfert 2 galaxy NGC 5252 (from the Chandra image in Dadina et al. 2010). The soft X-rays are known to trace the [OIII] ionization cones forming a biconical outflow/illumination pattern driven by the AGN which impacts all over the host galaxy (DSS optical contours indicated in white). *Right-top: Athena* X-IFU simulated spectrum of the Fe K emission line assuming the sum of a broad plus a narrow line component, from the BLR and molecular torus respectively. *Right-bottom: Athena* X-IFU simulated spectrum of a part of the plume of ionized emission south of the nucleus and attributed to 25% of shock (thermal) emission plus 75% of photoionized emission. Adapted from Cappi et al. (2013).

cient spatial resolution and sensitivity (Pounds & Vaughan 2011; Fischer et al. 2013). Fig. 3 illustrates the capabilities of an X-IFU, as proposed on *Athena*, for studying AGN feedback in nearby Seyfert galaxies. High spatial and energy resolution are needed to simultaneously resolve the most prominent components of soft-X-ray diffuse emission, and to spectrally map both the nuclear and extended outflow components. Finally, it is important to note that feeding and feedback are two intimately linked phases for SMBH and galaxy co-evolution and high-resolution, multi-wavelength imaging and spectroscopic observations, as offered by upcoming IFU detectors, are required to directly compare with numerical predictions (e.g., Gaspari & Sadowski 2017a, b; Gaspari et al. 2018).

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