Broad Line Region gas metallicity along the Quasar Main Sequence

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Unified model of Active Galactic Nuclei

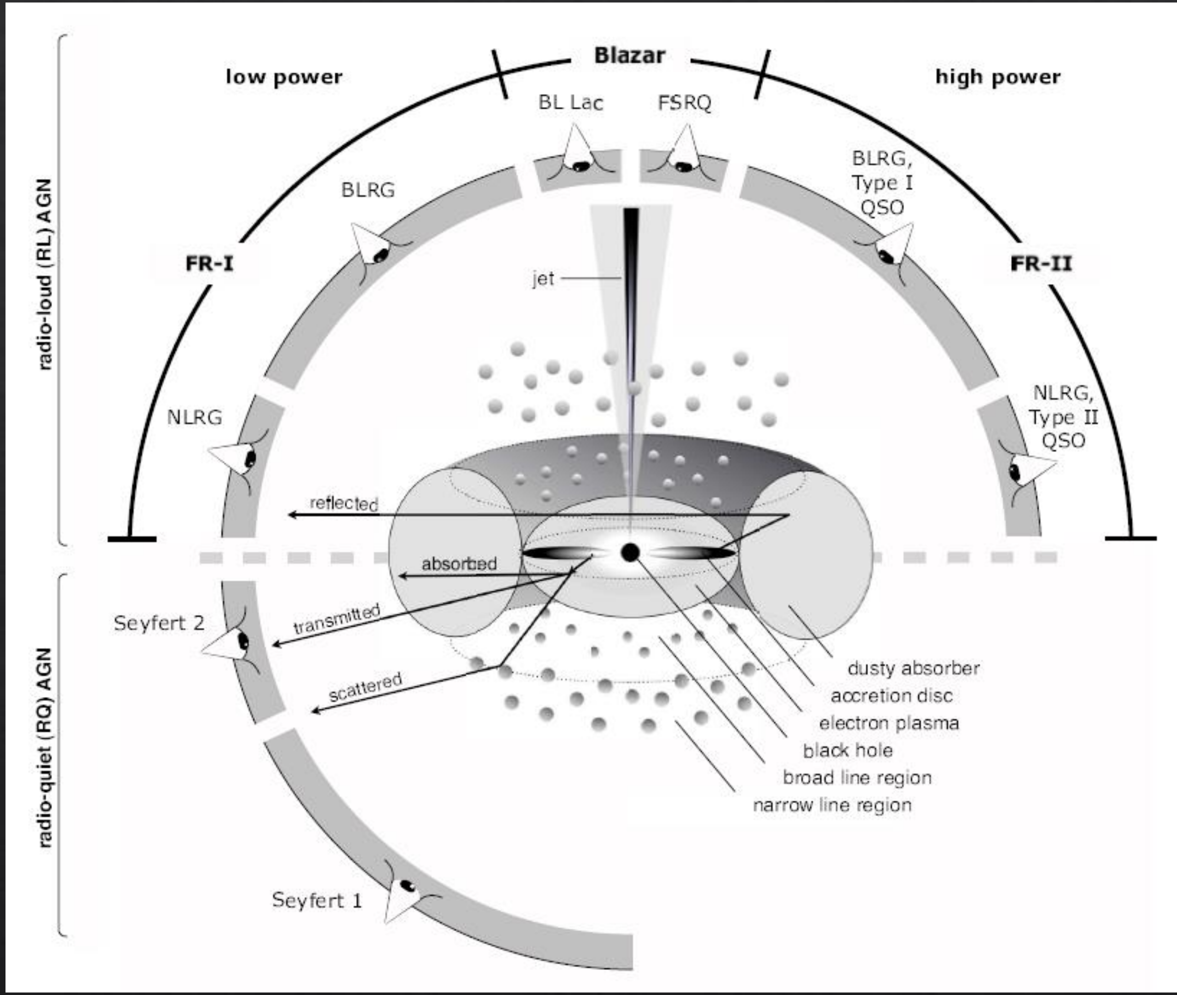
- Galaxies accreting matter onto their Supermassive Black Hole

- Differences among objects driven by:
  - Orientation

- UV and optical emission from:
  - Accretion Disk
  - Broad Line Region (BLR)
  - Narrow Line Region (NLR)

- We restrict ourselves to Type-I unobscured AGNs

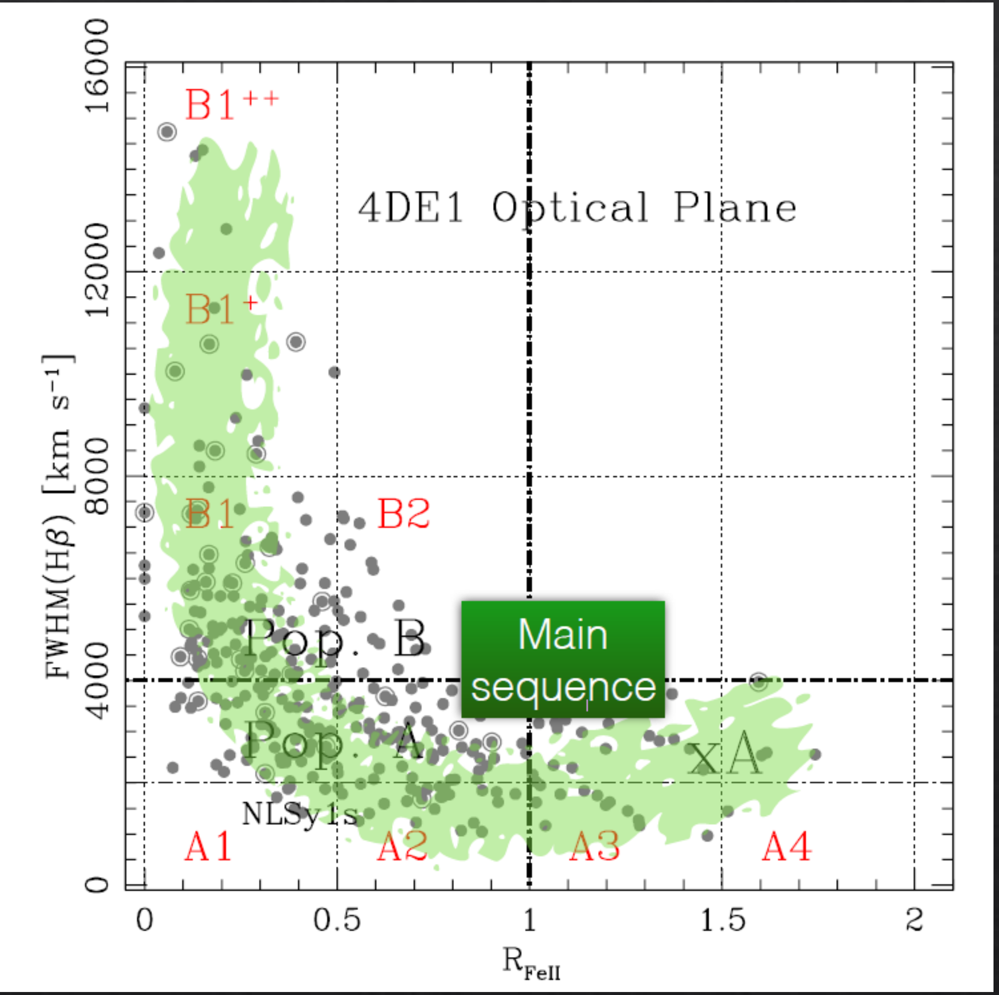
- Model does not describe well diversity inside Type-I AGNs



Beckmann & Shrader, 2012

Main Sequence of Quasars (MS)

- Principal Component Analysis discovered strong anticorrelation between two parameters (Boroson & Green, 1992):
  - FWHM(Hβ)
  - R_{FeII}



Marziani et al., 2018

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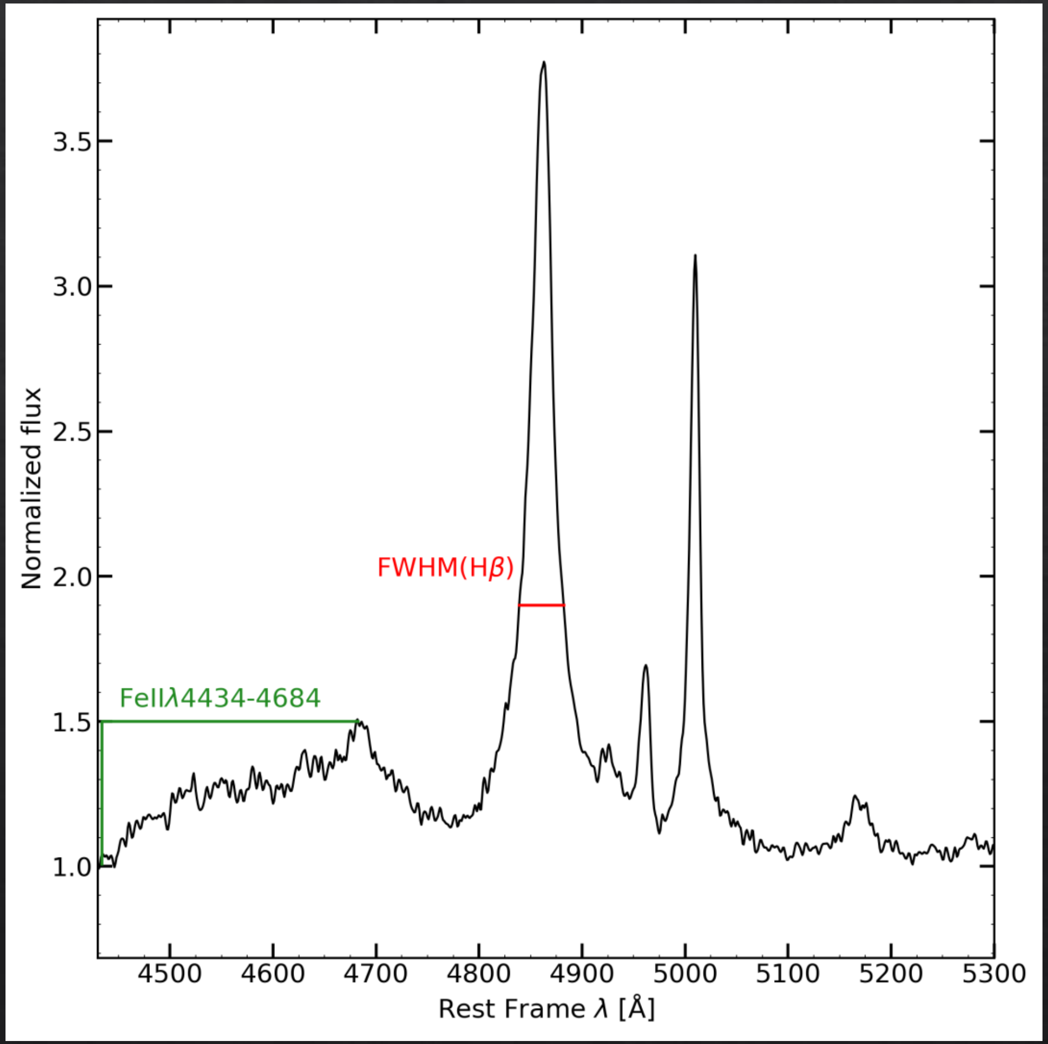
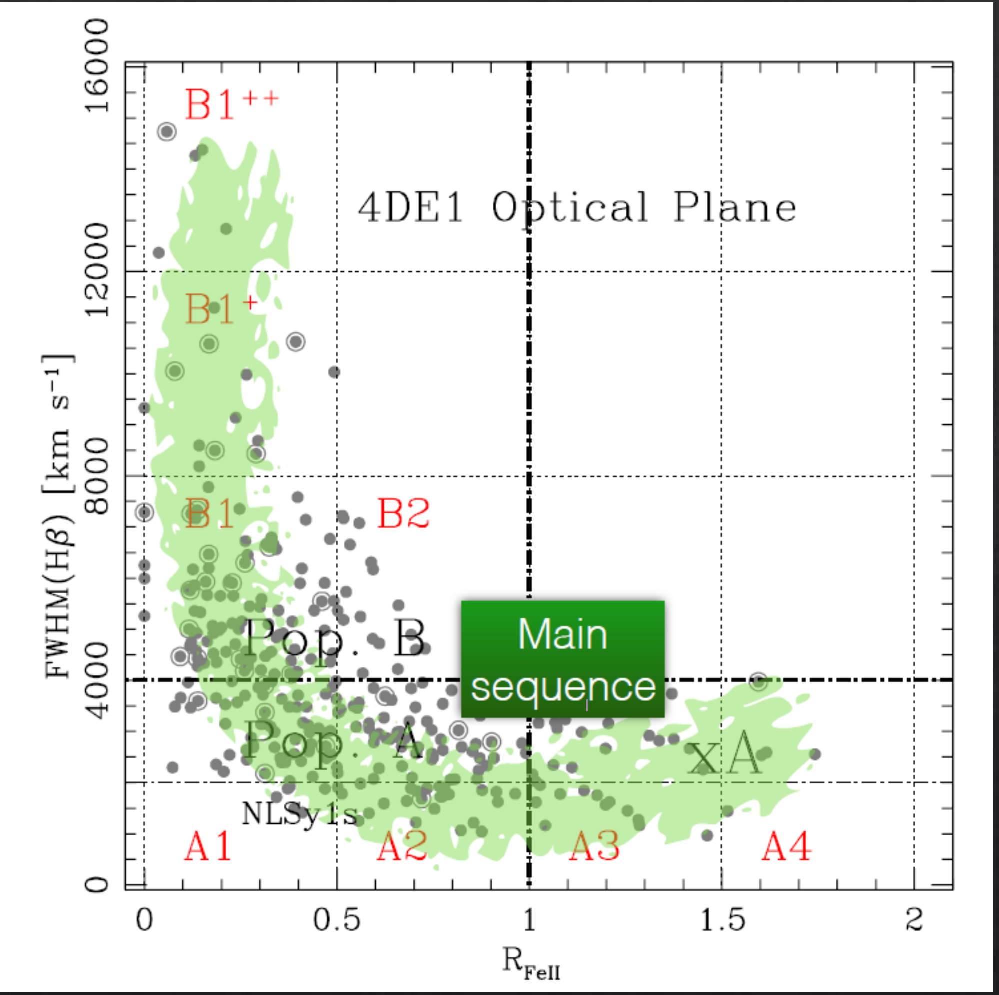


Main Sequence of Quasars (MS)

- Principal Component Analysis discovered strong anticorrelation between two parameters (Boroson & Green, 1992):
  - FWHM(Hβ)
  - R_{FeII}
- Three Populations of Type-I AGNs:
  - Population A
  - Extreme Population A (xA)
  - Population B
- Spectral types, in regions of the parameter space with different values of R_{FeII} and FWHM(Hβ)
- MS driven by Eddington ratio (∝ L/M) ?



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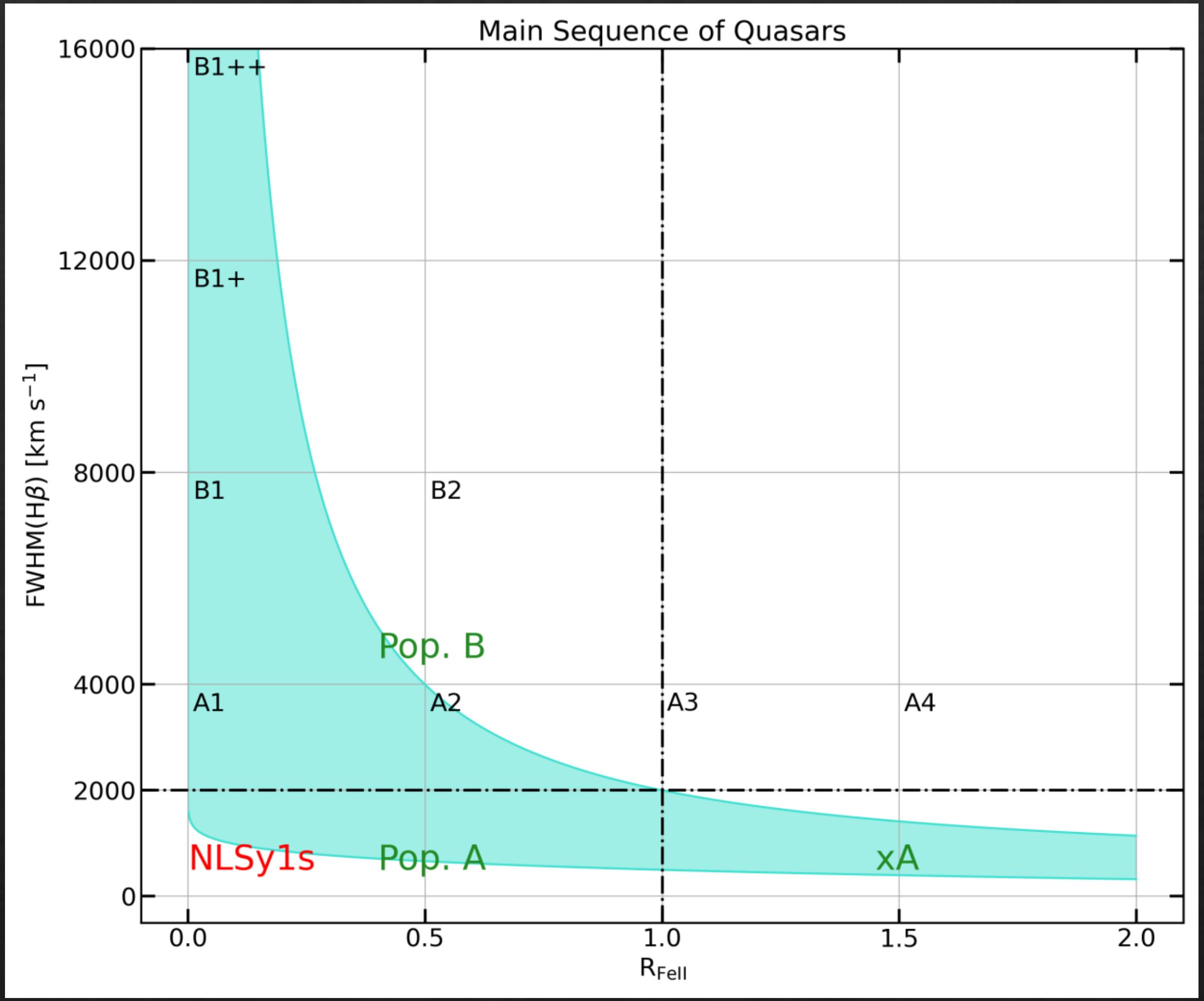
Main Sequence of Quasars (MS)

- Historically explored for different mass ranges
- Different tracks for different black hole masses
- NLSy1s found below quasars



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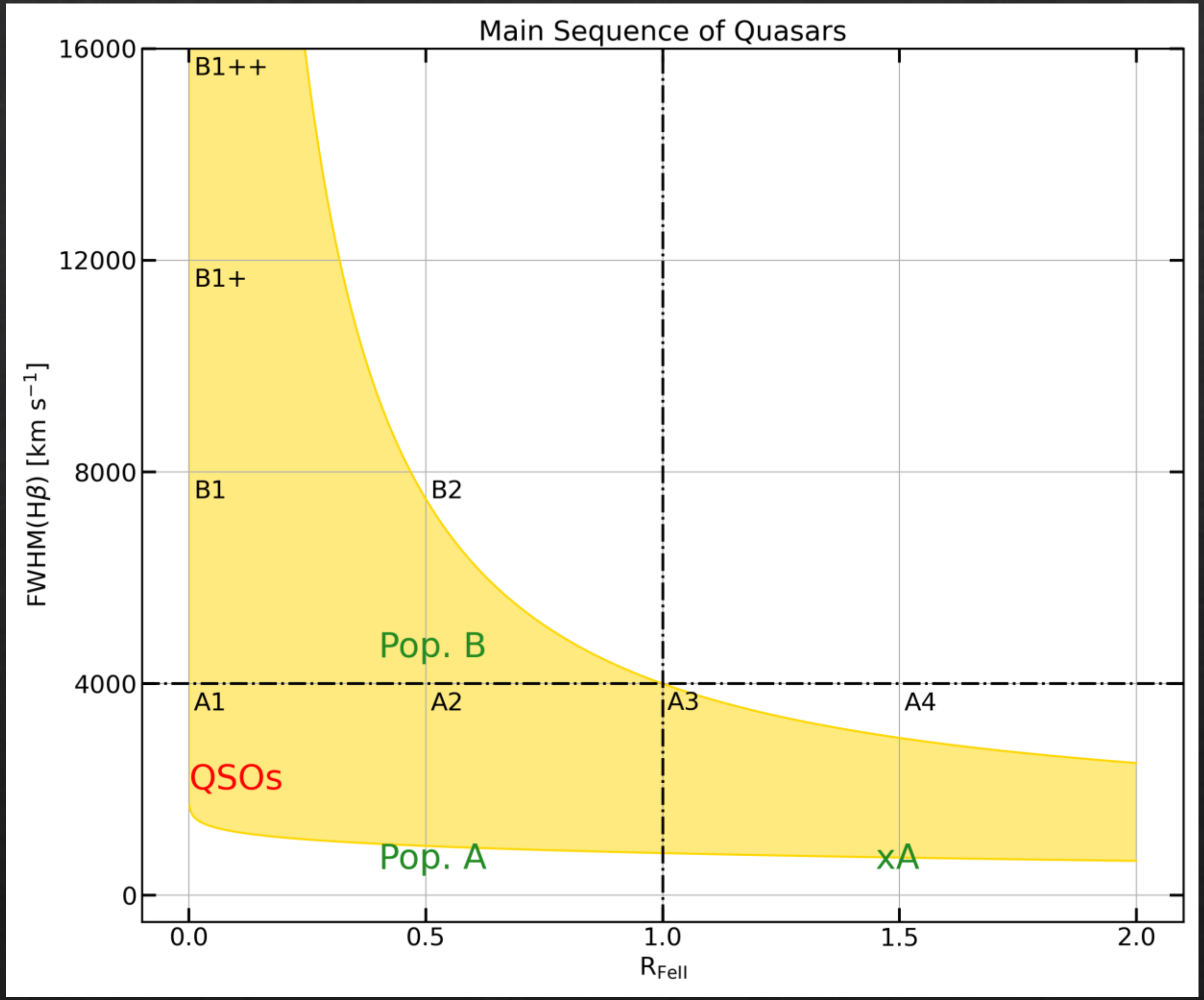

Main Sequence of Quasars (MS)

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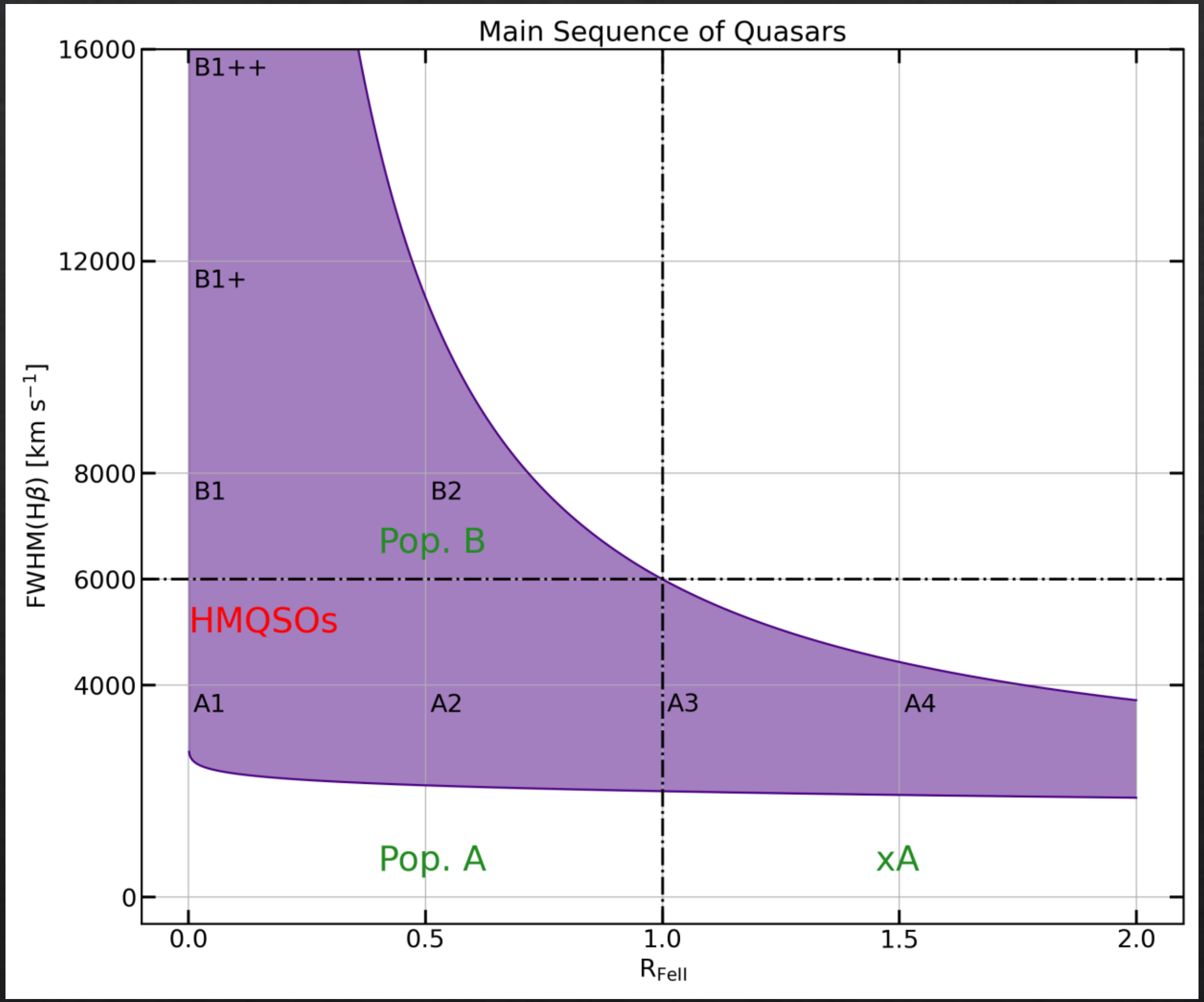
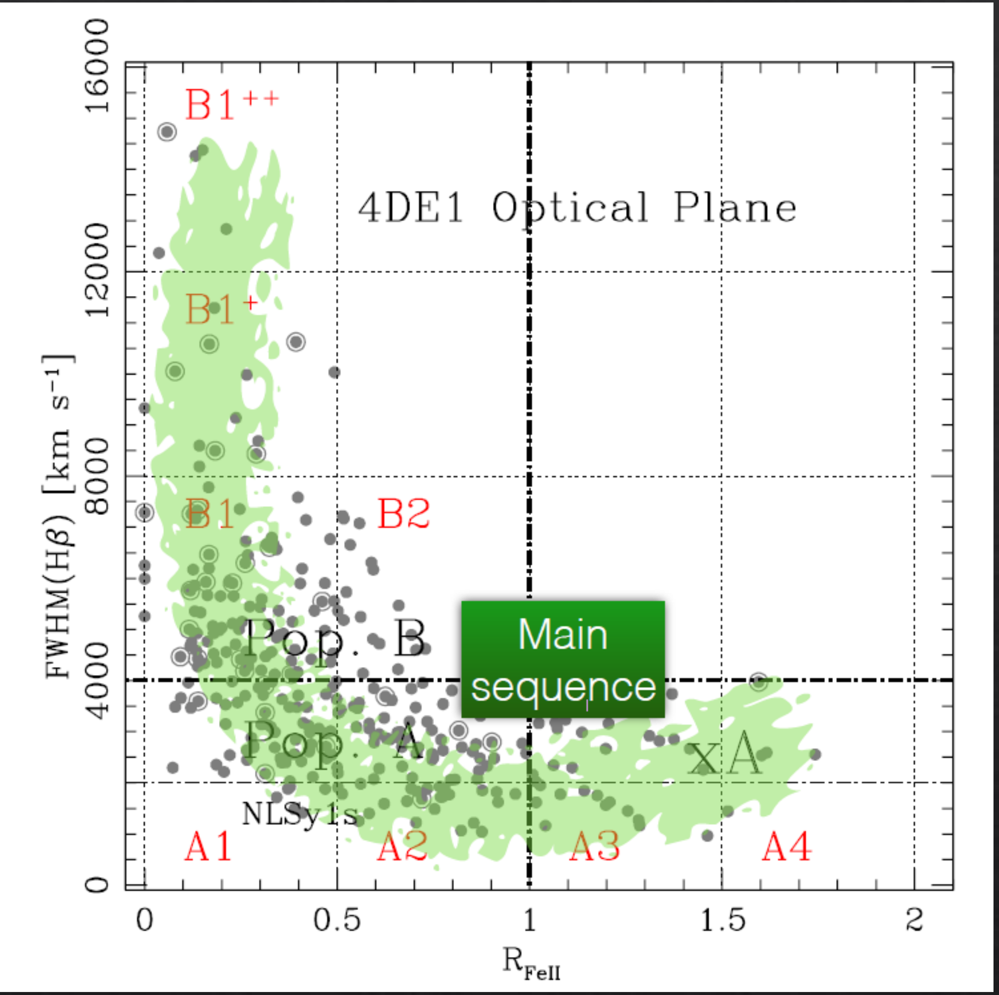
- Different tracks for different black hole masses
- NLSy1s found below quasars
- Quasars in the middle
- More massive objects found at higher thresholds of FWHM(Hβ)



Main Sequence of Quasars (MS)

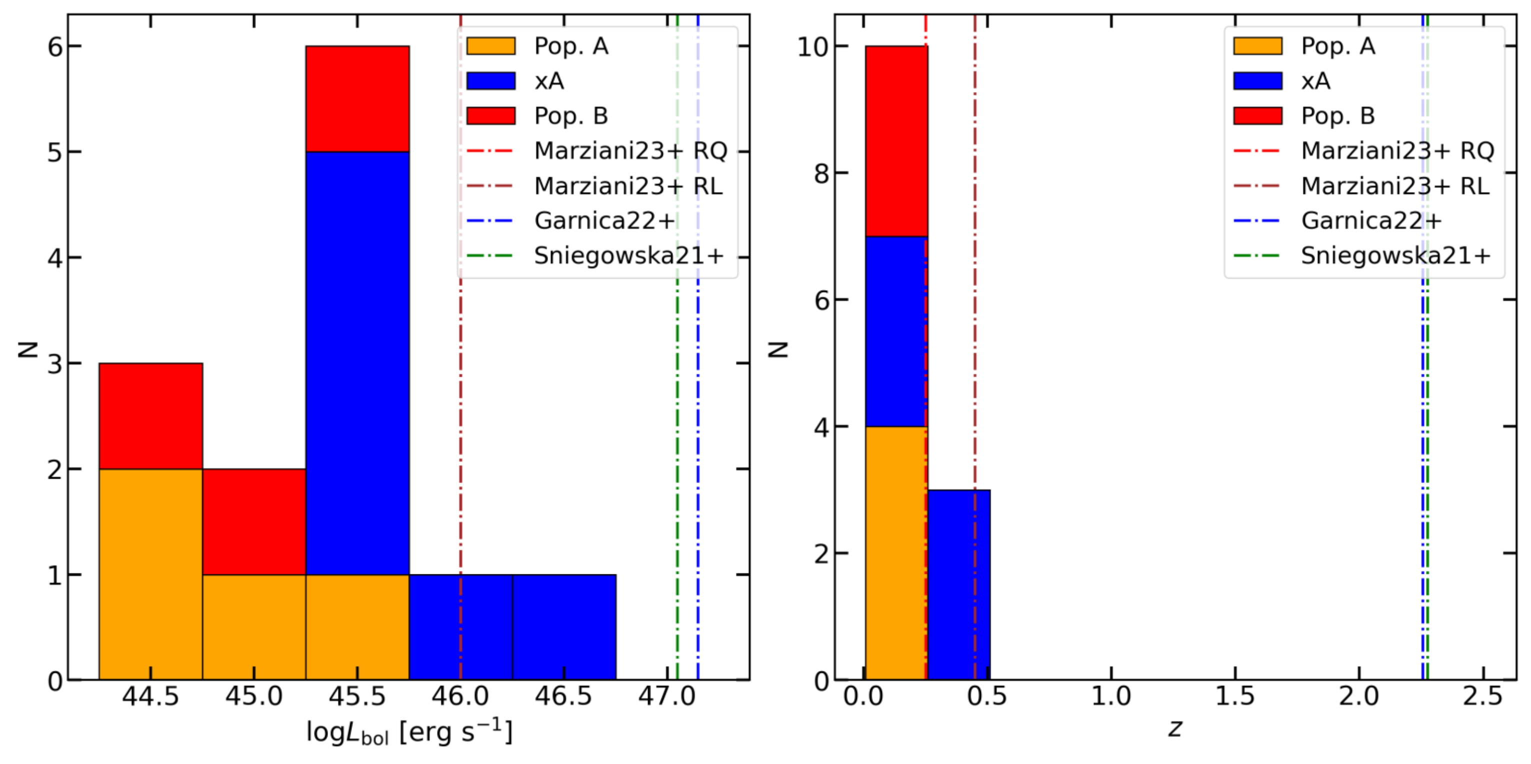
- Physical and geometrical properties of the BLR of AGNs not well understood
- Observed trends of ionization parameter U and density n_H along the MS
- Several works revealed discrepancy between metallicity Z in the BLR and metallicity of the host galaxy (Xu et al., 2018)
- Selective enrichment close to the Active Nucleus?



Marziani et al., 2018

Main Sequence of Quasars (MS)

- Previous works focused on:
  - Specific STs along the MS
  - Different luminosity bins, high $\log L_{\rm bol}$ (>47 erg/s)
  - Different z (>2)
- Pop. B objects explored in Marziani et al., 2023, xA sources in Sniegowska et al., 2021; Garnica et al., 2022
- Need to consider the whole MS at low z to do a systematic study of the trend



Floris et al., 2024

Sample definition and observations

- 13 Type-I AGNs at low-redshift ($0.009<z<0.472$) spread over the MS

- UV observations with HST:
  - COS (S/N ~ 50, 0.10 Å resolution)
  - FOS (S/N ~ 40, 0.25 Å resolution)
  - STIS (S/N ~ 40, 0.50 Å resolution)

- Optical observations (S/N ~ 60, 1 Å resolution):
  - KPNO 2.1m telescope
  - OAN 2.1m telescope
  - SOAR telescope
  - ESO 1.52m telescope

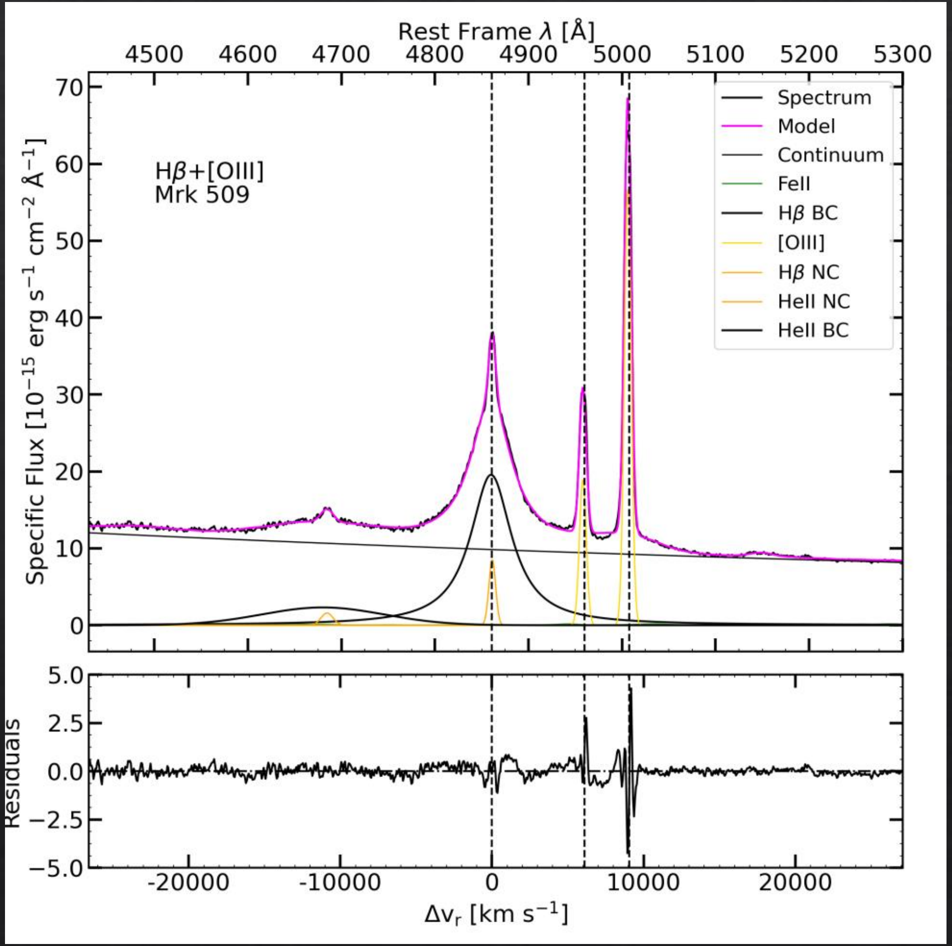
- Non-coeval spectra

Alberto Floris

Multi-component fitting

- Multi-component fitting using **Specfit** task from **IRAF**
- Broad lines decomposed in different components associated with different regions:
    - Broad Component (BC) – Virial
    - Very Broad Component (VBC) – Inner virial
    - Blueshifted Component (BLUE) – Outflow

Mrk 509 – Population A



Floris et al., 2024

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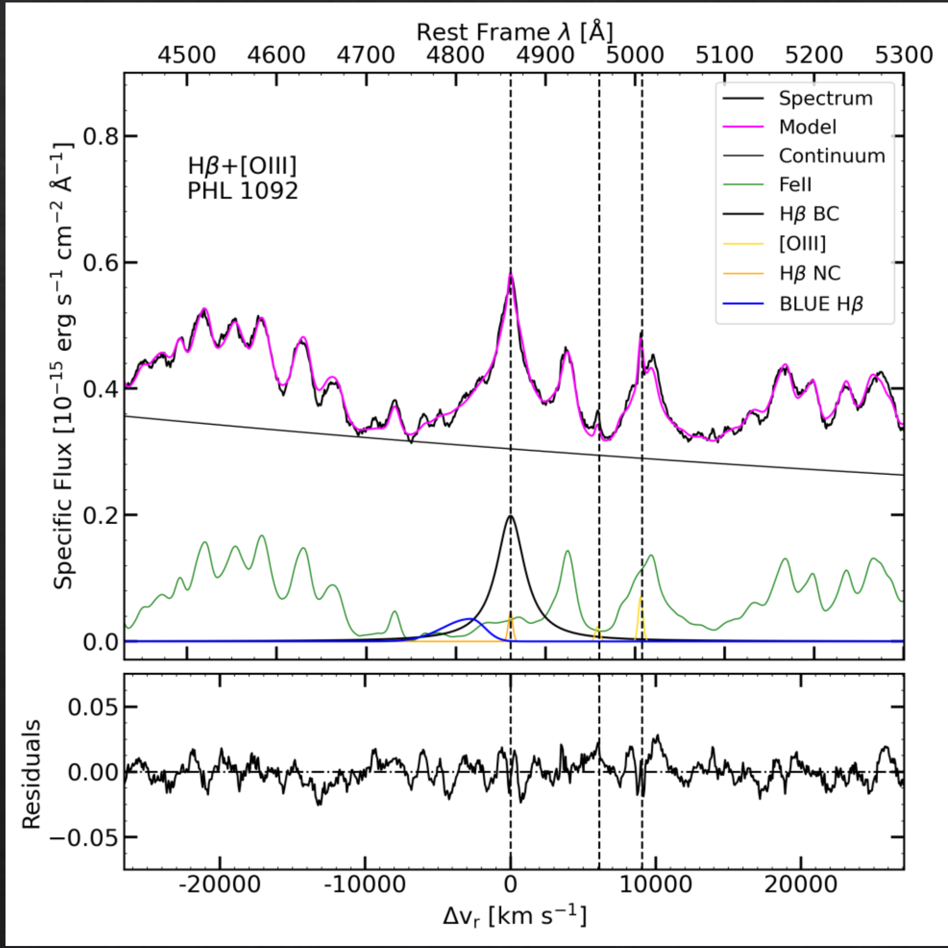
PHL 1092 – xA



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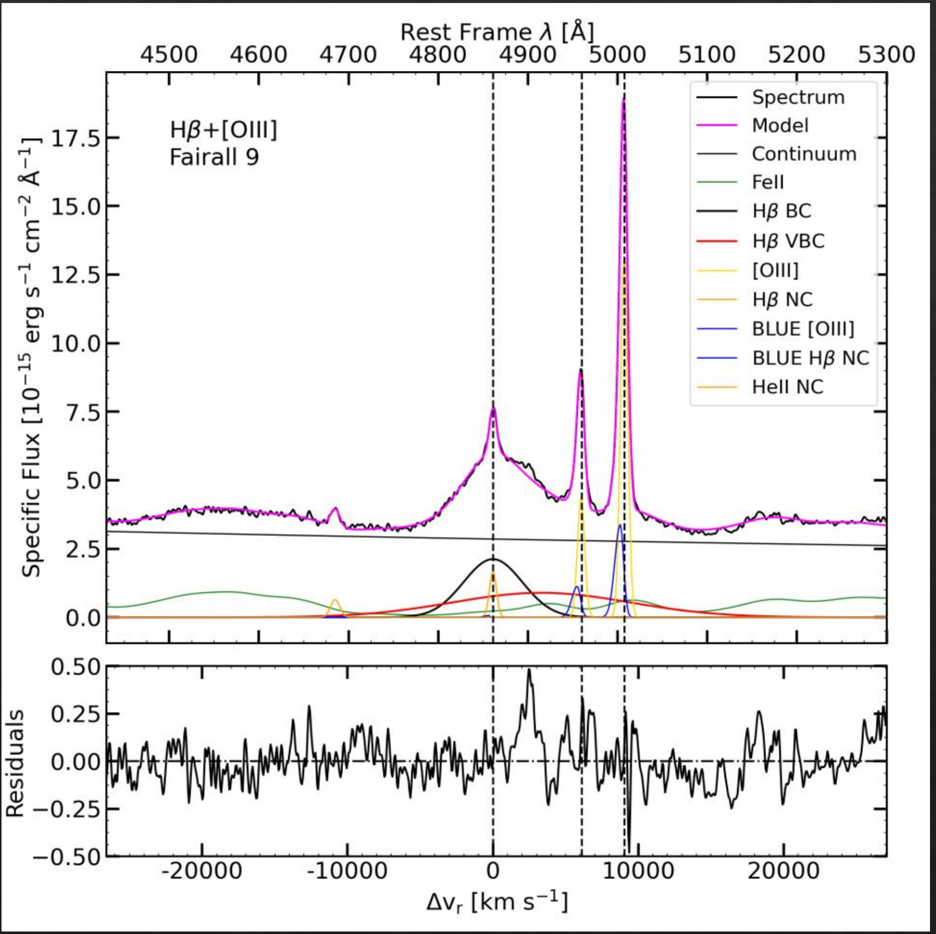
Fairall 9 – Population B



Floris et al., 2024

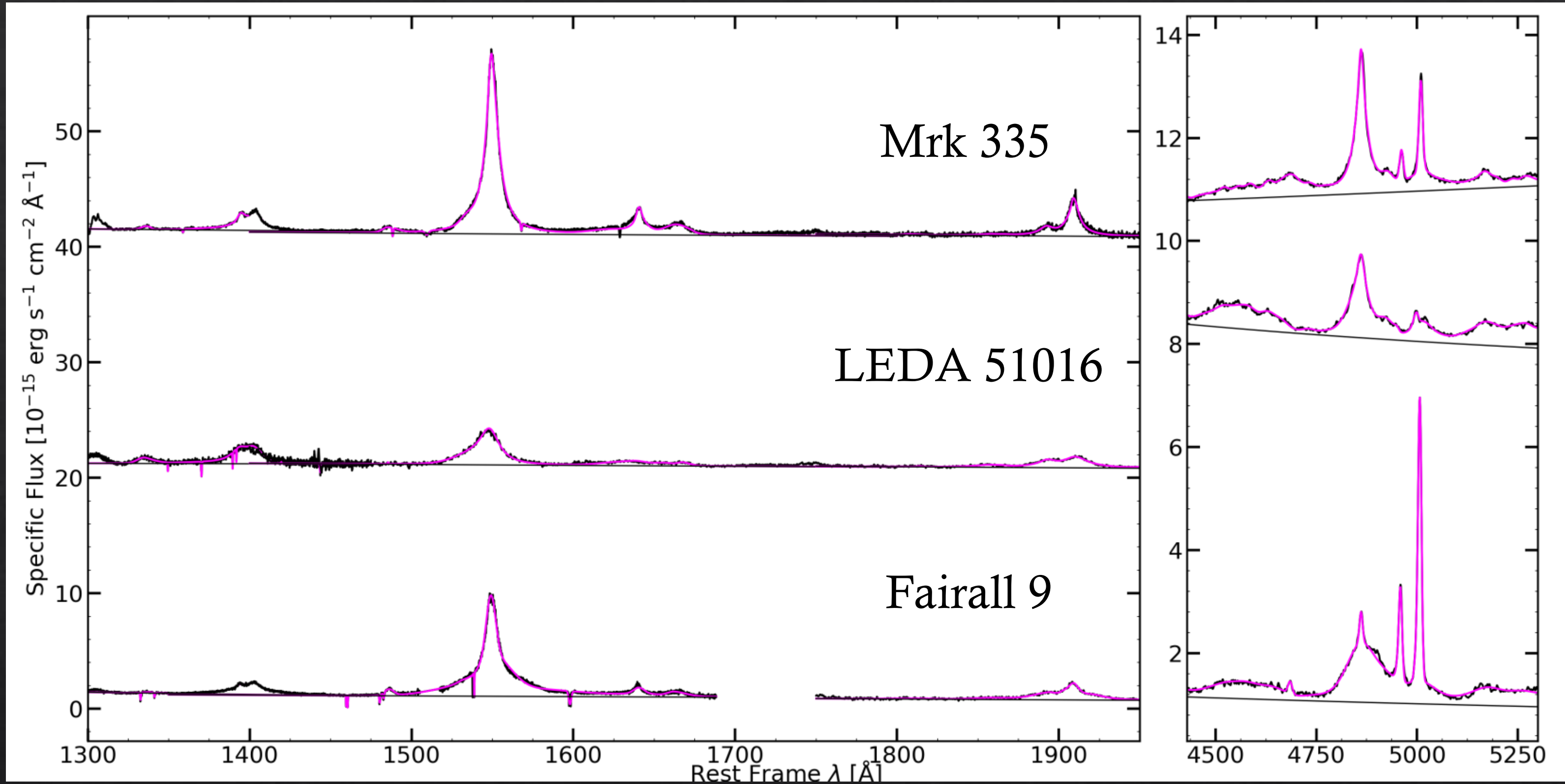
Multi-component fitting

- Lines: a tool to inspect the BLR

- Population A (Mrk 335):
  - BC

- Extreme Population A (LEDA 51016):
  - BC
  - BLUE

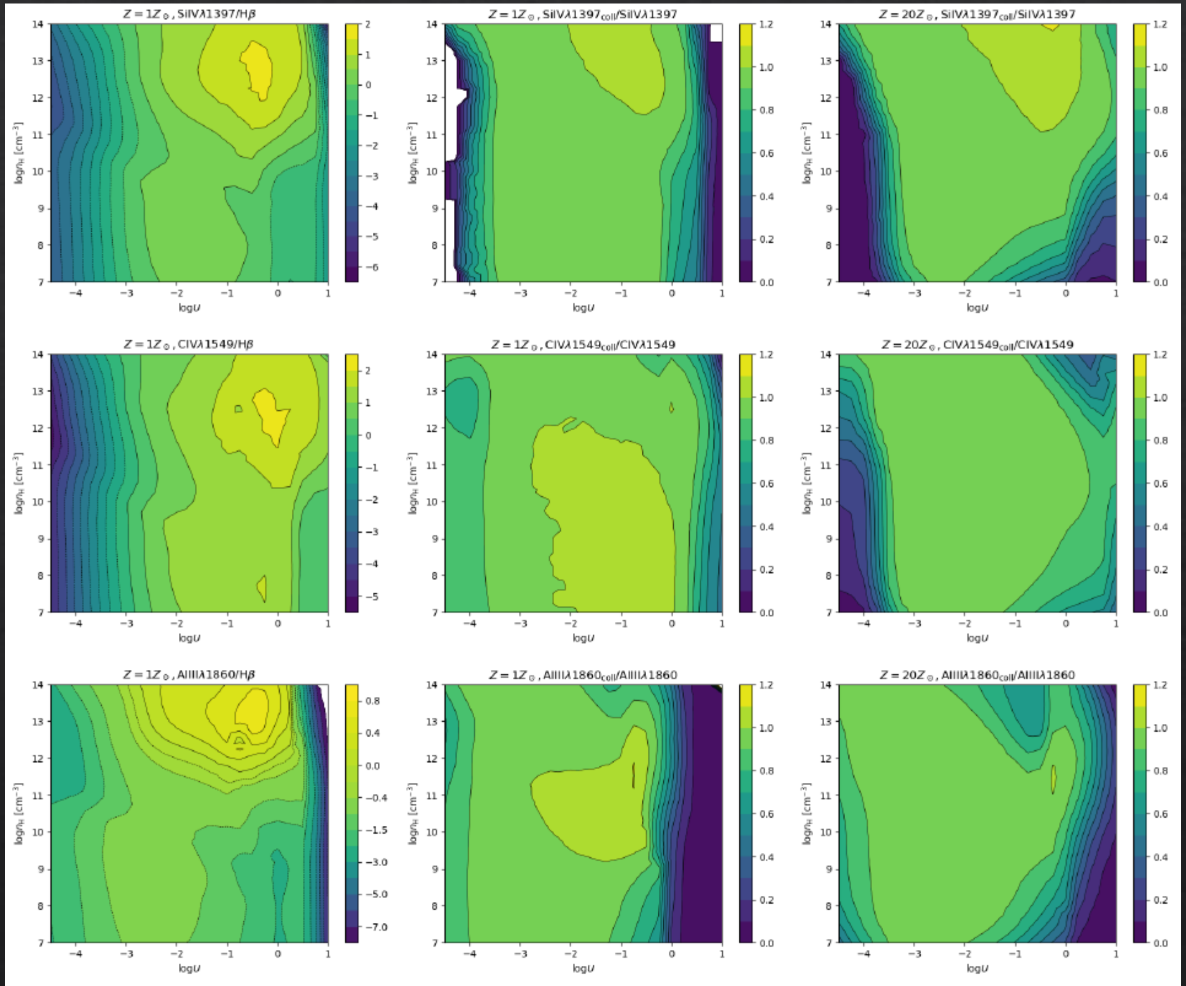
- Population B (Fairall 9):
  - BC
  - VBC



UV and optical spectra of Mrk 335, LEDA 51016 and Fairall 9

CLOUDY photoionization simulations

- 10 Diagnostic line ratios obtained from measured lines are used to infer properties of the gas
- Photoionization simulations spanning a wide range of values of Z ($10^{-3} - 10^{3} Z_{\odot}$), U and n_{H}
- Appropriately calculated for each population's SED
- χ^2 is computed to confront diagnostic ratios from measurements with those from simulations



Marziani et al., 2020

BLR parameter estimates

- Diagnostic ratios sensitive to density n_H, ionization parameter U and metallicity Z:
  - (SiIV+OIV])/CIV
  - (SiIV+OIV])/HeII
  - CIV/HeII
  - CIV/Hβ
  - AlIII/CIV
  - AlIII/SiIII]
  - SiIII]/CIII]
  - CIII]/CIV
  - FeII/Hβ
  - $HeII_{opt}$/Hβ

- Metallicity values and confidence regions at 1σ computed for minimum χ^2

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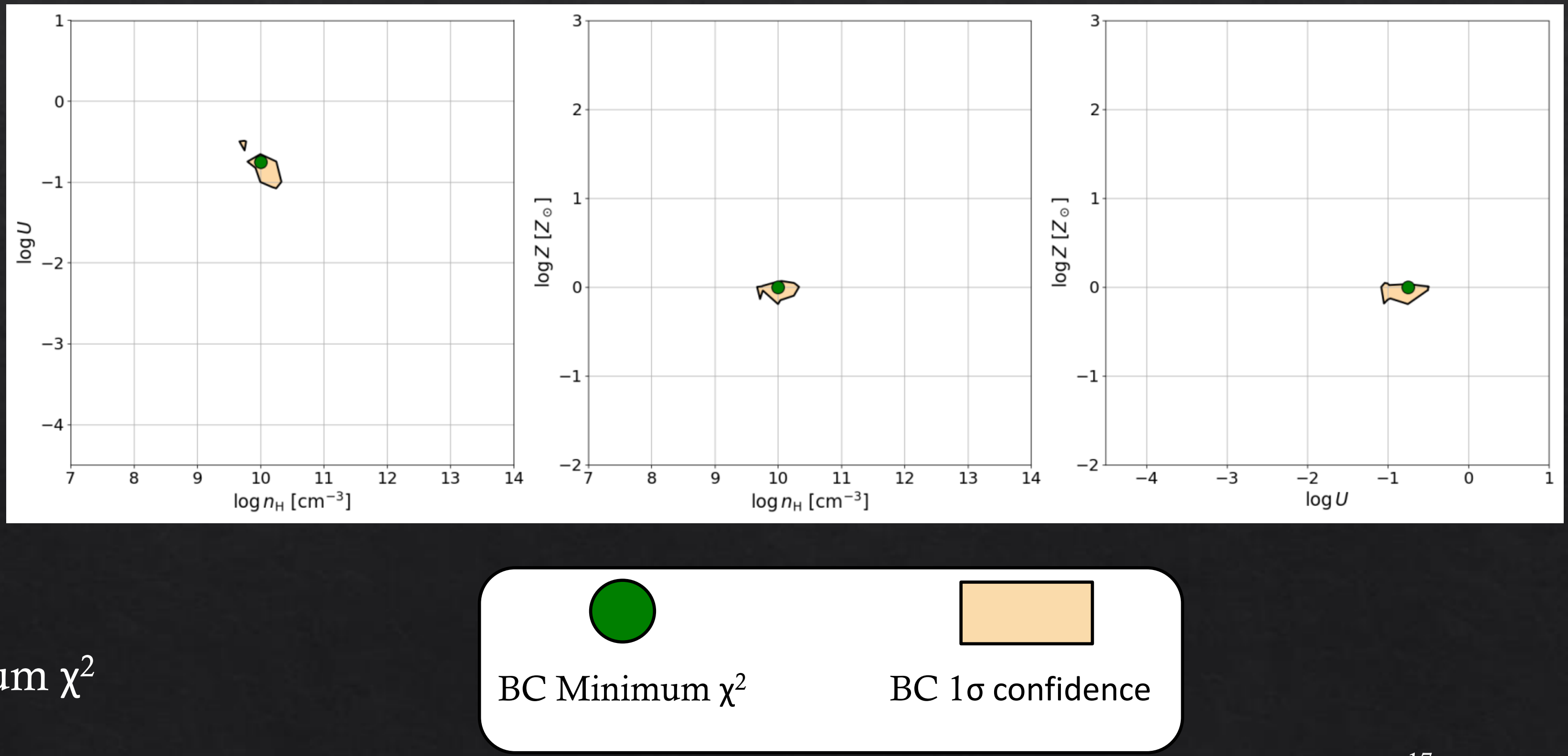

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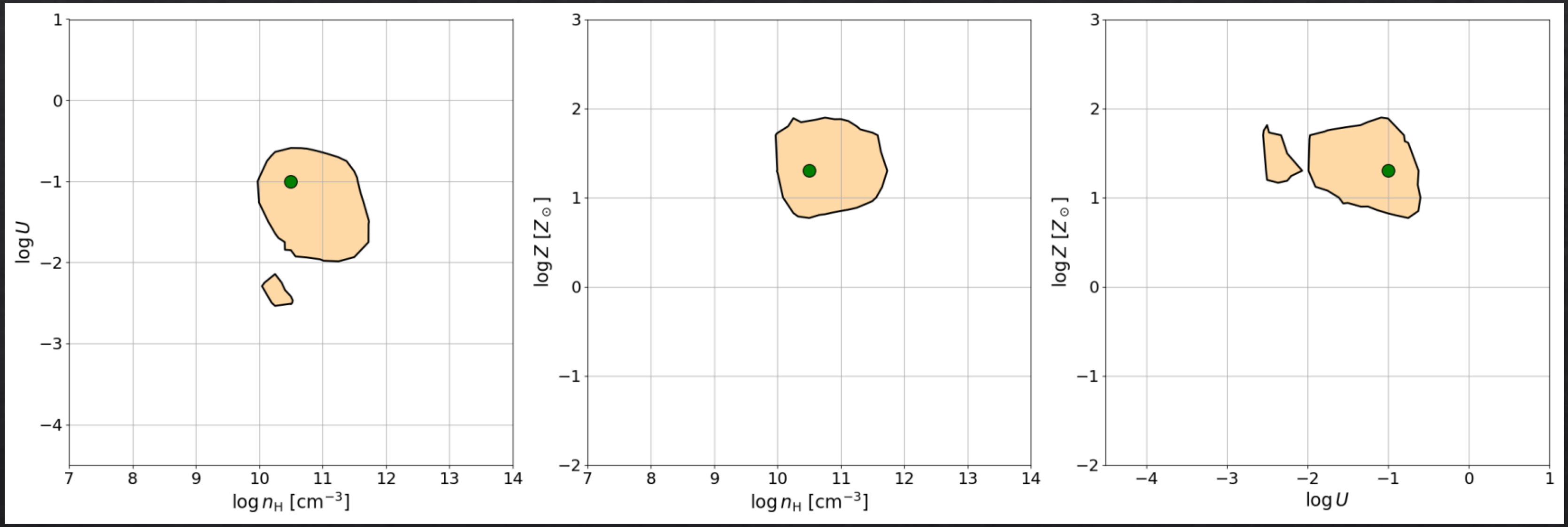

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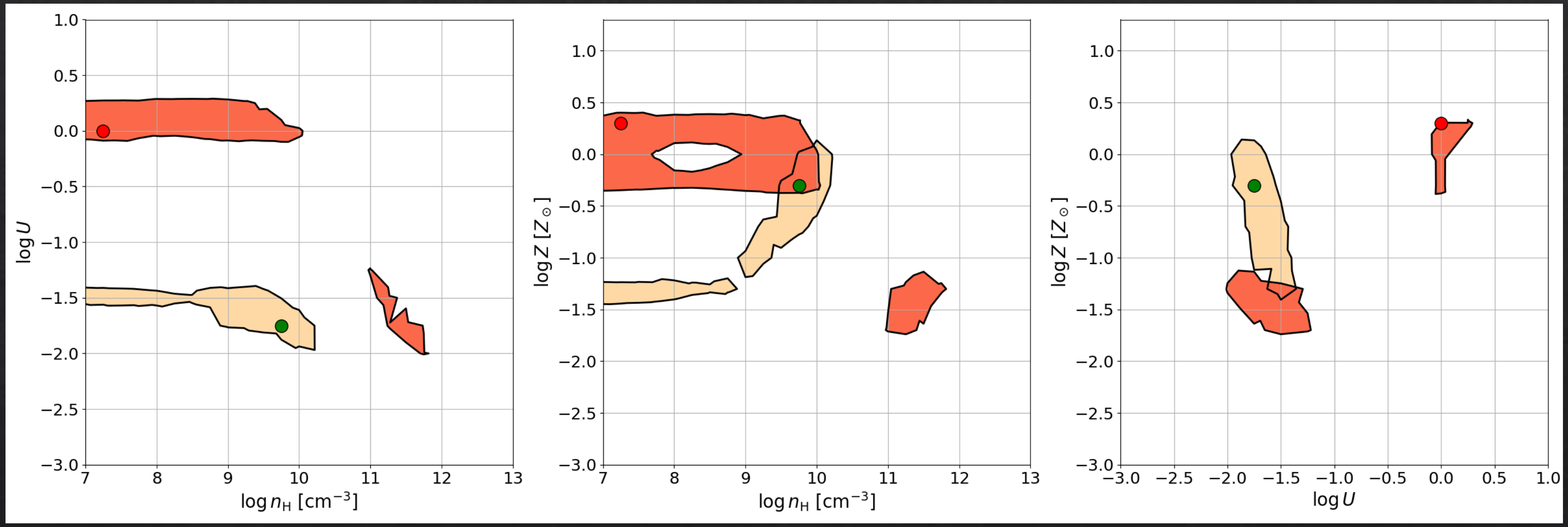
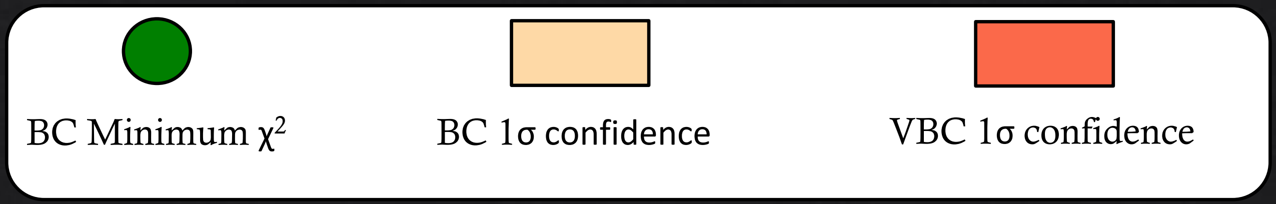
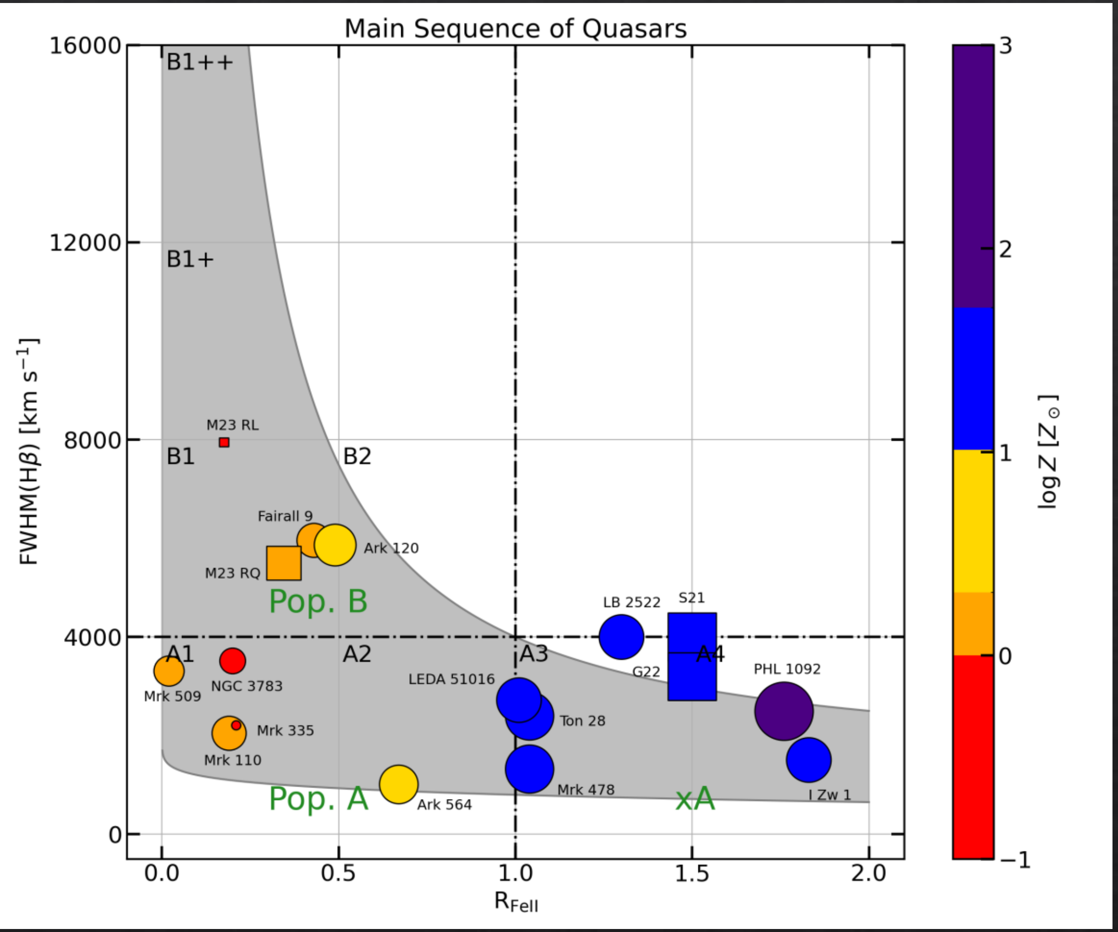
NGC 3783 – Population B





Main Sequence

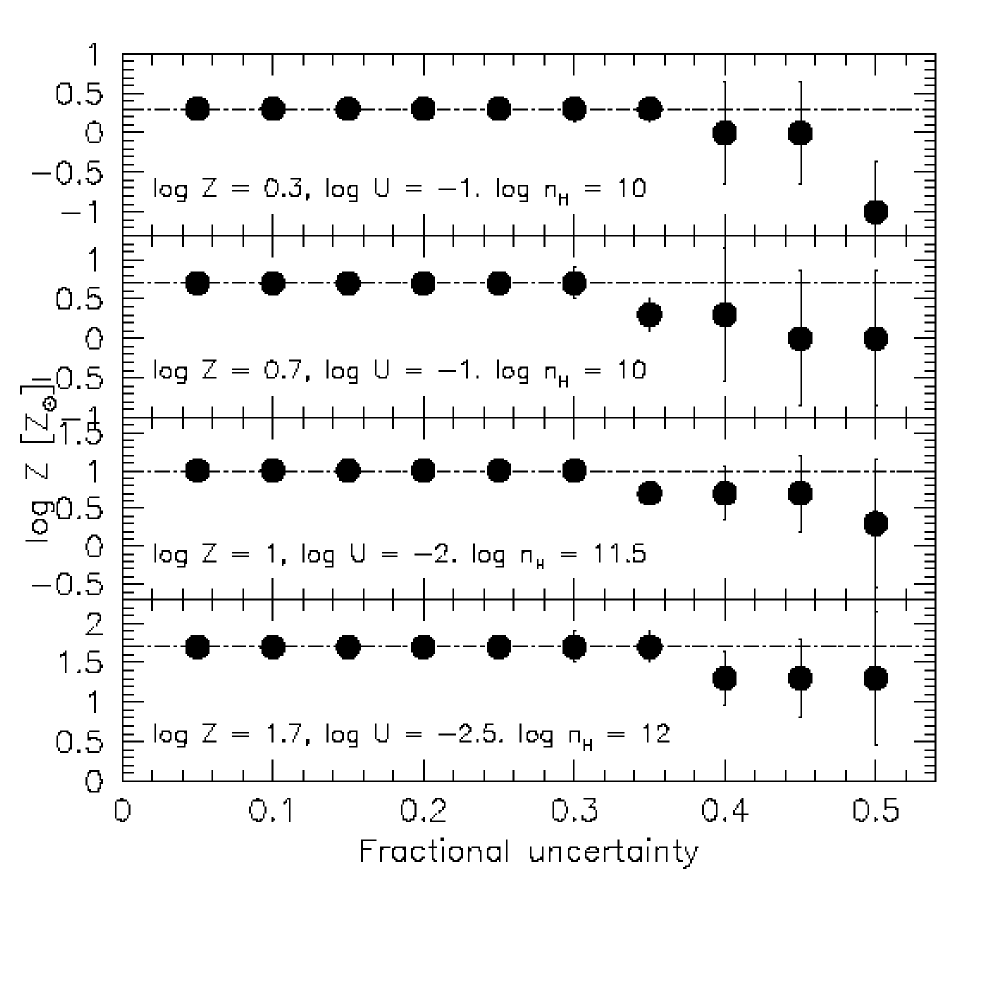
- Plotting the MS Optical Plane of our sample yields interesting results
- Clear difference in *Z* among spectral types
- Population B → metal-poor gas/solar?
- Population A → ~ solar metallicity
- Extreme Population A → highly metal rich gas ($Z > 10\ Z_{\odot}$)
- PHL 1092, Z~ 1000 $Z_{\odot}$ → Out-of-scale



Floris et al., 2024

High Z solutions

- Consensus that gas in BLR exhibits supersolar Z (Maiolino & Mannucci, 2019)
- 1000 $Z_{\odot}$ is still out of scale!
- Are high Z solutions the result of some bias?
- What could create this effect?
  - Statistical errors? → NO!



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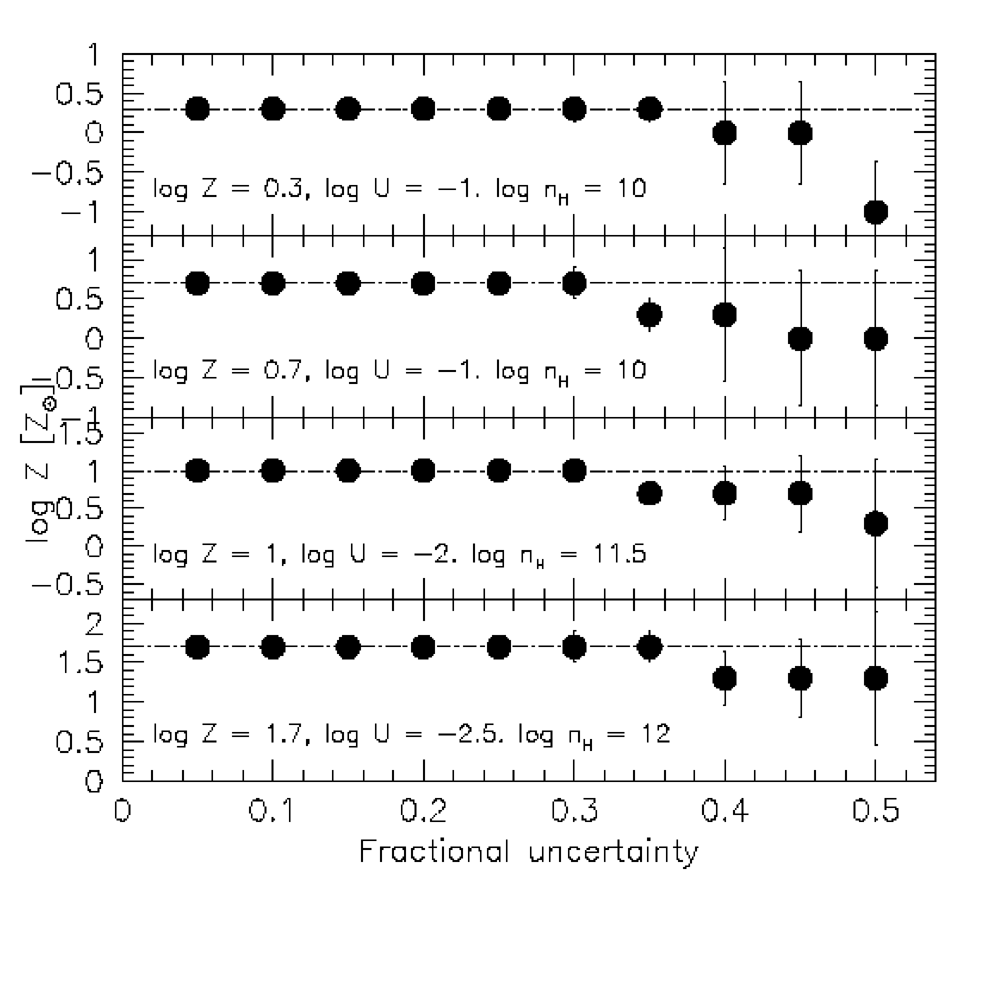

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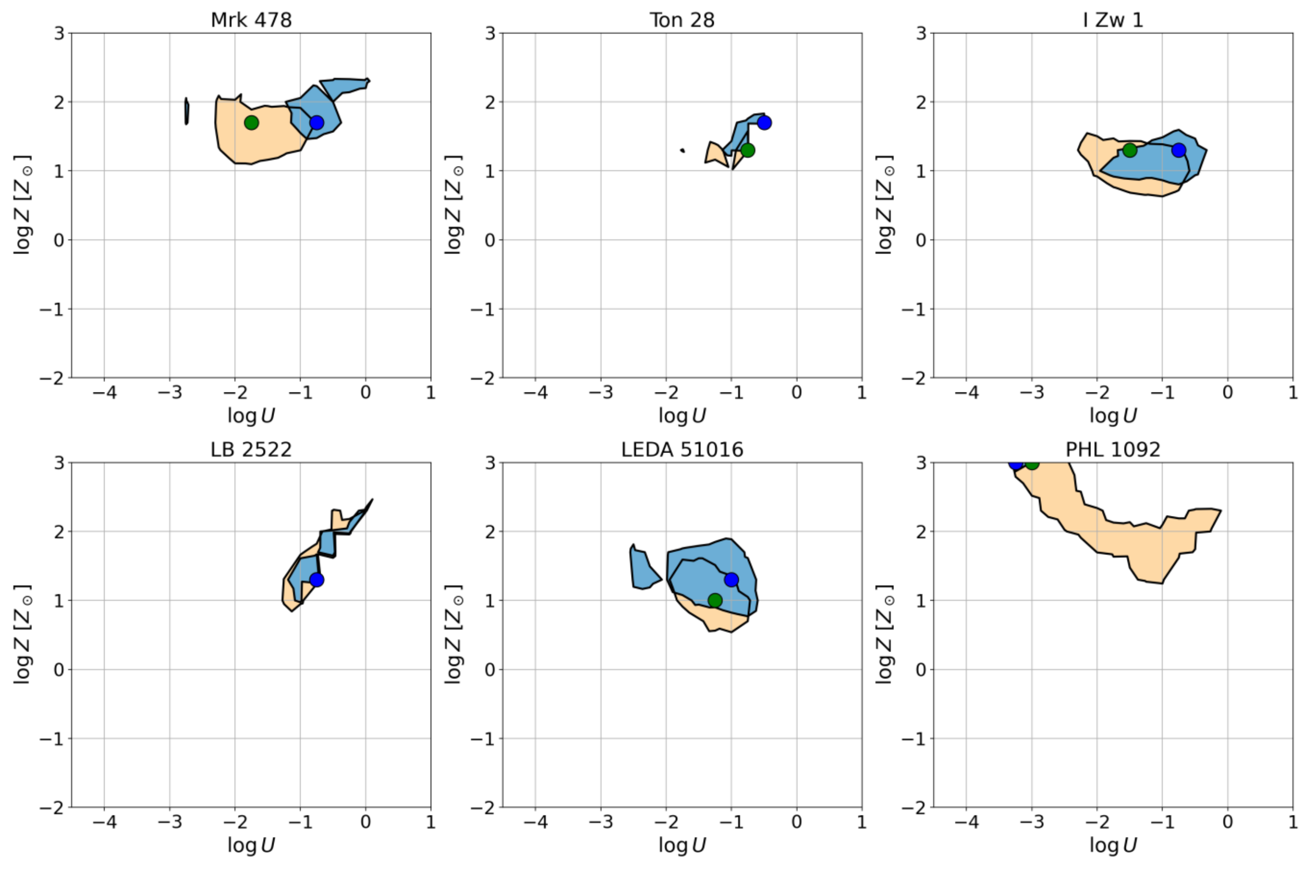

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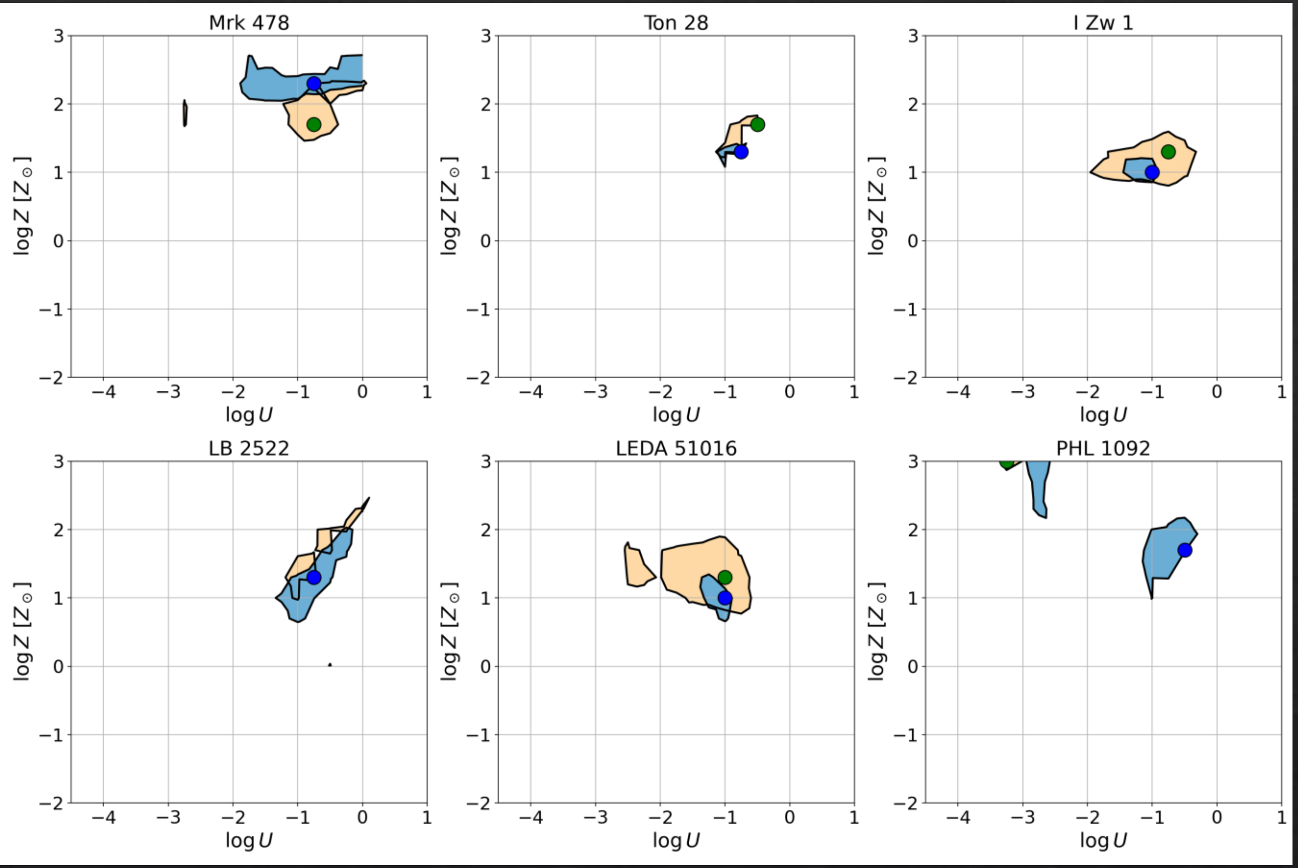
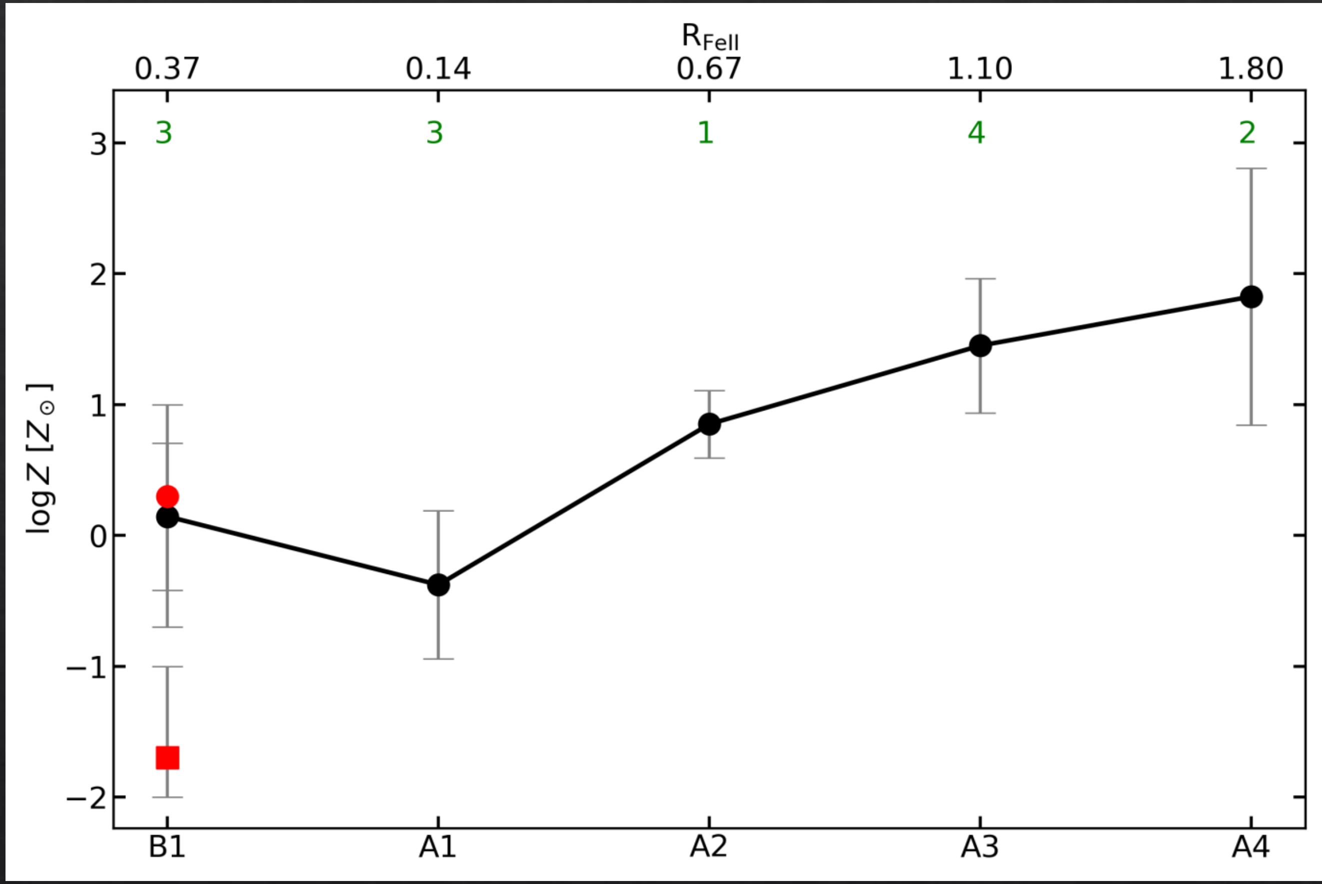
  - Inappropriate SED? → NO!
  - Microturbulence? → YES!



Floris et al., 2024

The trend

- **Trend of metallicity along the MS**
- Dip in A1 spectral type due to low- R_{FeII} sources
- Steady increase in Z with spectral types



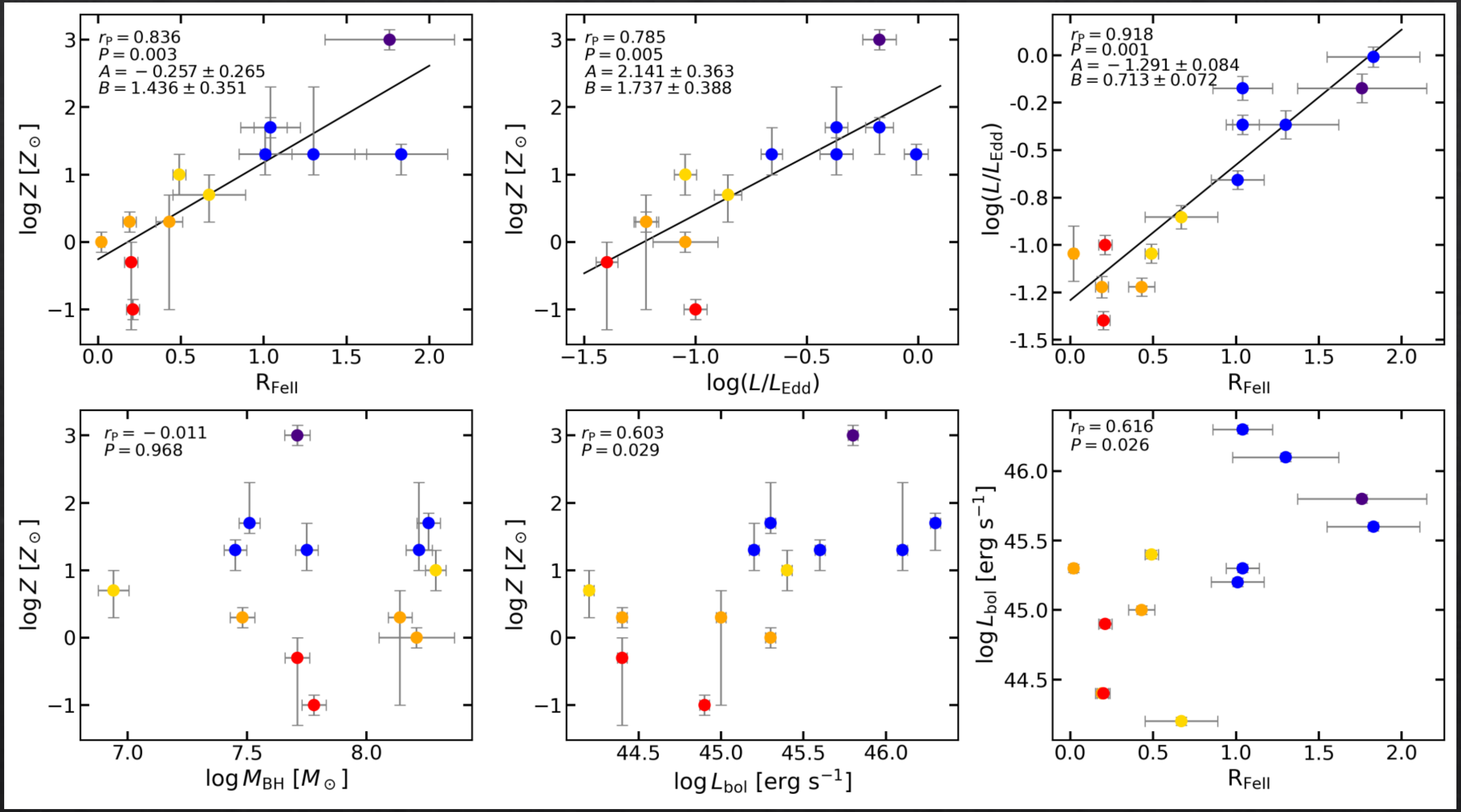
Floris et al., 2024

Discussion

- Strong correlations:
  - $R_{FeII} - Z$
  - $R_{FeII} - L/L_{Edd}$
  - $L/L_{Edd} - Z$

- M_{BH} does not correlate with Z → puzzling

- **Trend of metallicity along the MS**



Floris et al., 2024

Discussion

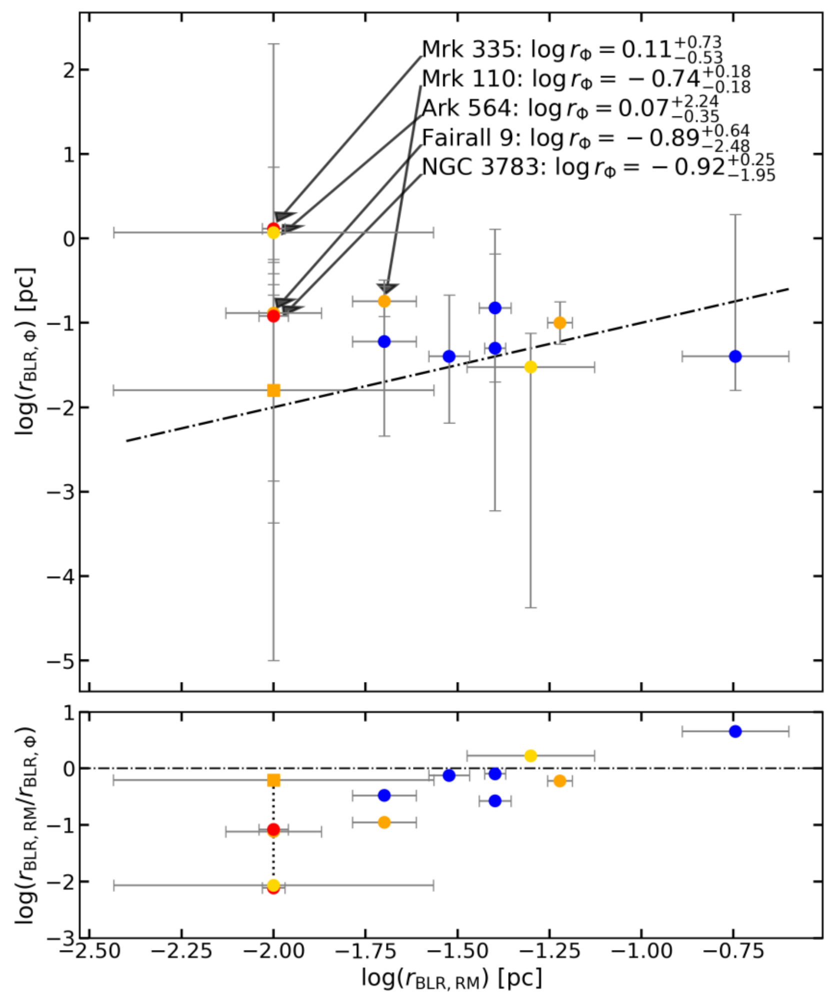
- CLOUDY simulations allow for an independent measurement of the BLR distance from the SMBH using two parameters determined from the best-fitting solution:

$$U = \frac{Q(\mathrm{H})}{4\pi r_{\mathrm{BLR}}{}^2 c n_{\mathrm{H}}}$$

- We can confront the inferred r_{BLR} with time-delays obtained from Hβ reverberation mapping for each object

- For most sources the two determinations are consistent within error

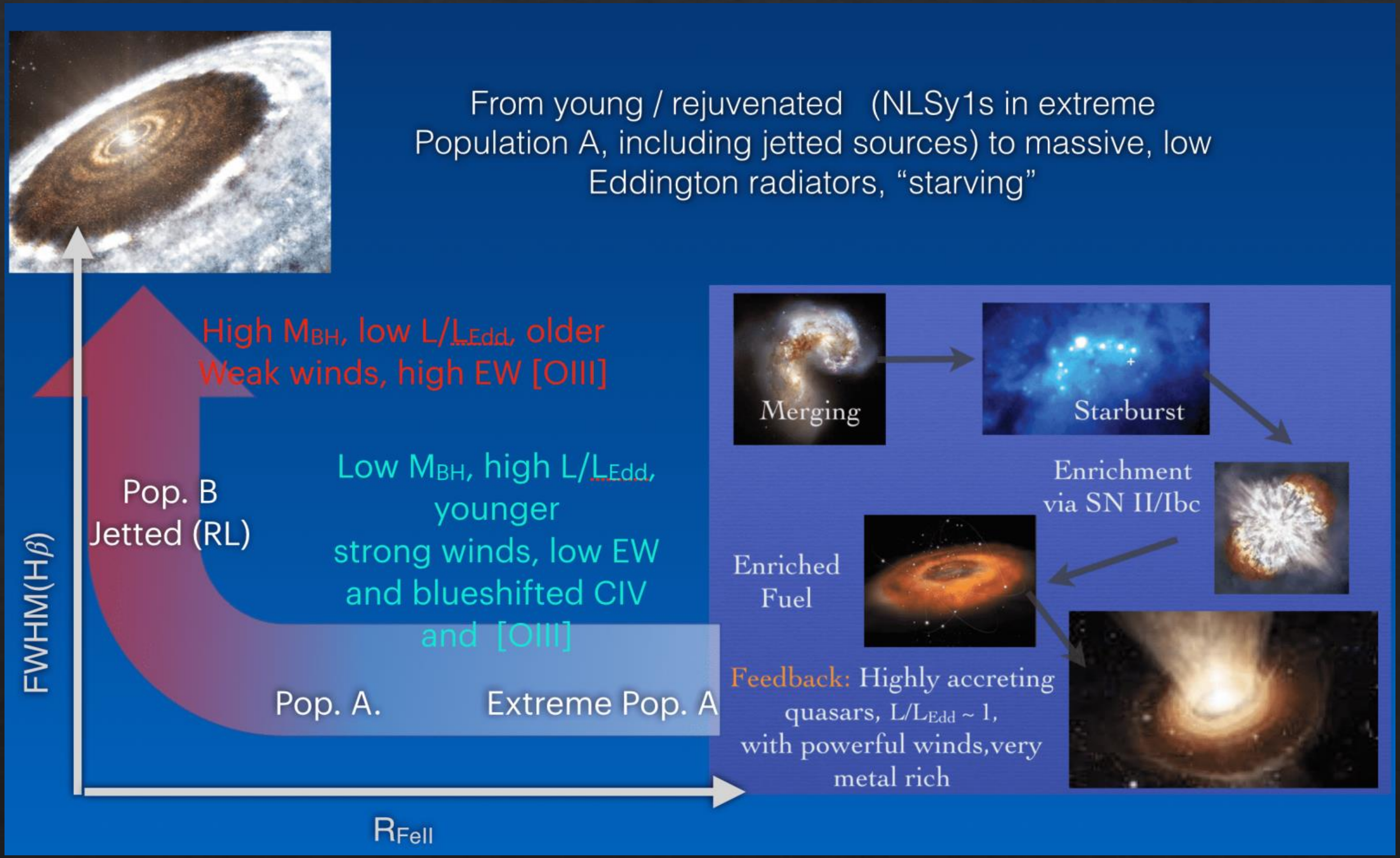
- Greatest source of uncertainty in this determination is the CIII] intensity measurement, pushing towards lower n_{H}



Floris et al., 2024

Discussion

- Evolutionary hypothesis
- xA Quasars:
  - Young objects experience powerful star formation after merger episodes
  - Accretion Modified Stars (AMS) accrete matter from the accretion disk of the SMBH
  - After reaching high mass explode as core-collapse Supernovae
  - Cascade of Supernova events occurs in the time of ~ Myr
  - Production of highly metallic gas (Wang et al., 2023)

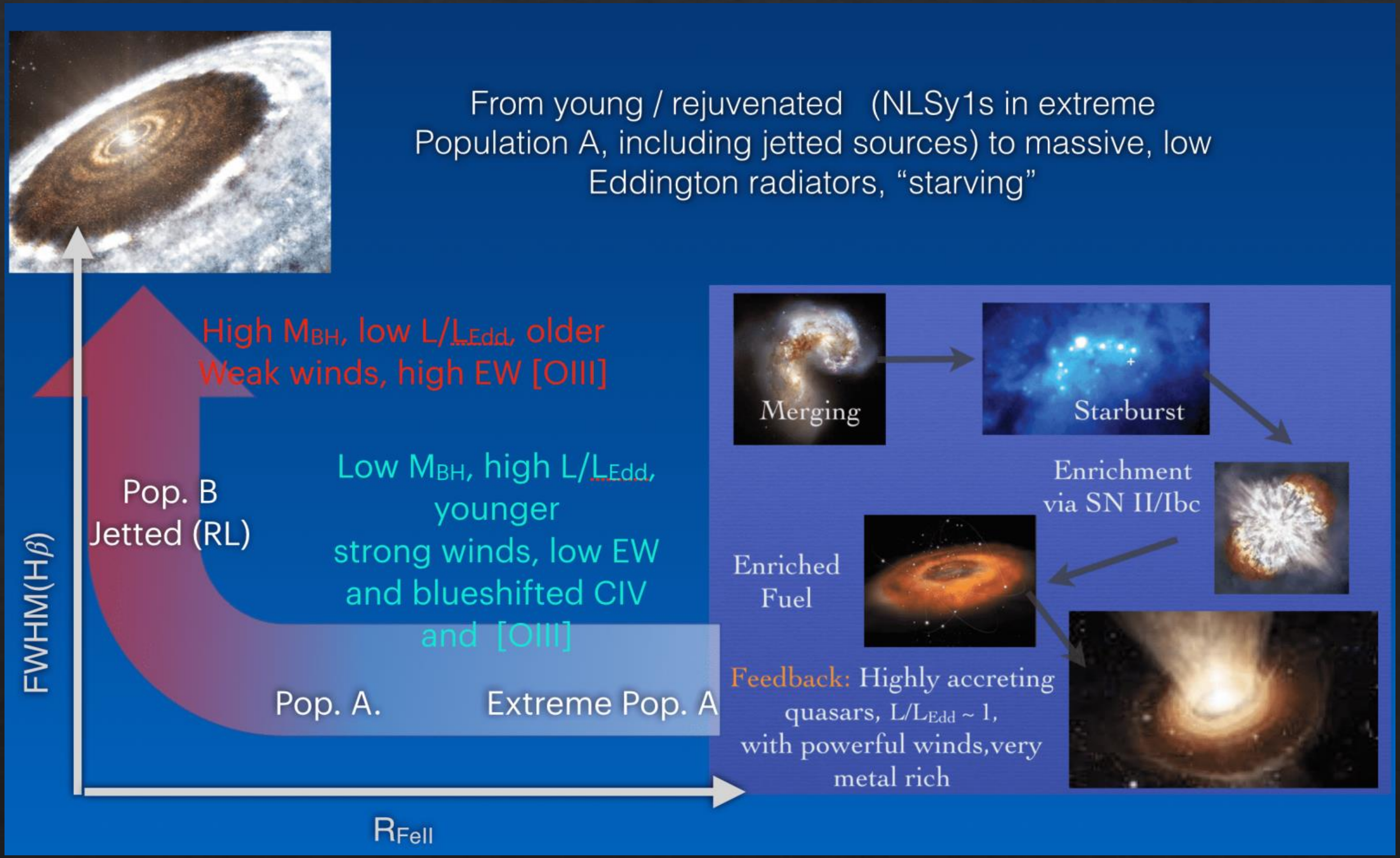


Marziani et al., 2023

Discussion

- Population A:
  - Strong winds develop in high L/L_{Edd} objects
  - xA objects gradually exhibit less extreme characteristics
  - Highly metal rich gas is slowly dispersed in the interstellar and intergalactic medium

- Population B:
  - The gas reservoir is depleted after some time
  - Metal poor gas
  - Older objects exhibit larger SMBHs and lower accretion rates



Marziani et al., 2023

Conclusions and future work

- Sample of 13 low-z Type-I AGNs
- Recipe: estimation of metallicity in the BLR using CLOUDY simulations and multi-component fitting
- Confirmed supersolar metallicity for xA sources
- Highest Z objects significantly affected by microturbulence
- Evidence of strong Z trend along the MS, from 0.1 to 50 $Z_{\odot}$
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- In the future:
  - Reduction of approximations in place
  - Use of simultaneous observations, with more diagnostic ratios in a wider wavelength range
  - Extending the use of this technique to larger sample, also at high-*z,* made possible by JWST

Thank you for your attention