(Active) Galactic Nuclei

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Draft Version, 20.6.2016

Executive summary

The study of galactic nuclei, and of the supermassive black holes that reside in there, is a complex, and far-reaching area of intense research within the astrophysical community worldwide, and in Germany in particular. Active Galactic Nuclei (AGN) and their dormant counterparts are unique physical laboratories (providing tests of strong gravity, extreme plasma conditions, high-energy particle acceleration and gravitational waves generation), but may also hold the keys of our understanding of galaxy evolution and Cosmology. Operatively, the study of galactic nuclei is a showcase for multi-wavelength astronomy, highlighting epistemological trends that will become more and more commonplace in astrophysics in the coming decades. Over the last decade, research carried out in Germany has had significant impact on the field of AGN studies. We summarize this here by presenting ten "success stories", followed by an outline of which will be the key questions in the field for the coming decades. In our Summary, we present a sketch of a roadmap intended to provide guidance towards addressing such question (including instrumental developments) and we highlight strengths and weaknesses of the German community in this area of research.

1. Introduction: What is a Galactic Nucleus?

Since the discovery in the late ‘90s that most, if not all, galaxies harbor a supermassive black hole, the study of galactic nuclei has received a vigorous impulse. These objects, whether in an active, growing phase, or in quiescence, represent among the best laboratories to study extreme physical processes pertaining to gravity theories and plasma physics. Because of the complex multi-scale nature of the AGN phenomenon, the interpretation of the data requires a profound knowledge of the many physical processes involved. Thus, astrophysical studies of black holes in galactic nuclei are, by their very nature, pan-chromatic and multi-messenger: high energy neutrinos, cosmic rays and gravitational waves are all useful complements to electromagnetic observations. As such, the study of galactic nuclei represents a showcase of multi-tracer astronomy, and may serve as a model for future holistic views of the Cosmos.

In the last decade, a combination of high sensitivity, high spatial resolution observations and of coordinated multi-wavelength surveys has revolutionized our view of black hole (BH) astrophysics. We now know that supermassive black holes in the nuclei of galaxies grow over cosmological times by accreting matter, interact and merge with each other, and in the process liberate enormous amounts of energy that influence dramatically the evolution of the surrounding gas and stars, and fill their immediate surroundings, and the whole Universe, with cosmic rays and magnetic fields, providing powerful self-regulatory mechanisms for galaxy and structure formation.

Indeed, the local supermassive black hole (SMBH) distribution is the outcome of the cosmological growth of structures and of the evolution of mass inflow towards (and within) the nuclear regions of galaxies, likely modulated by the mergers these nuclear black holes will experience as a result of the hierarchical galaxy-galaxy coalescences. Both in-depth studies of individual objects and population studies of evolving SMBHs via large multi-wavelength surveys have been fundamental avenues of research in the last decade, and will continue to do so in the next one. A better understanding of the SMBH population, and of its evolution, will inform and provide critical constraints to galaxy evolution studies and Cosmology, and will serve as a frame of reference in the pioneering years of gravitational wave astronomy (see Chapter 10, Kramer et al.) and astro-particle physics (see Chapter 16, Mannheim et al.).

In this document, we highlight the fundamental contributions that the German Astrophysics community has provided to the field in the last ten years, and outline a set of fundamental questions that we believe will dominate the landscape of (active) galactic nuclei research in the next decade(s).

2. Ten German success stories

Researchers working at German institutions on galactic nuclei have achieved a remarkable number of fundamental results. Here, we present a selection of ten success stories.

2.1 The Center of the Milky Way

At a distance of 25,000 light years only, the galactic center is a truly unique astrophysical laboratory for studying in unparalleled detail stars and gas around a massive black hole (Genzel et al. 2010). Using high-angular resolution techniques in the near-infrared we have moved closer and closer to an observational proof of existence of an astrophysical massive black hole. The compact radio source Sgr A* in the galactic center is associated with a black hole of roughly 4 million solar masses. The proof itself is as beautiful as simple: by monitoring individual, short-period stars on Keplerian orbits one can weigh the central mass to percent-level precision (see Figure 1; see also Schödel, Merritt, Eckart 2009).

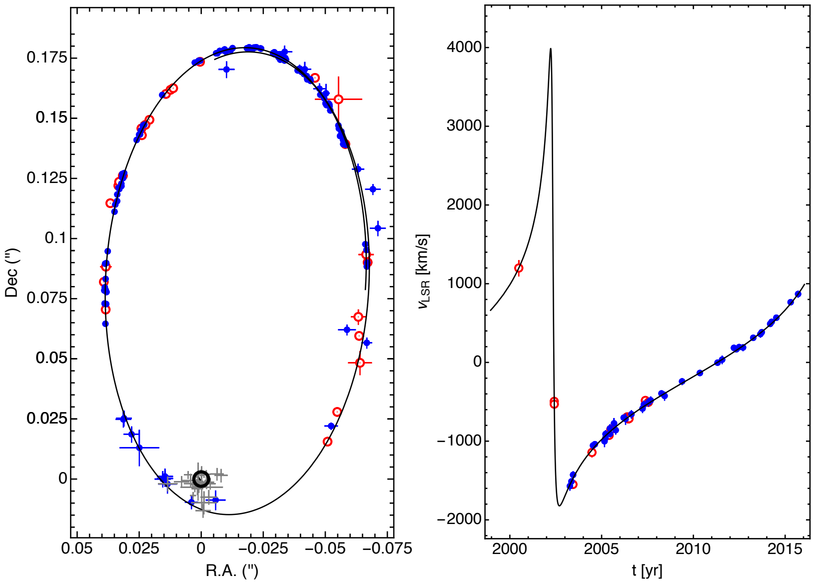


Figure 1: The orbit of the star S2 in the galactic center. *Left*: the data points are measurements of the positions from 1992 to 2015. The star is orbiting Sgr A* every 16 years on a Keplerian ellipse (best fit: black line). *Right*: The radial velocity data are fit simultaneously by the same orbit model (Gillessen et al. 2009, 2013).

As a surprise came in 2011 the discovery of a little 3-Earth-mass gas cloud, called G2, that was approaching quickly the massive black hole (Gillessen et al. 2012). It passed the pericenter of its orbit in Spring 2014. The data recorded shows in beautiful detail how G2 has been tidally disrupted by the gravitational force of the massive black hole - the first time that one can follow and study this process observationally. Since 2013 we have been able to see how the gas has swirled around the black hole. In this way, Sgr A* represents also a laboratory for the study of plasma physics processes in the strong gravitational field of a SMBH. The observed spectral energy distribution, both in quiescence and in the regularly observed flares, can be modeled to reveal details of the interaction between accreting matter and the black hole energy release (eee e.g. Dodds-Eden et al. 2011; Eckart et al. 2012; Ponti et al. 2015).

The near future will be exciting in galactic center research: The near-infrared observers will be able to use the VLT interferometer GRAVITY soon, increasing resolution and accuracy by more than a factor 10 of what is possible today (Eisenhauer et al. 2011). Similarly, observers in the mm-regime will soon use global VLBI to synthesize a radio telescope that has almost Earth diameter. Such an instrument might be able to form an actual image of the massive black hole in the galactic center. The European effort is bundled in the "Black Hole Cam" project, while the US colleagues brand the same idea as "Event Horizon Telescope".

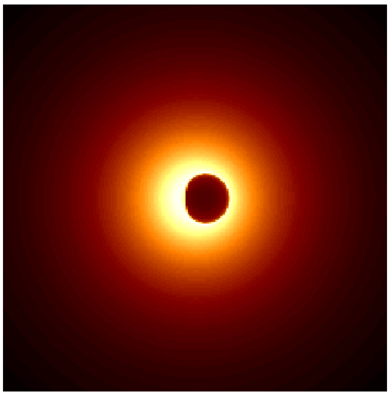


Figure 2: Simulated image of the massive black hole in the galactic center. Global mm-VLBI aims at obtaining such an image, in which the shadow from the event horizon appears as a distinct feature (Falcke, Melia & Agol 2000).

2.2 Resolved studies of feeding and feedback in nearby galactic nuclei

Infrared high-resolution techniques (namely adaptive optics and interferometric observations on very large telescopes) also excel at revealing the physical processes at play in other, nearby galactic nuclei. The German community occupies a favorable position in the field thanks to the development of PI instruments such as NACO, SINFONI, MIDI, GRAVITY, PACS. This has led to a number of fundamental discoveries, among which we mention here: (i) spatially and kinematically resolved studies of feeding and feedback in many galaxies (see e.g. Davies et al. 2007, 2014, and various papers based on IFU data) and (ii) interferometric observations resolving the (sub-)parsec-scale dust structures in nearby AGNs, leading to the realisation that there are at least two distinct components, one of which appears to trace the outflow (Meisenheimer et al. 2007, Tristram et al. 2014, Burtscher et al. 2013). The former provided the first clues of spatial and temporal correlation between gas consumption due to star formation and accretion onto the black in galactic nuclei; the latter helped us tracing the warm gas and dust that surrounds the innermost regions of AGN, provides the material for accretion onto the super-massive black hole, and is held responsible for the orientation-dependent obscuration of the central engine.

2.3 Tidal disruption events

At least some part of the fuel supply for AGN must come from stars, which abound within galactic nuclei, and will be tidally disrupted when dislodged into orbits passing close enough to the central black hole. The frequency of such events depends on the stellar dynamical properties of galactic nuclei, and is a non-trivial outcome of a series of complex processes. Indeed, there is substantial uncertainty in the true rate of tidal stellar disruption in galactic nuclei. Observational studies have mostly reported constraints on the tidal disruption event (TDE) rate that are up to one order of magnitude lower than most theoretical predictions. This apparent contradiction should not be surprising, as, observationally, the field is still in its infancy; only around two dozen TDE candidates have been identified so far by means of X-ray UV and optical observations (see Gezari 2013; Komossa 2015, for recent reviews). German scientists have played an important role in this early phase, with the first TDE discovered in the ROSAT data more than 10 years ago (Komossa et al. 2004). Today, the rate of discovery is increasing dramatically with the advent of large wide-area optical time-domain surveys (mostly driven by supernovae searches), such as the Catalina Real-Time Transient Survey, the Palomar Transient Factory, PanSTARRS and the All-Sky Automated Survey for Supernovae. The future promises even more rapid advances with next generation wide area X-ray (SRG/eROSITA, Merloni et al. 2012, Khabibullin et al., 2014), and optical (Skymapper, ZTF and LSST) surveys.

2.4 Black hole mass measurements based on resolved gas and stellar kinematics; BH-galaxy scaling relations

Astronomers in Germany have contributed significantly to the census of black holes at the centers of galaxies by observing and modeling the motion of gas and stars at very high spatial resolution using space observatories and ground based adaptive optics assisted facilities (Bender et al. 2005, Neumayer et al. 2007, Saglia et al. 2016). It has observationally been shown that every galaxy more massive than the Milky Way hosts a massive black hole at its center, with masses between a million to several billion solar masses. Surprisingly, the mass of the central black hole correlates tightly with the mass of the surrounding galaxy or galaxy bulge (see Figure 3) - often expressed in terms of the galaxy's velocity dispersion σ or by the galaxy luminosity (see e.g. Häring and Rix 2004, Beifiori et al. 2012, Saglia et al. 2016, Figure 4). This means the more massive the central black hole, the more massive is its host galaxy, and vice versa.

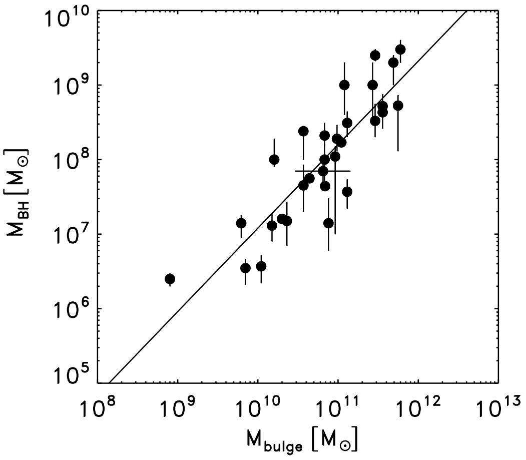


Figure 3 The relation between black hole mass and bulge mass for a sample of 30 galaxies. As these galaxies have been selected to be mainly elliptical galaxies, the bulge mass is equal to the total galaxy mass for most of the galaxies (from Häring & Rix 2004).

The tightness of this correlation seems surprising, because the black hole and the galaxy it sits in act on very different spatial scales. The galaxy does not feel the gravitational influence of the black hole and hence, the origin of the correlation was sought for in the common evolution of the black hole and its host galaxy. The cosmic evolution of the observed scaling relations is an important diagnostic in uncovering the possible coevolution (Merloni et al. 2010, Bongiorno et al. 2012), however, selection effects play a significant role in the analysis (Schulze & Wisotzki 2014). The effect of feedback of an active black hole on its surroundings (e.g. Di Matteo et al. 2005) has been challenged, as the observed correlation could also be explained solely by the hierarchical assembly of the black hole and its 'parent' galaxy (Jahnke & Macciò 2011).

Given all the widespread relevance attached to the scaling relations discussed above, one important question still remains open: How massive are the original "seed" black holes? (Neumayer & Walcher 2012, Latif et al. 2013). The future looks bright for research in this direction. High spatial resolution instrumentation, both from space (JWST) and from the ground (E-ELT) will be key in answering this important open question.

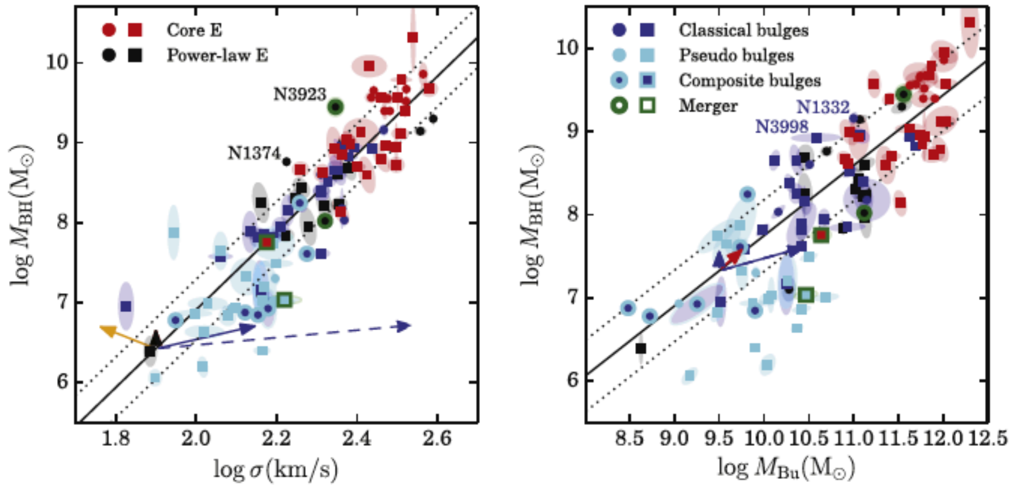


Figure 4: The relation between black hole mass and stellar velocity dispersion σ (left) and bulge mass (right) as presented in Saglia et al. (2016).

2.5 VLBI and relativistic jet kinematics

High-resolution radio observations with Very Long Baseline Interferometry (VLBI) are a powerful tool to reveal the innermost regions of active black holes, in particular the sites of particle acceleration at the base of relativistic jets. In the last few years, major progress has been made in understanding the characteristics of relativistic outflows at parsec scales and their kinematics from the MOJAVE program (Lister et al. 2009; 2013). Within Germany, the MPIfR and the Effelsberg telescope have played a major role in these endeavors. Abdo et al. (2010) and Fuhrmann et al. (2014) showed how the combination of radio and Fermi gamma-ray data reveals key features of the Spectral Energy Distribution (SED) of Blazars, those jetted AGN seen along the axis of the relativistic flow, and constrain the models for the emission processes in these systems. VLBI observations also proved crucial to map the acceleration of relativistic jets in nearby radio galaxies, providing the highest resolution view yet of such complex processes. Also here, mm-VLBI in the coming years (see section 2.1), by resolving sizes of the order of a few gravitational radii in M87 (see e.g. Krichbaum et al. 2006), is bound to revolutionize our understanding of jet formation and acceleration.

2.6 AGN in VHE gamma-rays

Almost at the opposite end of the electromagnetic spectrum, Blazars represent the prototypical class of Very High Energy gamma-ray sources. Most discoveries of astronomical sources, their classification, and the first population studies were done with instruments with a strong (and in most cases leading) German participation, such as the MAGIC and HESS telescopes. Among the key discoveries of the last ten years, we list here (i) the discovery of a PeVatron in the Galactic center (HESS), and (ii) the discovery of the ultra-short (on minute timescale) variability of blazars in VHE energies (HESS and MAGIC). Such a success story deserves more than the little space we have available here, and we refer the reader to Chapter 11 (Pohl et al.) for a more in-depth discussion of VHE gamma-ray astrophysics, including AGN studies.

2.7 AGN evolution

Given the observed population of supermassive black holes in galactic nuclei, a key question that have kept busy observers and theoreticians alike is the following: can we constrain models of their cosmological evolution to trace back the local population to their formation mechanisms and the main observable phases of growth, as identified by the entire AGN population?

As opposed to the case of galaxies, where the direct relationship between the evolving mass functions of the various galaxy types and the star formation distribution is not straightforward, due to their never-ending morphological and photometric transformation, black holes are characterized only by two physical properties (mass and spin), the evolution of which is regulated by analytical formulae, to the first order functions of the rate of mass accretion onto them. Thus, for any given “seed” black hole population, their full cosmological evolution can be reconstructed, and its end-point directly compared to any local observation, provided that their growth phases are fully sampled observationally. On the other hand, black holes growth erases all information on the initial conditions, while in galaxies dynamics and stellar populations can help us disentangling their formation history.

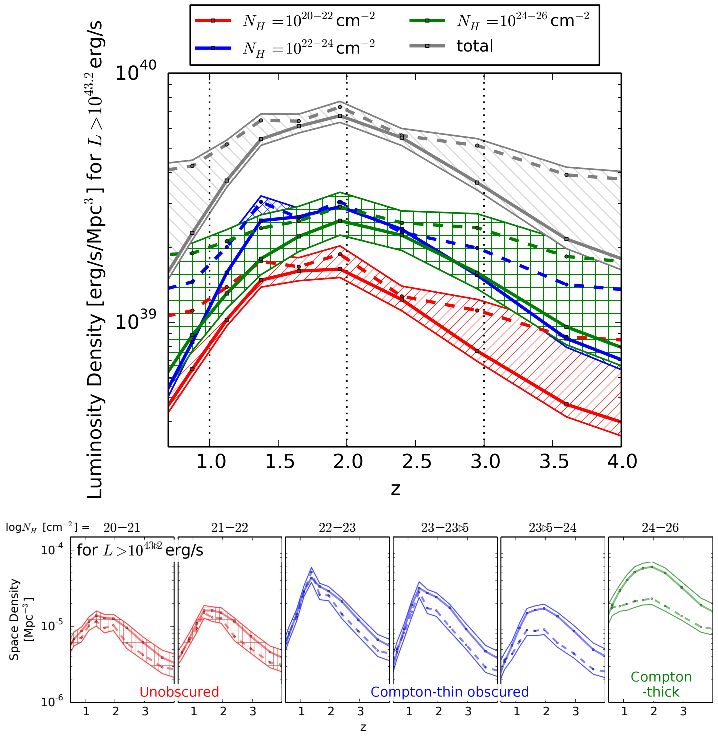


Figure 5 ***Top panel:*** **Evolution of the X-ray luminosity density of AGN with $L_X > 10^{43.2}$ erg/s, for various intervening column densities. The luminosity output of AGN experiences a rise and fall in density in the *z* = 1 - 3.5 range (total as top gray shaded region). The strongest contribution to the luminosity density is due to obscured, Compton-thin (blue shaded region) and Compton-thick AGN (green shaded region), which contribute in equal parts to the luminosity. The emission from un-obscured AGN (red shaded region, bottom) is significantly smaller.** ***Bottom panel:*** **Redshift evolution of space density of AGN split by the level of obscuration. Different panels correspond to different hydrogen column density interval as indicated at the top. From Buchner et al. (2015).**

This motivates ever more complete AGN searches (surveys). The level to which the desired completeness can be achieved in practice depends on the level of our understanding of the physical and electromagnetic processes that take place around accreting black holes. So, we cannot discuss the evolution of supermassive black holes without an in-depth understanding of AGN surveys, and of their results; but at the same time, we cannot understand properly these surveys if we do not understand the physics behind the observed AGN phenomenology.

For the study of AGN, X-rays have merits over other selection techniques, primarily a uniform and quantifiable selection function at all redshifts, and a reduced incidence of absorption due to intervening matter along the line of sight (mostly located in the immediate vicinity of the black hole itself) and host galaxy light dilution. This is critical, because in order to discriminate among the many and different models for the co-evolution of back holes and galaxies, we need an inventory of AGN as complete and homogeneous as possible (see Merloni 2016, for a recent review). The deepest surveys so far carried out in the soft X-ray energy range (0.5–2 keV), supplemented by the painstaking work of optical identification and redshift determination of the detected sources have provided the most accurate description of the overall evolution of the AGN luminosity function. Neither pure luminosity nor pure density evolution provide a satisfactory description of the X-ray LF evolution, with a good fit to the data achieved with a "Luminosity Dependent Density Evolution" (LDDE) model, or variations thereof. In their influential work, Hasinger et al. (2005) unambiguously demonstrated that in the observed soft X-ray energy band more luminous AGN peaked at higher redshift than lower luminosity ones. Thus, a qualitatively consistent picture of the main features of AGN evolution is emerging from the largest surveys of the sky in various energy bands. Strong (positive) redshift evolution of the overall number density, as well as marked differential evolution (with more luminous sources being more dominant at higher redshift) characterizes the population (see e.g. Schulze & Wisotzki 2010; Buchner et al. 2015, Figure 5).

2.8 Physics of Low-Luminosity AGN, fundamental plane of BH activity

The possibility to apply scaling relations to the properties of accreting black holes across the mass scale has been a long-standing goal of relativistic astrophysics. One step in that direction was the study of Merloni, Heinz & Di Matteo (2003), who examined the disc--jet connection in stellar mass and supermassive black holes by investigating the properties of their compact emission in the X-ray and radio bands, and demonstrate that the sources define a ``fundamental plane'' in the three-dimensional (log L_R, log L_X, log M_{BH}) space. This important empirical correlation has an elegant theoretical interpretation in terms of scale invariant jet models and can be directly used to constrain the dynamics of the accretion flow. The observed relation implies that the X-ray emission from black holes accreting at less than a few percent of the Eddington rate is produced by radiatively inefficient accretion flows.

In recent years, this result has been exploited to gain insight on the physical state of Low-Luminosity AGN (LLAGN), and on the impact of their energy release on their environments. The first direct evidence for feedback on the gas surrounding a black hole came with the arrival of high-resolution X-ray imaging: using ROSAT data, Böhringer et al. (1993) discovered that the radio galaxy Perseus A (powered by the supermassive black hole in the central cluster galaxy NGC 1275) excavates large cavities in the hot, X-ray emitting thermal gas that fills the Perseus cluster. The physics of this feedback was first simulated by Churazov et al. (2001) and Brüggen et al. (2002) for M87 in the Virgo cluster. The gas is pushed aside into dense shells and the excavated X-ray cavities are filled with radio emission by the lobes of the radio galaxy. In the Chandra and XMM era, direct evidence of LLAGN feedback in action has been found in the X-ray observations of many nearby galaxy clusters showing how black holes deposit large amounts of energy on kpc scales in response to radiative losses of the cluster gas. By studying the cavities, bubbles and weak shocks generated by the radio emitting jets in the intra-cluster medium (ICM) it appears that (low-luminosity, radio loud) AGN are energetically able to balance radiative losses from the ICM in the majority of cases.

At a global level, AGN feedback models hinge on the unknown *efficiency* with which growing black holes convert accreted rest mass into kinetic and/or radiative power. Merloni & Heinz (2007) showed that the output of low-luminosity AGN is truly dominated by kinetic energy rather than by radiation, and have allowed estimates of the kinetic luminosity function of AGN based on the observed radio emission of their jets. In those works, tantalizing evidence was found for the kinetic power output from low-luminosity AGN dominating the feedback at low redshift, which has been confirmed by studying of the *z<1* radio galaxies population in the COSMOS field (Körding et al. 2006; Smolcic et al. 2009).

2.9 The role of AGN feedback in models of structure formation

The tight scaling relations observed between the central black holes mass and various properties of their host spheroids that characterise the structure of nearby inactive galaxies have modified the way we conceive the physical link between galaxy and AGN evolution. As SMBH growth is due mainly to accretion during active AGN episodes, it is possible that most, if not all, galaxies went through a phase of nuclear activity in the past, during which a strong physical coupling (generally termed "feedback") might have established a long-lasting link between hosts and black hole properties. In recent years, attempts have been made to connect AGN and galaxy growth via 'evolutionary' scenarios, in which key observational properties of AGN, such as the degree of dust and gas obscuration of the nuclear activity are related to overall properties of galaxy evolution, such as gas consumption and star formation.

Distinguishing nuclear AGN emission from the surrounding galactic one requires high spatial resolution observations, but these are challenging, particularly because the resolving power of telescopes varies widely across the electromagnetic spectrum. Indeed, for more distant AGN, combining observations at the highest possible resolution at different wavelength on large, statistically significant samples, is nearly impossible, and one often resorts to less direct means of separating nuclear from galactic light.

Thus, most relevant studies require at the same large sample, and deep multi-wavelength characterization of the host properties of AGN. However, only for relatively few small pencil-beam fields (such as COSMOS, CANDLES, GOODS N and S) this is available. The first results on the study of the AGN hosts, however, give contradictory answers, with some indication that AGN populate uniformly both star-forming and passive galaxies and no clear evidence of a "smoking gun" for AGN feedback (Bongiorno et al. 2012; Santini et al. 2012; Rosario et al. 2013). More recent in-depth analysis, taking advantage of VLT NIR Integral Field spectrographs (SINFONI, KMOS), have begun to unveil the true incidence of AGN-driven outflows in the z~2 star-forming galaxies, i.e. those experiencing the most rapid and sustained growth phase (see e.g. Förster-Schreiber et al. 2014, Genzel et al. 2014).

2.10 Systematic searches for high-z QSOs

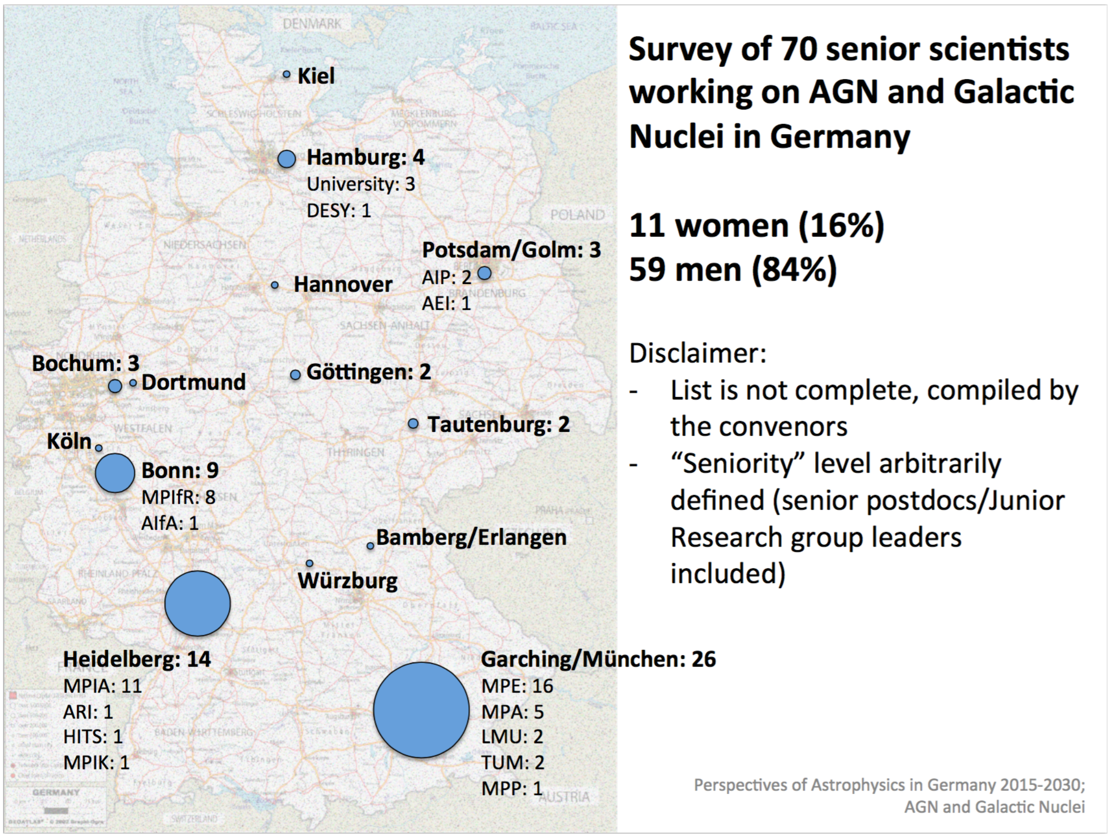
The AGN population at high redshift is fundamental to constrain structure formation models, but is still very poorly known. Until about ten years ago, only a handful of very luminous quasars were known at z>6. Very deep near-IR images are crucial to improve this situation and to study the role of AGN at the epoch of reionisation.

Today, more than 120 quasars have been found at redshift z>6, when the universe was less than 1 Gyr old. More than half of these have been found by astronomers in Germany. A physical characterization of these quasars has revealed the presence of billion solar mass black holes, large reservoirs of molecular gas, and active star formation in the host galaxies of these very early systems. As such, they provide unique constraints on early quasar activity and galaxy evolution.

Along these lines, one main focus will be pushing the redshift frontiers for quasars to z>8. This will enable studies of the early growth of black holes and their host galaxies way back into the epoch of reionisation. As such, they provide unique constraints on black hole- galaxy growth and early structure formation. German astrophysics is well positioned to continue to be a major player in the field. The search for the z>8 quasars will require large scale (~all sky) imaging in the IR bands, which will be provided by Euclid. This data will have to be complemented by optical surveys at matched depth (e.g. LSST or some other Pan-STARRSs successor).

3. Future key questions

In order to focus on the long-term perspective of this field of research, we have surveyed 70 senior scientists working on AGN and galactic nuclei in Germany. The list was compiled by the authors, without pretense of completeness, but with the aim of having it representative, relevant, balanced and, in case of doubt, broad. The term "senior" was not defined in terms of types of position held, but rather by judgment of the authors, as broadly defined "impact" in the field, and the level of seniority in the list typically ranges from full professor to senior postdocs. The list comprised 11 women and 59 men. Geographically, three clusters are apparent: 26 of the scientist work in the larger Munich area, 14 in Heidelberg and 9 in the Bonn/Cologne area (see Figure 6 for more details). The list contained all relevant wavebands, from radio, over mm, submm, IR, optical, X-ray to very high energies; it contained 10 theorists, and 2 scientists from the gravitational wave community.



Survey of 70 senior scientists working on AGN and Galactic Nuclei in Germany

11 women (16%)
59 men (84%)

Disclaimer:
- List is not complete, compiled by the convenors
- "Seniority" level arbitrarily defined (senior postdocs/Junior Research group leaders included)

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Figure 6: Map of the geographical distribution of the scientists active in the field of (active) galactic nuclei in Germany, as surveyed by the authors of this chapter before the RDS Denkschrift meeting in December 2015.

Below, we distil the outcome of our survey into what we believe constitutes the list of major key questions open in the field, which will drive its development, within and outside Germany, in the coming decades.

1. **Do central compact objects in galactic nuclei obey the general relativistic definition of a "Black Hole"?**
   In other words, are compact objects in galactic nuclei described by Einstein's general relativity (GR), and can we probe the geometry of spacetime around them? Despite the long and robust chain of evidences that point towards GR's black holes as the explanations of all the phenomenology we have described above, a formal, iron-clad proof of their existence is still missing, and undoubtedly scientists will continue to look for means to achieve this goal. This poses the question of whether it will be possible to image the event horizon of a black hole and, more generically, of what will constitute an observational proof of the existence of

(supermassive) black hole. The impact of these questions goes way beyond the realm of astrophysical research, and we believe the signs are positive that the German community will be at the forefront of the enterprise.

2. Can we characterize the physical processes that take place in the immediate vicinity of a black hole event horizon (accretion, jet acceleration)?

More specifically, how do accretion flows release energy in their inner regions, and what is the nature of disc turbulence and viscosity? Accretion disc theory is a mature subject, but, somewhat uncomfortably, fundamental open questions remain on how exactly do discs and jets transport angular momentum, and what is the actual geometry of the inner accretion flow around accreting black holes. On the other hand, the theory of jet production and acceleration in compact accreting objects is still lacking predictive power and many detailed questions are still open. How are particles accelerated in relativistic jets and near the event horizon? What is the structure of the inner jet? Are AGN jet VHE emission processes leptonic or hadronic? Are AGN the primary source of UHECR? Are highly energetic neutrinos produced by AGN? Are AGN the source of fast radio transients? Here our expectation is that progresses in multi-messenger astronomy, and a closer connection between theorists, observational astronomers, astro-particle physicists and gravitational wave scientists will bring forward many of the answers the community has been searching for.

3. How do black holes grow in galaxies, and how do they influence each other?

One of the most important open questions is how black holes get to the centers of galaxies in the first place. How do they evolve over cosmic time and from which initial seed mass do supermassive black holes start to grow? Starting from there, it will be important to find out to what extent do black hole and galaxies grow in lockstep, and what roles galaxies and black hole mergers play there. Do galaxy mergers trigger accretion episodes? Do galaxy mergers necessarily lead to SMBH-SMBH mergers? How are the central black holes fueled, and what is the AGN duty cycle and the power spectrum of variability over different timescales? The issue of AGN feedback and its role in the overall process of galaxy evolution will most likely remain subject of very intense investigation. The reason is the inherent complexity of galaxies as the nodes of the baryon cycle, where pristine gas gets reprocessed into stars. To make progress, we'll need to understand how star formation proceeds in the immediate environment of a SMBH, and, in some cases, resolve individual stars in nearby galaxies, and follow the dynamical interaction between stars and SMBHs. At the nuclear level, the interaction between SMBH and their host galaxies requires new tests of fundamental stellar dynamical theory (in a relativistic regime), as well as a deeper understanding of how SMBHs and the energy they release affect the ISM, and how the various phases of the observed outflows (ionized gas, molecular gas, dust) are related to each other. Proceeding towards larger and larger scales, we will be busy in the coming years with trying to understand what the relationship between outflows and star formation quenching is, and how black holes affect the thermodynamics of the circum-galactic and intra-cluster medium.

4. Can we use black holes to trace large-scale structure, and constrain Cosmology?

Finally, luminous, accreting black holes (quasars, QSOs) have a long tradition of being used as beacons to probe the most distant reaches of the Universe. Still, because only the tip of the iceberg has been unveiled, we need to quantify QSO/AGN contribution to the reionization process. The possibility to observe QSOs up to high distances also makes them unique tracers of large-scale structure. Wide area (imaging and spectroscopic surveys) have been instrumental in mapping the three-dimensional structure of the Universe, and future sensitive instruments (WEAVE, DESI, PFS, 4MOST) are being designed to allow to measure baryonic acoustic oscillations (a powerful "standard ruler" for cosmology) with AGN, which would give access to a wider redshift range than probed with galaxies alone. On the other hand, a better understanding of the physical processes giving rise to AGN emission (see question 2 above) may unlock the potential of quasars as "standardizable candles", able to probe the geometry of the Universe up to the highest redshifts.

4. Summary and Conclusions

There is little doubt that the area of research on galactic nuclei represents a major strength of the German astrophysics community. Almost every key topic is covered, and observations across the entire electromagnetic spectrum from world-class facilities provide highly valuable data sets. When projecting such developments into the coming decades, we need to make sure that all the many areas of excellence are preserved, trying, at the same time, to steer away from the "wavelength chauvinism", i.e. the perception that one's own instrument of choice is the unique carrier of the field. The very nature of AGN and galactic nuclei, as we have argued throughout this document, demands coordinated approaches. Nonetheless, in the section below, we briefly try to outline where we believe future developments will be most impetuous. At the end, we close by summarizing the strengths of our community and the areas where room for improvement has been identified.

3.1 Instrumental road map

We think that in the future **two prominent branches** of AGN research will be pursued. The first aims at observing **individual objects at the highest possible precision and in as much (spatial, temporal and spectral) detail as possible**. The aim is to understand in depth the astrophysical processes reigning galactic nuclei. Nearby galaxies and our own galactic center will be the prime targets, and the main parameter will be the achievable resolution. Near-Future instruments to this end are global-mm VLBI, the second-generation VLTI instruments (GRAVITY & MATISSE), next-generation adaptive optics instruments and the James-Webb Space Telescope (JWST). The high-resolution instrument suite of the European ELT and the ATHENA X-ray observatory are suited for the same approach, but further in the future.

The second approach will be of more statistical nature, i.e. one tries to gather **large data sets** covering many sources. The main parameter here will be the number of sources used. From a large sample one can derive not only average quantities, but also trends. As often in astronomy, this is one of the very few ways to learn about evolutionary sequences. Instruments to that end will be eROSITA (an X-ray all-sky survey); the Euclid ESA mission, and WFIRST on the NASA side; the multi-object wide-area optical spectroscopic instrument 4MOST at ESO's VISTA telescope, and the Large Synoptic Survey Telescope (LSST), as well as the radio telescope Square Kilometer Array (SKA). A prominent role of AGN in planning large surveys will guarantee due attention is given to multi-wavelength and multi-messenger synergies.

Further trends will be the shift to higher redshift (enabled by the use of larger telescopes, e.g. JWST and E-ELT), and the opening of a completely new channel by means of the space-based gravitational wave observatory eLISA. At the highest energies, the Cherenkov Telescope Array (CTA) will bring forward TeV ground-based astronomy, while the next generation of neutrino telescopes will enrich the multi-messenger approach.

3.2 Strengths

German groups are very visible, and have made many seminal contributions in the past. There is a healthy level of diversity in the approaches and scientific outputs, brought by the wide spectral coverage, very good multi-wavelength case, strong link between simulations and observations. In the last decade, research on galactic nuclei in Germany has produced outstanding results, both on individual objects, and on population studies. We firmly believe the main key to this string of successes is the privileged access of German groups to cutting-edge, top instrumentation, over a broad range of wavebands. Astrophysics is still, by and large, an observationally driven field. Most top research groups are embedded in international collaborations that go beyond a national context, but a high level of visibility seems to be well defended in many cases.

3.3 Room for improvement

A few areas have come up during the survey where the overall positive picture would profit from improvements:

- An even larger degree of coordination between different wavelengths would be desirable - since a single waveband is insufficient to fully understand the inherently complex galactic nuclei
- A major worry is that German researchers might miss prime access to two major, new facilities: The LSST (for time-domain astronomy) and the SKA (for radio astronomy).
- On the theory side, more support for theoretical/ numerical studies would be desirable. A link to computer scientists might be an example how to achieve more efficient code development.