Morphology and Orientation Research: Inclination of AGN (MORIA)

Delving Deeper into AGN with WISE and Euclid

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Abstract

The spaced-based Euclid survey will provide large-scale, high-resolution imagery of large areas of the sky. Among the publications that accompanied the Euclid Quick Release 1 (Q1) is a catalog of active galactic nuclei (AGN). This catalog is missing numerous AGN sources that are included in other catalogs, particularly the WISE (Wide-field Infrared Survey Explorer) AGN catalog. This research will use data analysis and statistical modeling to probe both the overlap and gaps between the Euclid Q1 AGN catalog and other AGN catalogs. By first comparing the Euclid Q1 AGN catalog with the WISE AGN catalog, we will explore the differences between the infrared (IR) and optical classifications of AGN to highlight the host galaxies' orientation and obscuration effects that are dominant at optical wavelengths.

Background Information

Active galactic nuclei (AGN) are important objects that are used to study the distant universe (distant in both space and time) as astronomers work to understand their evolution over cosmic time scales. An active galaxy has a black hole at its center which is accreting matter, unlike other galaxies, which do not. This accretion occurs in a disk surrounding the black hole where matter heats up as it spirals and ultimately falls into the black hole. Due to high temperatures from friction, compression, and magnetic processes, the accretion disk produces emission across the entire electromagnetic spectrum. Accretion is very efficient at converting matter into energy, making AGN among the most luminous objects known. This high luminosity makes AGN visible from very large distances ($z \geq 8.5$) (Kokorev et al., 2023).

Beyond the accretion disk there is the broad-line region (BLR), which lies within a few parsecs; the dusty torus, which lies within tens of parsecs; and the narrow-line region (NLR), which lies tens to hundreds of parsecs from the central black hole. The BLR consists of dense, high-velocity gas clouds that produce Doppler-broadened emission lines across the electromagnetic spectrum. The NLR is farther out, where ions are moving around 10% of the velocity of the ions in the BLR. The larger distance from the accretion disk means there is less energy to accelerate the gas to high velocities, allowing for atoms to emit less Doppler-broadened, and thus narrower, spectral features. In addition to these regions is the dusty torus, where dust absorbs the ultraviolet (UV) and optical light and re-emits continuum light at infrared (IR) wavelengths. Likely because of this region, AGN are divided into two main categories: Type 1 and Type 2. Type 1 AGN are those where the viewing angle to the BLR in the UV/optical is not obscured by the dusty torus and a broad-line spectrum is observed. Type 2 AGN are where a large portion of light from the BLR and accretion disk is being absorbed in the optical and other wavelengths by the intervening torus. This results in the NLR being the dominant factor in the observed spectrum.

The unified model (e.g., Urry, 2003) of AGN emphasizes the possible dependence of type determination on viewing angle. In other words, the category an active galactic nucleus is likely to fall into may be best explained by assuming a common structure for the area near the supermassive black hole but seen through differing amounts of obscuring dust (Figure 1).

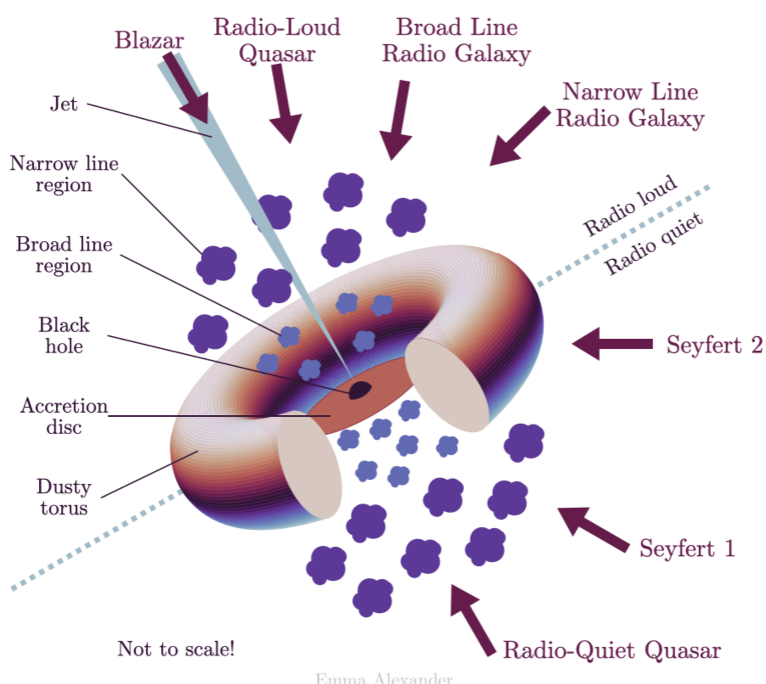

Figure 1. *Unified AGN Model Showing Classification and Viewing Angle Dependence. Note: Seyfert 1 and 2 are low luminosity cases of Type 1 and 2 AGN. (Alexander, 2022).*

If the UV/optical BLR emission is hidden by the dusty torus, then the classification is likely to be a Type 2 active galactic nucleus. If the UV/optical BLR emission is unobscured, the active galactic nucleus is likely classified as Type 1 (Alexander, 2022). Unfortunately, connecting observations to the unified model of AGN is far from straightforward. These classifications are not an absolute binary system for observers to use but provide a way to generally classify the observations being made. One of the confounding variables in classification is the contribution or interference from the host galaxy. To address this aspect, a large and uniform imaging database of active galaxies is needed. Such a database has now been provided by the Euclid mission.

The Euclid spacecraft was developed by the European Space Agency (ESA) and launched 1 July 2023. Euclid's primary mission is to measure the accelerating expansion of the universe. To do so, Euclid carries a visible-light instrument (Visible Imaging Channel - VIS), which uses a very broad single-band filter (550–900 nm) in addition to other instruments (ESA, 2026). Euclid will ultimately survey over 1/3 of the sky and image more than one billion galaxies out to a distance of about 10 billion light-years. Many of these galaxies will be AGN. Euclid's first data release, the Quick Data Release (Q1) covers 63.1 square degrees of sky from the Euclid Deep Fields (EDFs), containing approximately 30 million objects in three regions: near each of the ecliptic poles and the EDF Fornax field (Figure 2). The Euclid images have sufficient resolution (0.3 arcseconds per pixel in the optical) to study the details of the host galaxies.

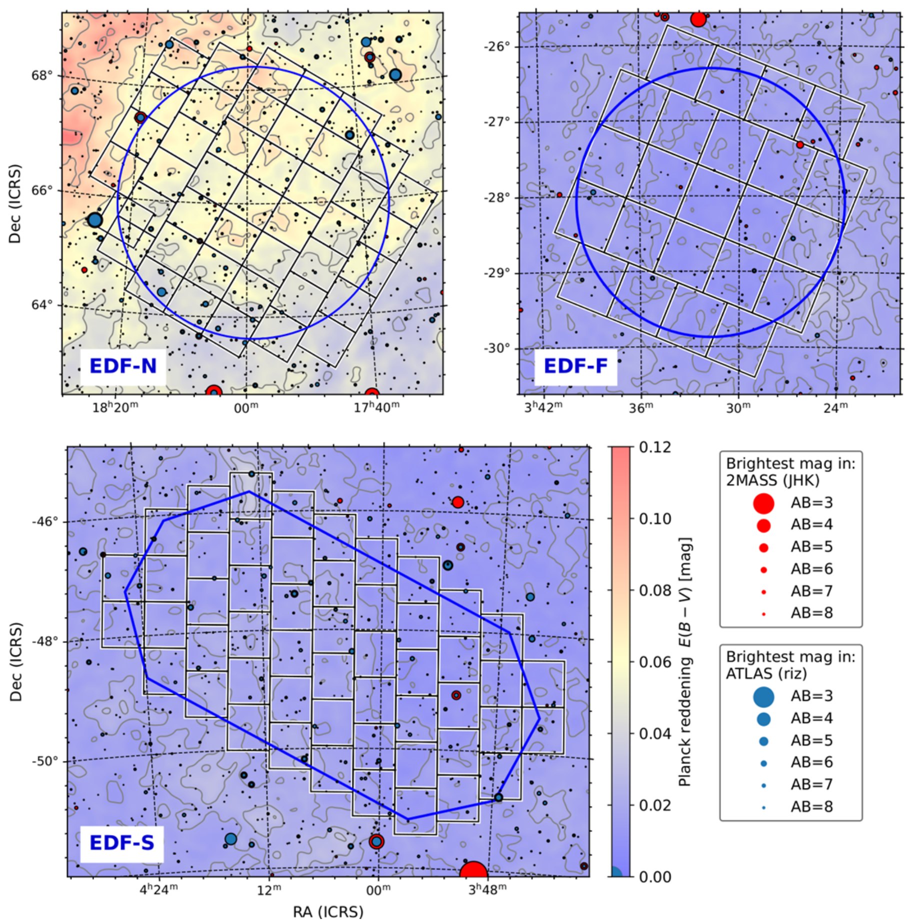

Figure 2. *The locations of the three survey fields observed by Euclid Q1. (Aussel, 2025)*

Another catalog with a large sample of identified AGN utilizes data from the Wide-Field Infrared Survey Explorer (WISE) (Wright et al., 2010), compiled by Assef and colleagues (2018). We will be focusing on combining WISE and Euclid data, both of which have identified AGN but with differing results. WISE takes images in the mid-infrared (mid-IR). For AGN, this light is being produced by the dusty torus. WISE operates in four mid-infrared bands: [W1] (3.46 μm), [W2] (4.6 μm), [W3] (12 μm), and [W4] (22 μm). As long as the host galaxy is not extremely bright, the [W1]-[W2] color is close to zero for nonactive galaxies, but for active galaxies the [W1]-[W2] color is greater than 0.8 due to re-emitted light in the mid-IR (Figure 3). This selection method reduces the torus viewing angle issue in identifying AGN due to re-emitted infrared from the dust itself.

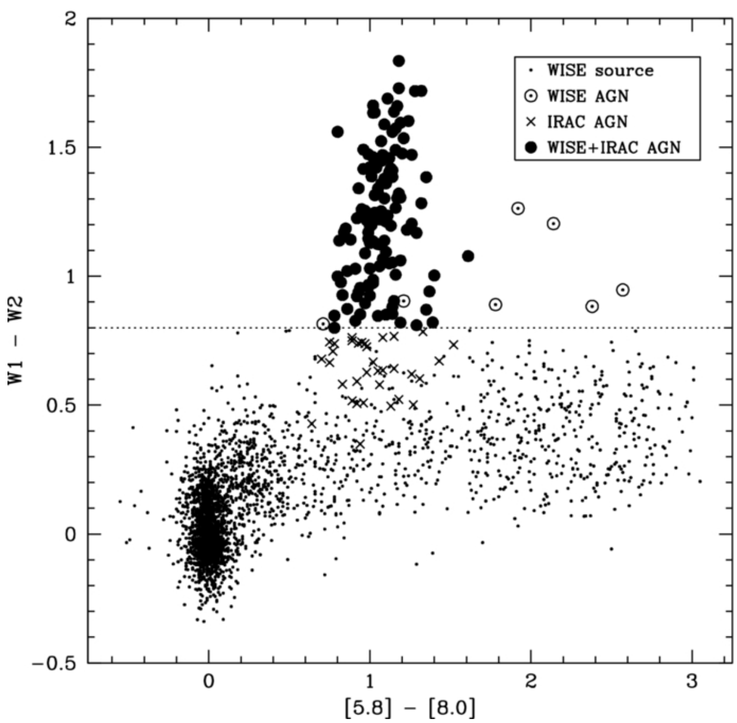

Figure 3. *IRAC color−color diagram of WISE−selected sources in the COSMOS field (Stern et al. 2012). We only plot sources with SN R ≥ 10 in W 1 and W 2, and we require [3.6] > 11 to avoid saturated stars. Sources with W 1− W 2 ≥ 0.8 are indicated with larger circles; filled circles indicate sources that were also identified as AGN using the Stern et al. (2005) mid−infrared color criteria. Sources identified as AGN using Spitzer criteria but not using the WISE criterion are indicated with exes.*

In comparison, Euclid data was used to identify AGN with point-source fitting of the central region of the galaxy. This method quantifies how much a galaxy's brightness at its center can be attributed to point-source contribution from an active galactic nucleus. This complements the WISE color-selection technique by identifying AGN where there is strong mid-IR emission from a bright host galaxy that may overwhelm the active galactic nucleus contribution. The Euclid identifications are more susceptible to obscuration by both the dusty torus and the host galaxy so, by comparing the Euclid and WISE AGN catalogs, we intend to quantify the amount of host galaxy obscuration compared to the dusty torus obscuration.

Analysis

Zatarain et al. (2025) fit Sérsic profiles to all the Q1 galaxies, providing a ready-made tool to analyze the host galaxies of AGN from both the WISE and Euclid Q1 catalogs. A Sérsic profile describes how the brightness of a galaxy changes with increasing distance from the galaxy's center (Vitral & Mamon, 2020). A Sérsic number of n=1 makes a good fit for spiral galaxies and a rough fit for dwarf elliptical galaxies, while a good fit for an active galactic nucleus would approach n=10. Other values of n correlate with other types of galaxies, such as ellipticals, which have higher n-values, and dwarf galaxies, which have lower n-values. (Figure 4). We will be using Sérsic profiles to quantify the effect of the host galaxies in all the released Q1 fields. While the Sérsic number is not directly correlated with galaxy orientation, for disk-dominated galaxies it can be used as a proxy for identifying the impact of the host galaxy in obscuring the active galactic nucleus.

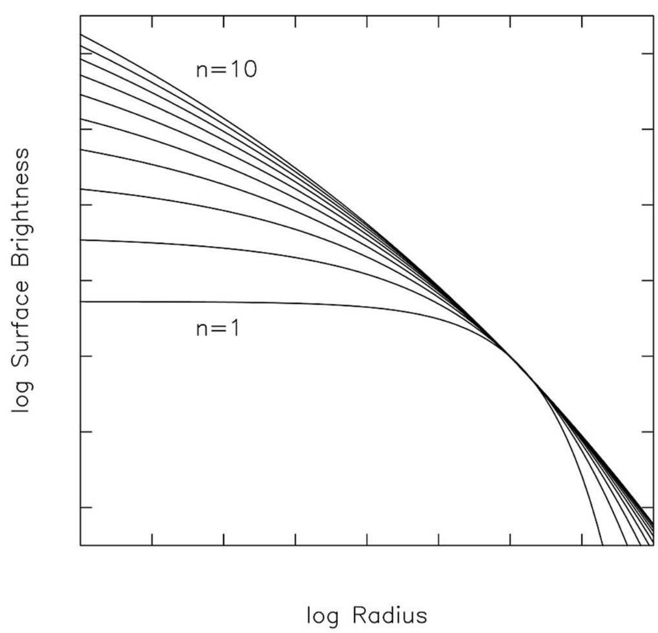

***Figure 4**. Sérsic profiles of various galaxy types showing how brightness drops off as one moves away from the center of the galaxy (Trujillo et al., 2004).*

Margalef-Bentabol et al. (2025) show there are already known discrepancies between the two catalogs. We will first construct a catalog of sources by cross-referencing the WISE AGN catalog with the Euclid Q1 AGN catalog. After determining objects identified as AGN by WISE but not by Euclid, we will then cross-reference that subset of objects with the larger Euclid Q1 catalog of galaxies. This final subset of sources will then comprise galaxies that have been determined in the IR to be AGN but on whose AGN classification Euclid does not agree. We will focus on discovering patterns in the following categories:

- Objects classified as AGN by only WISE
- Objects classified as AGN by only Euclid
- Objects classified as AGN by both Euclid and WISE

We will be able to determine if AGN in Euclid and WISE data are often classified differently and why, with our expectation being that Euclid data are primarily missing AGN based on Margalef-Bentabol et al. (2025).

	Percentage (%)	
AGN-selection method	$f_{PSF} > 0.2$	$f_{PSF} > 0.1$
X-ray (All)	35 ± 3	60 ± 4
X-ray (4XMM & CSC2)	30 ± 3	56 ± 5
X-ray (EROMAIN)	43 ± 5	63 ± 6
DESI Spectroscopic	31 ± 4	52 ± 6
MIR colours (C75, AllWISE)	13 ± 4	28 ± 1
MIR colours (R90, AllWISE)	29 ± 2	51 ± 3

Table 1. *Euclid-selected AGN compared to AGN selected by other surveys (Margalef-Bentabol et al. 2025). Note: The Euclid survey for AGN with a central point-source contribution of greater than 10% ($f_{psf} > 0.1$) recovers only about 1/2 of the WISE AGN.*

Using Sérsic numbers as a proxy, we will determine the frequency with which the catalogs disagree and will run a statistical analysis to see if the patterns found are significant.

Our chosen tool to start crossmatching the source catalogs is TOPCAT (Tool for Operations on Catalogs and Tables) which provides quick and efficient catalog matching (Taylor, 2005). More extensive catalog matching will be done with Python code, with initial extractions using both to validate the Python output.

One common way for astronomers to share standard tools and techniques for data access and analysis is through the use of Jupyter Notebooks (Kluyver, 2016), allowing users with various programming backgrounds to share live code and rich media along with text. IPAC has created a suite of tools for accessing, analyzing, and visualizing datasets across astrophysical disciplines. Following the lead of IPAC data scientists, we will produce a set of Jupyter Notebooks which can be later leveraged in the creation and curation of classroom materials and artifacts.

Outcomes

Outcomes for this project are significant no matter the direction of the results. If AGN discrepancies appear uncorrelated, there may be additional factors such as torus geometry or variability in the AGN as the cause. If there is a strong correlation between discrepancies and host galaxy morphology, such as AGN in edge-on galaxies being repeatedly missed by Euclid but not by WISE, this could provide a foundation to account for biases in classification for future AGN catalogs.

We will deliver a set of Jupyter notebooks to be used in the classroom or by novice researchers that would be capable of merging tables with group labels and characteristics related to morphology. Additionally, these programs will aid in combining the thousands of data points from Q1 and the future Euclid Quick Data Release 2 (Q2) to cross-categorize between WISE and Euclid.

Outreach

<u>James Newland</u>
Texas Advanced Computing Center, University of Texas at Austin

- Create at least two Jupyter Notebooks to use with science educators through various outreach programs at TACC as well as to be used in BINAP/NITARP programs moving forward
- Publish a curriculum artifact tied to bringing high-performance computing (HPC) to K-12 education spaces that can be used in classrooms
- Present results of NITARP 2026 as a data science education tool at the Data Science Education K-12 Research to Practice Conference through Data Science 4 Everyone
- Present results of NITARP 2026 at both national and regional levels (AAPT, APS, CAST, WTCS Summit, ASP Conference Series, CSTA, etc.)
- Incorporate resources and skills into various teacher professional development programs focused on computing and data science pedagogy integration across the curriculum (Texas Computer Science Pipeline Data Science Hub)

<u>Thomas Rutherford</u>
King University, Bristol, TN; East Tennessee State University, Johnson City, TN

- Give a public talk about the project (and the results) at a monthly meeting of the Bays Mountain Astronomy Club
- Poster presentation at the January, 2027 AAS meeting in Salt Lake City, UT
- Give a public talk about the project before the physics department (faculty and students) at an ETSU Physics seminar.
- Present the project to my astronomy classes at King University
- Presentation about NITARP (including this project) at the Spring 2027 NSTA meeting in Boston.

<u>Justin Hickey</u>
Episcopal High School, Bellaire, TX
Presentations to other educators about the NITARP program/my experience:

- EHS Science Department Meetings, August 2026 and February 2027
- University of Texas EXES Teacher Program Meeting, Spring 2027

Presentations to the public about research:

- EHS Admissions events, 2026-27 school year

Publications featuring our work:

- EHS Pillars magazine, Spring 2027

Educational Initiatives:

- Using IRSA data and Jupyter notebooks as part of curriculum for one-semester Astro 101-type elective course at EHS

Eden Pfahler
Falmouth High School, Falmouth, ME

- Reach out to present education material and/or classroom resources created at the New England Section (AAPT-NES) meeting
- Integrate research methods and data analysis from this project into AP Research coursework, giving students hands-on experience with real astronomical data and archival tools
- Use the project as a foundation for developing a student research pathway at FHS, where students can engage with archival astronomical data through independent study or AP Research
- Present research and NITARP experience to the FHS school board at the end of the program

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