Optical Variability of Quasars at 0.4 < z < 0.5 with ZTF: Double-Peaked vs Non-Double-Peaked Sources.

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Abstract

An optical variability analysis was conducted for a sample of low-redshift quasars (0.4 < z < 0.5) using forced photometry data from the Zwicky Transient Facility (ZTF). The primary objective was to investigate how photometric variability, quantified via the fractional variability amplitude (F_{var}), correlates with physical and spectral properties of quasars, and whether distinct patterns of variability and properties emerge among different spectral classes. To this end, the sample was divided into three subsamples—double-peaked (DP), intermediate (IM), and non-double-peaked (NDP)—based on a visual classification of the Hα and Hβ emission line profiles (Storchi-Bergmann et al. 2017).

Physical and spectral parameters were obtained from the catalogs of Lyke et al. (2020) and Wu & Shen (2022). Strong, moderate, and no separation was observed among the subsamples across various AGN properties. Statistically significant trends were found between variability and several physical properties, suggesting that variability is closely linked to underlying quasar characteristics.

A particularly clear separation in black hole mass estimates led to a more detailed investigation, revealing that mass estimates based on line widths (as in Wu & Shen 2022) are likely overestimated for DP and IM quasars. To address this, an alternative method proposed by Benati et al. (2025) was applied, in which the Eddington ratio is inferred from F_{var} and, combined with the bolometric luminosity, provides a revised estimate of the black hole mass.

This work is currently in its final stages and will be submitted for publication shortly. The forthcoming paper will include a full discussion of the findings and supporting arguments presented here, along with potential directions for future research.

Sample

The initial sample was drawn from Lyke et al. (2020), with most of the physical and spectral properties obtained from the catalog by Wu & Shen (2022). To ensure the reliability of both spectral and photometric measurements, we applied a series of quality cuts, including a signal-to-noise ratio (S/N) greater than 20 in the SDSS spectra and more than 100 observation nights in the light curves. After these selections, the final sample comprised 472 quasars, which were then classified into three categories — DP, IM, and NDP — based on the shape of the Hβ and Hα emission lines, as illustrated in the images below.

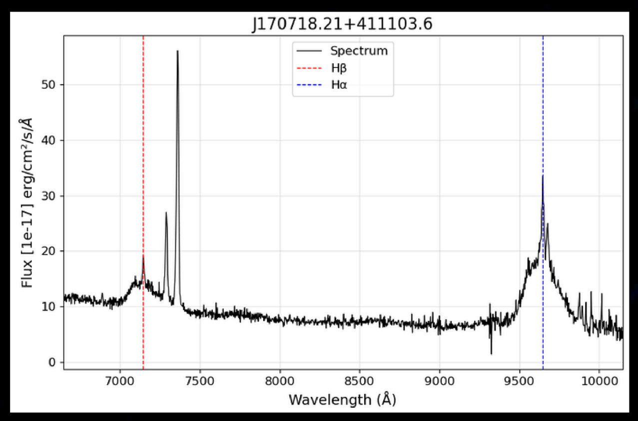

Figure 1: DP spectrum

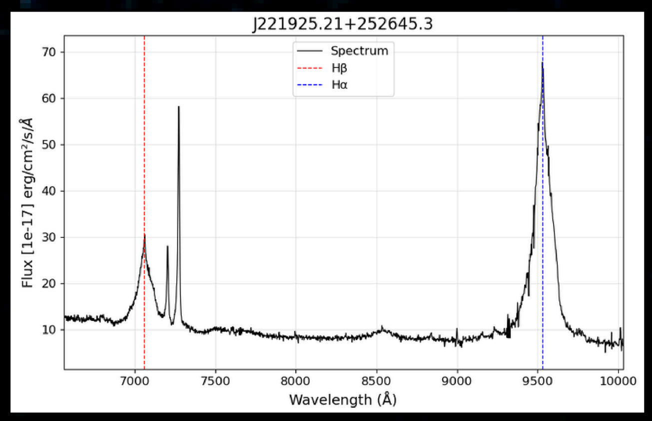

Figure 2: IM spectrum

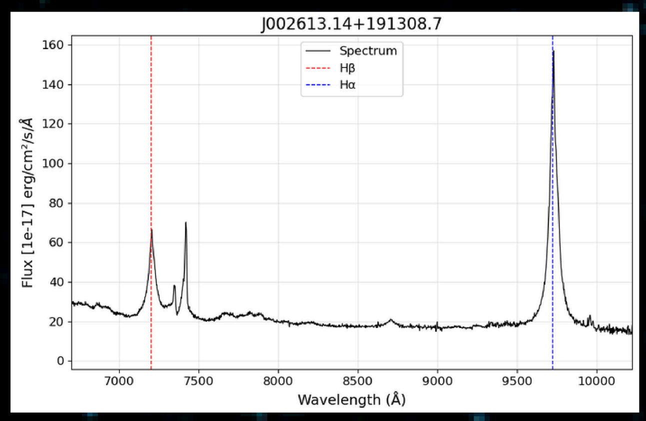

Figure 3: NDP spectrum

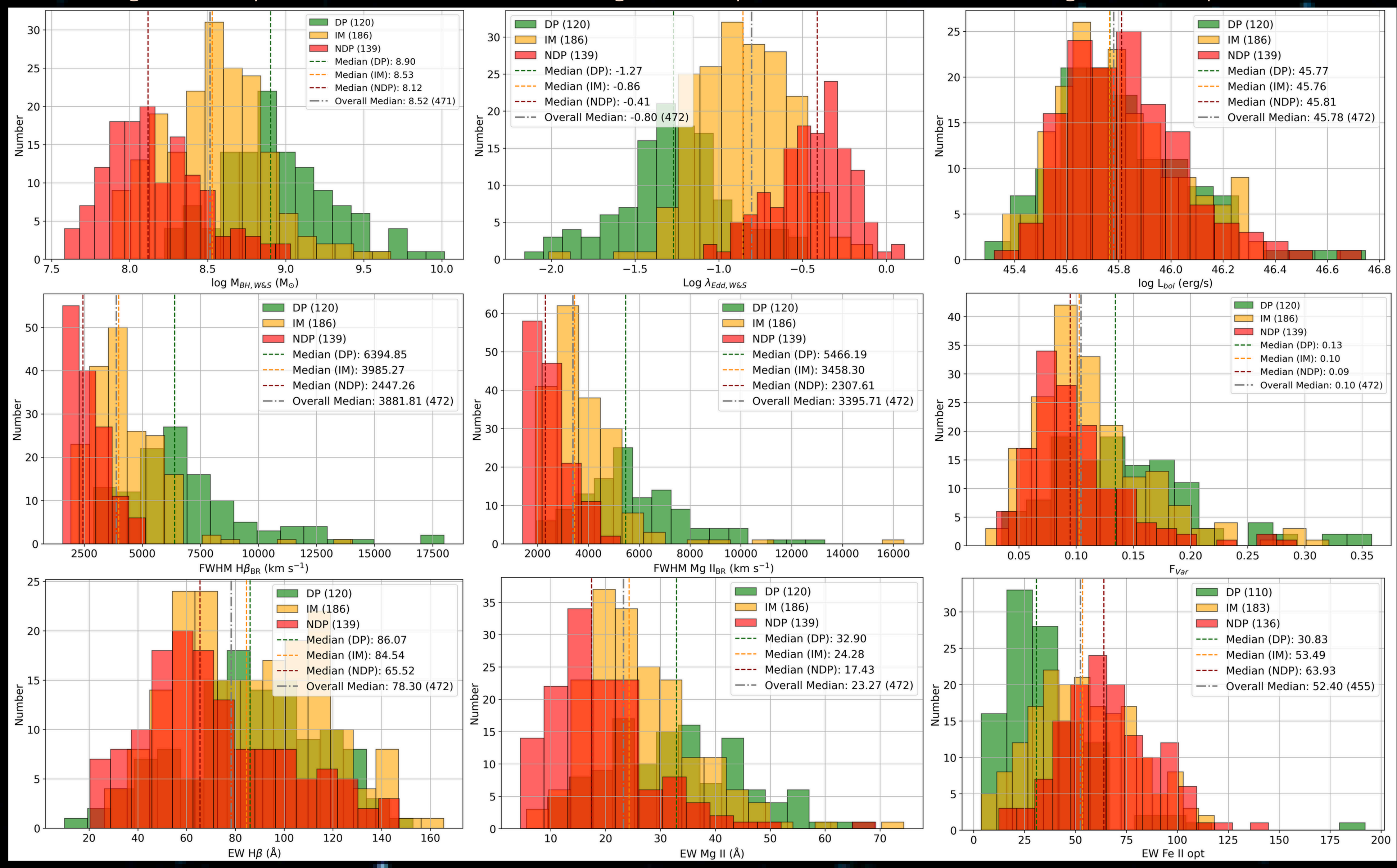

Figure 4: Histograms comparing physical and spectral parameters obtained from the catalog of Wu & Shen (2022) and from ZTF data. The top row shows distributions of black hole mass, Eddington ratio, and bolometric luminosity, respectively. The middle row presents the FWHM of Hβ, FWHM of Mg II, and F_{var}, respectively. The bottom row shows the EW of Hβ, MgII and Fe II in the optical, respectively.

ZTF Data

With the long-term goal of applying this methodology to LSST data, forced photometry data from the ZTF were used to calculate variability and generate light curves.

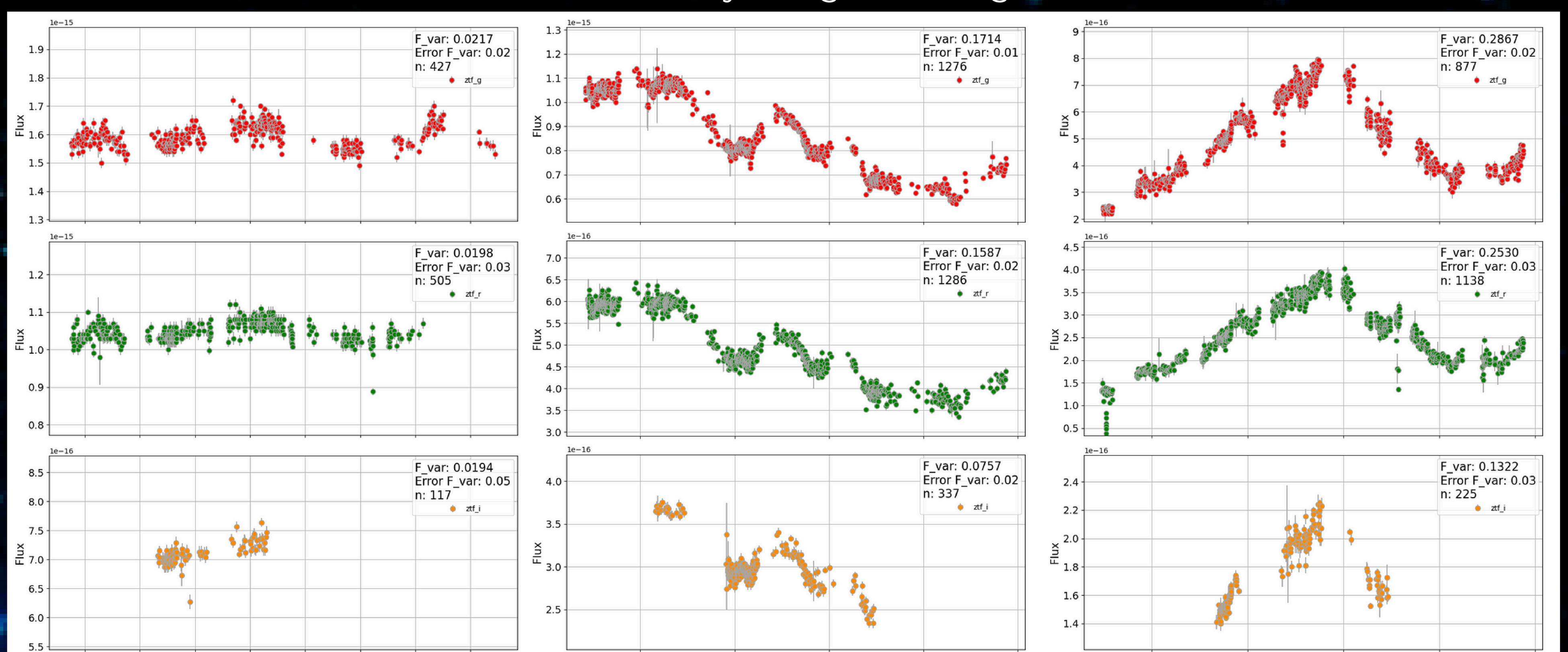

Figure 5: Example light curves from ZTF data illustrating sources with low, medium, and high variability, respectively.

Results

Variability was estimated using Fvar, a standard approach in such analyses, calculated from the equations below using light curve data.

$$F_{\rm var} = \sqrt{\frac{S^2 - \langle \sigma_{\rm err}^2 \rangle}{\langle F \rangle^2}}$$

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (F_i - \langle F \rangle)^2$$

To determine whether there is any correlation between F_{var} and other AGN properties. To investigate this, we compared each property with F_{var} using log–log plots and analyzed the trends. The most relevant correlations were identified:

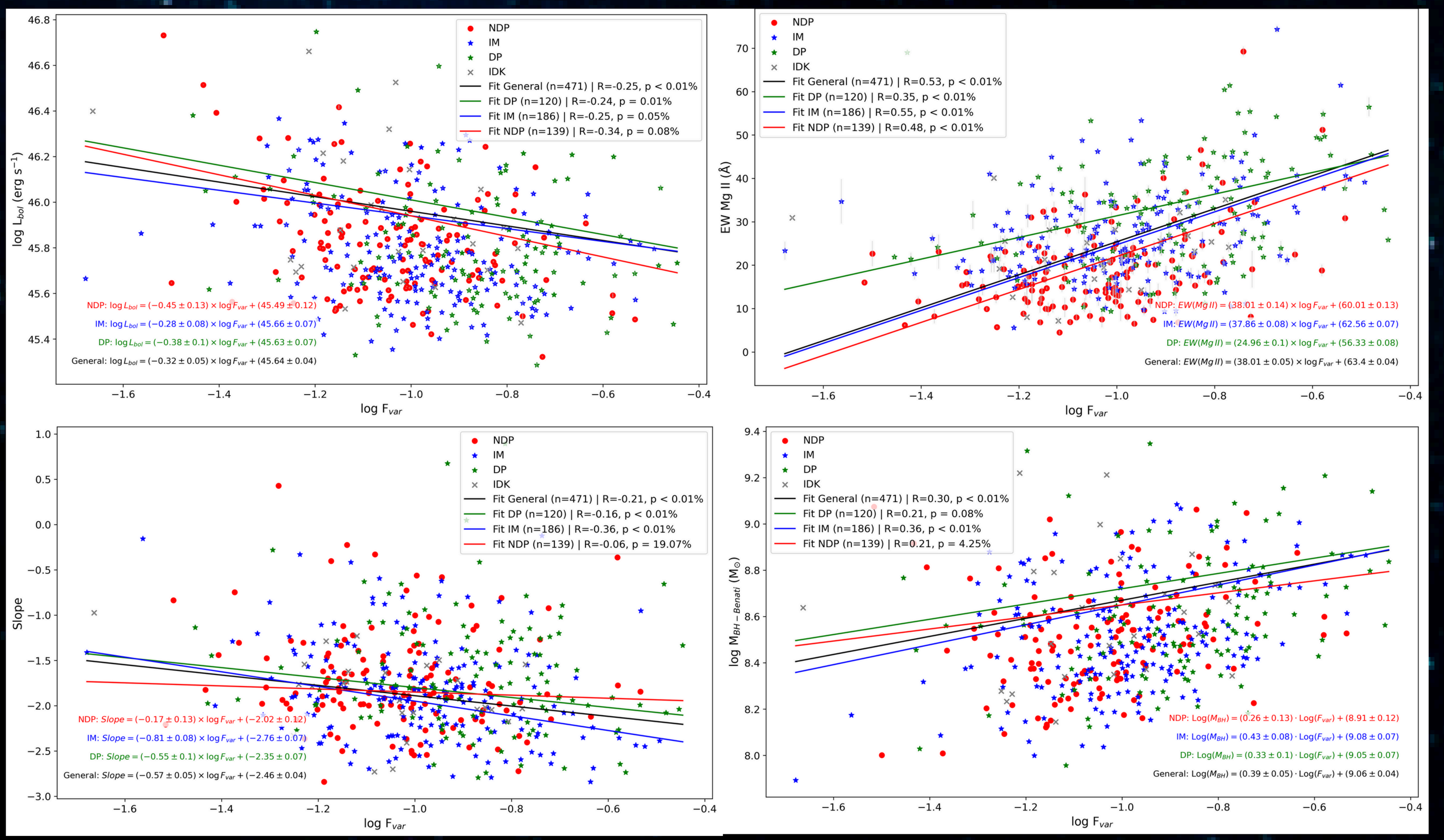

Figure 6: Correlations between physical and spectral properties of AGNs and log F_{var}. Each panel shows a linear regression fit (with corresponding equation and confidence metrics) for the full sample (black), and for the DP (green), IM (blue), and NDP (red) subsamples. **Top row:** bolometric luminosity and Mg II equivalent width, from Wu & Shen (2022). **Bottom row:** spectral slope of the continuum between 3100–4100 Å and black hole mass estimated using the method of Benatti et al. (2025).

An alternative approach was explored to estimate the central black hole mass. The relation proposed by Benati et al. (2025), which derives the Eddington ratio from Fvar, was employed; combined with the luminosity, this enabled the estimation of a new black hole mass. Using this revised mass estimate, a moderate correlation between black hole mass and F_{var} was found.

An anti-correlation between bolometric luminosity and F_{var} was observed.

A power-law fit was applied to estimate the continuum between 3100 Å and 4100 Å, and the slope of this power law was calculated. It was found that the steeper this region is, the more variable the object tends to be.

Conclusions

The observed black hole mass segregation among DP, IM, and NDP quasars is likely not intrinsic. Instead, line-width-based mass estimates (e.g., Wu & Shen 2022) are biased for sources with double-peaked features, as the line broadening includes not only gravitational effects but also kinematic and geometric contributions.

Using Benati et al. (2025)'s method to estimate a new Eddington ratio and derive M_{BH}, the mass separation among subsamples became insignificant.

It was observed that the DP sample tended to exhibit slightly higher F_{var} values.

Mg II equivalent width shows a strong positive correlation with F_{var}.

A strong separation between the subsamples was observed in black hole mass, Eddington ratio, FWHM of Hα, Hβ, and Mg II, as well as in the optical Fe II equivalent width. Moderate separation was found for the FWHM of [O III], it's luminosity and the equivalent widths of Hα, Hβ, Mg II, and [O III]. No significant separation was observed for bolometric luminosity and UV Fe II equivalent width. Some of these histograms were not included in the poster due to space limitations and concerns about visual clarity; instead, the most representative plots were selected to highlight the most relevant trends in the data.

The observed separation among the subsamples suggests that inclination effects—particularly those related to the geometry of the accretion disk and broad-line region (BLR)—play a central role in driving the differences seen among DP, IM, and NDP quasars. However, inclination alone does not appear to fully account for the diversity in properties and variability, indicating that additional mechanisms are likely involved (Gaskell 1983; Peterson et al. 1987; Zheng et al. 1990; Wanders et al. 1995; Goad & Wanders 1996; Eracleous & Halpern 2003; Storchi-Bergmann et al. 2017; Ward et al. 2024).

More robust methods are needed to accurately estimate black hole masses in highly luminous quasars.

The relations discussed here involving F_{var} will be particularly valuable for future studies of AGN properties using LSST. Its superior depth, resolution, and broad filter coverage will allow us to probe fainter and more distant quasars across the Universe. Additionally, the high-cadence, multi-band photometry combined with refined filtering techniques will significantly enhance our understanding of AGN physics in upcoming surveys.

This work is in progress, with only the most relevant results are shown here. The full data, analyses, discussion, and future research directions will be included in the upcoming paper.