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Active Galactic Nuclei in galaxy surveys

Empirical paths to the fiery hearts of cosmic beasts

BEATRIZ VILLARROEL



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Abstract

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Some galaxies emit excessive amounts of light from their centers, caused by accretion of gas onto super-massive black holes (SMBH). These galactic cores are often referred to as Active Galactic Nuclei (AGN) and they come in many different forms, distinguishable by their emission properties. The AGN classes fall into two major categories: those with narrow Balmer lines, and those with broad Balmer lines. The AGN Unification theory of radio-quiet AGN predicts the two classes to differ mainly in the viewing angle of the observer who may, or may not, see the central engine due to dust obscuration in the foreground.

In this PhD thesis, I explore the limits of the radio-quiet AGN Unification. In its most famous and simple form, the obscurer is a parsec-sized dust doughnut surrounding the accretion disk. I show that the galaxy neighbours to the two types of AGN are different, in disagreement with the simplest form of unification (Paper I). The two AGN classes differ in their [OIII]5007 luminosity, as well as in their star-formation history (Paper II), suggesting that we must incorporate galactic dust into the concept of AGN Unification, as well as differences in the luminosity of the central engine. I also present a novel, data-driven method to pinpoint the relative spatial origin of certain emission lines in AGN (Paper III). Finally, we conclude the thesis by discussing an anti-transient survey targeted at finding signatures of extra-terrestrial intelligence (Paper IV). This survey can, as a side effect, also be useful to find extreme, variable AGN that challenge both AGN Unification and evolutionary theories.

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Art, like Nature, has her monsters, things of bestial shape and with hideous voices. – Oscar Wilde

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I **Villarroel, B.** & Korn, A. J. “*The different neighbours around Type-1 and Type-2 active galactic nuclei*”, 2014, *Nature Physics*, 10, 417
- II **Villarroel, B.**, Nyholm, A., Karlsson, T., Cómerón, S, Korn, A. J., Sollerman, J. & Zackrisson, E., “*The Different Star-formation Histories of Type-1 and Type-2 AGN in the Eyes of Supernovae*”, in review.
- III **Villarroel, B.** & Korn, A. J., “*Data-driven dissection of emission-line regions in Seyfert galaxies*”, 2016, *Astronomy & Astrophysics*, 596, A20.
- IV **Villarroel, B.**, Imaz, I., & Bergstedt, J., “*Our sky now and then: searches for lost stars and impossible effects as probes of advanced extra-terrestrial civilisations*”, 2016, *Astronomical Journal*, 152, 76,

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Additional papers not included in this thesis

- I. **Villarroel, B.**, 2012, “*In the neighbourhood of tame monsters*”, *Astronomy & Astrophysics*, 542, A72

- II. Gupta A.C., Agarwal A., Mishra A., Gaur H., Wiita P.J., Gu M.F., Kurtanidze O.M., Damljjanovic G., Uemura M., Semkov E., Strigachev A., Bachev R., Vince O., Zhang Z., **Villarroel B.**, Kushwaha P., Pandey A. et al., “*Multiband optical variability of the blazar OJ 287 during its double peaked outburst in 2015 – 2016*”, 2016, in press, *Monthly Notices of the Royal Astronomical Society*.

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1. Active Galactic Nuclei

While the light of most galaxies is dominated by stars, a significant fraction of galaxies have excessive light coming from the very center. The intensity of the light can in extreme cases be up to thousand times larger than what all stars in the galaxy emit together. This strong light comes from a very compact region, not much larger than our Solar System.

The compact “nuclear” objects are often referred to as “Active Galactic Nuclei” (AGN), and the most luminous are known as quasi-stellar radio sources (“quasars”) or quasi-stellar objects (QSOs), a name that has followed since their discovery (Schmidt, 1963) as these point-like objects at first were confused with stars. With their dramatic life, extreme variability on short time scales and sudden death, AGN have kept observers and theoreticians mesmerized over decades. So where does all this light come from?

The AGN emission is believed to be driven by **accretion** of hot gas onto super-massive black holes (SMBH; Rees 1984, Lynden-Bell 1969), leading to light production so strong that the gas surrounding the accretion disk is photoionized. Some of the AGN show powerful **radio jets** coming from the center of the AGN. There are many different classes of AGN that vary in the properties of their spectra, host galaxy appearances and general phenomenology. Two examples of AGN are shown in Figure 1.1. The AGN can be spotted by the compact, luminous nucleus, sometimes only visible through hard X-rays.

AGN are suitable for studying black-hole environments. They are the key to understanding the formation of SMBH and how these black-hole environments look. A long-standing discussion (see e.g. Volonteri, 2010) has been whether the SMBHs form from initial seeds at high redshift ($z > 6$) or whether **mergers and interactions** between galaxies are responsible. While one scenario is not excluding the other, with the increased fraction of AGN in merging galaxies (e.g. Ellison et al., 2011), we know that mergers of galaxies are one of the key triggers to AGN activity. In the merger the black hole grows in size. The accretion of gas drives the AGN, at least until reaching the Eddington limit at which the radiative pressure from the AGN becomes so strong that accretion seizes.

It is obvious that clues to AGN formation may be reflected in the types of neighbour galaxies surrounding the AGN host, meaning in the **environment of AGN**. At large scale, the cosmological structure-formation scenarios are of importance; at small scales also the AGN physics itself. The interplay between the environment, the host galaxy and the SMBH physics leads to the many observable features among the AGN classes, and vice versa (Hopkins



Figure 1.1. Two active galactic nuclei. The left image shows the Seyfert-1 galaxy NGC 5548 (ESA/Hubble). The right image shows the Seyfert-2 galaxy Circinus (NASA/Hubble).

et al., 2006). But the exact details are unknown to us. Now, add to this a poorly understood connection between star formation in the host galaxy and the SMBH – does the one fuel or quench the other? – and the complexity increases further.

Of course, these are all questions tricky to answer. In this PhD thesis, we have taken a look at one particular but relevant problem in the field of AGN structure – namely **AGN Unification**. The AGN Unification model (Antonucci, 1993), describing how two major spectral classes of AGN are connected via the viewing angle, shall be discussed rigorously in Chapter 4, with its more specific forms in Chapter 5. But first, we are going to make a journey through the necessary background.

2. Nomenclature, classes and selection methods

*Justamente hoy quisiera recordarles que en algún lugar del Universo existen los duendes, los colocolos, los minotaurios...
Grandes, verdaderos. De carne y hueso.
Quisiera decirles que todo lo que imaginamos existe.
En algún lugar del Universo existe.*

AGN come in many colours and flavours. Many AGN are easy to spot by the point-like source in an image near the center of a galaxy. Sometimes other indicators such as a nonstellar continuum in the spectra, broad Balmer line widths or characteristic emission line ratios are of great help to recognize an AGN. Their overall spectral energy distributions (SEDs) give witness of a non-stellar origin.

Historically, one likes to divide AGN into quasars (or QSOs), blazars, Seyfert galaxies, Low-ionization Nuclear Emission-line Regions (LINERs), radio galaxies, BLLacs, Ultraluminous Infrared Galaxies (ULIRGs). These are all AGN with different properties in terms of luminosity, the wavelength of the excess light from the nucleus, host galaxy morphology and spectral line ratios. As our observations are becoming more comprehensive, more and more new AGN classes are being discovered, nowadays occupying all sort of letter combinations: HOT Dogs, XBONGs, NELGs, BALs, NLSy1s, OVV, etc. It is not our intention to overwhelm the reader with a long list of used nomenclature in the field, but rather to touch upon what is most important to know about AGN identification and selection.

Something important to keep in mind is the distinction between radio-quiet and radio-loud AGN, as well as high-excitation and low-excitation AGN. The emission in **radio-quiet AGN** is associated with a powerful photoionizing source in the center giving rise to high emission line ratios and are often referred to as **high-excitation AGN**. The high line ratios arise as the photons from the non-thermal processes in AGN usually can reach much higher energies than those from massive stars, which leads to a larger ratio of line strengths between collisionally excited lines and lines produced by recombination. The radio-quiet AGN are commonly found in gas-rich galaxies like spirals and lenticulars. **Radio-loud** ones have the same core, but show also

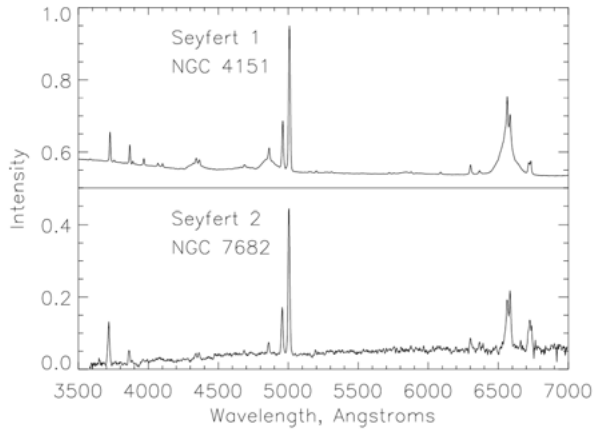


Figure 2.1. Optical spectra of Seyfert-1 vs Seyfert-2 galaxies. The picture shows the spectra of the Seyfert-1 galaxy NGC 4151 and NGC 7682. Note the difference in line width of the Balmer lines e.g. the $H\alpha$ 6563 line. With permission borrowed from William C. Keel's homepage at <http://pages.astronomy.ua.edu/keel/billkeel.html>.

radio lobes and compact radio cores. They include many **low-excitation** AGN as they cannot as easily be identified by the line ratios. Most radio-loud AGN are found in gas-poor, giant ellipticals. The drivers of radio-loudness in radio-loud objects are believed to be jet-related processes. Some objects like LINERs have very weak photoionization but are also radio-quiet AGN (also they are commonly referred to as low-excitation AGN).

In this thesis, the two most important groups are so-called Type-1 and Type-2 AGN. **Type-1 AGN** (or **broad-line AGN**) are easy to identify already in the optical alone with their very wide Balmer lines. The Balmer lines are Doppler broadened as the gas clouds near the SMBH move with high velocities larger than 1000 - 2000 km/s. The Type-1 AGN also have a strong non-stellar continuum visible in their spectra. **Type-2 AGN** (or **narrow-line AGN**), on the other hand, have narrow Balmer line widths. For those AGN with high-excitation, the line ratios of Type-1 and Type-2 AGN are believed to be fairly similar and we often refer to these Type-1 and Type-2 AGN as "Seyfert-1" and "Seyfert-2" galaxies, named after their discoverer Carl Seyfert (1943). Typical spectra of Seyfert galaxies of each family are shown in Figure 2.1. Quasars are fairly similar to Seyfert-1s and Seyfert-2s, but more luminous. The only real distinction between Seyfert galaxies and quasars is an arbitrarily set limit in luminosity.

As the reader certainly has guessed by now, the diagnosis of an AGN is a challenging task due to the characteristics of each individual case. Certain markers are common, yet the absence of evidence is never evidence of absence. This has caused many AGN, especially those at lower luminosities, to stay undetected, buried deeply inside heavily star-forming galaxies. Certain

methods have been put forward to simplify the detection. Of course, every new wavelength interval brings both opportunities and biases. X-ray selection tends to lead to more luminous AGN being selected. In the optical, it is easy to miss AGN obscured by dust or intrinsic low-luminosity objects. While the infrared (IR) is good for finding obscured AGN, the IR-colour methods are very inefficient for identifying AGN at low redshift. Utmost care is needed during selection to control for various selection biases.

2.1 X-ray/Ultraviolet

In X-rays, the detection of an AGN is pretty straightforward. Is the galaxy core luminous enough ($L > 10^{42}$ erg/s) in the X-rays, it is an AGN. Naturally, this is therefore considered as the most reliable method. Catalogues from space missions such as Chandra and XMM-Newton have yielded thousands of X-ray detected AGN.

One can detect AGN either by soft X-rays (< 5 keV) or hard X-rays (> 5 keV). Type-1 AGN are visible already in the soft X-rays, while Type-2 AGN are found with hard X-rays. However, with too large column densities N_H of obscuring gas in front of the central source (about $N_H > 10^{24}$ cm $^{-2}$), X-rays do not manage to pass through. While the images of AGN in the X-ray typically only show a point, their spectra are quite interesting, showing e.g. the iron K-alpha line at 6.4 keV (more often detected in Type-2 AGN than in Type-1 AGN). The X-ray emission in AGN is believed to arise in the hot corona surrounding the accretion disk of AGN. It is only a small fraction of the total luminosity of an AGN.

2.2 Optical

Most data we have today of AGN is in the optical regime. Large galaxy databases like the Sloan Digital Sky Survey (SDSS; York et al. 2000) have discovered hundreds of thousands of AGN thanks to the identification through optical photometry or optical spectroscopy. At optical wavelengths, one can spot AGN by their compact luminous cores. At low redshifts, this core is rather weak in comparison to the host galaxy. As we look to higher redshifts, the luminosity of the AGN relative to the host galaxy increases, and sometimes it becomes so strong that only the AGN is seen.

To detect an AGN, the most popular method nowadays is the use of **line ratios** or **line-ratio diagrams** for high-ionization objects. An example of such is the Baldwin-Phillips & Terlevich (BPT)-diagram (Baldwin, Phillips & Terlevich, 1981) that uses $[\text{OIII}]/\text{H}\beta$ and $[\text{NII}]/\text{H}\alpha$ line ratios, as shown in Figure 2.2. The BPT diagram is an empirical construction believed to differentiate between star-forming objects and AGN that occupy different regions in

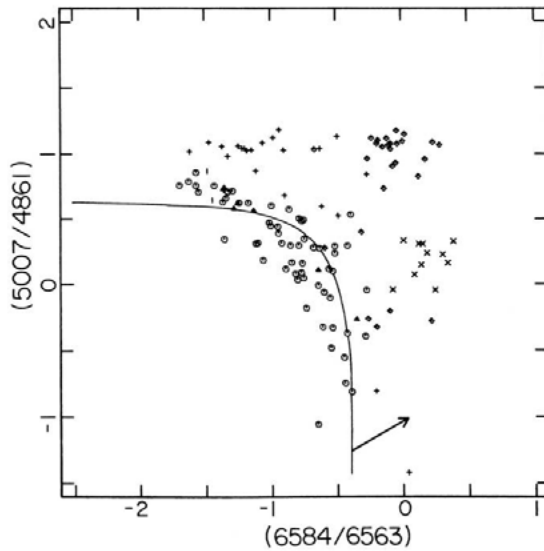


Figure 2.2. The first BPT-diagram, adopted from Baldwin, Phillips & Terlevich (1981), Publications of the Astronomical Society of the Pacific, 93, 5. The $[OIII]5007/H\beta 4861$ and $[NII]6584/H\alpha 6563$ line ratios are plotted for a sample of galaxies. Objects above the demarcation line are dominated by AGN, while the objects below are dominated by galactic star-formation. Copyright Astronomical Society of the Pacific, reprinted with permission of the authors (R.T.).

the diagram. With time, theoreticians and observers alike have refined the diagram so that it also accounts for line ratios caused by shock excitation (as from heavy star-formation or at the front of a jet), making it possible to also identify LINERs with the BPT diagram. Several different diagrams of the same type exist and they are continuously being improved and developed. Naturally, also this method has biases and many AGN are missed in the optical regime, e.g. optically elusive AGN (strong X-ray, no optical) or low-excitation AGN. Still, this technique can help us to find many Type-2 AGN. To find Type-1 AGN, all we need is the Balmer line width. We use optical line ratios and the Balmer line width to define our samples in Papers I-III.

2.3 Infrared

Large IR surveys like the Wide-field Infrared Survey Explorer (WISE), Herschel and Spitzer surveys have led to the identification of many AGN highly obscured by lots of dust. At the shorter wavelengths ($\sim 1\text{-}5\ \mu\text{m}$) the dust emission is **hot**. A large fraction of this light is emitted within 1 pc from the AGN. At longer wavelengths ($\sim 22\text{--}60\ \mu\text{m}$), the IR emission is dominated by **cold**

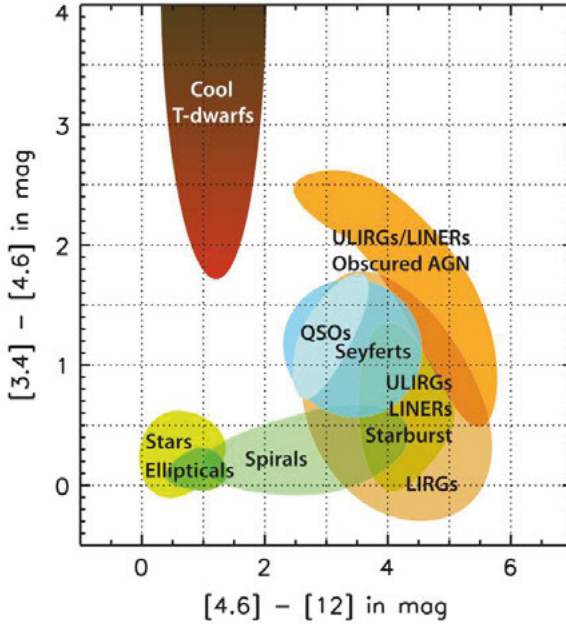


Figure 2.3. IR colour-colour diagram based on WISE photometry, adopted from Wright et al. (2010), The Astronomical Journal, 140, 1868. Different types of astronomical objects fall into different parts of the diagram.

dust emission from the gaseous regions heated by stars further out. Knowing this, one can use the infrared colours to separate between hot and cold dust emission to detect AGN through a selection in IR colour or **IR colour-colour diagrams**.

To select AGN using the WISE survey with the accompanying WISE four-band photometry $3.4 \mu\text{m}$ (“w1”), $4.6 \mu\text{m}$ (“w2”), $12 \mu\text{m}$ (“w3”), and $22 \mu\text{m}$ (“w4”), two methods are common: the first, defines AGN as an object fulfilling $w1 - w2 > 0.5$ (Wright et al., 2010), the second as $w1 - w2 > 0.8$ (Assef et al., 2012).

Figure 2.3 shows a colour-colour diagram. We see how typical objects fall into the different categories depending on their star formation and AGN activity. Spiral and elliptical galaxies are found in different parts of the diagrams. A pitfall of the method is that the detection mostly fails at low redshifts ($z < 0.8$) and most AGN are simply missed. Some AGN are so heavily obscured, that they can only be identified with the IR methods.

In Paper II, we use IR diagnostics to investigate our optically selected samples before we match them in redshift and the $w4$ magnitude.

2.4 Radio

Stars are not amazing emitters in the radio regime, but AGN are. The dichotomy between radio-quiet and radio-loud AGN allows to find radio-loud AGN by simply either taking the **total radio luminosity** or by measuring the **ratio between the radio to optical luminosities**. Surveys like the Very Large Array (VLA) FIRST survey (Becker et al., 1995) have allowed identification of a large number of radio-loud AGN that had never been identified in any other wavelength regime.

In Paper III, we use radio-selected samples to check if the results we obtain from our data-driven dissection of AGN emission-line regions in elliptical versus spiral host galaxies are not just reflecting the difference in radio-loudness.

3. Painting an AGN

Figure 3.1 shows a simple, schematic picture of an AGN with its main components. The different components are believed to give different characteristic signatures in AGN spectra. Let us go through the various elements one by one.

An ordinary, rotating black hole, is a remnant from a rotating star that ended its life in a supernova (and so the black hole will rotate). In the center is the singularity where all mass is gathered – flattened, ring-like – surrounded by an event horizon. Any light on the inside of the event horizon cannot escape as the gravitational pull is too large. This event horizon defines the gravitational radius r_g of a black hole

$$r_g = \frac{GM}{c^2} \quad (3.1)$$

where M is the black hole mass, G is the gravitational constant and c is the speed of light.

A **super-massive black hole (SMBH)** is similar to an ordinary black hole, but many orders of magnitudes heavier. The suspicion of the presence of black holes in the center of AGN dates back to the early 1970s (Lynden-Bell, 1969; Rees, 1984) that explained how accreting super-massive black holes lead to excessive light production in the core of a galaxy. More recently, IR imaging of stars orbiting around an invisible dark mass in the heart of our Milky Way have revealed the presence of something very heavy and compact – more than $10^6 M_\odot$ (Genzel et al., 1996; Ghez et al., 1998). This was the smoking gun evidence for the existence of a super-massive black hole in the center of the Milky Way.

While SMBH mass is crucial to understand the total mass and mass growth of an AGN, the spin of a black hole governs the fraction of gravitational energy that can be converted into light during the accretion processes.

Accretion disks are commonly found throughout the cosmos: around proto-stars, accreting binaries. Accretion disks might be the most efficiently accreting systems. The exact geometry of the accretion in AGN is a challenging task to constrain, yet it determines the efficiency of the accretion. The currently favoured models contain a thin disk with an innermost radius of a few r_g . In the accretion “disk”, hot gas spiralling towards the center is colliding, giving rise to energetic photons in the UV-optical. The intense light from the accretion flow is the continuum visible in Type-1 AGN spectra and is so strong that it is capable of photoionizing the surrounding gas. The continuum-source

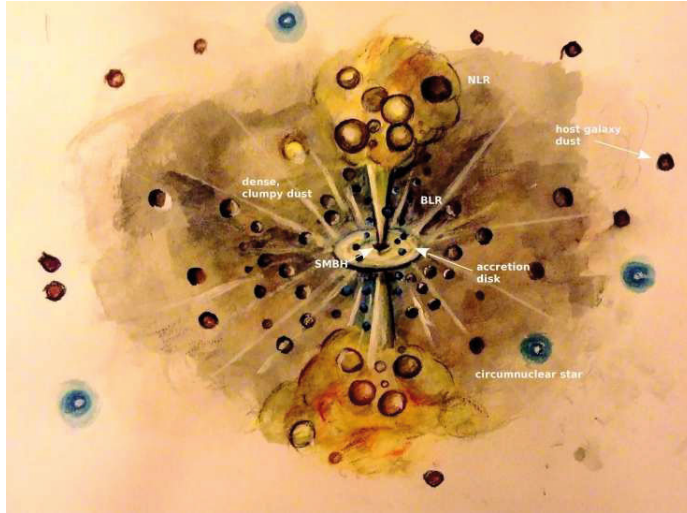


Figure 3.1. The cartoon depicts the main components in an AGN: the supermassive black hole, the accretion disk, the broad-line region, the narrow-line region. Dense, clumpy dust (often called “torus”) can obscure the inner regions. The observational signatures are contaminated by properties of the host galaxy.

light can in extreme cases vary on short time scales over just a few hours or days, which can be used to constrain the size of the region.

Near, or as a part of, the accretion disk, there is a **corona** of hot electrons believed to irradiate the disk, causing Comptonization of the disk photons which results in a X-ray power law in the wavelength range 0.2 – 100 keV. The physical connection between the disk and hot corona is not well understood.

Outside the corona is the so-called **broad-line region (BLR)** where dense light-emitting clouds move at high velocities larger than 1000 km/s, as detected by the Doppler broadening of the Balmer lines. The temperature in this region is about 10000 – 25000 K and the optically thick clouds are mostly highly ionized. From the absence of strong forbidden lines in the optical like [OIII]5007, yet presence of some semi-forbidden lines, it is possible to infer that the BLR clouds have typical electron densities of between $N_e \sim 10^8 \text{ cm}^{-3}$ and $N_e \sim 10^{10} \text{ cm}^{-3}$.

The photoionized BLR gas extends fairly far, although how far precisely is a matter of debate. From studies with reverberation mapping – a method where the size of the BLR is estimated from measuring the time delay between the continuum-light variations in an AGN and the BLR responses on the change in incident flux – the BLR size is about 10 – 100 light days. In the inner regions, the density and temperature is the highest, it is too hot for dust grains to survive. At radii where the temperature drops below the sublimation temperature (for silicate grains about $T \sim 1400 \text{ K}$), clumpy grains of dust assemble into an optically and geometrically thick structure, the “**torus**”, that

blocks the view of the BLR and the continuum source. This is typically just a few parsecs in extension. As the ionizing photons leak through the opening of the torus, ionization cones extend through the openings, as gas out to a few hundred parsecs is further ionized and excited by the leaked photons. Such ionization cones indicative of a doughnut-like obscurer have been found in a number of AGN.

The ionized gas region outside the torus is called the **narrow-line region (NLR)** due to the narrow Balmer lines and strong, narrow forbidden lines like [OIII]5007, [NII]6550,6585, [SII]4072,6718,6732 associated with its emission. Selecting AGN using narrow-line ratios typical of strong photoionization from an AGN is therefore common practice. The NLR gas is considerably less dense than the BLR gas, $10^3 < N_e < 10^6 \text{ cm}^{-3}$ and consists of optically thin clouds.

There are some claims (e.g. van Groningen & de Bruyn, 1988; Murayama & Taniguchi, 1998) about an **intermediate-line region (ILR)** between the BLR and NLR, or perhaps at the inner edge of the torus due to some observations of narrow, forbidden lines at scales much smaller than the NLR. The presence of an ILR would be in disagreement with the well-defined dichotomy of the BLR and NLR and a sign of a fairly smooth gas density decrease at larger and larger radii from the central black hole. In Paper III, we discuss the possible detection of an ILR.

Outside this central engine is the **host galaxy** itself, where star formation, supernova activity and all the physics typical of normal galaxies take place. The role of the host galaxy will be further discussed in Chapter 5.

Radio-loud AGN differ somewhat from the mentioned picture through the additional presence of a **radio jet**. The radio-loud AGN have large black hole masses and show signs of radiatively inefficient accretion of matter upon the black hole. Here, the accreting gas loses its angular momentum through the ejection of a jet. Most radio-loud AGN also have weak NLRs, perhaps due to the lack of interstellar medium (ISM) in the gas-depleted host galaxies.

There are different techniques to study the components of AGN. High-resolution imaging and spectra in different wavelength intervals are the most obvious ones, although not powerful enough yet to study the innermost 1 kpc of an AGN. IR interferometry (Jaffe et al., 2004) has successfully measured the size of the dust torus. Reverberation mapping can measure the size of the gas region and its ionization structure, if the emission varies over sufficiently short time. This works well for the BLR, but not the NLR that has much larger radius. In Paper III we propose a new method based on multiple spectra to trace the origin of a spectral feature.

4. The Unification theory

For decades astronomers have tried to understand how Type-1 and Type-2 AGN are actually connected. The first hints came already in 1979 from a small sample of Seyferts in the Palomar Sky Survey, when William C. Keel discovered that Seyfert 1 galaxies are preferentially found in host galaxies with a “face-on” inclination (the whole disk shown to the observer), while Seyfert 2 galaxies have no preferential inclination (Keel, 1980).

A few years later, Robert Antonucci and Joseph Miller performed spectropolarimetric studies of the first discovered Seyfert-2 galaxy NGC 1068. Spectropolarimetric studies are interesting, as the technique can reveal e.g. the presence of dust in the foreground of the emitting light source leading to polarization of the light. Indeed, Antonucci and Miller find that the polarized flux spectrum of NGC 1068 looks like the normal flux spectrum of a Seyfert-1 (Antonucci & Miller, 1985). Moreover, their study suggests that the continuum and broad-line polarization is caused by scattering of free electrons and that the central engine is located inside a geometrically and optically thick disk, making it possible for the observer to see the central engine only from certain viewing angle.

And so the idea of the torus was born. If looking directly into the center of the AGN, one sees the continuum light from the accretion disk and the broad-line region. But if the observer has a more unfavourable viewing angle towards the accretion disk, the dust from the torus blocks the light and the spectrum is dominated by narrow lines located outside the torus. The Unification Theory explains the connection between Type-1 (broad-line) and Type-2 (narrow-line) AGN based on the viewing angle. Soon, it was suggested that the same principle can unify the radio-loud quasars and radio galaxies (Barthel, 1989), where the radio-loud quasars are beamed towards us and the radio galaxies constitute the unbeamed population. The unified schemes got developed first to explain the radio-quiet Unification of Seyferts using the torus (Antonucci, 1993), and then (Urry & Padovani, 1995) of the radio-loud objects at high luminosities (mainly quasars and strong radio galaxies) with radio-loud AGN at low luminosities (BL Lac objects and low-luminosity radio galaxies). A famous, early sketch of the AGN Unification concept is shown in Figure 4.1.

The most important take-home message for the radio-quiet Unification is that **a Seyfert-2 nucleus is a Seyfert-1 nucleus obscured by dust**. This dust has to be dense enough to cause complete obscuration of the broad-line region, which is why a geometrically and optically thick torus surrounding the AGN was suggested. Hereonafter, we focus on the radio-quiet Unification.

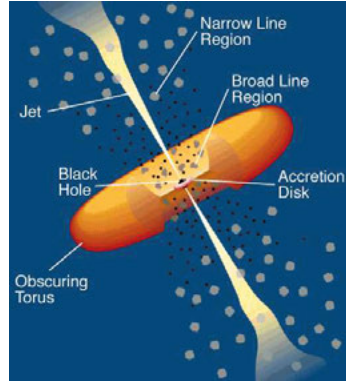


Figure 4.1. A historic depiction of the AGN Unification, adopted from Urry & Padovani (1995), Publications of the Astronomical Society of the Pacific, 107, 715. In Type-2 AGN, the obscuring doughnut-like torus hides the central accretion disk and the broad-line region from the observer’s view. Copyright Astronomical Society of the Pacific, reprinted with permission of the authors.

In X-rays, the Seyfert-2s are defined as those having an absorbing column density of $N_H > 10^{22} \text{ cm}^{-2}$, named obscured, and Seyfert-1s as those with X-ray absorbing column less than $N_H < 10^{22} \text{ cm}^{-2}$, named unobscured. Of course, as the dust is very close to the AGN, it is hot and has a temperature about $T \sim 1200 - 1500 \text{ K}$ peaking at about $\sim 30 \mu\text{m}$ in the infrared. Obscured AGN are (supposedly) those with largest IR excess. We note the need of caution when dealing with the definitions of “obscured” and “unobscured”. This nomenclature is used widely for all AGN over the wavelengths, but the radio-quiet Unification was defined on optically-classified AGN. This means, while Seyfert-1s and Seyfert-2s are believed to be “obscured” and “unobscured” according to the AGN Unification theory, not everything detected as “unobscured” or “obscured” in e.g. the X-ray or IR is actually a Seyfert-1 or Seyfert-2 AGN! The liberal use of the terms throughout the literature has lead to a fair amount of confusion in the statistical tests of Unification. Indeed, without the optical classifications one cannot probe the Unification theory.

4.1 Challenging the Unification theory

At this moment, it is adequate to ask what are the important caveats of the radio-quiet AGN Unification theory. Surely, it depends on how one precisely defines the Unification, but the two most important points of the theory predict the presence of a Seyfert-1 core (a hidden BLR) in every Seyfert-2 AGN and – if one is more bold – the presence of a dusty parsec-size obscurer in every AGN causing a viewing-angle dependent classification of Seyfert-1s and Seyfert-2s.

There are two things that certainly could challenge the Unification theory at its very core:

1. The absence of a hidden BLR in a Seyfert-2 nucleus.
2. Objects where the dust obscuration is not responsible for the Seyfert-1/Seyfert-2 classification.

So are there any indications of (1)? Well, only 30 – 50% of all Seyfert-2 objects clearly reveal a hidden BLR when studied with spectropolarimetry (Tran, 2001, 2003). This has caused a passionate debate about what the remaining “true Seyfert-2s” lacking a BLR actually are. Do they disprove the entire Unification theory? Or is maybe Unification only valid for AGN having a certain, minimum accretion rate (Nicastro, 2000; Elitzur, 2008)? Or could it be that the Seyfert-1 nucleus was not found because the spectropolarimetric observations are simply of poor quality (Antonucci, 2012)? Absence of evidence is not equal to evidence of absence. A recent study (Ramos-Almeida et al., 2016), has shown that in eight objects previously reported to lack the hidden BLR, it was ultimately discovered in five of them.

As for the second category of challenges (2), there are reports of objects that switch between being a Seyfert-1 and Seyfert-2 objects over the course of just a few years. These are called **changing-look AGN**. Of course, if we imagine that the dusty obscurer is clumpy and the clumps only from time to time pass in front of the central engine to hide it from our view, an explanation using the Unification Model comes naturally. However, a deep study into the changing-look quasar SDSS J015957.64+003310.5 (LaMassa et al., 2015) demonstrates that possible obscuring dust is not the cause of the switch between the two classes. Rather, the findings are suggestive of an origin in the central engine itself.

Another example of changing-look objects, although changing type between Seyfert-1s and ordinary star-forming galaxies, are some dwarf galaxies where the broad Balmer line emission just disappeared over a few years and the spectrum from the later epoch showed a very normal, non-AGN galaxy (Baldassare et al., 2016). The authors suggest an appealing explanation: in some galaxies, especially dwarf galaxies, the Balmer line width becomes broadened by the presence of core-collapse supernovae. So, some Seyfert-1 galaxies might be ordinary galaxies where many core-collapse supernovae (SNe) are changing the spectral properties of the galaxies.

In Paper II that deals with SNe in Type-1 and Type-2 AGN, we show that Type-2 AGN have considerably more of SNe going off, which is why this hypothesis can safely be excluded for most Type-1 AGN.

5. The “torus”

So far, we have kept things fairly simple by not defining precisely what we mean by AGN Unification. We have not defined the nature of the obscurer, nor its size, shape or exact physical origin. The common picture is a doughnut-shaped dust torus, safely located around the central engine, protecting it from the observer’s stare. But considering the torus is only a few parsecs in size and our telescopes have limited resolution, it is terribly difficult to directly image without interferometry (and even with interferometry). Therefore, we do not know the precise physical nature of the torus. But there are a couple of interesting ideas currently being explored, see e.g. the review by Elitzur (2006). Besides the typical Seyfert-1 and Seyfert-2 features discussed throughout the work, each model has to explain a variety of observations:

- Observed spectral energy distribution (SED) over all wavelengths;
- Physical size of the torus. From interferometry, it is shown that the torus size is typically only a few pc;
- Observed dust features in Seyfert-1 and Seyfert-2 AGN;
- Lifetime of the torus (if you can explain everything else but the torus can’t survive more than a day, the model is not too successful).

5.1 Straw Person Model?

The Straw Person Model (SPM; Antonucci 1993) is the famous “doughnut-model” of Unification. The doughnut has a smooth, uniform density of small dust grains of micrometer size. It cannot form too close to the accretion disk as the temperatures there are too high for dust grains to survive, so the inner radius of the doughnut equals the dust sublimation radius of the AGN. The dust sublimation radius depends on the luminosity of the AGN and the sublimation temperature of the dust grains. For silicate grains the inner radius scales like (Netzer, 2013)

$$r_{sub} \simeq 1.3L_{46}^{1/2} \left[\frac{1500}{T_{sub}} \right]^{2.6} \text{ pc}, \quad (5.1)$$

where L_{46} is the luminosity in units of 10^{46} erg/s and T_{sub} is the sublimation temperature of silicates (typically 1400 K). The larger the luminosity, the larger the inner radius of the smooth torus. The outer torus radius is less well-defined, but it is believed the torus is about one hundred to three hundred parsecs (Pier & Krolik, 1992; Granato et al., 1994, 1997).

In this model and with simple statistics, the relative numbers of Type-1 and Type-2 can be used to estimate the **torus opening angle** – assumed to be the same in every AGN – from which further the scale height H/R (ratio between height H and radius R) can be estimated. When the opening angle is 90 degrees, the scale height is $H/R \sim 1$ (Schmitt et al., 2001), showing that the torus is **geometrically thick**.

The fine, continuous dust distribution that comes with the Straw Person Model fails, however, at reproducing the observed torus sizes. Another problem is to theoretically sustain the torus without it collapsing due to its own gravity.

In the Straw Person Model (or Simplest Unification) the NLR is assumed to be isotropic in luminosity and if one selects a Type-1 and Type-2 AGN by matching their [OIII]5007 luminosity (so that they either have the same luminosity or the same minimum luminosity) the two AGN should have the same properties of their host galaxies. This is also what we mean when discussing an **isotropic property**. Considering that the [OIII]5007 is found in the ionization cones that have a direction, many astronomers mean that [OIII]5007 cannot be a good isotropic indicator. But the lack of [OIII]5007 in polarized spectra of Seyfert-2 AGN suggest it is formed outside of the torus (Antonucci, 1993) which means the [OIII]5007 emission is fairly isotropic in luminosity anyway.

In Paper I, we perform a test of the Straw Person Model by looking at environments of Type-1 and Type-2 AGN. In an additional test we match the AGN samples by the [OIII]5007 luminosity.

5.2 Clumpy torus?

A problem with the smooth, continuous torus models is that the indirectly observed tori are typically significantly smaller than the theoretically predicted tori (Elitzur, 2006). In NGC 1068, interferometry has suggested a torus size about $R \sim 1-2$ pc (Jaffe et al., 2004), similar to the compact sizes found for Centaurus A and Circinus (Prieto et al., 2004; Packham et al., 2005). But the smooth torus models predict tori that are a few hundred parsecs in size. Clearly, the predicted and observed sizes do not match. The dust grains survive at much more compact radii than should be possible in the smooth model. Something must shield the microscopic grains from getting destroyed by the strong, nuclear radiation.

A solution to the problem would be to assume that the torus consists of larger, individual clumps of varying sizes rather than following a smooth density distribution. The larger clumps can then survive stronger radiation. Each clump (at all distances) has one illuminated, hot side and one dark, cold side. This weakens the relation between the temperature of the dust grain and the distance from the accretion disk.

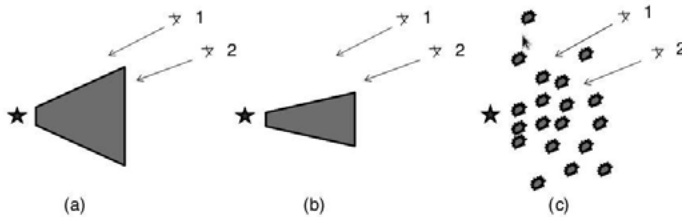


Figure 5.1. The difference between smooth and clumpy torus models, figure adopted from Elitzur, 2012, the *Astrophysical Journal Letters*, 747, L33. When a smooth torus as in (a) has a larger covering factor (and smaller opening angle), the observer will more likely see a Type-2 AGN. (b) With smaller covering factor (and larger opening angle), the observer has larger probability to see a Type-1 AGN. But if the torus is (c) clumpy, the probability to observe a Type-1 or Type-2 AGN depends on the distribution of the clumps, which varies between individual AGN.

The most important consequence (in the context of this thesis) is that what matters now is whether the emergent flux is dominated by the clumps or by the central engine, see Figure 5.1. The classification of Type-1 vs Type-2 objects is no longer deterministic as in the smooth model, but becomes a question of probability. An object with a larger covering factor of the dusty torus has a larger chance to be classified as a Type-2 object. This leads to an extremely important selection effect (Elitzur, 2012): Type-2 AGN are preferentially drawn from distributions with large torus covering factors, while Type-1 AGN are preferentially drawn from distributions with small torus covering factors. This difference in Type-1 and Type-2 covering factors is indeed verified in the IR (Ramos-Almeida et al., 2011; Ricci et al., 2011). For this very reason, it becomes impossible to fairly compare intrinsic properties of Type-1 and Type-2 AGN. Whether we compare the luminosity of an object, or of an emission-line, each observed quantity carries a bias due to the clumpiness of the obscuring medium. In Paper I (supplementary information), we propose and perform a test (“the Hypothetical Luminosity Test”) to check for possible biases in the results due to clumpy tori.

The estimated dust masses from clumpy-torus models vary, but scale with the mass of the SMBH and the luminosity (Mor et al., 2009). Fitting Spitzer/IRS 2 – 35 μm spectra of 26 QSOs, they estimate the range of dust mass within the torus silicate dust sublimation radius to vary between $M \sim 8 * 10^4$ and $M \sim 3 * 10^7 M_{\odot}$. ALMA studies for NGC 1068 (Garcia-Burillo et al., 2014) estimate the dust mass within a radius $r < 20$ pc from the nucleus to be about $M \sim 10^5 M_{\odot}$.

5.3 A receding torus?

A problem for the torus models is that the Type-1/Type-2 number ratio appears to increase with AGN luminosity (Simpson, 2005; Lusso et al., 2013). To explain this, it is suggested that the opening angle of the torus increases with luminosity (Lawrence et al., 1991). At lower luminosities the torus covers most of the central engine, while at higher luminosities the dust distribution becomes flatter and more and more ring-like (doughnut-like).

A number of observations support this idea (e.g. Oknyanskij et al., 1999; Ricci et al., 2011; Kishimoto et al., 2013). On the other hand, a recent study of geometrical covering factors of dusty tori in an X-ray selected sample of 227 AGN claims that the receding torus effect is visible and significant only for Type-1 AGN, but very small for Type-2 AGN (Mateos et al., 2016) – demonstrating a clear disagreement with the general idea of a receding torus.

5.4 Host-galaxy obscuration

A Type-1 AGN can be obscured by more things than just the torus. The review by Bianchi, Maiolino & Risaliti (2012) nicely illustrates how obscuration happens at all scales, from gas in the BLR, the torus and the host galaxy itself. This is interesting, as it could potentially mean that a considerable fraction of the Type-1/Type-2 dichotomy is caused by obscuration on larger scales than the torus. The very observation that led to the obscuration paradigm – that Type-1 AGN more rarely are found in edge-on systems (Keel, 1980) – suggests that the host-galaxy obscuration might be important enough to cause the dichotomy by itself.

Important support in favour of galactic obscuration comes from a study by Malkan, Gorijian & Tam (1998) where they find that carefully matched Seyfert-2 AGN have more dust lanes and dust patches near their nuclei than Seyfert-1 AGN. They estimate the column density of galactic dust at $r \sim 100$ pc to be $N_H = 0.2 - 1 * 10^{23} \text{ cm}^{-2}$, or at $r \sim 500$ pc the column density is $N_H = 4 * 10^{22} \text{ cm}^{-2}$, which is enough dust to cause at least partial obscuration. Only for the very obscured AGN with large FeII equivalent widths (like NGC 1068) one needs a considerably higher column density, $N_H > 10^{24} \text{ cm}^{-2}$.

Summarizing, the host galaxies are capable of providing the needed amount of dust, at least in low-luminosity AGN (Burtscher et al., 2016). Interestingly, some high-resolution studies performed with Hubble Space Telescope data, suggest the kpc-size dust lanes in Seyfert-2 galaxies can be traced the whole way into the nucleus (Prieto et al., 2014).

In Paper II, we show that Seyfert-2 galaxies have larger supernova counts than Seyfert-1 galaxies, suggesting different age distributions in the stellar populations of the host galaxies.

5.5 The origin of the torus

The origin of the parsec-sized obscuration is heavily debated. There are different ways of approaching it from a modelling point of view, one idea pictures it as a hydrostatic doughnut where molecular clouds are accreted from the host galaxy (Krolik & Begelman, 1988). Preventing this doughnut from collapsing and sustaining the torus is, however, quite a problem.

Another idea is that the origin of a torus is an accretion-disk wind (Blandford & Payne, 1982). A more comprehensive scenario is where the torus is the clumpy, geometrically and optically thick part of a hydromagnetic accretion-disk wind (Elitzur & Shlosman, 2006). It allows for a continuous transition between accretion disk and “toroidal obscuration region” that forms outside the dust sublimation radius of the outflow. The mass outflow rate will depend on the accretion rate of the disk. At high luminosities the Unification should be fully alive, while once the accretion drops the molecular outflow becomes weaker – first the torus disappears, and at even lower accretion rates even the broad-line region disappears. With this idea, one therefore can predict both the lack of tori in some AGN, as well as the lack of a BLR in many Type-2 AGN.

The torus could also be just a part of the galaxy itself. Some observations find nuclear starbursts in Type-2 AGN at small radii $r < 100$ pc. This means that maybe the torus is nothing but a heavily star-forming nuclear region where dust is produced by core-collapse supernovae (Wada & Norman, 2002, 2016) – a circumnuclear molecular disk with stars. The obscuring dust keeps a geometrical thickness as supernovae cause internal turbulence, and for column densities $N_H > 10^{23}$ cm⁻², the estimated covering factor of the “torus” is about $f \sim 0.4$. Besides the obvious viewing angle into the accretion disk, they suggest that the strength of the nuclear starburst must be incorporated into the Unified Model.

Near-infrared integral field spectroscopy of the Seyfert-1 galaxy NGC 3227’s innermost nucleus shows the presence of a starburst, so strong that it accounts for 20 – 60% of the galaxy’s total luminosity (Davies et al., 2006). The dust produced within 80 pc has a column density about $N_H \sim 10^{24} - 10^{25}$ cm⁻². The presence of signatures indicative of past starbursts in five other AGN at radii smaller than a few hundred parsecs indicates that the star-formation recently stopped (Davies et al., 2016). In three out of five of the same AGN, molecular outflows are seen.

In Paper II we look at the supernovae in Type-1 and Type-2 hosts and find differences in the host galaxy supernova rates and we discuss the possibility of the torus being a receding molecular disk.

6. The picture gets more complex

The AGN Unification picture we paint has so far been rather concentrated on the small scale (a few to hundreds of parsecs), without too carefully discussing the interplay between the AGN nucleus and the big galaxy it resides in. But so many theoretical, numerical and observational works show that the physical processes on the large scales influence the small-scale physics – and vice versa. This is not entirely intuitive, as the masses of SMBHs typically are less than a percentage of the total mass of the galaxy (Kormendy & Gebhardt, 2001; Merritt & Ferrarese, 2001) and the overall stellar mass dominates over the black hole mass (unless within the radius-of-influence of the SMBH on scales of $r < 100$ pc).

A famous piece of evidence in favour of the black hole – host galaxy co-evolution is a strong relation between the mass of the black hole and the stellar velocity dispersion of a galaxy bulge, which also goes under the mass-stellar velocity dispersion relation, **M - σ relation** (Ferrarese & Merritt, 2000). The M - σ relation shows a tight connection between the two properties – something that could not happen unless some sort of “regulation” happened that connect the physics of the small scale with the physics at the large scale. Processes such as gas-rich mergers and interactions between galaxies, on the contrary, would increase the scatter.

However, the M - σ relation is poorly constrained at low masses. There are also many bulgeless galaxies that have small SMBHs with the typical masses of $10^5 - 10^6 M_{\odot}$ (Kormendy & Ho, 2013), including some dwarf galaxies with even lighter black holes e.g. RCG 118 that has an accreting black hole of a mass of $M \sim 50\,000 M_{\odot}$ (Baldassare et al., 2015).

The necessity for some sort of regulatory mechanism also comes from the bimodal colour distribution of galaxies that exists (e.g. Strateva et al., 2001) – the passive, red (or dead) and the star-forming, blue galaxies, instead of one unimodal distribution. Of course, there are more conservative explanations for this phenomenon such as stripping of gas (Gunn & Gott, 1972), feedback from star-formation where the massive stars ionize the surrounding neutral medium so that new stars cannot form, feedback from supernovae that heat the medium, or mergers (Toomre & Toomre, 1972; Barnes & Hernquist, 1992), but **AGN feedback models** are becoming increasingly popular to explain the bimodality (Tabor & Binney, 1993; Hopkins et al., 2006; Schawinski et al., 2007). It is not surprising, as the output energy from an AGN is enough to cause havoc in a galaxy and blow out most of the gas (Silk & Rees, 1998; Fabian, 1999) if only a small percent of this energy is funneled into a wind!

As the masses of black holes never exceed $10^{10} M_{\odot}$ despite continued fuelling, independent of redshift (e.g. Trakhtenbrot & Netzer, 2012), perhaps AGN feedback also regulates the black hole growth and/or can explain the cosmic downsizing of SMBH masses. An excellent review for the interested reader of the role of AGN feedback in galaxy evolution is the one by Kormendy & Ho (2013), where the different “regimes” of AGN feedback are discussed.

6.1 Modes of AGN feedback

Since the energy released by the black hole accretion ($E_{BH} = M_{BH}c^2$) well exceeds the binding energy of the galaxy bulge ($E_{gal} = M_{gal} * \sigma^2$) at typical bulge velocity dispersions so that $E_{BH}/E_{gal} > 80$ (Kormendy & Gebhardt 2001; see review by Fabian 2012), we know that the energy and momentum from black-hole accretion is powerful enough to disturb the gas in the entire host galaxy.

The AGN feedback mechanisms mainly come in two modes: the radiative mode (“quasar-mode”, “wind-mode”), or the mechanical mode (or “kinetic” or “radio-mode”). The **quasar-mode feedback** happens when an AGN becomes so luminous that it starts radiating near its Eddington luminosity. The Eddington luminosity of the AGN is the largest luminosity at which the gravitational force (inwards) and the radiative force (out) from the accretion disk are still in balance (in hydrostatic equilibrium). Once the luminosity exceeds this limit, transportation of fuel inwards will seize and the radiation pressure starts driving an outflow or a wind. These winds can be very powerful and reach far enough to impact the cold molecular gas in the host galaxy itself, in some cases even clear the galaxy of cold gas so that new stars cannot form. In the most massive galaxies, there are also signs of **radio-mode feedback**. We recall that radio galaxies often are low-excitation galaxies with weak accretion of matter upon the central black holes. Instead, their jets seem to inject kinetic energy into the surrounding gas and have an impact on the long-term star formation in the galaxy by influencing the hot-gas cooling (Croton et al., 2006).

6.2 Outflows

As neither the galaxy, nor the AGN, is a closed-box system, one can expect both inflows and outflows to take place near the nucleus. The inflows might either come from the inner part of the host galaxy through secular processes or be encouraged via gas-rich mergers and accretion of satellites.

The outflows, on the other hand, can come from any part of the AGN e.g. the accretion disk or the BLR. But, also stellar winds and supernovae in the

nucleus may create some outflows. The outflows can be molecular, atomic or ionized and vary in scale from pc-scale (see e.g. Aalto et al., 2012) to much more powerful at the kiloparsec scale (see e.g. Cicone et al., 2014). Some of them are so strong, reaching outflow velocities of thousands of kilometers per second, and could in principle empty the cold-gas reservoir inside the AGN on time-scales $10^6 - 10^8$ years (Netzer, 2013). The outflows are usually detected via blueshifted absorption lines, coming from absorbing gas moving towards us. Many of the neutral atomic gas outflows are visible in the NaI λ 5890,5896 “D” absorption lines, while the molecular outflows are seen in the OH molecule at e.g. $79 \mu\text{m}$.

Ionized gas outflows are also seen in [OIII]5007 at high redshift $z \sim 2.5$ in some AGN (Zakamska et al., 2015). They are strong (2600 – 5000 km/s) and show 3% efficiency in converting bolometric luminosity to a powerful outflow, extending on kiloparsec scales. This is strong support of negative AGN feedback where the AGN sweeps the galaxy empty of gas.

The connection between the torus and the outflows is especially intriguing, as one can learn much about the nature and geometry of the hypothetical torus by studying the outflows in the closest one hundred parsec region from the AGN.

6.3 Mergers and environment

In the hierarchical structure-formation scenario of Cold Dark Matter models, the build-up of SMBHs comes from the merging of smaller building blocks into larger ones. Already at high redshift ($z \sim 7$), one can find very heavy SMBHs in the centers of galaxies, which suggests that the accretion of mass happened very early. How the early black holes themselves formed – whether gas directly collapsed inside big dark matter halos, or whether from primordial “seed” black holes whose progenitors at extremely high redshifts ($z > 10 - 15$) were the massive population III stars – is a different question.

Mergers are violent mass-accretion episodes lasting about 1 – 2 Gyrs where two galaxies pulled by each other’s gravity start interacting, spin around each other in a destructive dance and ultimately coalesce, forming one single large body. The two SMBHs are then thought to also coalesce. Such mergers are believed to at first cause short-lived starbursts. Over longer times, mergers are thought to be responsible for the bulges in some spiral galaxies as well as the gas-poor elliptical galaxies where the stars are generally old and move in random directions in the galaxy (Toomre & Toomre, 1972; Barnes & Hernquist, 1992). Our own Milky Way shows signs of mergers through the presence of several galaxy components with varying ages on their stellar populations.

These violent mass-accretion episodes on the SMBH are associated with strong AGN activity (Soltan, 1982; Rees, 1984) suggesting that not only the SMBH accretes mass during this time, but also AGN activity is triggered. The

merger not only provides fuel to the SMBH, but it also transports the fuel so that accretion becomes possible. Through gas-rich mergers, the gas in galaxies can lose angular momentum making it spiral towards the central region of the galaxy and later towards the black hole where an accretion disk forms. If enough gas is present and depending on the overall ratios in mass between two coalescing SMBHs, also the spin and mass of the SMBH might change (Volonteri, 2010), giving rise to detectable gravitational-wave signatures.

In the high-redshift Universe ($z \sim 2 - 3$), the merger rate is believed to have been large and we can see the strongest peak of quasars in terms of number density and luminosity at this redshift. As the Universe expands, the distances between the galaxies also becomes greater, decreasing the overall probability and rate of mergers.

Much evidence shows a connection between signatures of interactions and AGN activity. Half of the quasars show signs of interactions or mergers e.g. morphological asymmetries or post-starburst populations (e.g. Canalizo & Stockton, 1997). The presence of a companion could indicate an overdense environment where mergers frequently happen, but does not necessarily prove a past merger. Studies of interacting pairs of galaxies show a strong increase of the fraction of optically selected Type-2 AGN at close projected separations $d < 50$ kpc (Ellison et al., 2011, 2013). An even larger fraction of AGN in interacting pairs is actually found if one looks at IR-selected AGN (Satyapal et al., 2014). The presence of blue companions near low-redshift quasars at $z < 0.2$ (e.g. Villarroel, 2012) and the increase of merger fraction with AGN luminosity (Fan et al., 2016) agrees with this idea. AGN host galaxies with different kind of morphological disturbances (Gehren et al., 1984; Hutchings et al., 1984) are perhaps safer indicators of past mergers.

But even if there is much evidence in favour of mergers as AGN triggers, some problems in our understanding persist. There is a confusion about how the fraction of AGN showing signs of mergers depends on redshift, luminosity and AGN selection method. Additional complexity comes from the simple time-scale argument: while the time scale of the entire merger is on Gyr scale, the typical black-hole mass growth period where the AGN activity is visible is estimated to last about $\sim 10^8$ years (Chiaberge et al., 2015). This means that the AGN phase in a galaxy might already be over when we observe the signatures of mergers!

In the Blandford-Znajek mechanism (Blandford & Znajek, 1977), a system with a magnetized accretion disk around a rapidly spinning black hole can extract spin energy from the black hole, launching a relativistic jet. Mergers can change the spin of the SMBH, so that it increases. This could lead to an interesting effect: an increase in spin could cause the separation between radio-loud and radio-quiet objects (Blandford, 1990). Interestingly, many radio-loud quasars have merger morphologies (Heckman, 1986; Ramos-Almeida et al., 2012) and radio-loud Type-2 AGN at high redshift ($z > 1$) are three times more likely to be in mergers than radio-quiet Type-2 AGN (Chiaberge et al.,

2016), supporting that the merger is necessary to launch the relativistic jets from the SMBH. Some other studies of low-excitation radio galaxies contradict this hypothesis (Ellison et al., 2015).

Mergers could also be responsible for the Type-1 / Type-2 AGN dichotomy. Theoretical works (Sanders et al., 1988; Hopkins et al., 2006) illustrate an evolutionary scenario where two gas-rich colliding galaxies merge under an intense starburst phase (triggered by strong interactions or mergers). During the intense starburst, gas inflows feed the SMBH (that becomes heavier), forming an accretion disk near the black hole, obscured by the heavy star formation. The dust produced by the starburst is so optically thick that very little emission from the weak AGN is seen; our AGN is a buried but very alive monster!

As many LIRGs show strong starbursts in their centers (Soifer et al., 1984) and the most luminous of them, the ULIRGs, in many cases reveal not only merger signatures (Sanders & Mirabel, 1996) but also the presence of low-luminosity AGN in more than 60% of the cases (Risaliti et al., 2010), they are excellent candidates for this phase. As the AGN grows and the starburst relaxes, the dust-enshrouded AGN becomes stronger and stronger, forming a torus from all the dust, soon strong enough to show the signatures of an obscured AGN. With the AGN becoming stronger, also feedback processes set in together with a blowout phase as the AGN starts approaching its maximum possible luminosity. When this happens both the gas and the dust will together be removed, clearing the AGN from obscuring elements for the viewer and an unobscured AGN can be detected.

Perhaps, this is how one connects the formation of a spheroid morphology to black-hole growth. Support for this evolutionary idea soon came from studies of neighbours to Seyfert-1 and Seyfert-2 galaxies, where the obscuration became interpreted rather in an evolutionary picture than in a simple torus model (Krongold et al., 2002).

The role of mergers in Unification can perhaps most easily be investigated by looking at the **environments** of Type-1 and Type-2 AGN. Already before the Unification Model was introduced, it was suggested that the two AGN types had different neighbour counts (Petrosian, 1982), where Type-2 AGN showed more neighbours. More follow-up works (Laurikainen & Salo, 1995; Dultzin-Hacyan et al., 1999) showed an excess of neighbour galaxies to Type-2 AGN – evidence against the Straw Person Model of Seyfert galaxies. This is also the central theme of Paper I, where we show that Type-1 and Type-2 AGN reside in different environments at small scales $d < 350$ kpc, where Type-2 AGN have bluer neighbour galaxies than Type-1 AGN (Villarroel & Korn, 2014).

The last few years, some reports claim different environments of objects at even larger scales, at Mpc scales (Donoso et al., 2014; DiPompeo et al., 2014). These reports mainly look at IR-selected AGN that are defined as “obscured” or “unobscured” (not selected by optical diagnostics) and find that the “obscured” AGN are more clustered, suggesting that the latter type resides in

more massive dark matter halos. Other studies of similar samples find no differences (Mendez et al., 2016) when matching by the stellar mass, saying that the measured clustering depends on the host galaxy. But using X-ray diagnostics and high redshift X-ray obscured and unobscured AGN one can arrive at the contradicting conclusion that the unobscured AGN reside in more massive halos (Allevato et al., 2014). Different ways of selecting the AGN, the chosen redshifts, AGN luminosities, survey instrumental limitations, different environment scales (pc, kpc or Mpc) will all influence the measured environment of Type-1 and Type-2 AGN.

Naturally, just from looking at the environments of Type-1 and Type-2 AGN one cannot directly draw firm conclusions about the **merger history** of each AGN class. The companions we see have not merged yet. Furthermore, to have a different number of satellites near the AGN one does not need mergers – already in monolithic collapse models smaller objects form near more massive ones as the gas collapses within the gravitational well of the same halo (Press & Schechter 1974). There are more things than mergers can influence a galaxy in a given environment: as galaxies move through the intergalactic medium they can lose gas through ram pressure stripping. Cooling flows and galaxy dynamics in a cluster will influence the host galaxy. High-velocity encounters between galaxies can cause disturbances in the galaxy morphology.

The mergers by themselves are also sensitive to the environment: if the environment is too sparse, the merger rate is too low. If the environment is too dense, the velocities of the cluster galaxies will be too high for mergers to be efficient. Quasars and luminous AGN tend to avoid high-density environments (e.g. Lietzen 2009). The increased merger rate in denser environments is thought to cause the **morphology-density relation** that shows how the fraction of spiral galaxies decreases in denser environments. Curiously, the host galaxies of Seyfert-2 AGN do not show a simple obedience of the morphology-density relation (Villarroel & Korn, 2014; De Souza et al., 2016; Davies et al., 2016).

6.4 Episodic AGN activity

AGN go through different phases in the cosmic life cycle, where the modes and mechanisms behind black-hole triggering and accretion can be linked to the different spectral classes of AGN (e.g. Hopkins et al., 2006). Possibly, each larger galaxy with a SMBH in the Universe has at some point been an AGN, including the many passive galaxies in our local universe at $z \sim 0$. As much of the relevant physics happens on long time scales for us short-lived humans, there is no way we can directly follow these mechanisms as they happen. Sometimes, a statistical or data-mining approach is more feasible. The **AGN duty cycle** defines what fraction of a lifetime a galaxy spends as an AGN, assuming each galaxy has been, is or will be an AGN at some point

in time. The AGN duty cycle is interesting as it can constrain the black-hole triggering, accretion and feedback mechanisms.

The active lifetime of an AGN can be constrained in two major ways. One way of estimating it is by simply multiplying the average lifetime of a galaxy (approx. 10^{10} years) with the duty cycle, where the duty cycle can roughly be estimated from the fraction of such AGN among all galaxies. The time spent as an AGN is about $10^7 - 10^9$ years. Another way of getting the lifetime for radio AGN with clear radio lobes, is to measure the physical extensions of these radio lobes and use the lobe separation and speed of the radio jets to constrain the expected time it takes for the jets to cause lobes at these distances, assuming each AGN phase results in jet emission.

Perhaps a typical AGN doesn't only have one longer phase where it is on and accreting, but perhaps many small, short phases where it is active and builds up the mass. In the **AGN flickering** scenario (Schawinski et al., 2015), the AGN can switch on fast and accretes mass in short bursts of 10^5 years. The flickering idea naturally explains why some AGN have only X-rays but no optical lines – it takes some time for the ionizing radiation to ionize the host galaxy gas when the AGN just turned on, and in this phase an optically elusive AGN (or XBONG that has X-ray signatures but can't be classified as AGN according to the line ratio diagrams is visible). This phase might last about 10^4 years. The opposite scenario, where an AGN just turned off but it takes some time for the lines in the NLR to recombine, will have optical line ratios similar to an AGN but no X-ray source. Hanny's Voorwerpje and other "quasar light echos" (Lintott et al., 2009) could be such dead states that last about $10^4 - 10^5$ years, as shown in Figure 6.1.

The existence of different AGN phases can be seen from the fact that AGN are variable on very different time scales of just a few hours or days. Others might appear static to our human eyes, while they vary much slower. The changing-look AGN mentioned earlier, switch between Type-1 and Type-2 states on just a few years (Lyutyi et al., 1984; Matt et al., 2003) and make the question particularly interesting: it recently has been shown that the switch in a changing-look AGN was not caused by obscuration as the switch was not accompanied by any change in the reddening, but rather caused by intrinsic differences in the central engine (LaMassa et al., 2015). This puts both the Unification and evolutionary ideas into trouble. Does it then mean that the Type-1 and Type-2 AGN is a distinction that is independent of any obscuration effect and what we rather are seeing is an on/off behaviour of AGN where the Type-2 state is "off" and Type-1 state is "on"? If Seyfert-1 and Seyfert-2 states are just different states in the cosmic cycle of AGN, where and how does the Unification fit in?

In Paper IV, the method we propose to search for extra-terrestrial intelligence by searching for objects that vanish over a few epochs has an interesting side-effect: we might find some extreme variable objects. This means, using

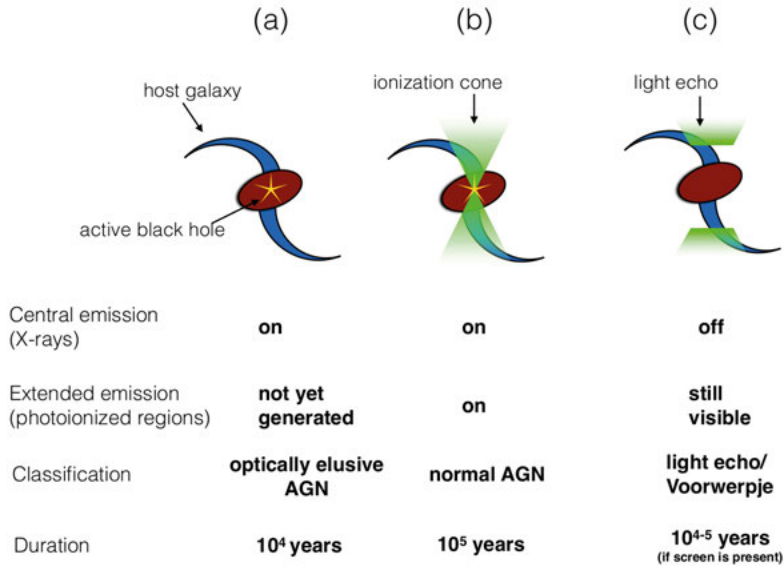


Figure 6.1. The AGN flickering model, adopted from Schawinski et al. (2015), Monthly Notices of the Royal Astronomical Society, 451, 2517. In many short cycles, the AGN turns on and accretes mass. If the AGN just turned on as in (a), the X-rays are visible but the extended NLR emission has not yet been produced. In (b) both the AGN is on and the NLR can be seen. In (c), the AGN has just turned off, the NLR emission is still visible but not the X-ray emission. The AGN flickering model assumes that the AGN goes through thousands of these cycles during a given total mass accretion event.

this method we may be able to identify the faintest and/or the most distant variable AGN, for example the most extreme changing-look objects.

7. Summary and future plans

Active galactic nuclei (AGN) are heavily accreting super-massive black holes in the center of galaxies. They come in many forms. A long-standing problem is how the two major spectral classes of AGN, Type-1 and Type-2 AGN, are physically connected. The AGN Unification theory describes a Type-2 AGN as a Type-1 AGN viewed through a lot of dust. In the most simplified form of the AGN Unification theory, this dust is located in a small, parsec-size doughnut around the (same) central engine and the viewing angle into the center solely determines the Type-1/Type-2 classification.

In this thesis, I have worked with some (more or less) novel approaches to obtain constraints on the applicability of AGN Unification. I have done so using open-access data from various surveys. I have also tried to use as few assumptions as possible in my approaches.

My main conclusions are:

- Type-1 and Type-2 AGN neighbours have different optical colours. The difference can not be explained within a pure viewing-angle dependence in a parsec-sized torus – whether smooth or clumpy (Villarroel & Korn, 2014).
- Type-1 and Type-2 AGN host galaxies have different star-formation histories as seen by their supernova counts (Villarroel et al., 2016a).
- Type-1 and Type-2 AGN selected to be in similar host galaxies differ in [OIII]5007 luminosity (Villarroel et al., 2016a). As the host galaxies differ, this is unlikely to be a result of a “receding-torus effect”.
- The dispersion of the [OIII]5007 line is rather similar for Type-1 and Type-2 AGN (Villarroel et al., 2016a) and significantly broader than in star-forming galaxies.
- From Colocative Correlation Analysis (CoCoA), we find no evidence for any substantial differences in the narrow-line region between Seyfert-1 and Seyfert-2 galaxies (Villarroel & Korn, 2016). This supports the well-established assumption of a common physical mechanism driving the formation of narrow lines in both Seyfert-1s and Seyfert-2s.
- The two classes share same engine, but the engine differs in luminosity, and the host galaxies differ by their star-formation histories (causing a difference in obscuration on large scales).

The existence of dust in the central parsecs of AGN (a “torus”) has been established through IR interferometry and imaging and is needed to explain some of the most heavily obscured AGN. But the torus-only models of AGN Unification underestimate the role of the host-galaxy dust in the obscuration

paradigm. Naturally, different star-formation leads to a different amount and density of dust in the host galaxy. But is the large-scale dust fuelling the parsec-sized “torus” as well?

The two regimes of obscuration could both contribute to the total obscuration, but independently of each other; they could also be interdependent. This will be the next step of my research work. I hope to derive some constraints from observational data. If I, or anybody else, find a reliable connection between the large-scale dust and the “torus dust”, it will be important to theoretically understand how and why this connection exists.

Despite the indications in this thesis, we are still plagued by the existence of changing-look AGN, whose switching between the classes cannot be explained through the simple obscuration ideas. While certainly not the most efficient way of finding the largest number of changing-look AGN, a side-project on an entirely different, a little more hedonist topic (Villarroel et al., 2016b) might perhaps yield the faintest and/or most distant changing-look AGN.

Meanwhile, CoCoA must be tested on multiple synthetic spectra to see if the potential prediction of time lags of emission lines is theoretically possible. If so, I sense what path my future research will take.

8. Contributions

Paper I

I came up with the idea. I obtained and analyzed the data, interpreted the results and wrote the first version of the manuscript.

Paper II

Together with A.N., I came up with the idea of looking for SNe in AGN hosts. I constructed the galaxy samples and plotted Figure 1, 2, 3 & 5. I analyzed the refined samples of face-on spiral hosts. I have written the bulk of the manuscript, **not** sections 2.1, 2.2, 2.5, 4.3 (where I contributed) and section 5. I have interpreted the results.

Paper III

I came up with the idea and carried it out. I interpreted the results. I wrote the first draft of the manuscript.

Paper IV

I came up with the idea. I did all data handling, collection and analysis, except for the visual examination of 300 000 objects (that was split fairly over all three authors). I checked for false positives and false negatives. I wrote the manuscript.

9. Populärvetenskaplig sammanfattning¹

En betydande del av galaxers ljus kommer från stjärnor – men inte allt ljus och inte i alla galaxer. Det existerar nämligen en klass av objekt, aktiva galaxer, som utsänder mer ljus än andra. Emellanåt kan det sammanlagda ljuset från alla glödande stjärnor i tusentals galaxer liknande vår egen Vintergata uppmäta sig med ljuset från en enda aktiv. Men ljuset i en aktiv galax kommer inte från dess stjärnor. Det kommer från ett litet område i galaxens mittersta centrum, ett oansenligt område knappt större än vårt eget solsystem och ofta så bländande att resten av objektet överglänses.

Spektra avslöjar åtskilliga släkter av aktiva galaxkärnor. Kvasarerna är de mest ljusstarka av alla. Somliga strålar i radiovåglängder och har framträdande flöden från kärnan. Seyfertgalaxerna är enklare: de visar inga sådana flöden eller jetstrålar och är betydligt mer blygsamma än kvasarerna i sin skepnad. Blasarer kan däremot blända med sina oförutsägbara växlingar i sitt ljussken. De tros vara kvasarer med jetstrålar och vars ena stråle man som observatör råkar kika rakt in i.

Trots skillnaderna som förekommer mellan olika klasser, förenas speciellt Seyfertgalaxer av de spektra som alla uppvisar skarpa vätelinjer och “förbjudna emissionslinjer” från bland annat joniserat syre och kväve. Jonisationen kan uppstå antingen från att energirika ljuspartiklar slår bort elektroner i gasatomerna eller att atomerna förlorar elektroner i häftiga kollisioner. I praktiken medför det att endera måste en intensiv och högenergetisk ljuskälla gömma sig i hjärtat av dessa kosmiska vidunder eller att kraftiga chockvågor från våldsamma processer i gasen måste vålla jonisationen.

På 1980-talet florerade alla tänkbara, vilda idéer om vad som finns i mittpunkten av en aktiv galaxkärna. Kunde möjligen maskhål, dessa hypotetiska tidsmaskiner från relativitetsteorin där dvälja, gömda i galaxkärnans innersta väsen? Eller kunde möjligen kolossala stjärnor finnas där, tyngre än teorierna anat och alltför massiva för att leva längre än ett övergående kosmisk ögonblick, för att strax efter födseln fullborda sina liv i explosiva supernovor?

Teorierna kring galaxkärnorna blomstrade och snart blev astronomerna varse om att oavsett vad som fanns i centrum måste det nämligen uppfylla vissa förväntade egenskaper. Först måste tinget jonisera den omgivande gasen och för var tionde aktiv galaxkärna måste det även frambringe radiojetstrålar. De flesta aktiva galaxkärnor faller inom två huvudklasser: de vars vätelinjer är breda (typ-1) och de som har smala vätelinjer (typ-2), och tinget måste förklara båda huvudklassernas existens. Nu började de teorier som tidigare frodats även mattas av. Långsamt började observationer stapla sig på varandra: vad

som än fanns i kärnan av en aktiva galax band den närliggande gasen gravitationellt till sig. Något riktigt, utomordentligt tungt måste finnas i kärnans mitt. Idag vet vi att det rör sig om ett supermassivt svart hål.

I en aktiv galax är det supermassiva svarta hålet inte bara mycket tyngre (kanske tusen gånger mer massivt än Vintergatans svarta hål) utan även mer aktivt. Den mest utforskade hypotesen idag är att ansamling av stora mängder het gas kring det supermassiva svarta hålet är vad som driver den intensiva produktionen av ljus i aktiva galaxkärnor. Utgår man från att jonisationen i omgivande gas sker genom att energirika fotoner från gasansamlingen slår ut elektronerna i gasatomerna, måste man undra varför man bara ser breda vätelinjer i galaxer av typ-1 men inte i typ-2-galaxer.

Den enklaste s.k. unifikationsteorin vilar på ett enkelt geometriskt koncept där betraktelsevinkeln är den egenskap som används för att skilja på typ-1-galaxer och typ-2-galaxer. Teorin utgår från att alla aktiva galaxkärnor har en ansamlingsskiva i mitten som vidare omges av het gas. Runt gasen tros en liten och tät "stofftorus" finnas. Råkar man titta rakt in i själva ansamlingsskivan eller gasen kring den, kan man se täta gasmoln som snabbt roterar. I praktiken skulle detta synas som en breddning av vätelinjerna i spektrumet. Men skulle ljuset från samma ansamlingsskiva istället färdas genom stofftorusen och spridas på vägen, kommer det att förlora energi och få längre våglängd. På det här sättet kan ultraviolett ljus från skivan omvandlas till infrarött. Det infraröda ljuset blir torusens viktigaste signatur och man erhåller spektrumet för en typ-2-kärna med smala linjer. Unifikationsteorin förutspår därmed att alla typ-2-galaxer måste visa tecken på en typ-1-kärna om de observeras med polariserat ljus – någonting som dessvärre ännu inte kunnat bekräftas.

Att testa unifikationsteorin innebär många praktiska svårigheter. För att kunna säga någonting alls om populationen av aktiva galaxkärnor, måste man jobba med mängder av objekt och därmed statistiska studier. Samtidigt är det svårt att hantera olika tekniska begränsningar som på verkar observationsmöjligheterna för galaxkärnorna av typ-1 och 2.

I den här avhandlingen har vi med hjälp av galaxstatistik undersökt förutsättningarna för unifikationsteorins giltighet. Vi ser att den enklaste modellen med en enkel stofftorus inte kan stämma, eftersom de två klasserna av galaxkärnor befinner sig i väldigt olika miljöer. Dessutom tycks värdgalaxens stoftegenskaper väga in minst lika mycket som själva stofftorusens, då vi i våra supernovastudier visar att typ-2-kärnor är vanliga i stjärnbildande galaxer med mycket stoft. Men förutom olika ljusstyrka, ser vi inga anmärkningsvärda skillnader i de mekanismer som driver ljusproduktionen.

Vi tar med läsaren på en färd in i den aktiva galaxkärnan samt unifikationsteorins begränsningar och möjligheter. Vi berättar om hur de skilda studier och metoder vi använt kan belysa teorins mest fundamentala frågor.

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