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Dissecting Fe II lines in AGN spectra: revealing the complex physics of the broad-line region

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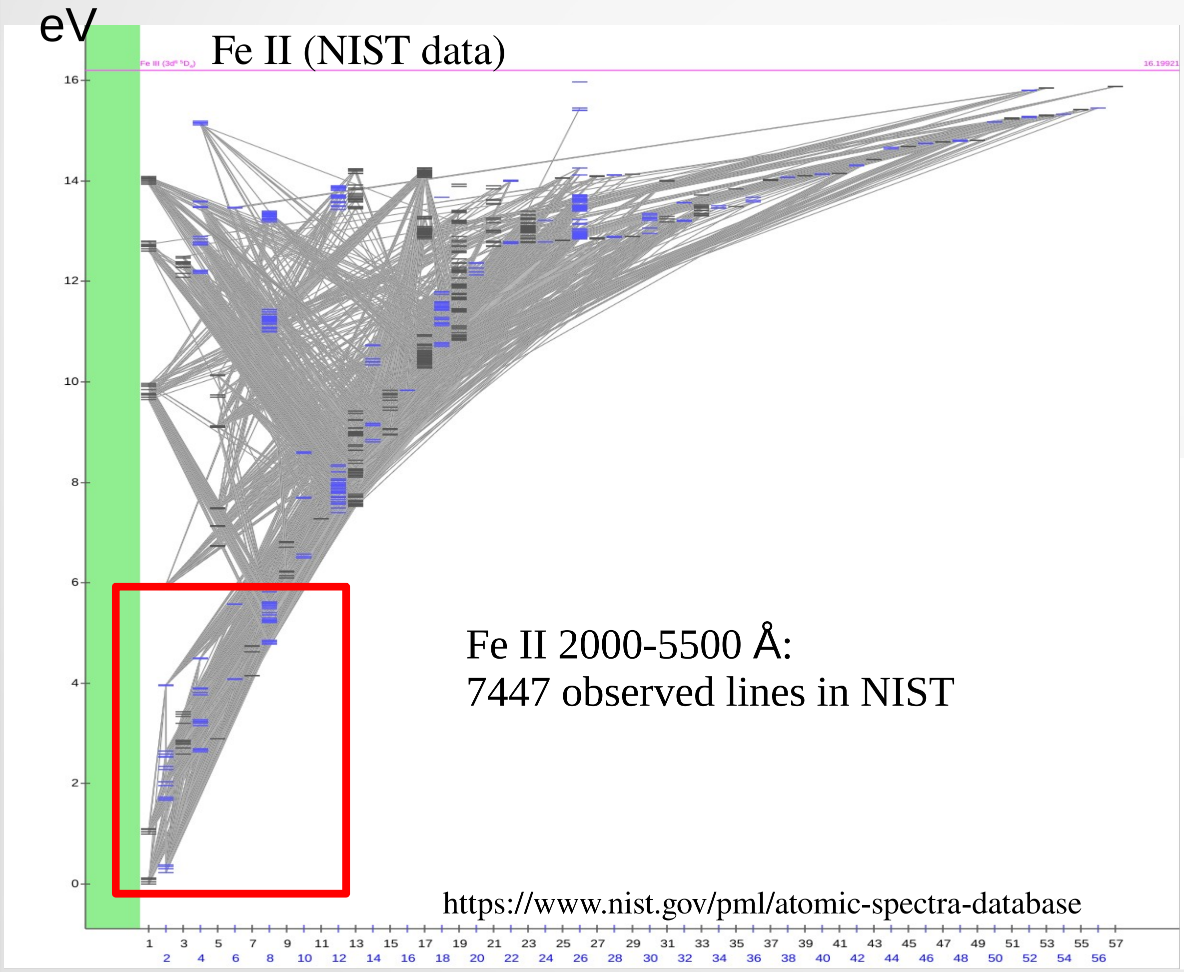
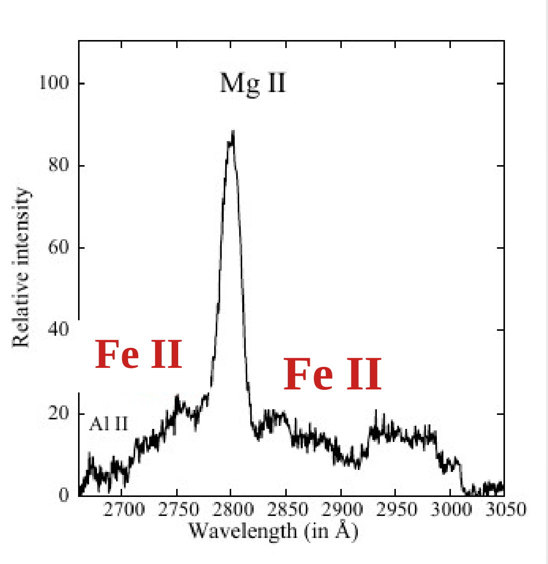
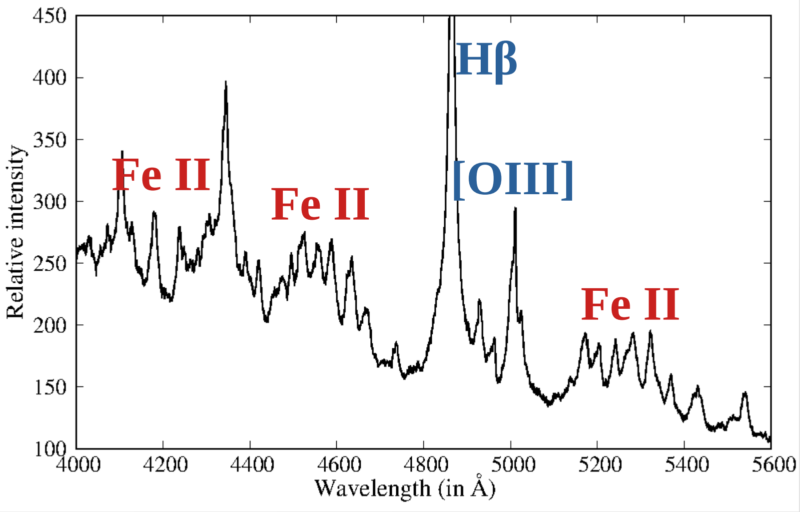
Complex Fe II emission in AGN spectra

- The Fe II - characterized by a very large number of closely spaced energy levels and, consequently, numerous possible transitions.
- The complex atomic structure of Fe II enables a wide range of atomic processes.
- This property distinguishes Fe II from other atomic species, making it a unique probe of BLR physics.







Unexplained properties of Fe II lines in AGN spectra

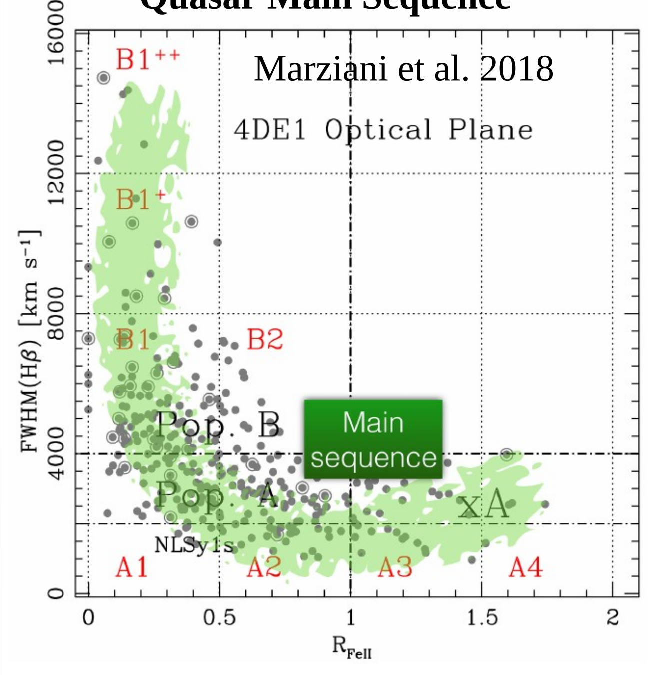
- Fe II lines are surprisingly strong in some spectra! Their emission could be even ~ 30% of the total emitted energy from the Broad Line Region - **not expected!**
  (Wills et al. 1985; Joly 1987; Collin-Souffrin et al. 1988)

- Several unexplained correlations among Fe II lines and other spectral properties as EV1 correlations: FWHM Hβ vs. Fe II/Hβ (R_{FeII}), EW Fe II vs. EW [OIII].
  (Boroson & Green 1992)

- It is found that EV1 correlations are governed by Eddington ratio (R_{Edd}) and orientation.
  (Boroson & Green 1992, Sulentic et al. 2000, Marziani et al. 2001, Shen & Ho 2014,…)

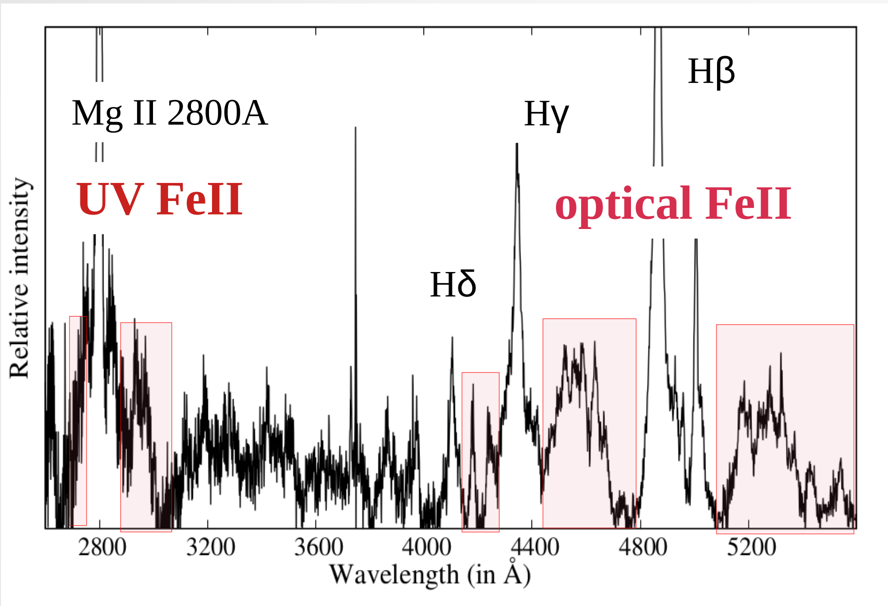
However, the physical mechanism still remains unclear!

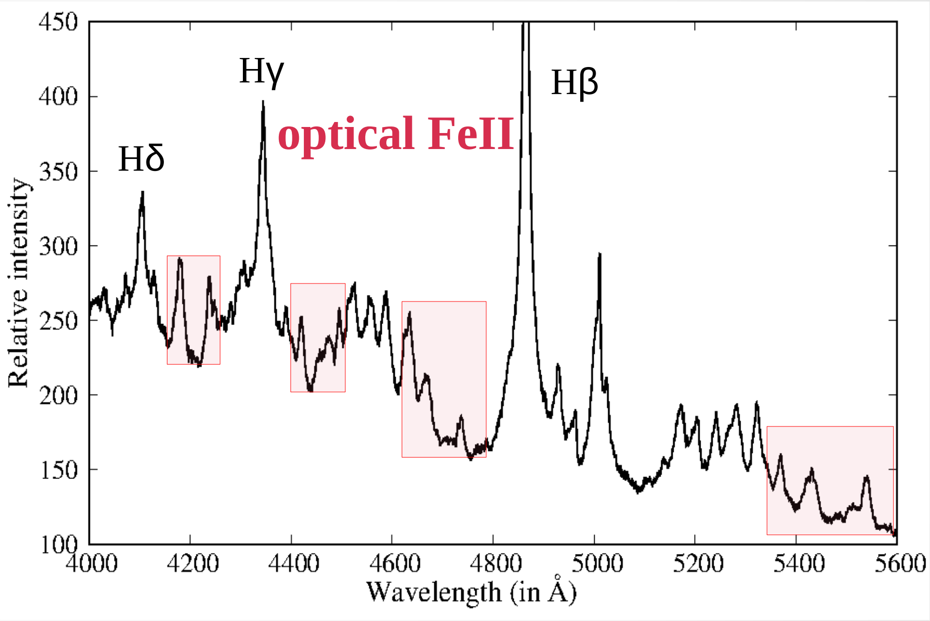
Quasar Main Sequence

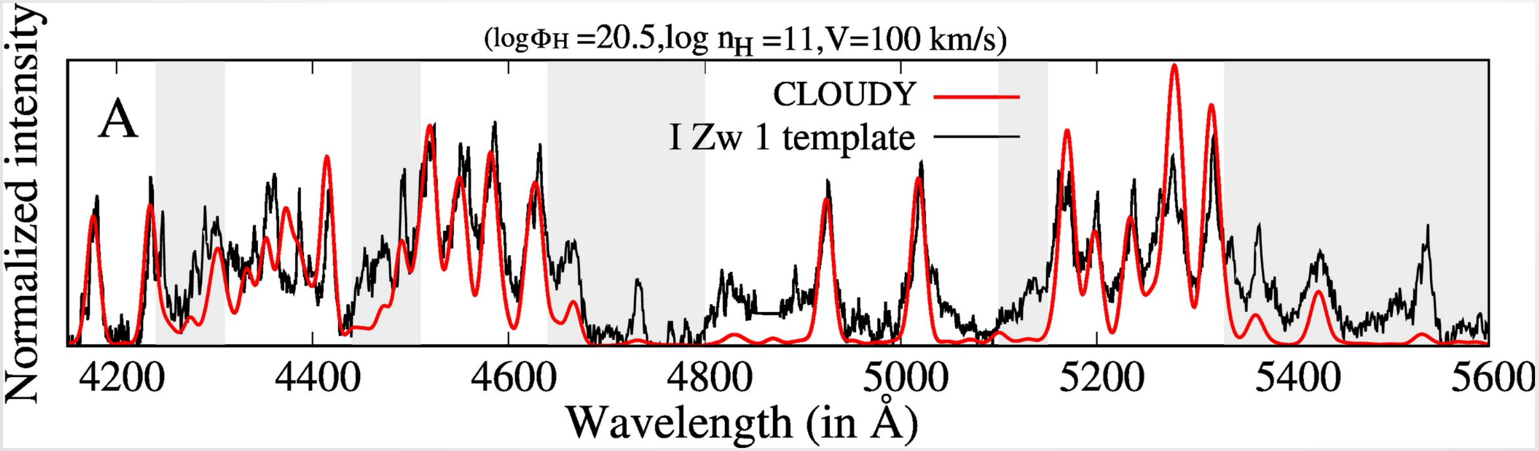


Violated relative intensities between Fe II lines

- The relative intensities of Fe II lines in AGN spectra *deviate* from theoretical calculations!



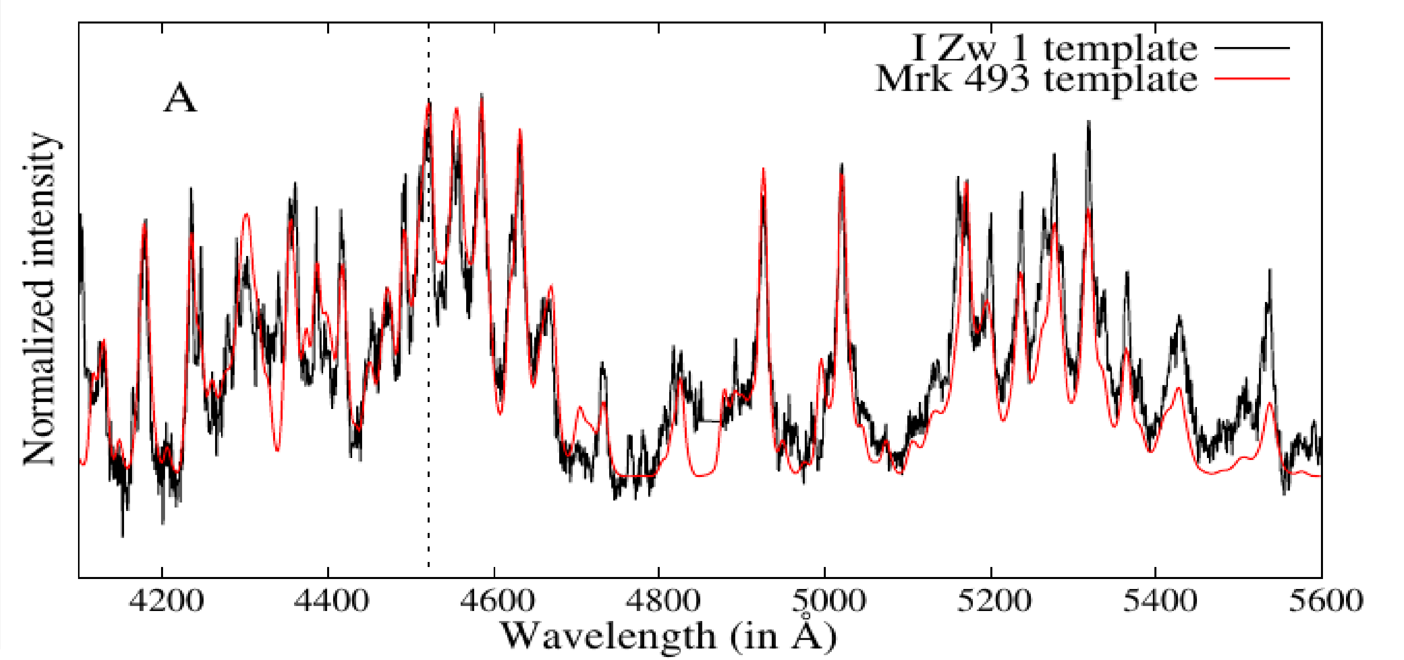


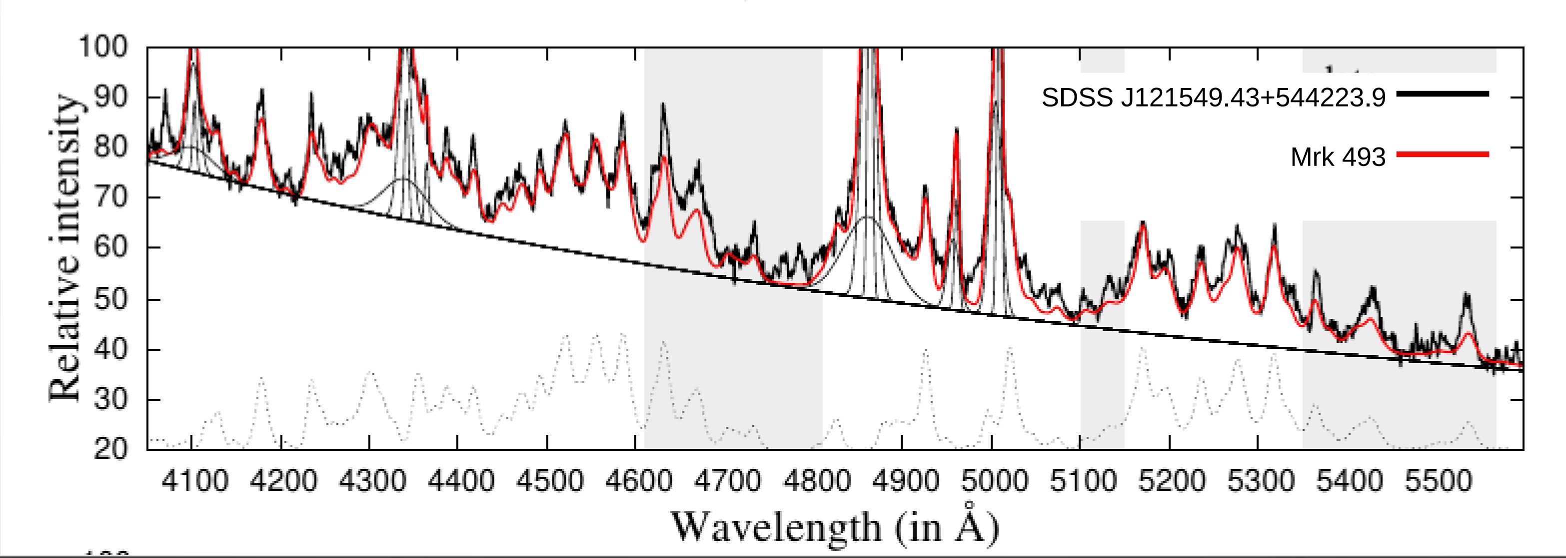


spectral synthesis code Cloudy

Pandey et al. 2024,
Zhang et al. 2024

Variations of relative intensities among Fe II lines in different AGNs





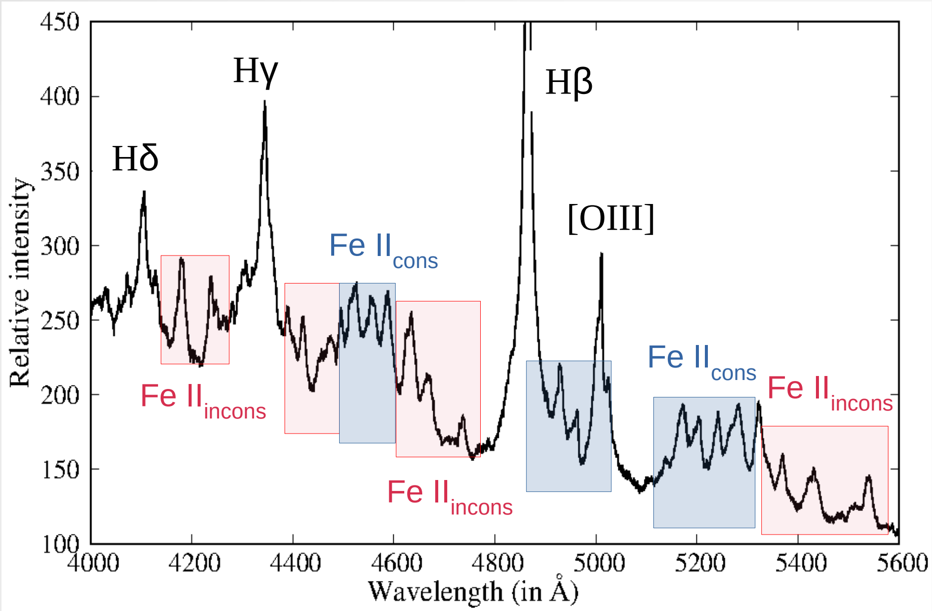
Aims

- We use a large sample of Type 1 active galactic nuclei spectra (SDSS) in order to investigate:

  - atomic processes responsible for observed properties of Fe II emission lines;

  - correlations between Fe II lines and other spectral parameters, with special focus on the quasar main sequence, whose underlying physics is crucial for understanding the structure and physical conditions of the BLR.

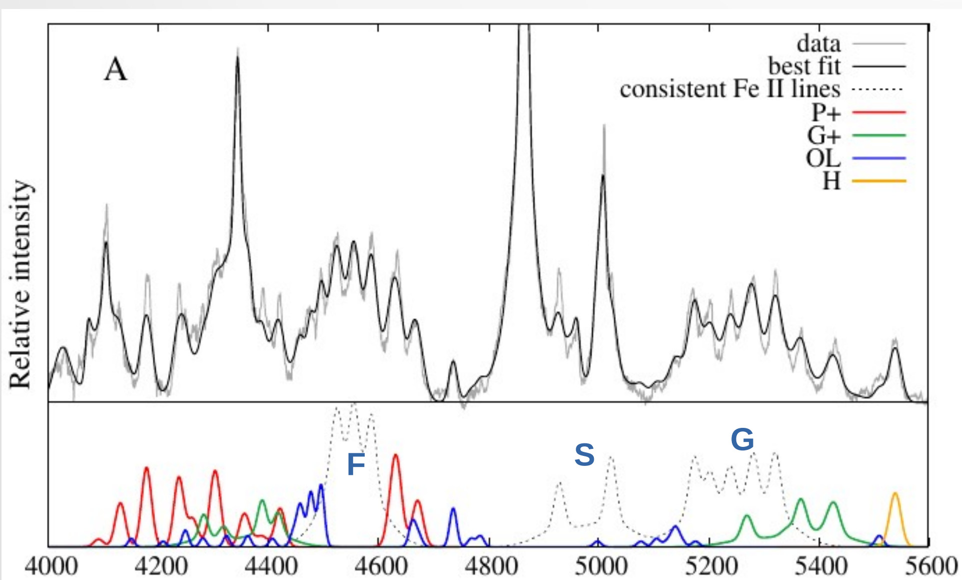
Tool for analysis: complex and flexible Fe II template



- free intensity parameters for different FeII line groups, enabling us to follow the small variations in their relative intensities across different spectra.

- the Fe II line groups are formed following the atomic characteristics.

(Kovačević et al. 2010, Kovačević-Dojčinović et al. 2025)

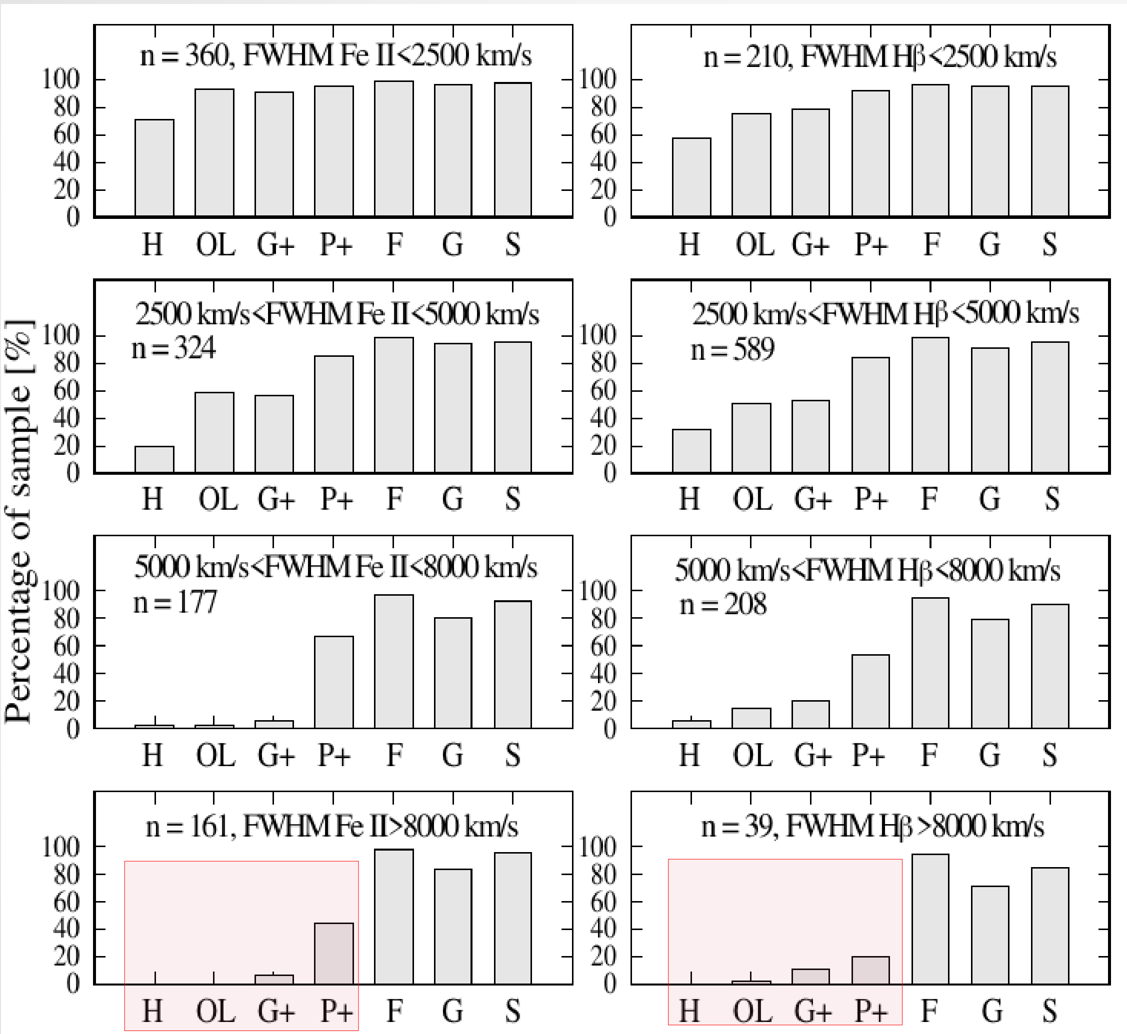


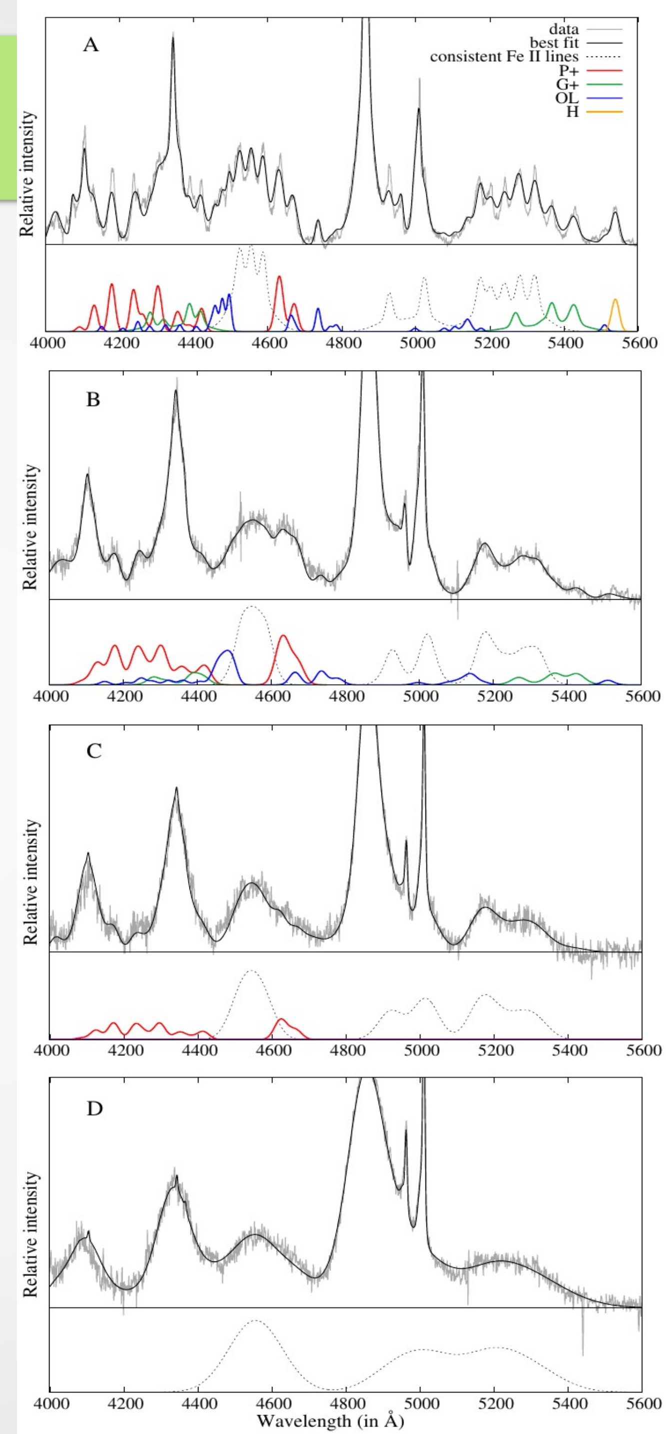
optical Fe II lines [4000-5600 Å]

consistent ($Fe\ II_{cons}$) → F, S, G

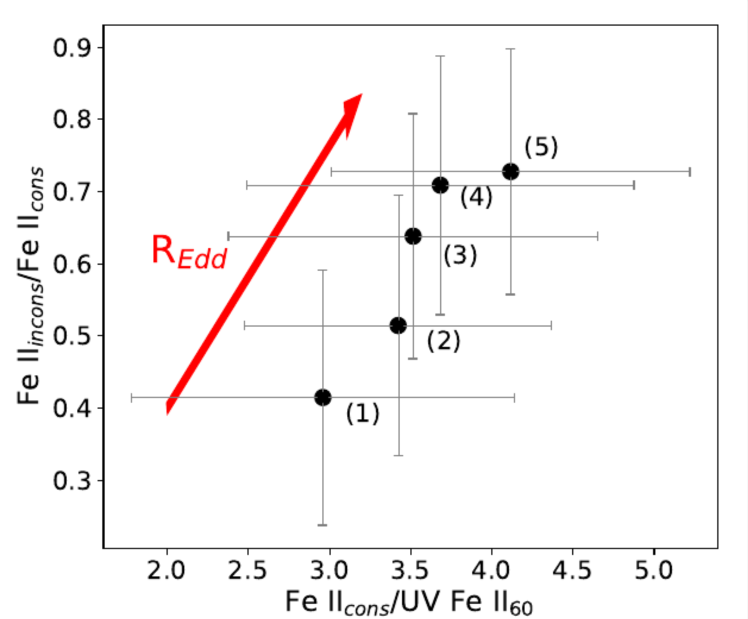
inconsistent ($Fe\ II_{incons}$) → P+, G+, H, OL

Results: Fe II$_{incons}$ missing in broad line spectra

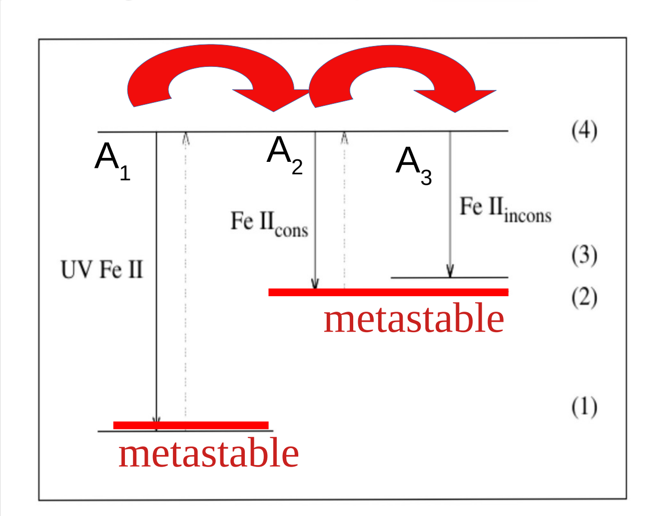




Results: What causes the violated relative intensities among the Fe II lines?



(1) logR_{Edd}<-1 (14 objects), (2) -1<logR_{Edd}<-0.75 (40 objects), (3) -0.75<logR_{Edd}<-0.5 (79 objects), (4) -0.5<logR_{Edd}<-0.25 (48 objects), and (5) logR_{Edd}>-0.25 (39 objects).

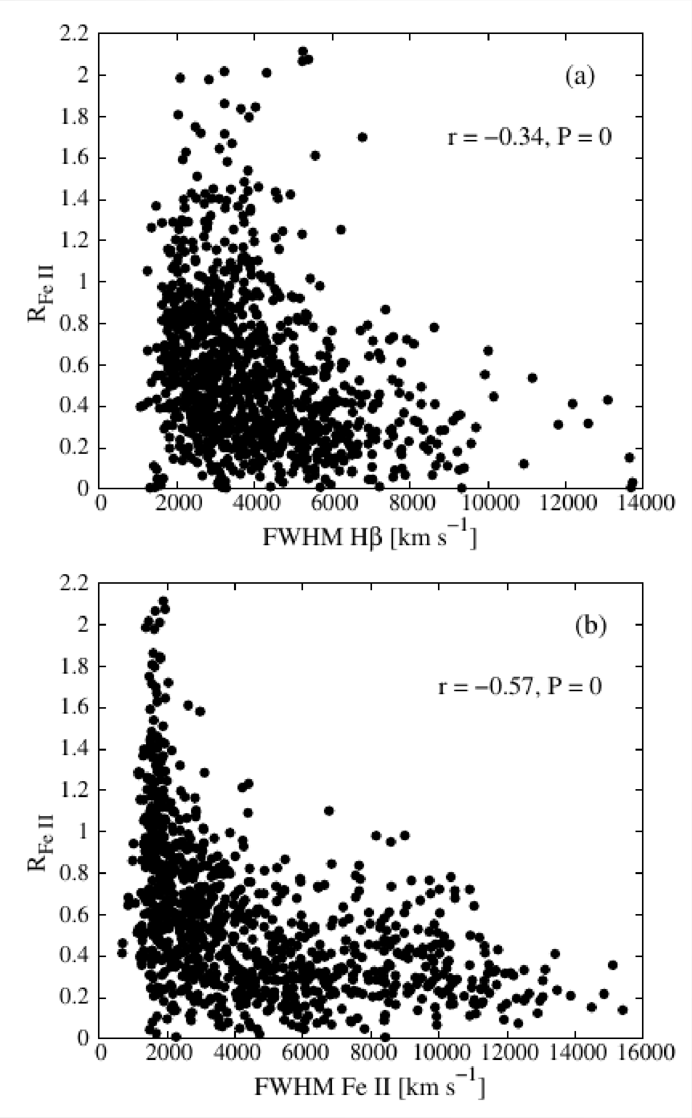


- The ratios Fe II$_{opt}$/Fe II$_{UV}$ and Fe II$_{incons}$ /Fe II$_{cons}$ both increase with an increase in the Eddington ratio (R_{Edd}).
- The violated relative intensities among the Fe II lines could be caused by self-absorption processes that redistribute energy from the UV to the optical Fe II emission and, analogous to that, from the Fe II$_{cons}$ to the Fe II$_{incons}$.
- In this scenario, the high Eddington ratio causes an increase in the optical depth in Fe II lines, which results in the triggering of the process of self-absorption.

Einstein coefficients for spontaneous emission:

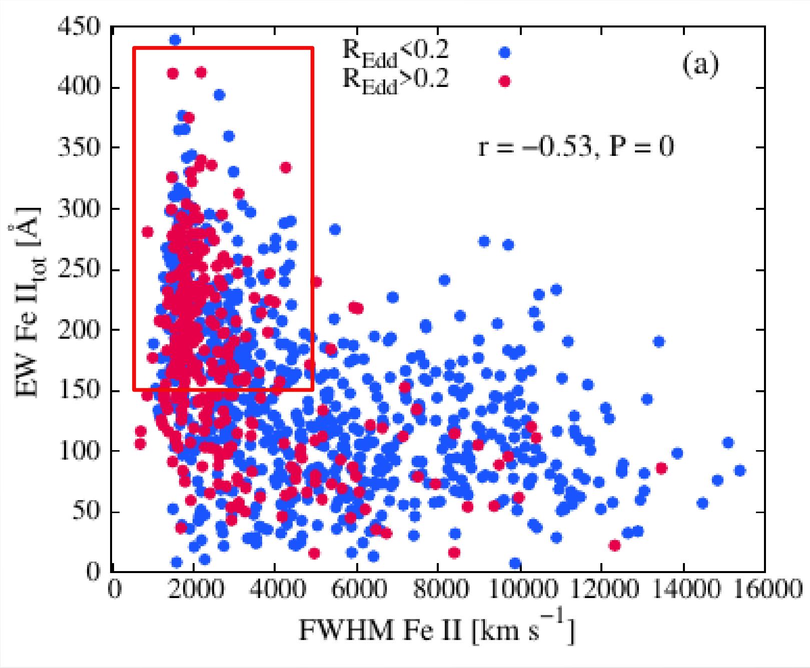
$A_1 \sim 10^8\ s^{-1} > A_2 \sim 10^5\ s^{-1} > A_3 \sim 10^3\ s^{-1}$

Results: Dissecting the Fe II in quasar main sequence

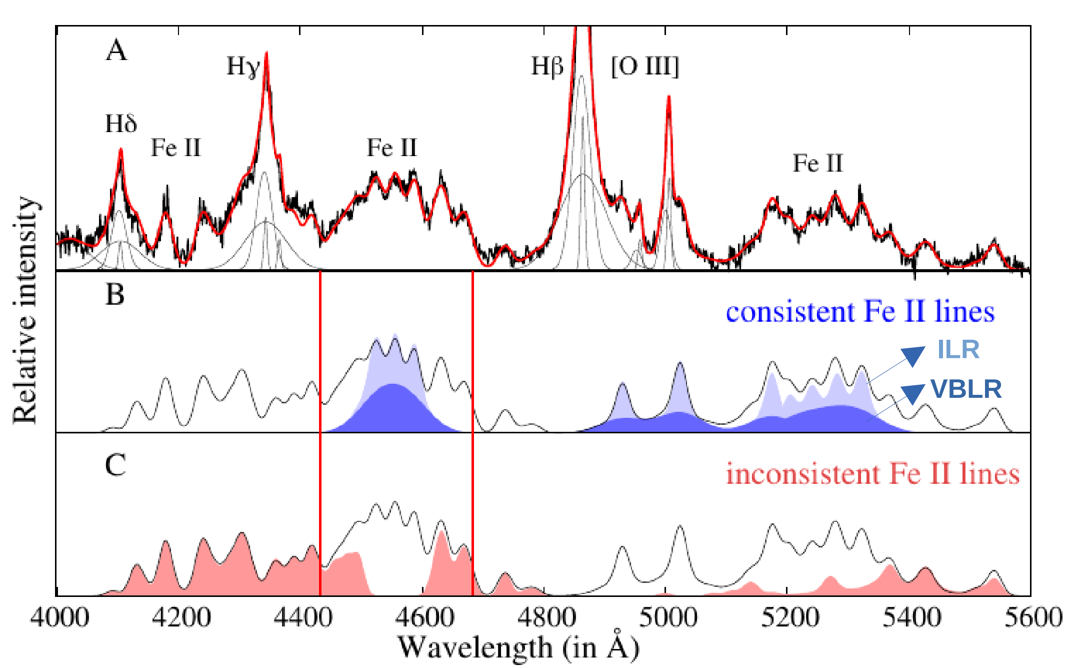


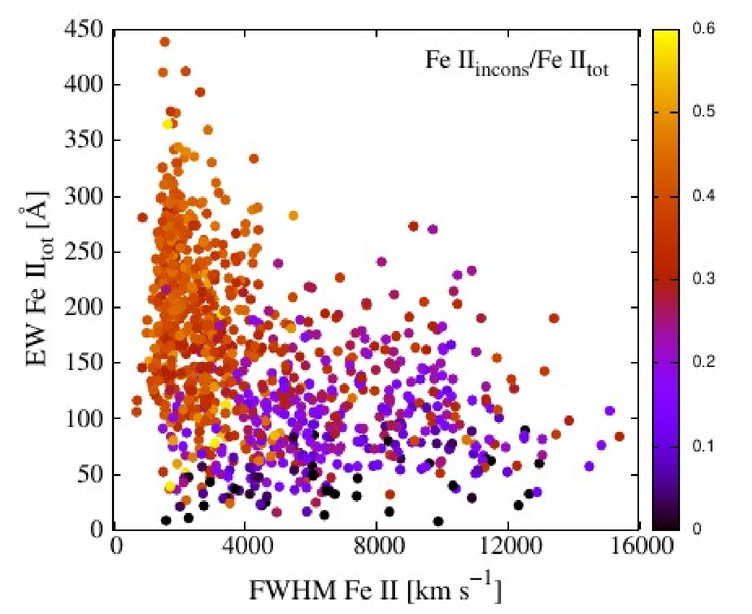
- EW Fe II vs. FWHM Fe II is probably more fundamental relation underlying the quasar main sequence, FeII/Hβ (R_{FeII}) vs. FWHM Hβ.

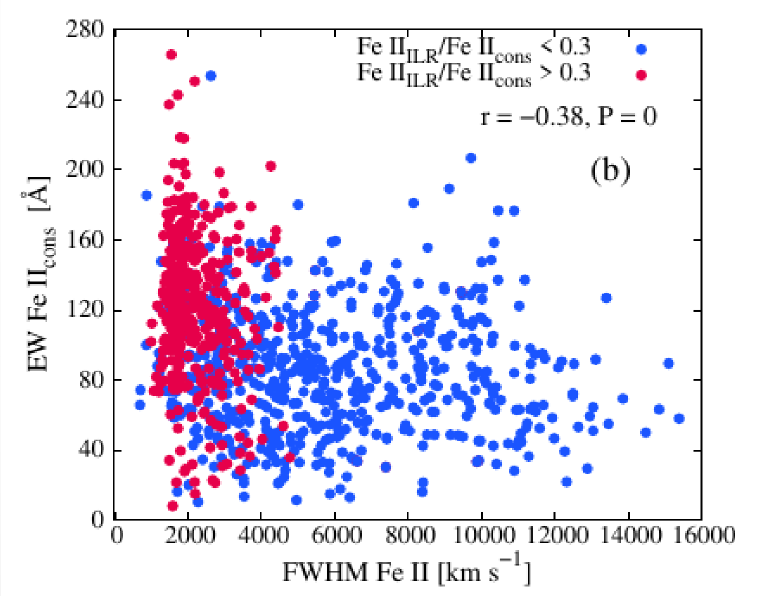
- Objects with EW Fe II > 150 Å have higher $R_{Edd.}$



Results: Dissecting the Fe II in quasar main sequence

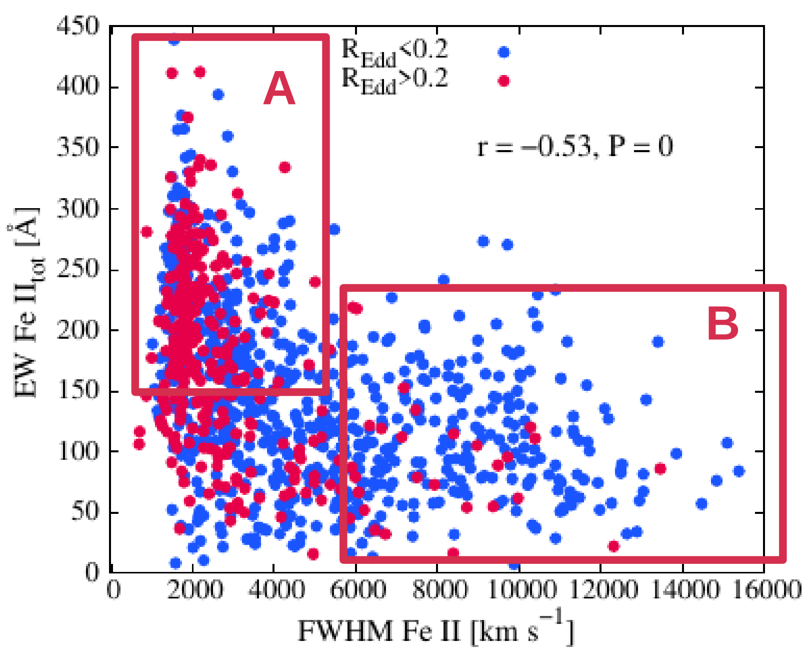




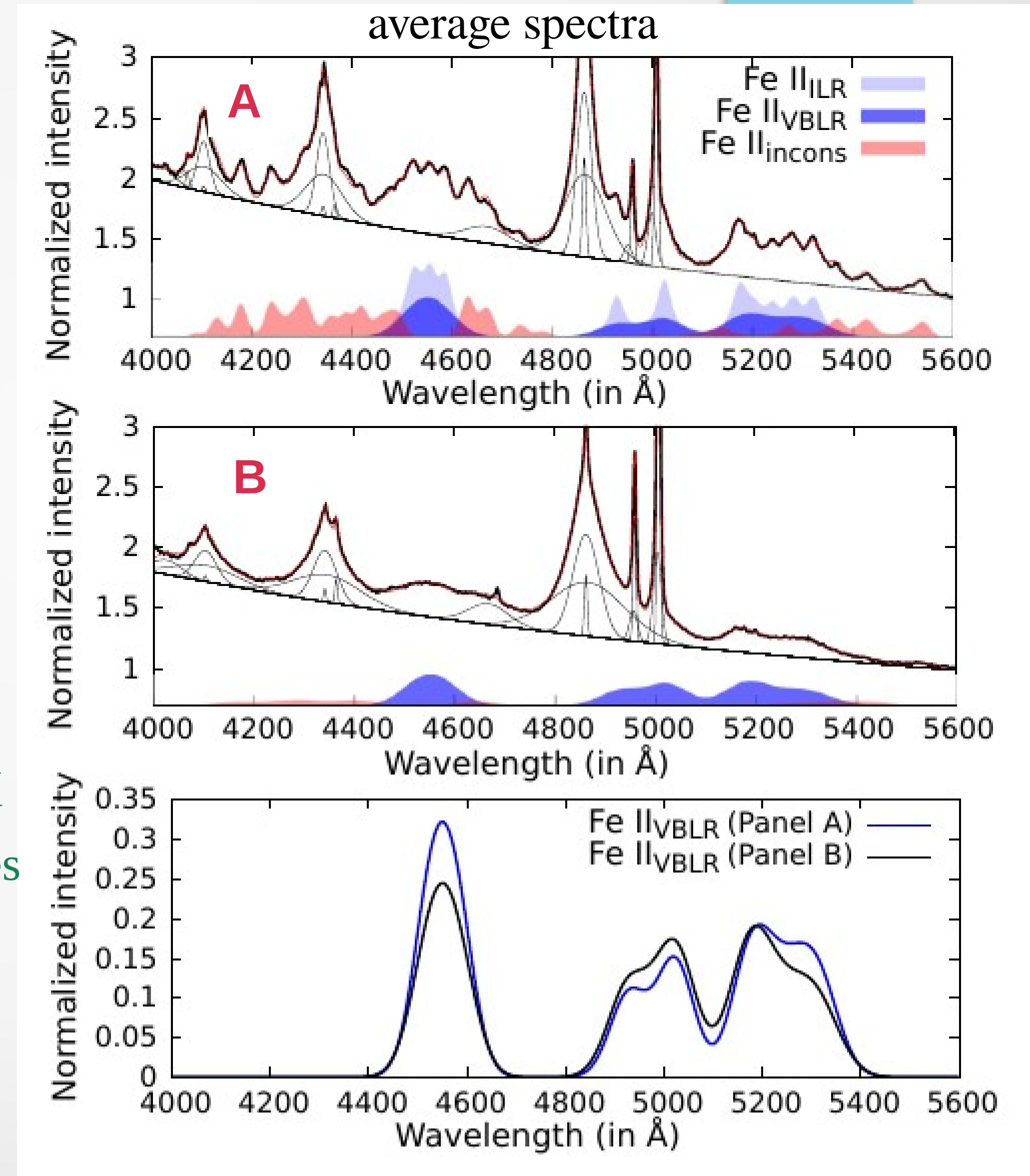


- Objects with EW Fe II > 150 Å higher contribution of the Fe II$_{incons}$ and ILR components of Fe II$_{cons}$.

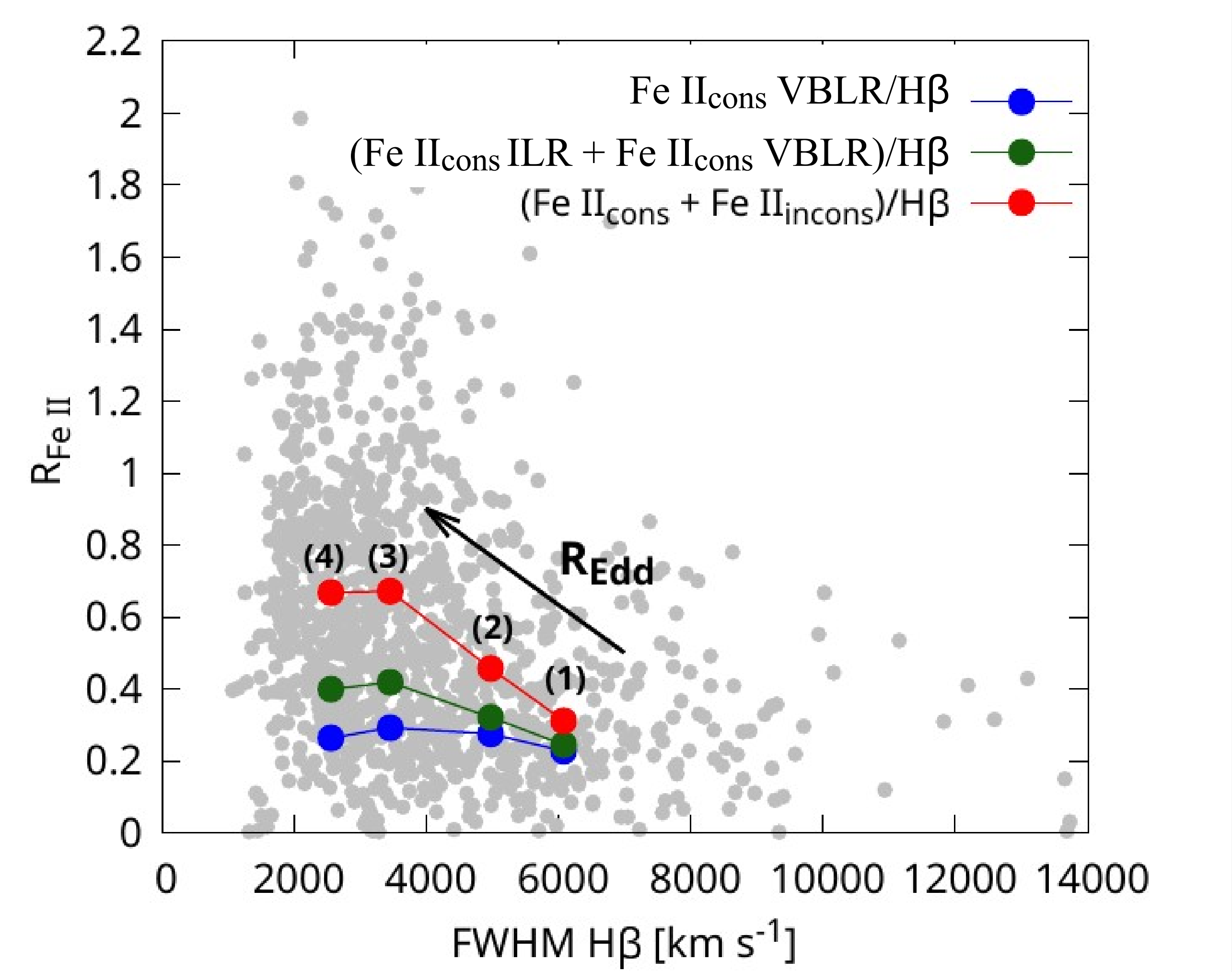
Dissecting the Fe II in quasar main sequence



- The increase in EW Fe II for objects with EW Fe II > 150 Å, is primarily caused by the strengthening of the EW Fe II_{incons} lines and EW Fe II_{ILR} components, while EW of Fe II_{VBLR}, on average, do not significantly changes along the quasar main sequence.

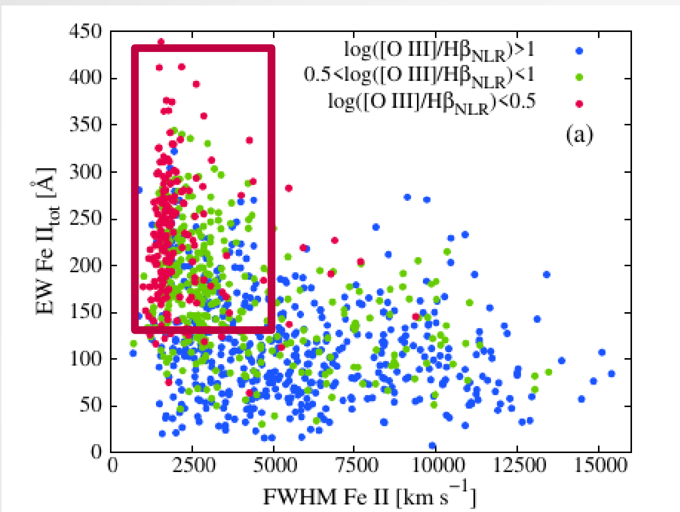


Growth of different Fe II components in the quasar main sequence

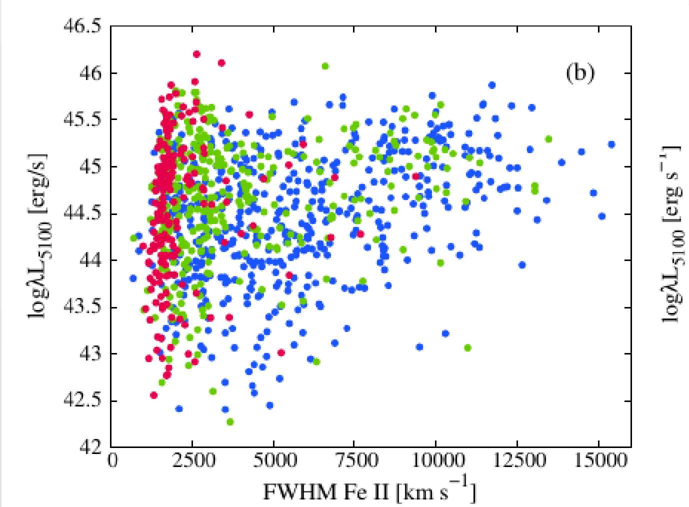


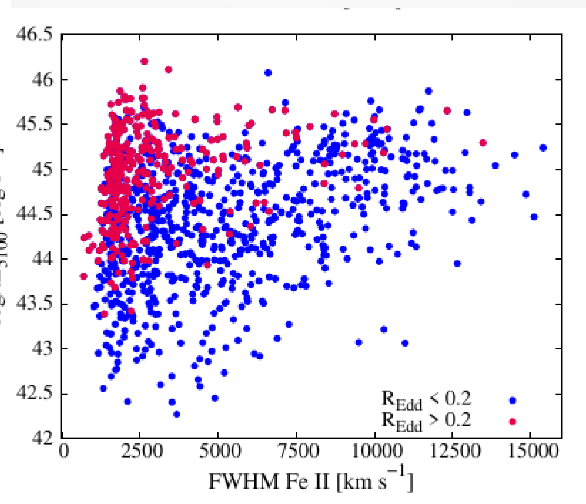
The sample is divided into four subsets according to R_{Edd} : (1) $R_{Edd} < 0.03$ (71 objects), (2) $0.03 < R_{Edd} < 0.1$ (325 objects), (3) $0.1 < R_{Edd} < 0.3$ (471 objects), and (4) $R_{Edd} > 0.3$ (154 objects).

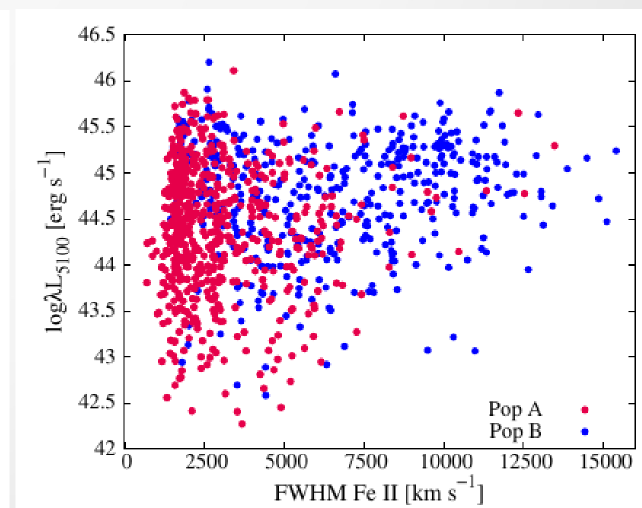
Fe II lines - a signature of the AGN dichotomy

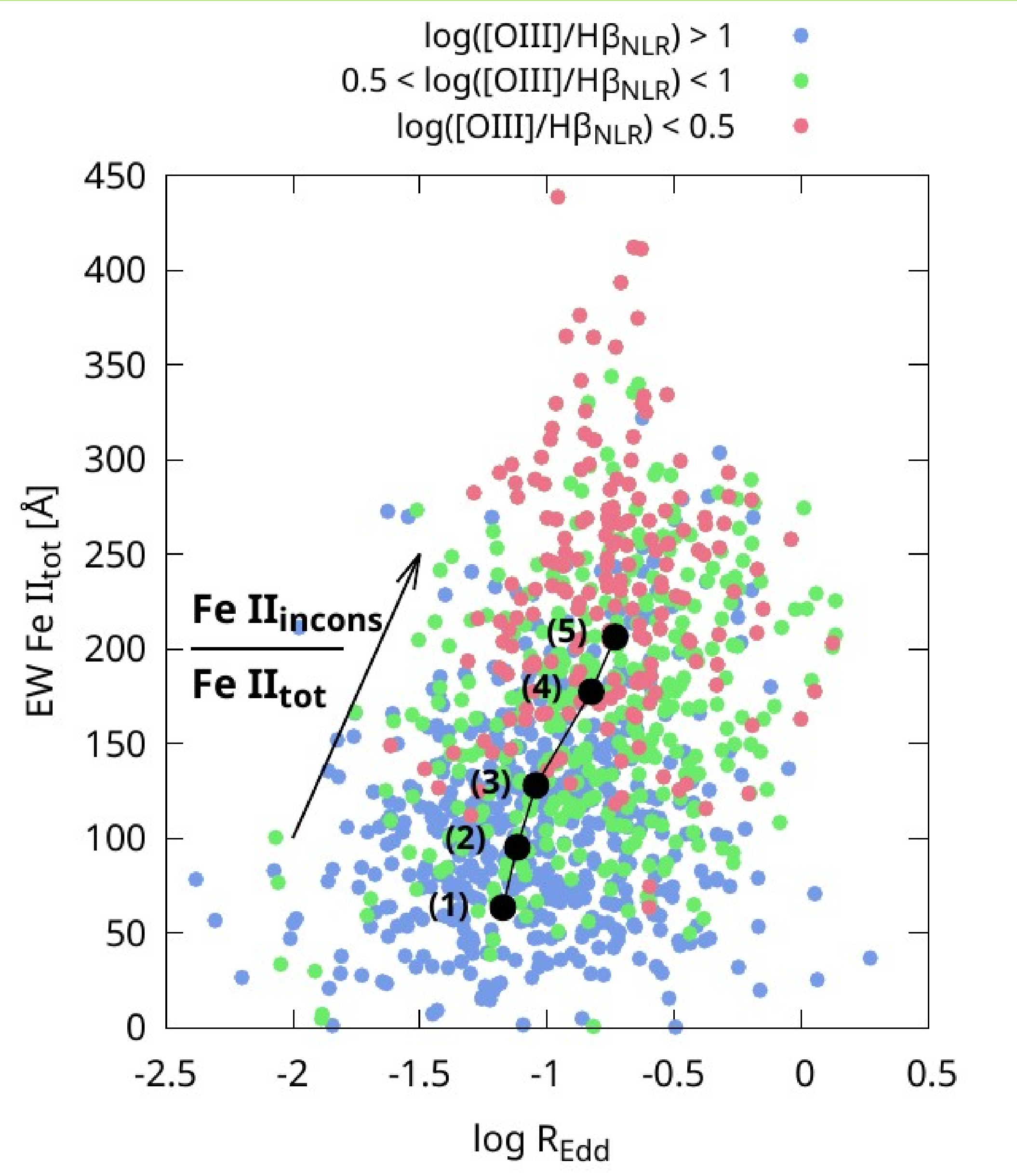


- The observed variation of the [OIII]/$H\beta_{NLR}$ ratio along the quasar main sequence can be interpreted as a change in the shape of the ionizing continuum within the NLR (Baldwin et al. 1981).
- Softer ionizing continuum, would contribute to a more efficient excitation of the optical Fe II lines, since they have low energy of ionization (7.9 eV) and excitation (5 eV).
- Several theoretical models predict a softening of the ionizing continuum for the sources with high Eddington ratio (Kubota & Done 2018; Ferland et al. 2020; Garnica et al. 2025).









(1) Fe II_{incons}/Fe II_{tot} < 0.1 (87 objects)

(2) 0.1 < Fe II_{incons}/Fe II_{tot} < 0.2 (134 objects)

(3) 0.2 < Fe II_{incons} /Fe II_{tot} < 0.3 (187 objects)

(4) 0.3 < Fe II_{incons} /Fe II_{tot} < 0.4 (320 objects)

(5) Fe II_{incons}/Fe II_{tot} > 0.4 (293 objects).

Conclusions:

- A high Eddington ratio could be associated with modifications in disk and BLR structure, leading to triggering additional atomic processes which contribute to Fe II emission.

- This may result in the appearance of Fe $\mathrm{II}_{\mathrm{incons}}$ lines and Fe $\mathrm{II}_{\mathrm{ILR}}$ components, which consequently increase the optical Fe II strength, making the characteristic distribution of sources along the quasar main sequence.

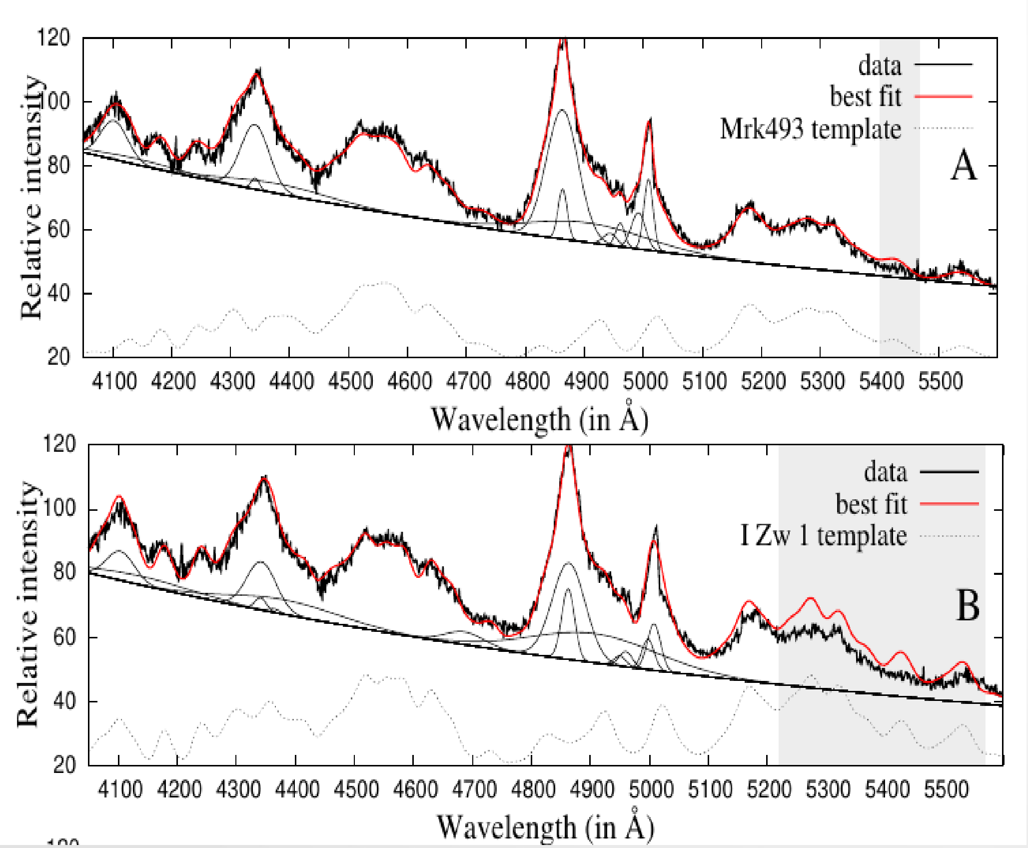
Kovačević-Dojčinović, J. et al. 2025, A&A, 694, A289

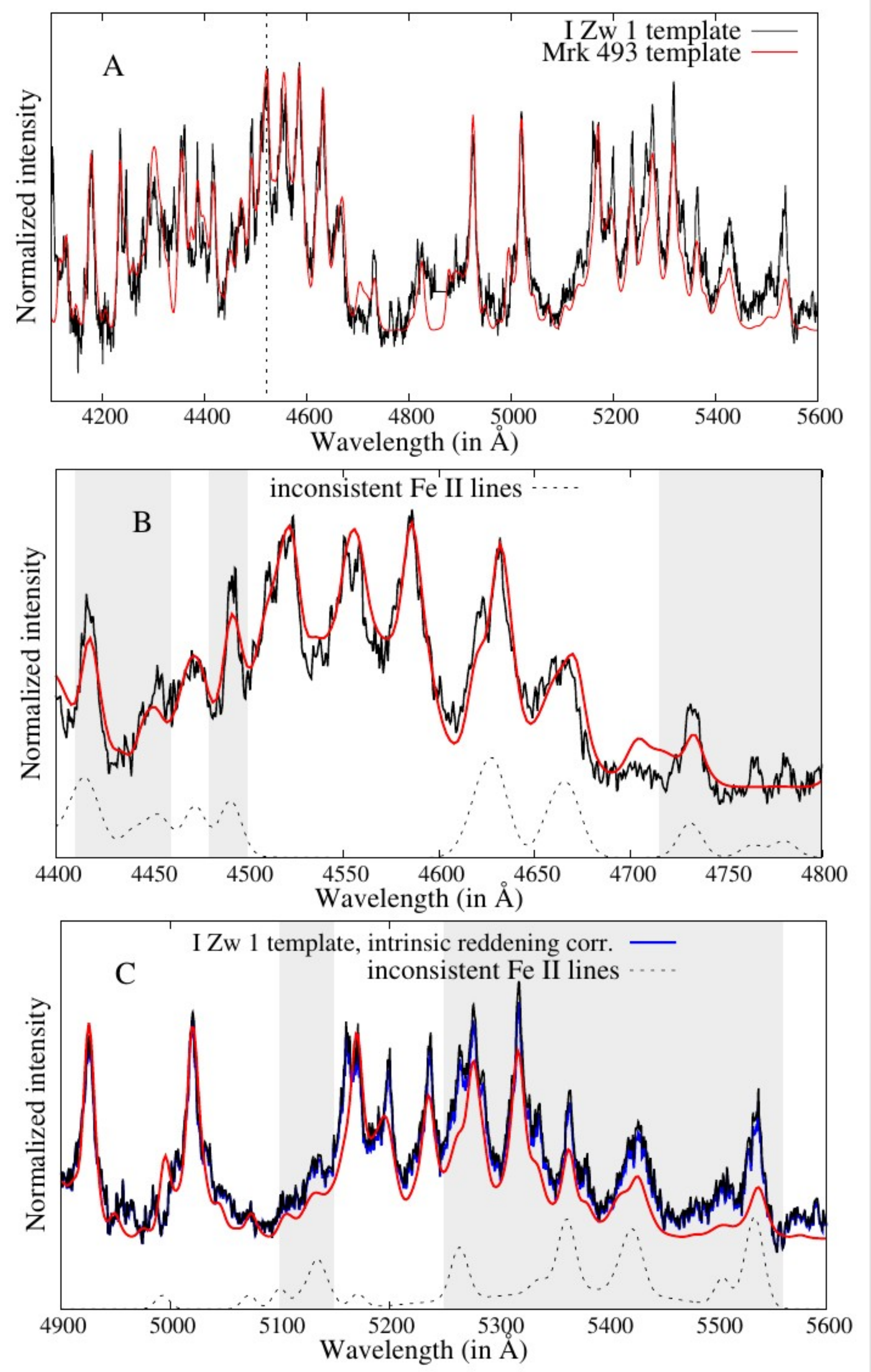
Kovačević-Dojčinović, J. et al. 2026, A&A, 710, A66

Thank you for your attention!

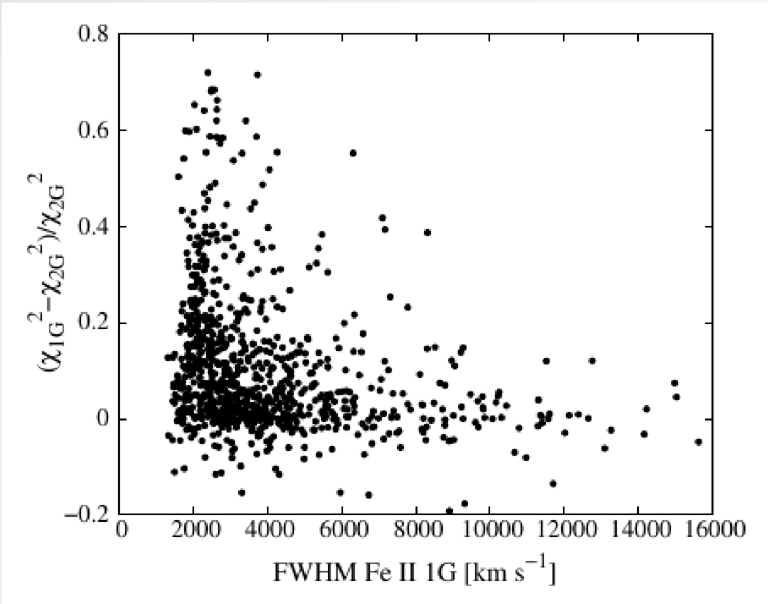
Variations among relative intensities of the optical Fe II lines

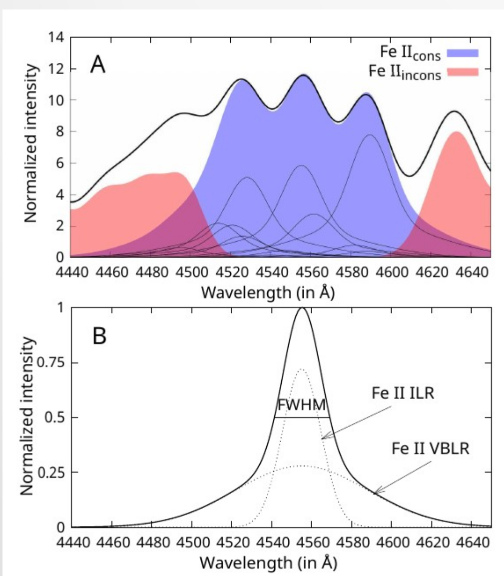
- Whether is disappearance of the Fe II$_{incons}$ with the increase of FWHM Fe II linked to the effect of smearing out or to intrinsic atomic processes?





Two-component model of Fe II lines





- We found that application of the two-component Fe II model is justified for spectra with Fe II widths smaller than FWHM Fe II$_{1G}$ ~ 5000 km s^{-1}, because it gives significantly better fit than single-component model.

- For spectra with very broad Fe II lines (FWHM Fe II1G > 5000 km s^{-1}), fitting the Fe II with the two-Gaussian model is unreliable because it does not have a unique decomposition and does not improve the quality of the fit compared to the single-Gaussian model.

Distribution of the sources with different properties in the logλL_{5100} vs. FWHM Fe II diagram