# The Broad Line Region in Quasars

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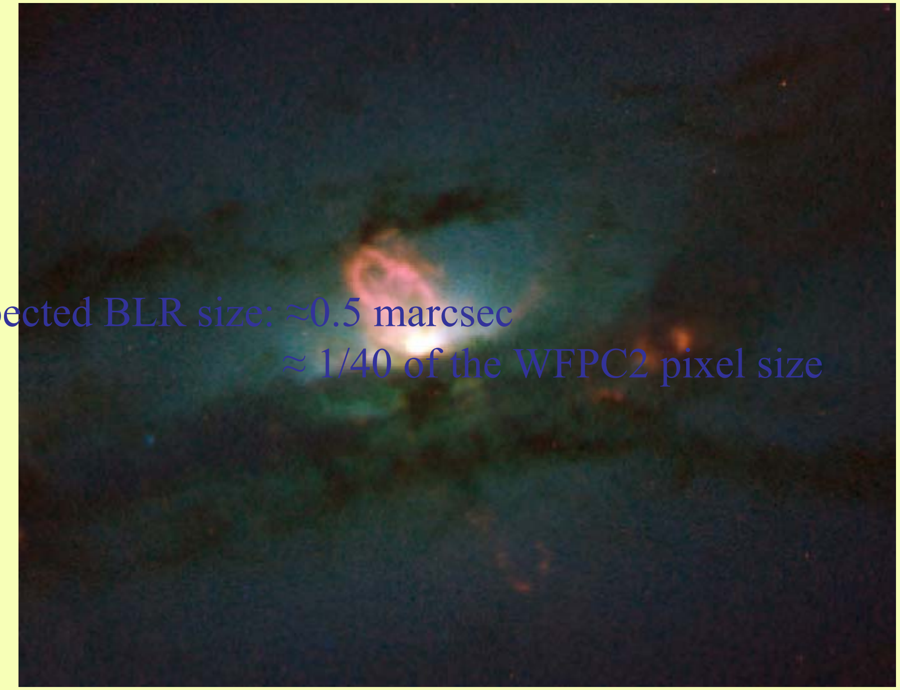


. The dot is the expected BLR size: ≈0.5 marcsec
≈ 1/40 of the WFPC2 pixel size

10”

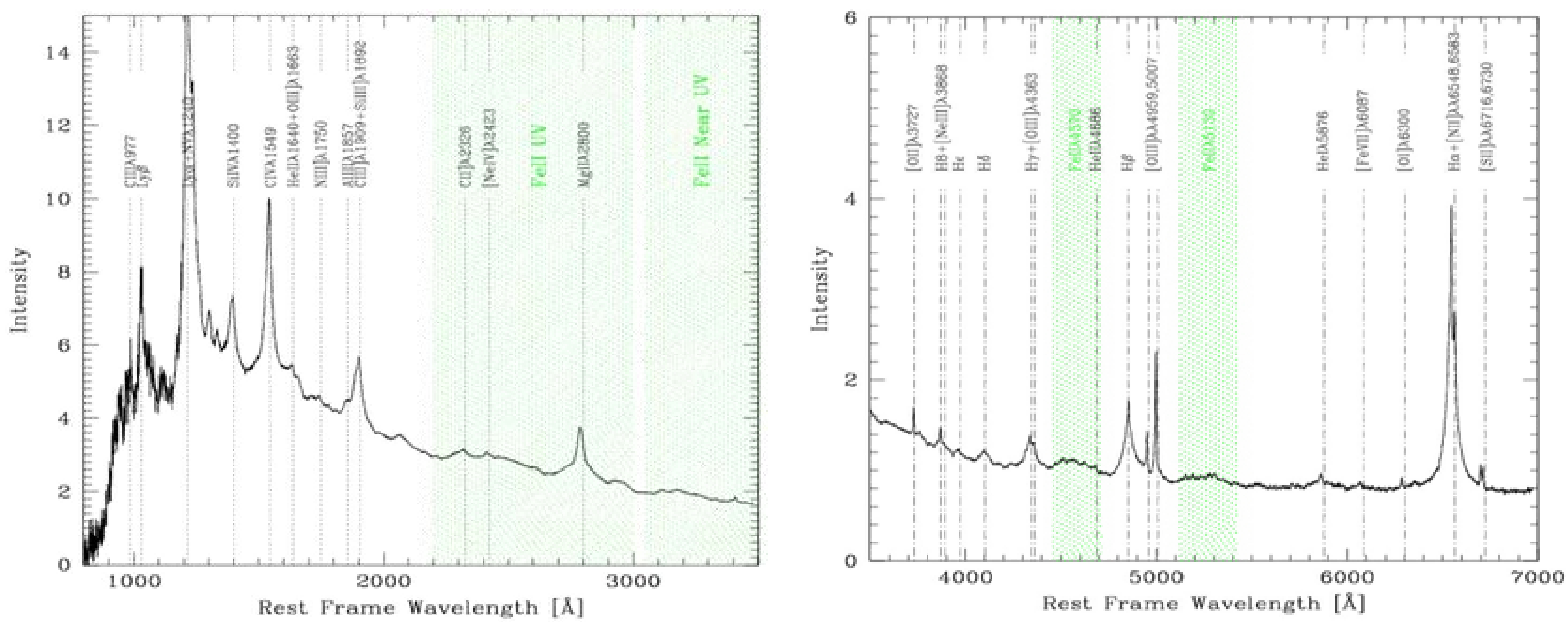
NGC 4388

D. P. Cox, conference summary at the Astrophysical Plasma conference, held in Mexico City in Nov. 1999:

## 7. IMAGES VERSUS SPECTRA

We heard the usual, "*A spectrum is worth a thousand pictures*", extended by Deborah Dultzin-Hacyan to "*A thousand spectra are worth more than one average spectrum*". After that she showed that from many spectra one could get hints of the image, an image that in her case was totally unavailable because of the extremely small scale being sampled, somewhat turning things around, you might say. One could hear a yearning within

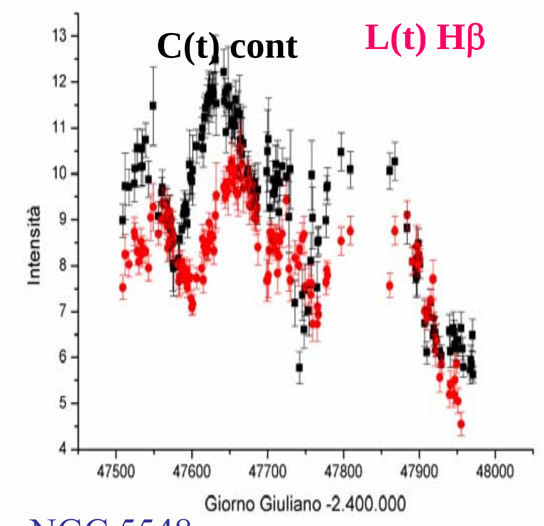
The average quasar spectrum from the SDSS (Van den Berk et al.)




green bands: ranges where FeII emission is strong and can be easily measured

The "one thousand" spectra are needed to exploit…

# 1) Spectral Variability (reverberation mapping)




Optical/UV broad emission lines vary following continuum changes. An emissivity-weighted measure of the Broad Line Region linear distance $r_{BLR}$ from the continuum source is provided by the centroid of the cross correlation function between the continuum and any emission line light curve.

$r_{BLR}$ from Hβ monitoring is available for 37 low-$z$ AGN as of Dec. 2006 (Kaspi et al. 2005, 2007)

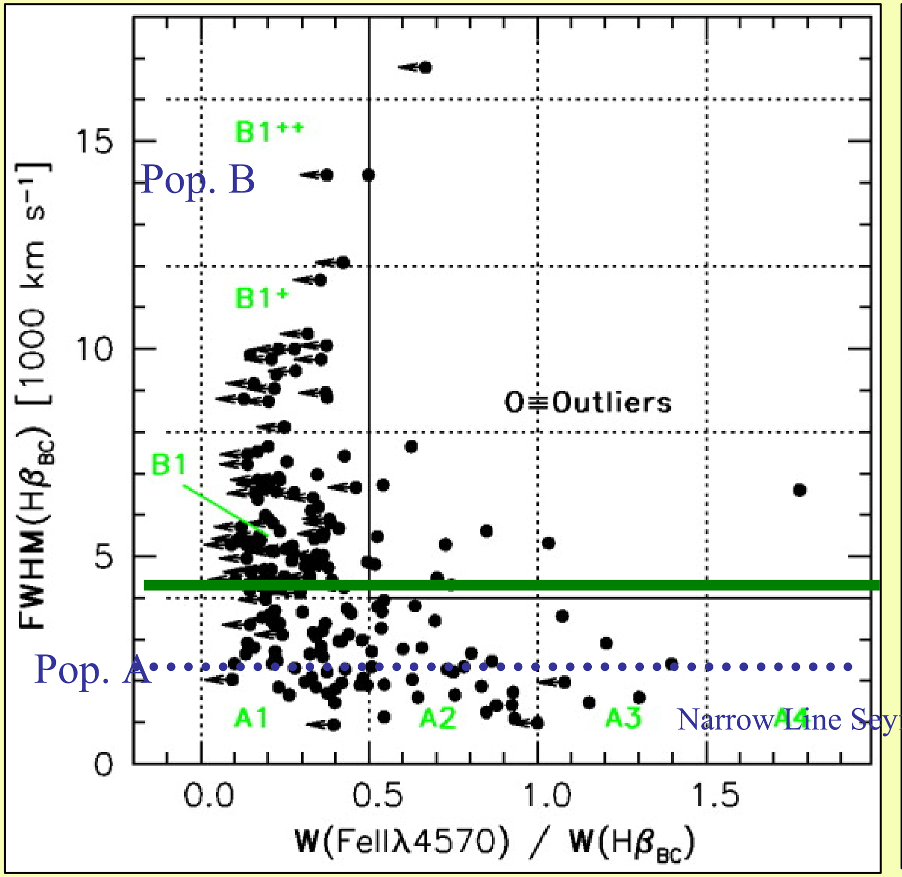
It turns out to be most useful to group emission lines depending on the ionization potential of their emitting ionic species:
High ionization lines (HILs: ~40-50 eV): CIVλ1549, OIV]+SiIVλ1400 HeIIλ1640 HeIIλ4686
Low ionization lines (LILs: <20 eV): Balmer lines, FeII, CII, MgIIλ2800.

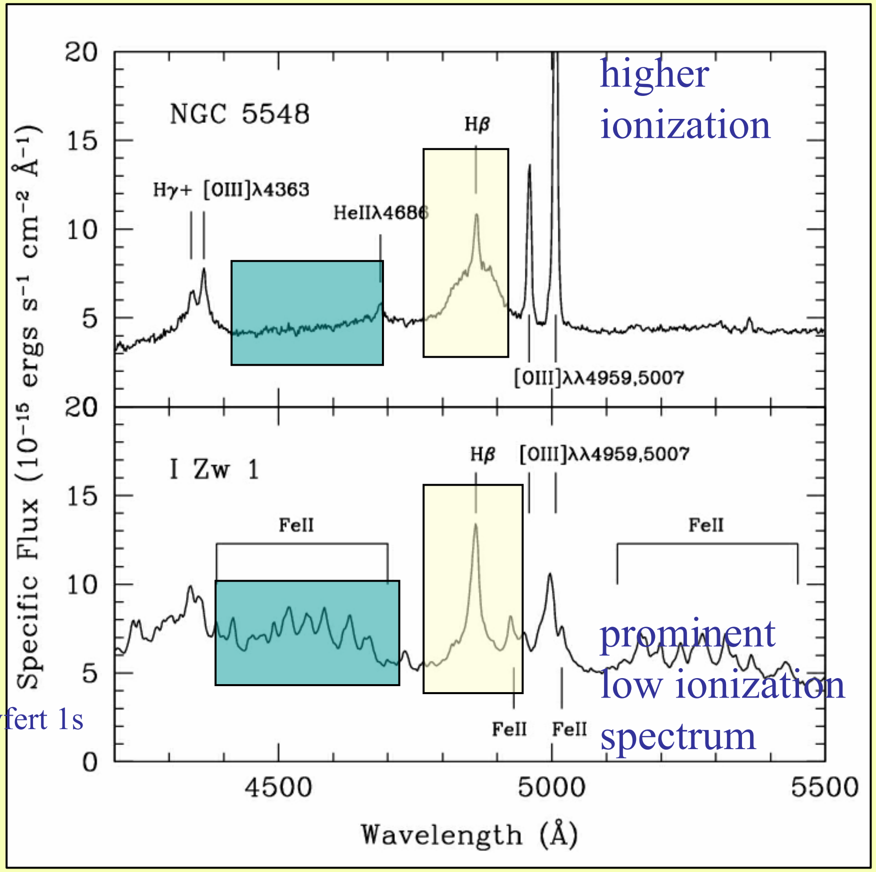
Monitoring of several low and high-ionization lines in the same object already provide structural clues, since HILs usually respond on shorter timescales than LILs. In NGC 5548, the delay in response is 2 lt days for HILs and 20 lt days for LILs. See the heroic efforts by Korista et al. (1995); and Wanders et al. (1995, also notable for a 2D reverberation mapping attempt). It suggests that BLR gas may see an anisotropic continuum, and that the motion of gas is predominantly virial in the LILs.

This last finding needs contextualization. The last decade saw many robust observational advances in constraining the BLR structure through an appreciation of quasar spectral diversity, even if the image is of course still missing...

# 2) Spectral Diversity

Sulentic, Marziani, & Dultzin-Hacyan 2000

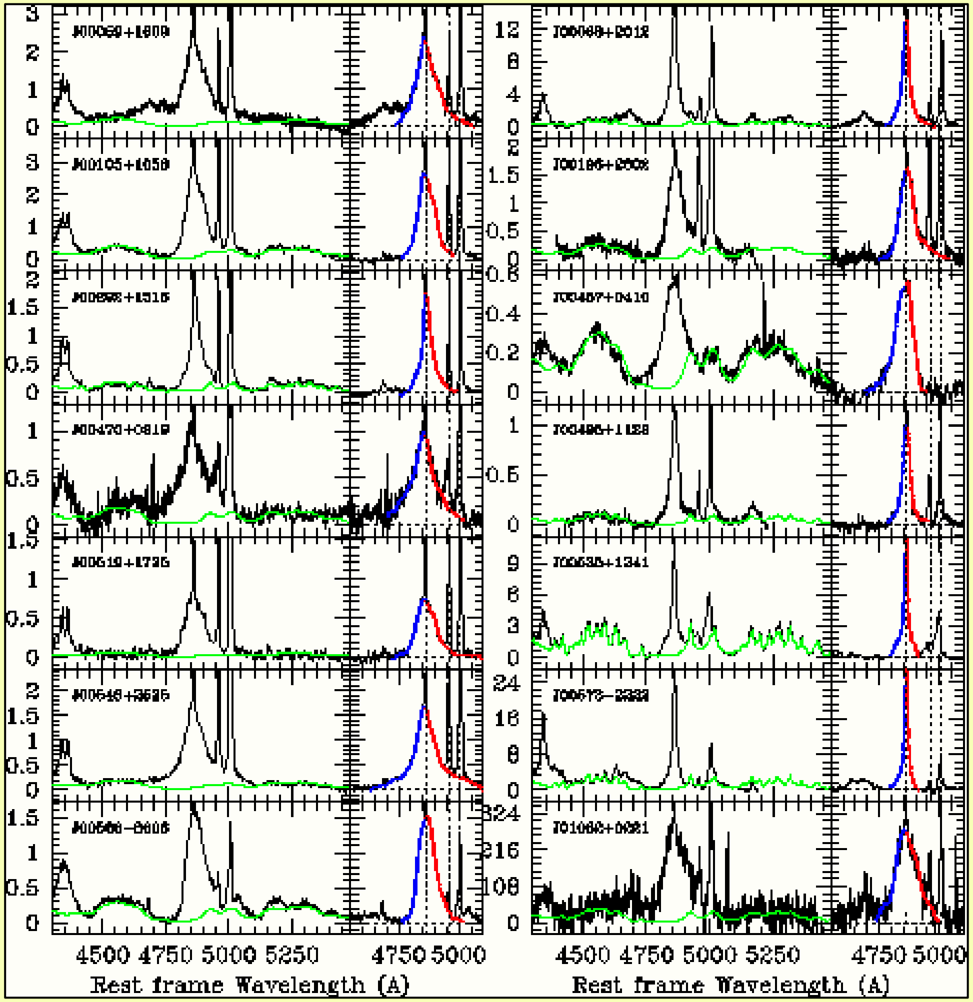



Emission line properties of quasars do not scatter randomly with reasonable dispersion around an average,

Average spectra can be taken on bins in the ``Eigenvector 1 optical plane'', or at least for Population A [FWHM(Hβ$_{BC}$)≤4000 km s$^{-1}$] and B(roader) sources . Narrow Line Seyfert 1s (NLSY1s) are in many ways undistinguished among Population A sources, as it will be shown in the next slides.

Continuum-subtracted spectra in the Hβ range from Marziani et al. 2003, ASpectral atlas of 215 low-z AGNs



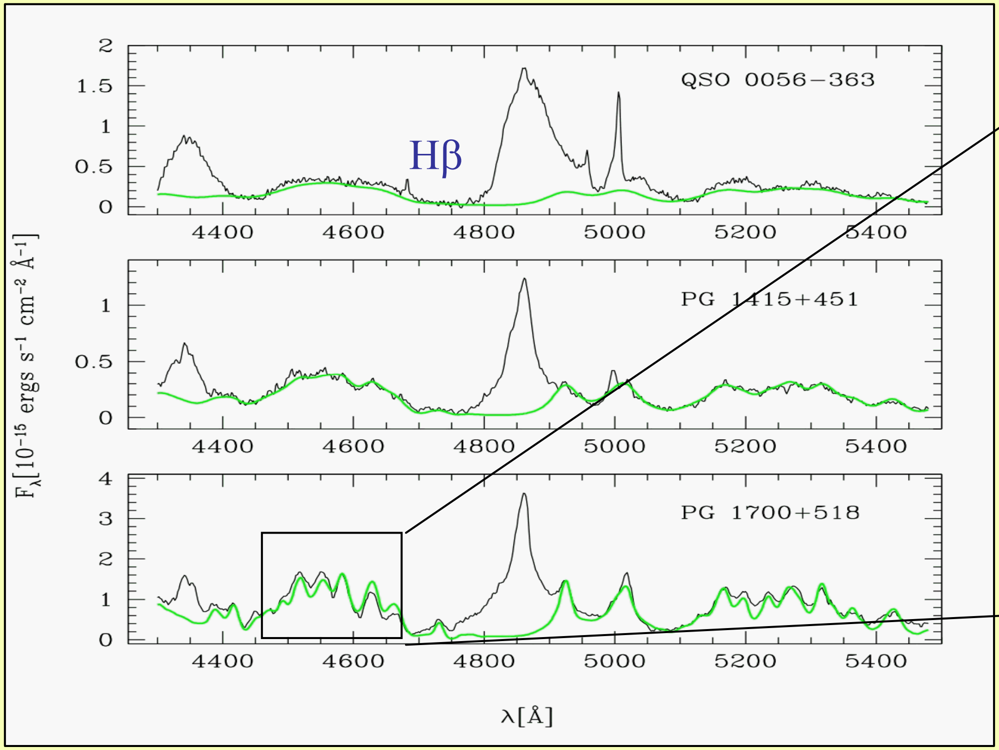

Diversity can be appreciated if spectral resolution and S/N are enough to:

1. Deconvolve broad and narrow components;
2. Measure broad profile parameters of relevant lines (e.g., $H\beta_{BC}$, LIL, & $CIV\lambda1549_{BC}$, HIL);
3. Subtract and measure intensity and FWHM of optical FeII lines, almost ubiquitous.

These conditions are met by

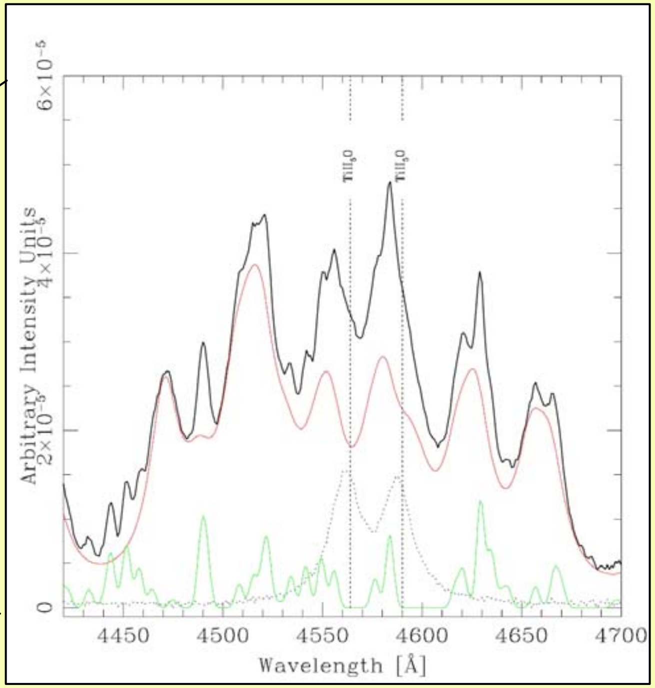
- the spectra for ~ 350 mainly low-*z* (<1) quasars collected at San Pedro Martir, ESO, ESO/VLT, KPNO, Asiago,Calar Alto, in the last 15 years (S/N≈20 and resolution $\lambda/\Delta\lambda \approx 1000$);
- ~700 HST archived FOS/STIS spectra of 140 1ow-*z* AGNs;
- the SDSS spectra.

Continuum subtracted spectra in the Hβ range




<u>Within common S/N and λ/Δλ limits, at least optical FeII emission is self-similar in almost all sources</u>, so that an intensity-scaled and broadened template provides an effective measurement and correction tool (Boroson & Green 1992; Marziani et al. 1996,2003). This has been known for almost 30 years (e.g., Phillips 1978).

A more and more complex view is emerging as data improve…




Appearance of the blue blend of FeII emission at λ4750, in simulated data with the S/N (>400) and dispersion expected for the VLT/FORS data.

red lines: FeII and FeII] broad spectrum
green line: narrow, low-ionization (mainly FeII and [FeII]) lines
(cf.Veron-Cetty et al. 2004).

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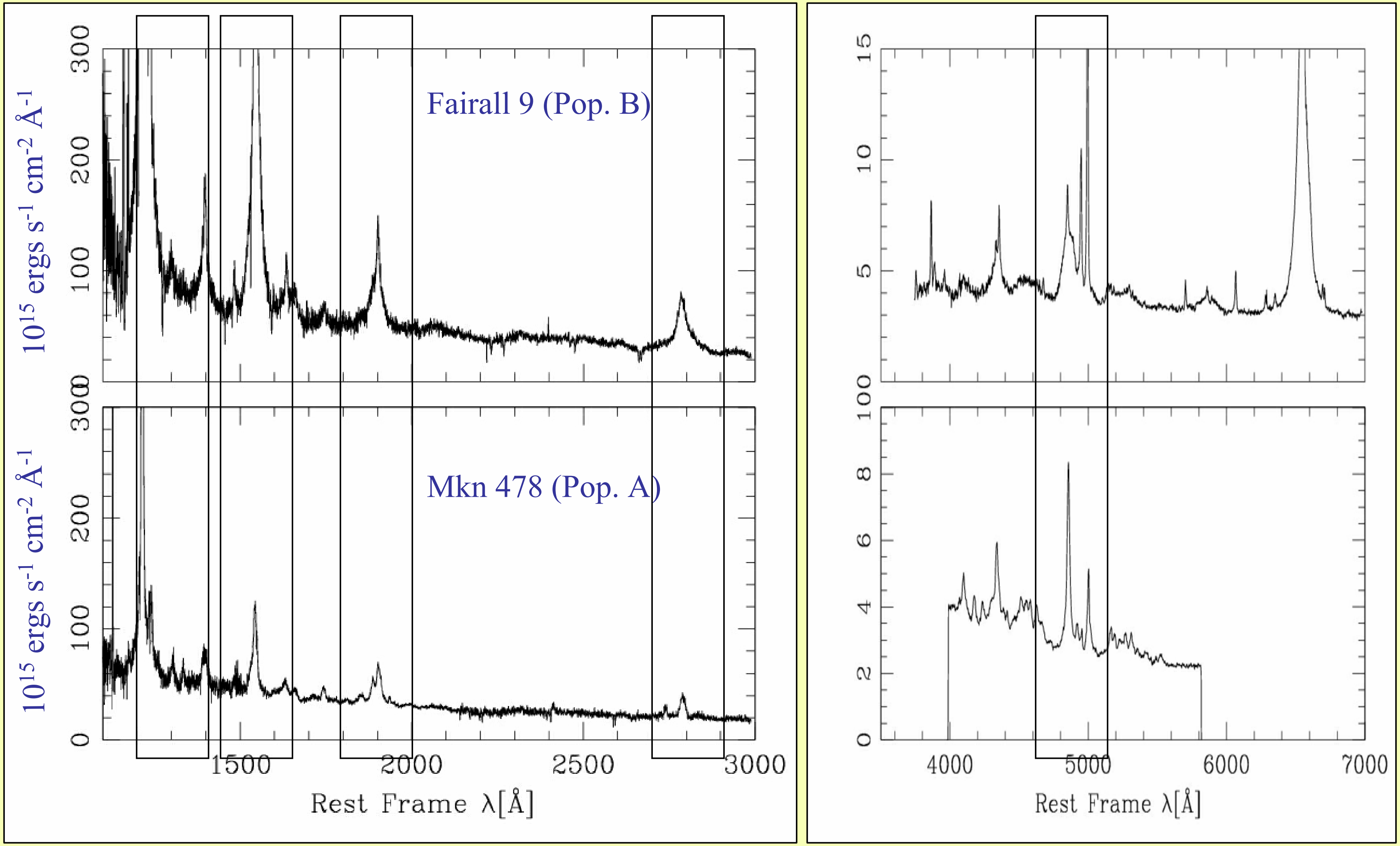
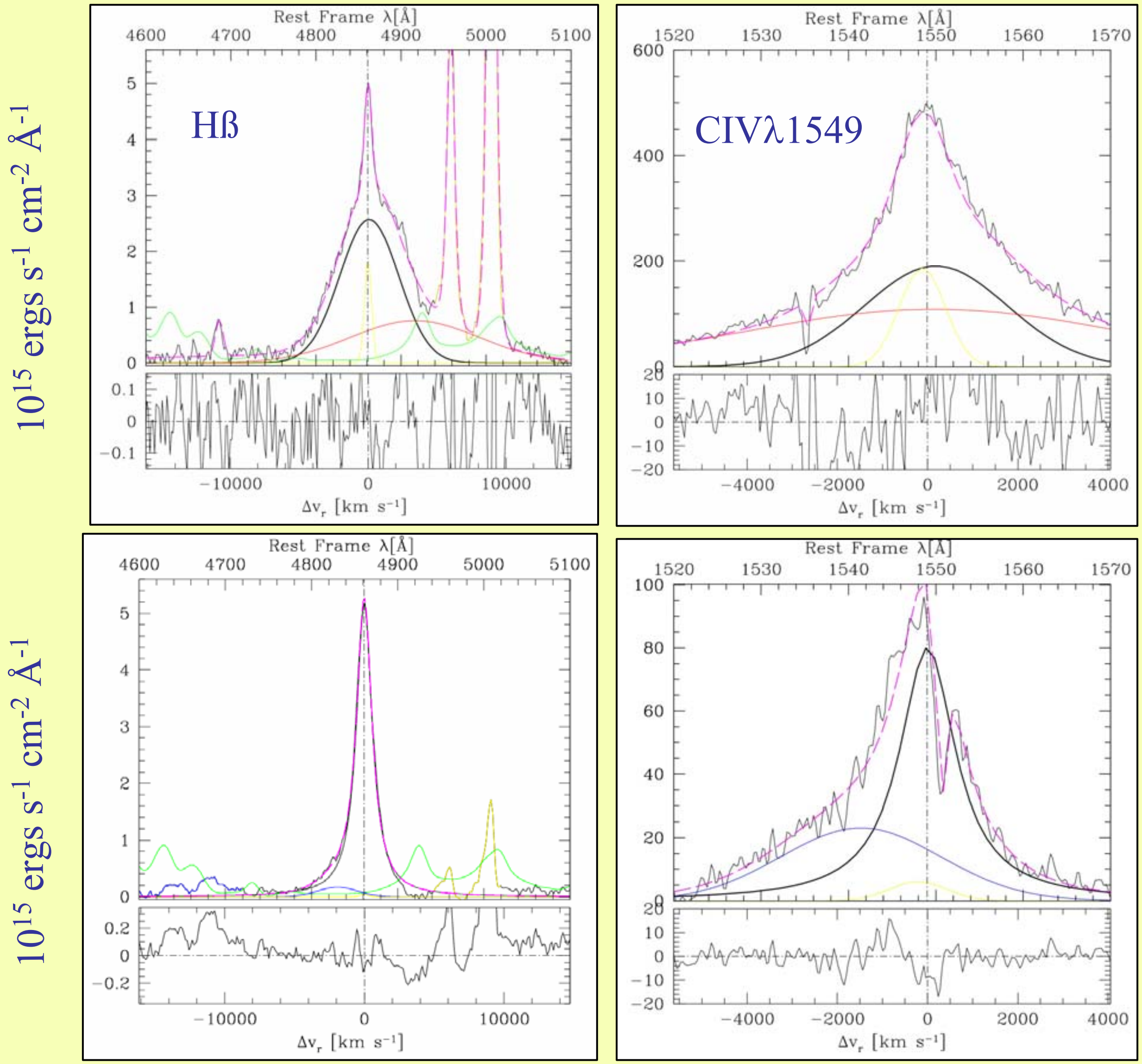
Two representative sources with HST/optical data covering the ranges 1000-3000 Å and 4200-5500 Å




Lyα CIV CIII+SiIII+ AlIII MgIIλ2800 Hβ

# UV/optical spectrophotometric comparison of 2 proto-typical Pop. A (FWHM ≤ 4000 km/s) and B sources



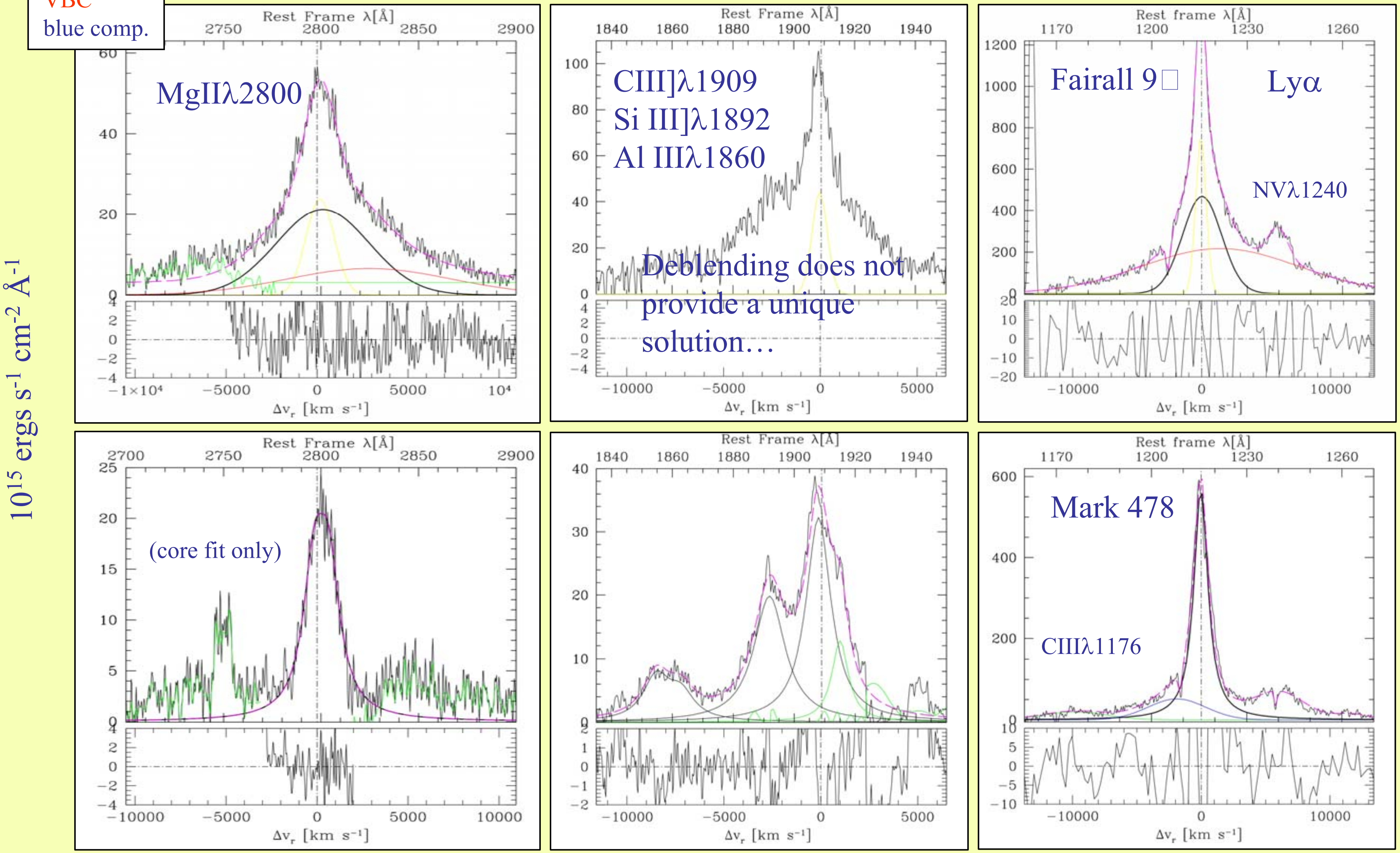

NC
FeII/FeIII
model
**BC**
VBC
blue comp.

Fairall 9, Pop B
Double Gaussian
VBC redshifted

Mkn 478, Pop. A
Lorentzian
blueshifted component
very weak in Hβ

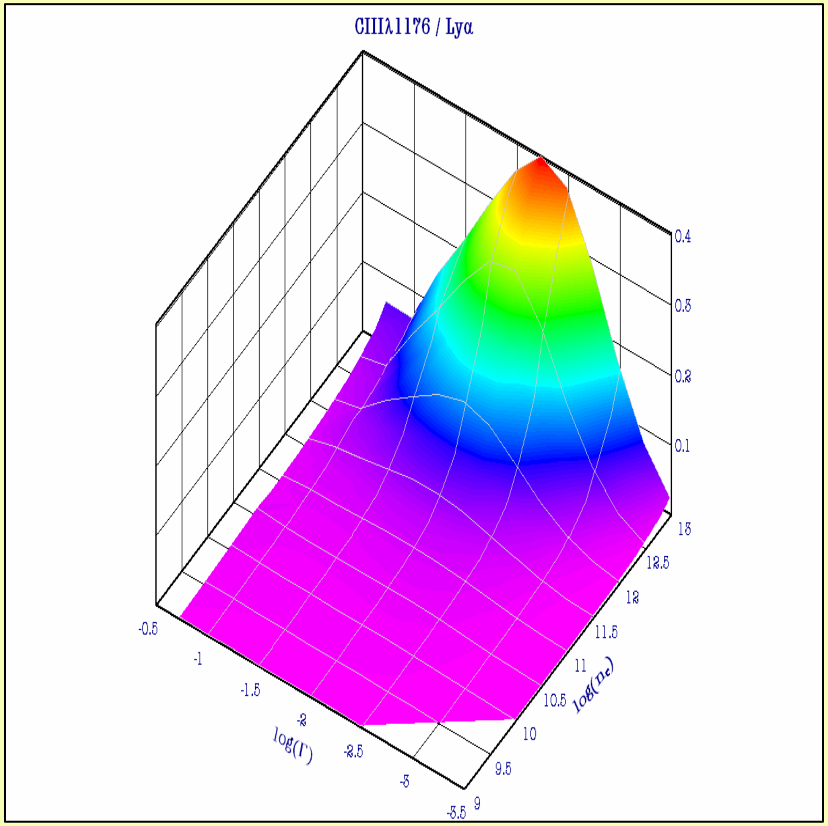
NC
FeII/FeIII
model
**BC**
VBC
blue comp.

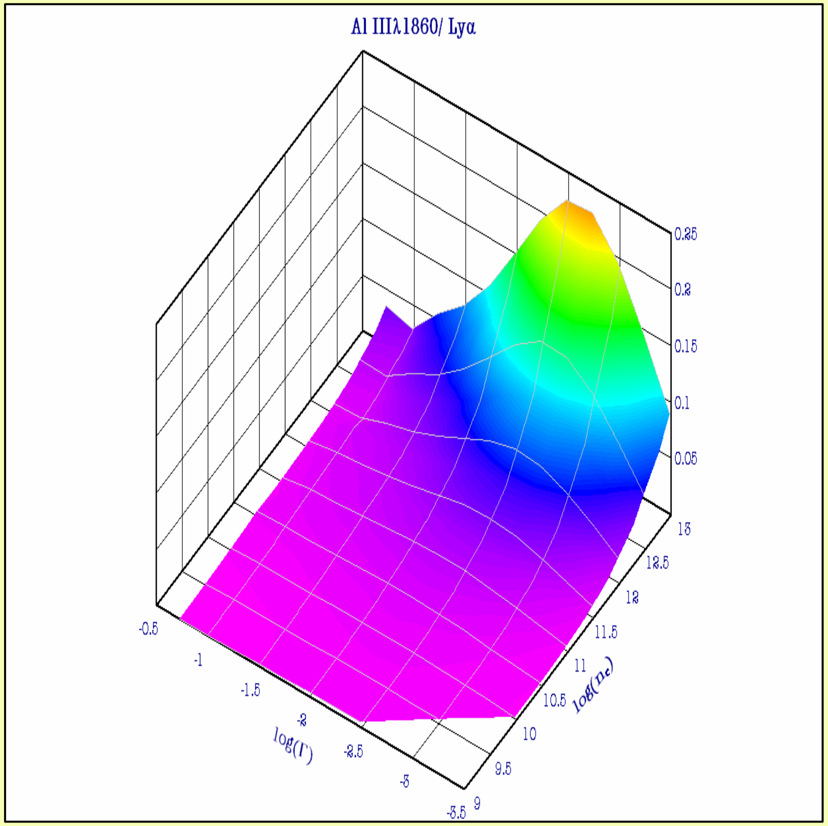
# Strongest UV lines can be consistently fit with the VBC/BC identified on Hβ and CIVλ1549



Cloudy simulations following Korista et. (1997), $N_H = 10^{23}$ cm$^{-2}$, solar abundances

↳ Noticeable AlIIIλ1860 and CIII* λ1176 emission suggests high density and low ionization




Ionization parameter Γ ($=n_\gamma/n_e$) vs. electron density $n_e$

# Optical (normalized to Hβ) and UV (normalized to Lyα) Observed Emission Line Ratios

Explorative Cloudy 7.0 photoionization computations incorporate Verner et al. (1999) 287-levels FeII, $N_H = 10^{23}$ cm$^{-2}$, standard Laor et al. (1997) or Mathews & Ferland (1986) continuum, solar abundances

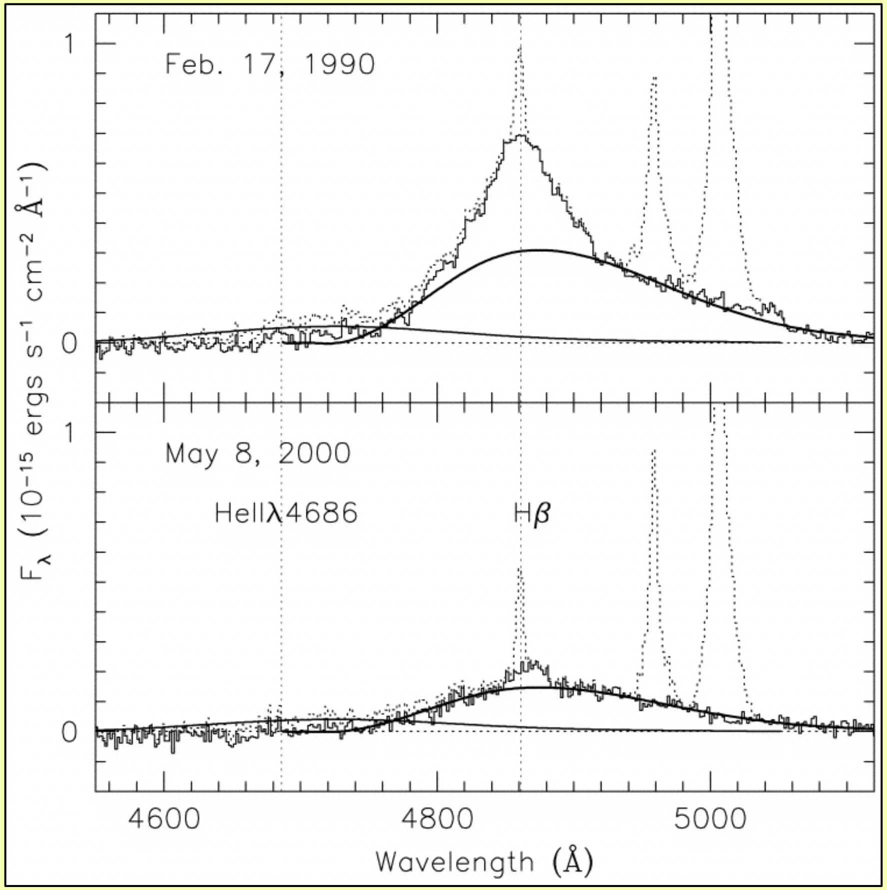
| | Pop. B → Fairall 9 | | | Mkn 478 ←Pop. A | |
|---|---|---|---|---|---|
| | BC | VBC | BC+VBC | BC | VBC |
| Hβ<br>FeIIλ4570<br>HeIIλ4686<br><br><br>Fe UV 2000-3000<br>MgIIλ2800<br>CIII]λ1909<br>SiIII]λ1892<br>AlIIIλ1860<br>FeIIIλ1915<br>CIVλ1549<br>HeIIλ1640<br>Lyα<br>CIII]λ1176 Detected | LogΓ ~-2; $n_e \sim 10^{11-12}$ cm$^{-3}$ **Some caveats, but low ionization degree supported by FeUV and, if really present, CIII*** | Log Γ ~ -0.5 ÷ -1.0; $n_e \sim 10^{9.5÷10}$ cm$^{-3}$ **High ionization, well accounted for. Canonical, may dominate Hβ emission in Pop. B.** | ~~1.00~~<br>~~0.43~~<br>~~0.07~~<br><br><br>~~0.14~~<br>~~0.09~~<br>~~0.07~~<br>~~0.03~~<br>~~0.04~~<br>~~0.00~~<br>~~0.48~~<br>~~0.07~~<br>~~1.00~~<br>~~...~~ | FeII UV → Log Γ ≤ -2; $n_e \geq 10^{12}$ cm$^{-3}$ **Very low ion., high density** Gives the “low ionization look” to Pop. A sources. | Log Γ ~ -1 ÷-0.5; $n_e \sim 10^{11}$ cm$^{-3}$ **High ion., very weak in Balmer and other LILs** |

deblend not unique for BC of F9 but consistent with SiIII]~CIII] and presence of Al III emission

**VBC: high ionization, lower density. Well accounted for within a narrow range of Γ,$n_e$**

**BC: some puzzling aspects, but nothing really new: see Laor et al. (1997) findings for I Zw 1.**

# PG 1416-129




It is the low ionization, broad component that seems (in some cases) to respond more strongly to continuum changes.

The high-ionization VBC may be dominant in the sources with very weak FeII.

TABLE 2

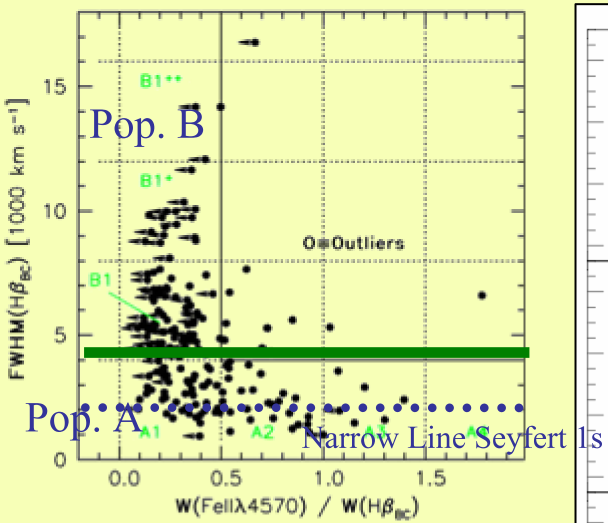
PG 1416−129 Hβ Emission-Line Variability

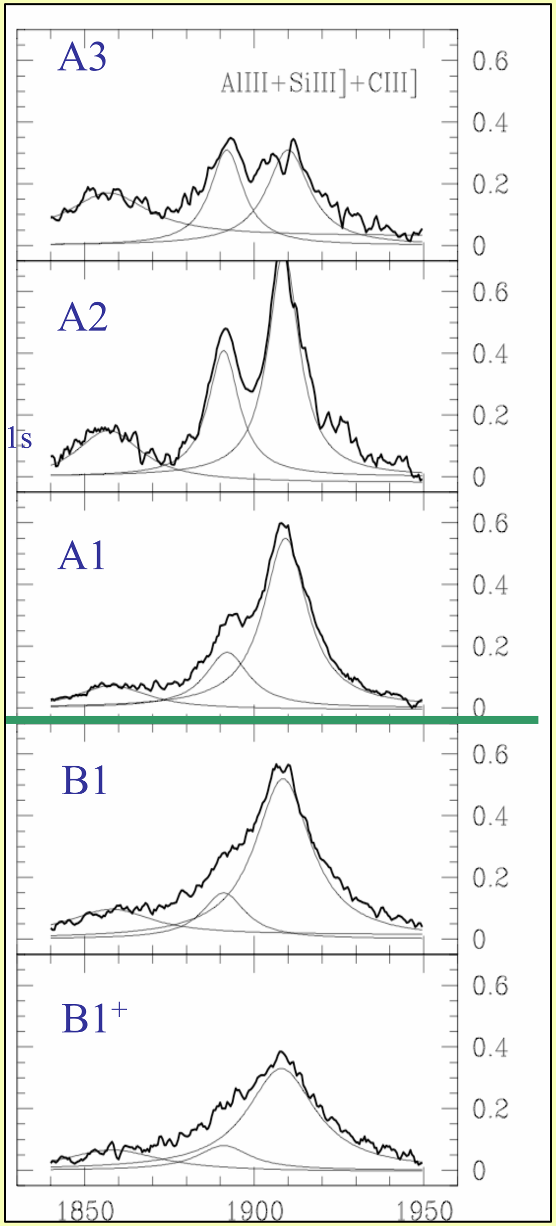
| | 1990 February 17[a] | | | 2000 May 8[b] | | |
|---|---|---|---|---|---|---|
| Line Identification | Flux | W (Å) | FWHM (km s$^{-1}$) | Flux | W (Å) | FWHM (km s$^{-1}$) |
| $H\beta_{BC+VBC}$ ........... | 86.0 | 160 | 6000 | 40.0 | 300 | 9000 |
| $H\beta_{BC}$ ................. | 23.0 | 47 | 4000 | 2.0 | 13 | 1450 |
| $H\beta_{VBC}$ ................ | 63.0 | 110 | 13000 | 38.0 | 220 | 13000 |

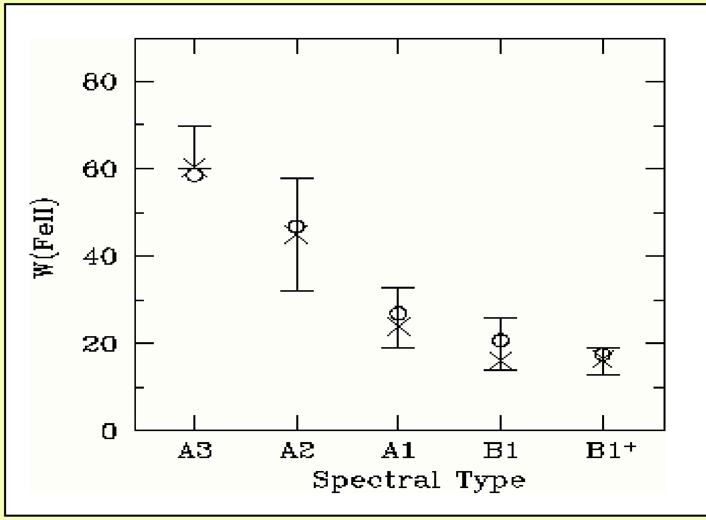
[a] Specific flux at 4500 Å, $F_\lambda \approx 7.5 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$.
[b] Specific flux at 4500 Å, $F_\lambda \approx 1.9 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

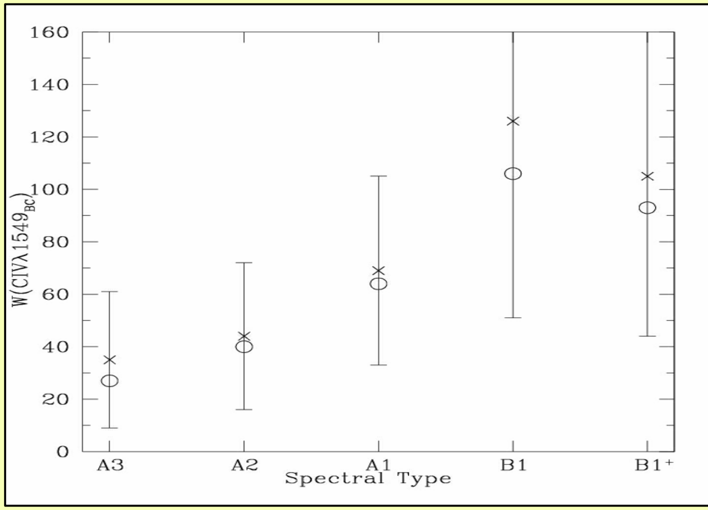
Sulentic et al. 2000, 2006.

# CIII]+Si III +AlIII



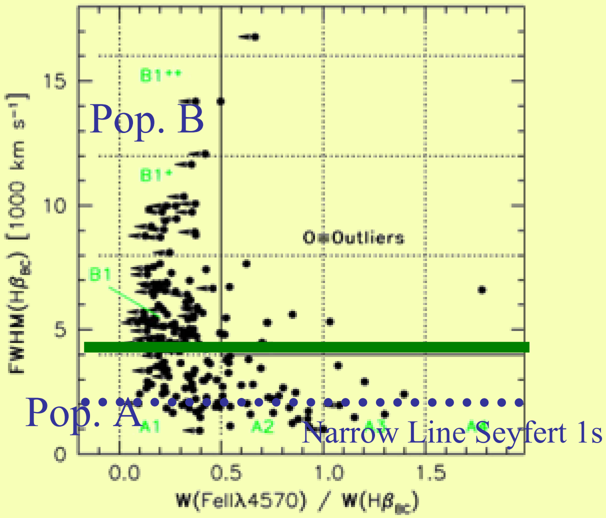



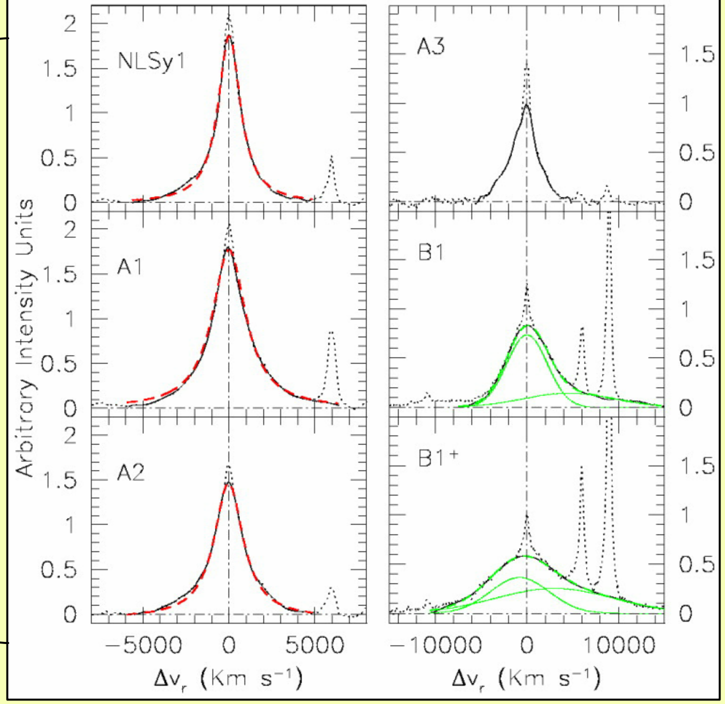

Statistical evidence confirms systematic trends in ionization and density along the sequence of spectral types.

(Bachev et al . 2004; no VBC+BC decomposition)




Median spectra

$H\beta_{BC}$




Pop. A

Pop. B

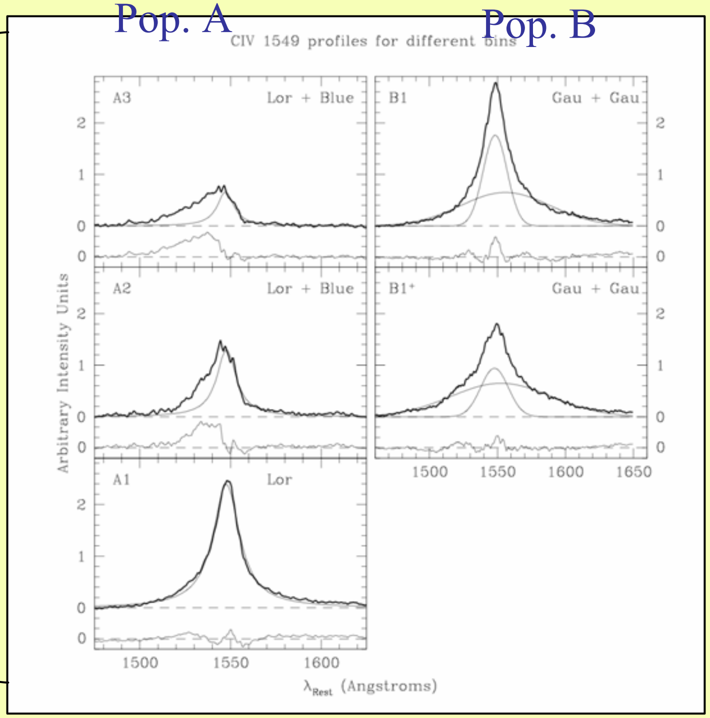
BLR Structural Difference between Population A and B sources (Sulentic et al. 2002, Bachev et al. 2004) is suggested by:

$H\beta_{BC}$

Pop. A.: Lorentzian $H\beta_{BC}$, symmetric (most often), or with blueward asymmetry

Pop. B.: Double Gaussian $H\beta_{BC}$, most often redward asymmetric

CIV




CIV$\lambda$1549

Pop. A.: Blueward asymmetric and blueshifted (most often),

Pop. B.: Double Gaussian, redward asymmetric or symmetric

# Further statistical hints at structural differences in the BLR

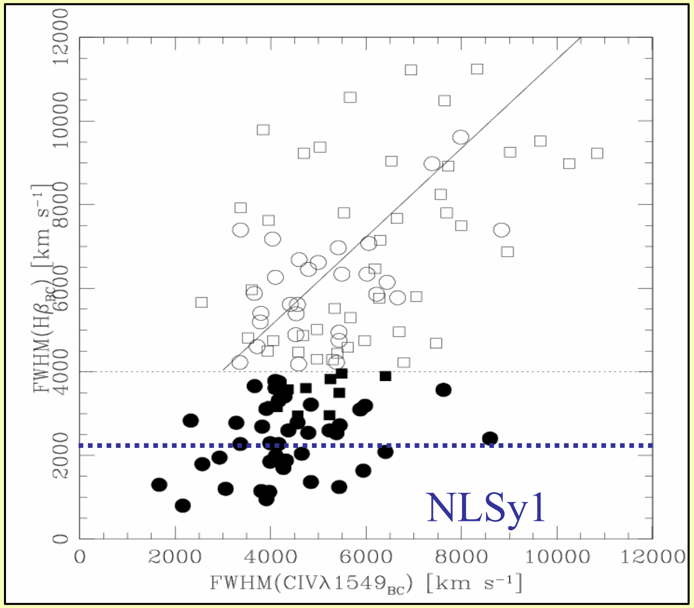
Pop B: FWHM(Civλ1549) and FWHM(H$\beta_{BC}$) correlated, distribution not significantly different

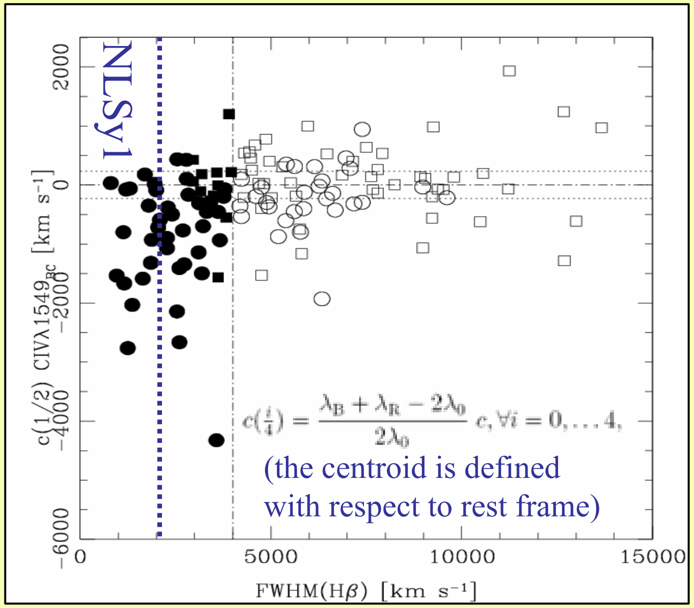
Pop A FWHM(Civλ1549) and FWHM(H$\beta_{BC}$) and significantly different

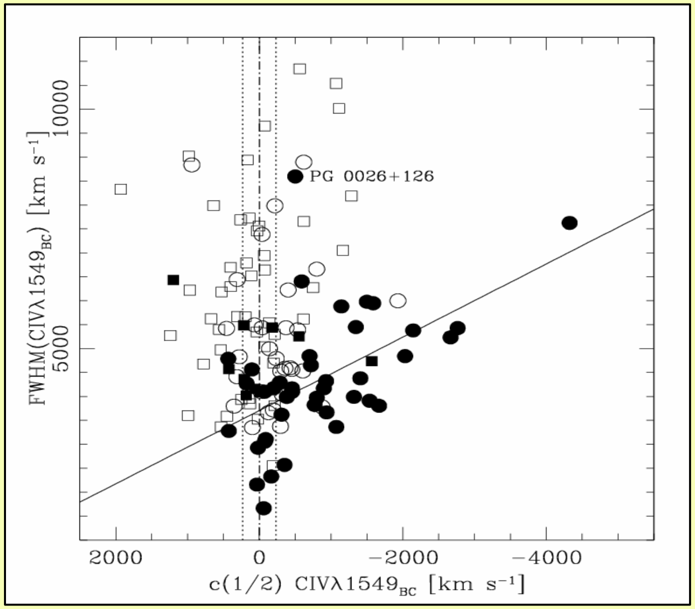
Civλ1549 blueshifts: likely for Pop. A

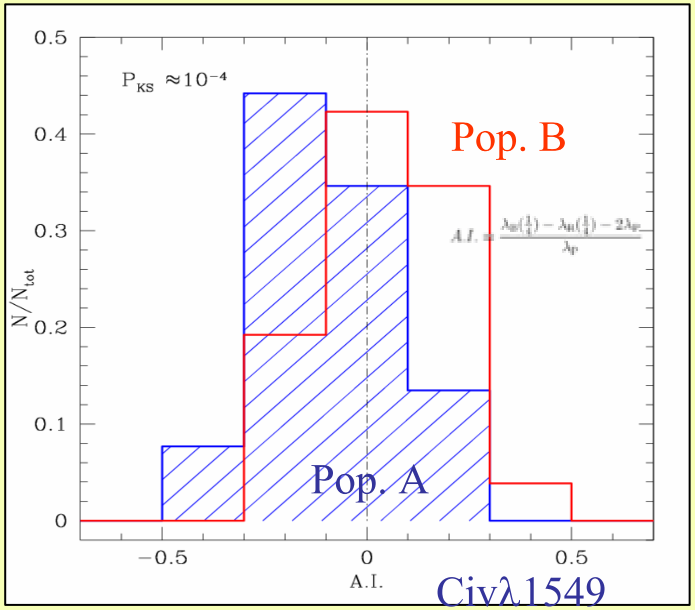
Pop. A Civλ1549 shift and FWHM correlated, Pop. B uncorrelated.

Asymmetry index:
Pop. A Civλ1549: Blueward asymmetric
Pop. B Civλ1549: symmetric or slightly redward asymmetric, more like H$\beta_{BC}$ .




Data from Bachev et al. 2004; Sulentic et al. 2007

# A first summary:

*NLSy1s don't have peculiar BLRs.*

*Low-z quasars remain similar to NLSy1s up to FWHM(H$\beta_{BC}$)≈4000 km s$^{-1}$.*

*This limit seems better justified than 2000 km s$^{-1}$, since several observational properties change at 4000 km s$^{-1}$ but not at 2000 km s$^{-1}$.*

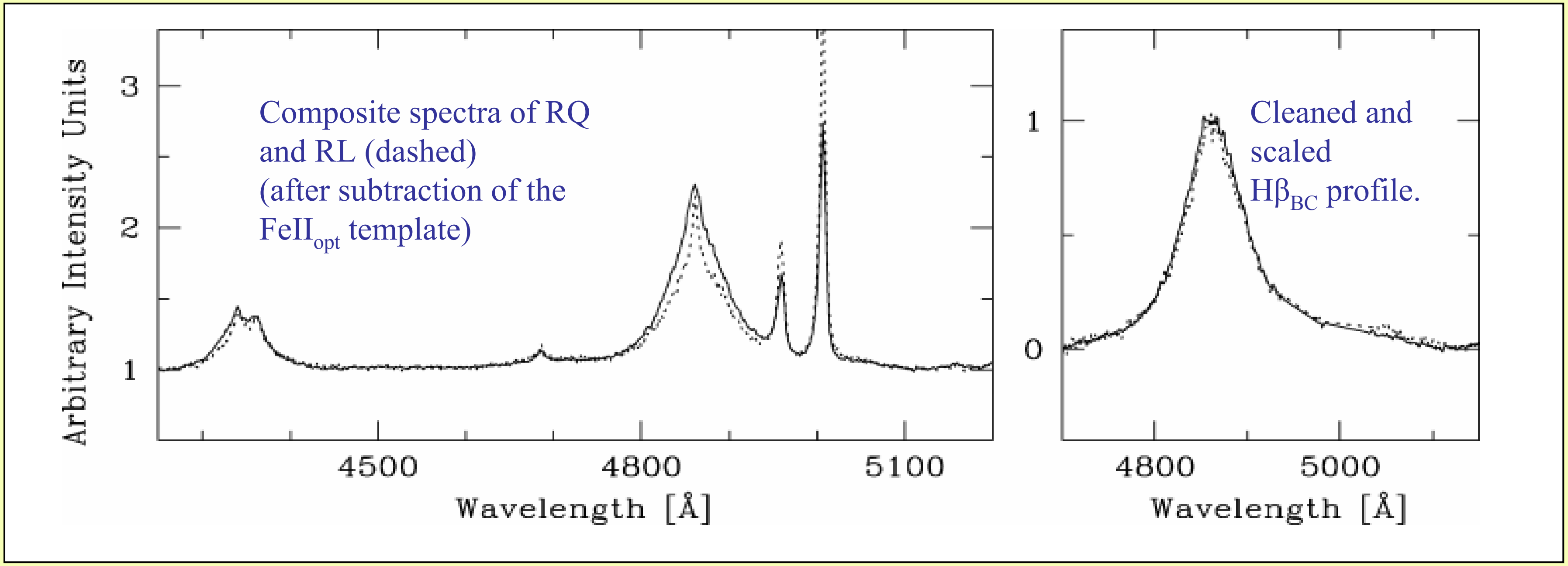
*Ionization is lower in Pop. A, and high ionization emission appears weak in the Balmer lines, and partially decoupled as well.*

*CIV (HIL) and H$\beta$ (LIL) are somewhat correlated in Pop. B. The high-ionization very broad emission may be dominant in Pop. B, even in the Balmer lines.*

*Pop. A and Pop. B sources show different BLR ionization conditions and kinematics, but both may share a low-ionization region, and the difference may be due to a very broad component.*

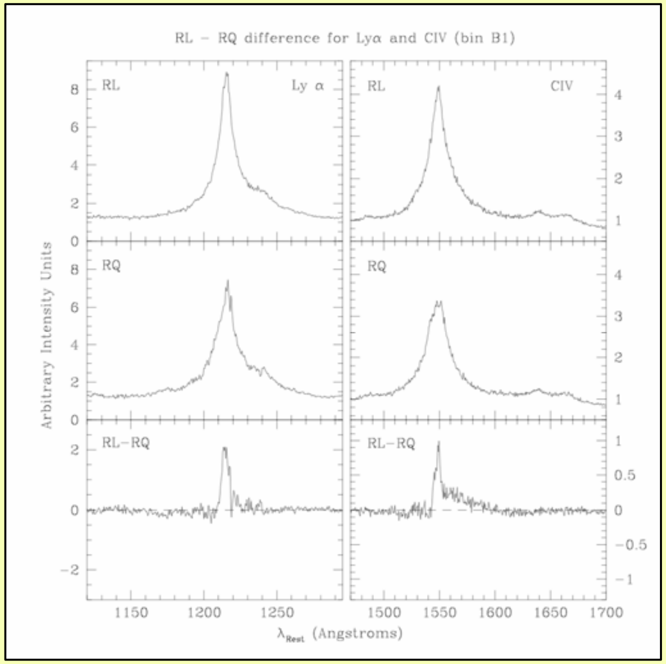
*Several of these findings were already discussed in the context of radio-loud and radio-quiet samples (Dultzin-Hacyan et al. 2000). An open question then and now is what is the physical reason for the BLR difference?*

# Radio Loudness?



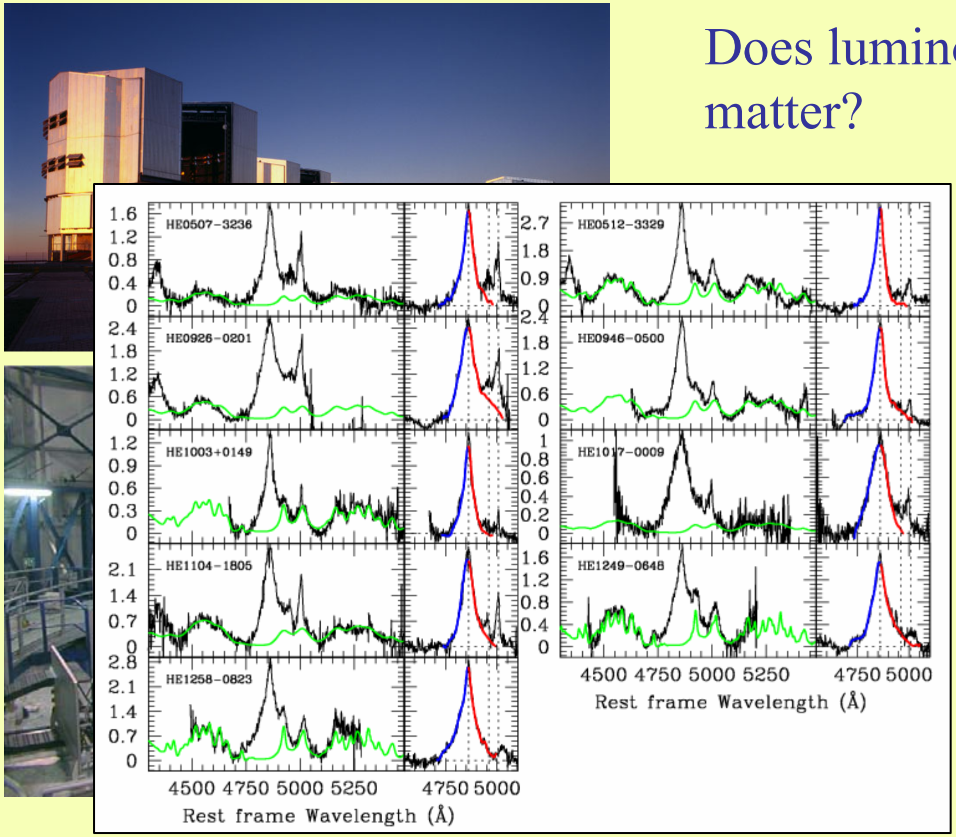

RQ and RL objects in the mass interval 8.5 < log $M$< 9.5 and any $L/M$ ratio ($N_{RQ}$= 56, $N_{RL}$= 36; Marziani et al. 2003).

The $H\beta_{BC}$ profiles of RQ and RL are almost identical. The BLR (but not the NLR) seems to be “transparent” to radio loudness .

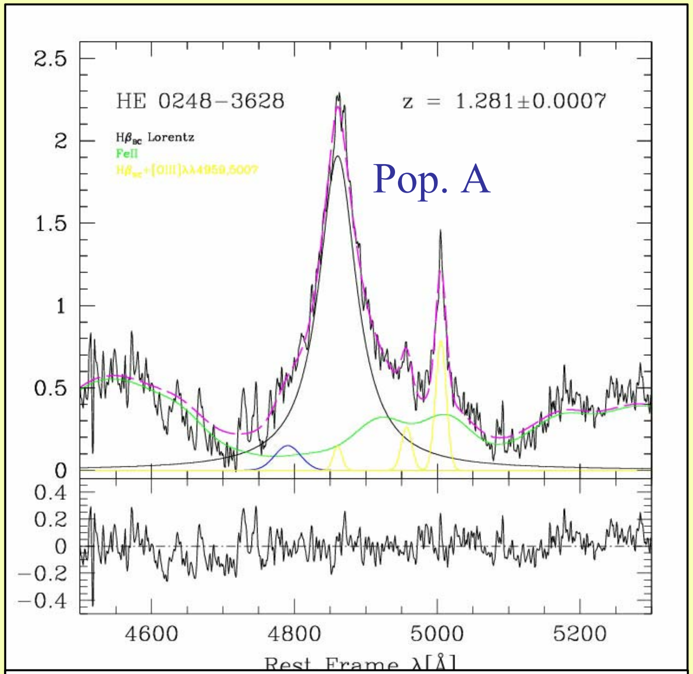


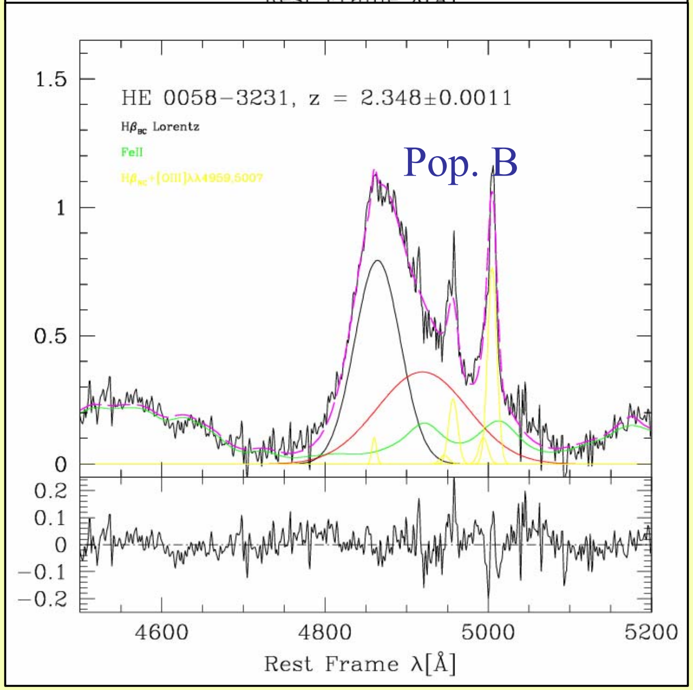

The few RL NLSy1 revealed until now do not look much different from RQ NLSy1s, although…

# Does luminosity matter?

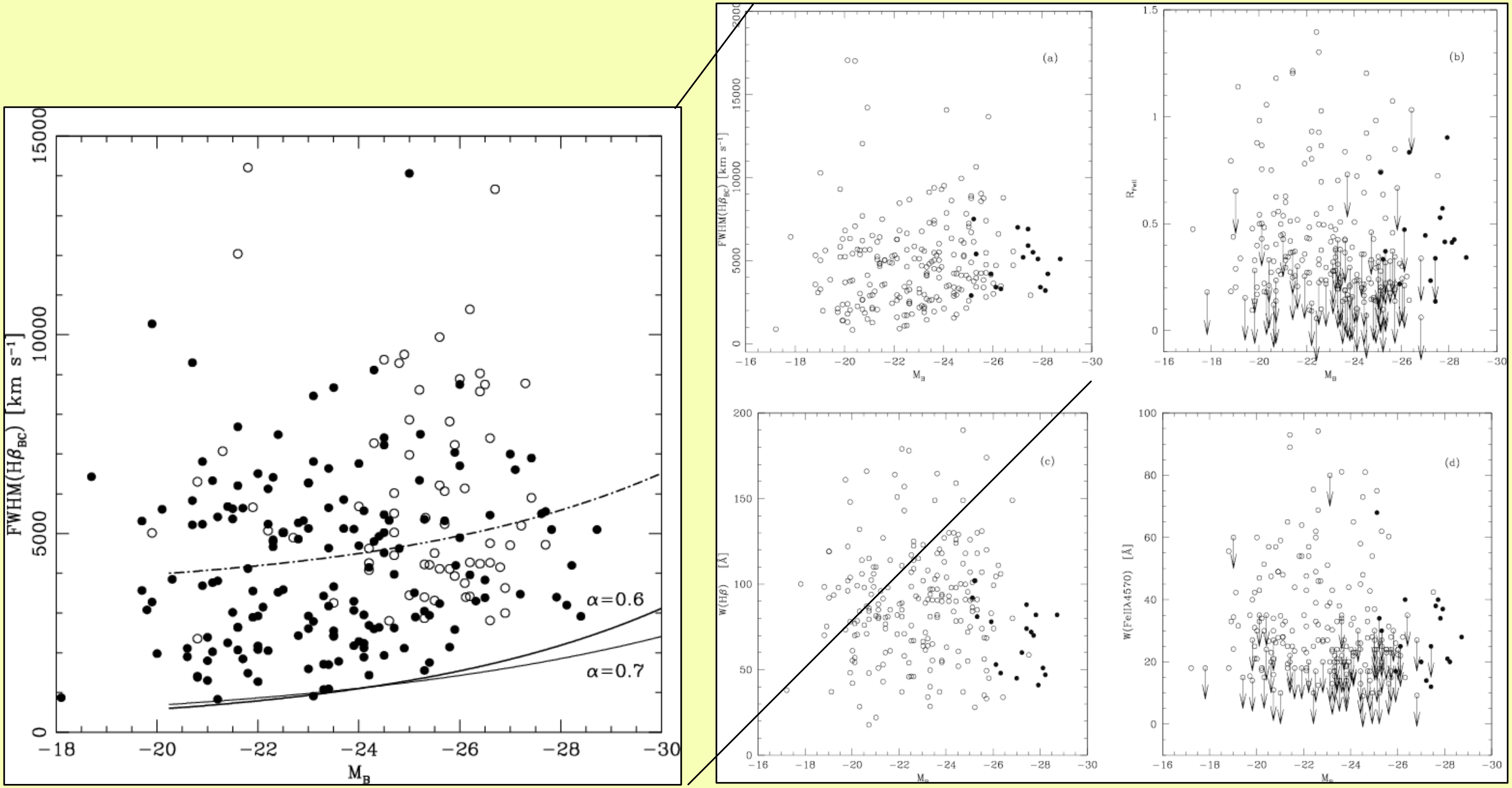



VLT/ISAAC data: resolution and S/N of NIR spectra similar to the optical data in the Hβ spectral range; 50 sources observed.




Luminous Quasars at z>1:
still the same BLR dichotomy:
Pop. A and Pop. B "types"




Unremarkable dependence
even on a $\Delta m \sim 10$ range
for low ionization lines

A very shallow trend is expected for the minimum FWHM($H\beta_{BC}$):

$$FWHM_{\min} \propto 10^{-0.08 M_B}$$

for a radiator at Eddington limit, if broadening of Hβ is due to gas virial motion, and $r_{BLR} \propto L^{0.7}$ (see Sulentic et al. 2004 for details)

# Black hole mass and Eddington Ratio Estimate

The correlation between $r_{BLR}$ and luminosity, $r_{BLR} \propto L^{\alpha}$ with $\alpha \approx$ 0.5 – 0.65 for the optical continuum and Hβ (Kaspi et al. 2005; Vestergaard & Peterson 2006) can be used to infer the black hole mass if the gas motion is virial:

$$M_{BH} = f \frac{r_{BLR} FWHM^2}{G}$$

$f$ factor depending on BLR geometry, ~1
G, gravitational constant

Observed profiles suggest that the virial assumption is at least reasonable for Low Ionization Lines ($H\beta_{BC}$ or MgIIλ2800). Uncertainty in $M_{BH}$ is anyway large, a factor 2-3 at best(e.g.: Peterson & Wandel 2000; Krolik 2001; see also Sulentic et al. 2006; Marziani et al. 2006, and references therein)

Assuming a bolometric correction … (e.g.,Shang et al. 2004) $L_{bol} \approx 10\, L_{opt}$

… it is possible to compute the Eddington ratio ($\propto L_{bol}/M_{BH}$) from a single-epoch observation.

This techniques has been applied to samples with hundreds and even thousands of AGN; it makes sense in spite of the uncertainty since $M_{BH}$ spans 4 orders of magnitudes.
(e.g., Mc Lure & Dunlop 2004; Sulentic et al. 2006; Marziani et al. 2003)

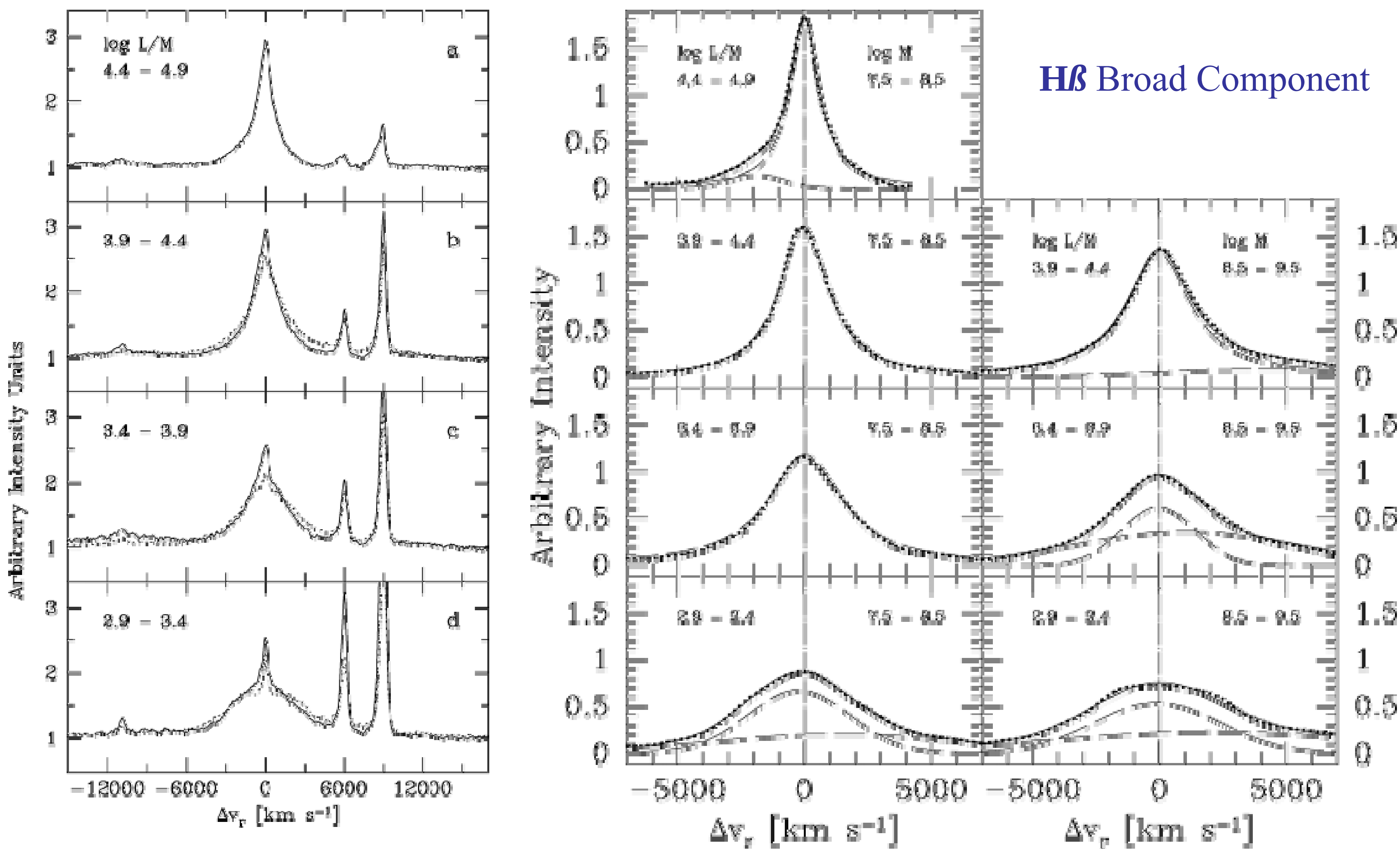
**Hß** + [OIII]

Solid: 7.3 ≤ log M ≤ 8.3

Dashed: 8.3 < log M ≤ 9.3

# Eddington Ratio matters

$M_{BH}$ gives a second-order effect, mainly on the line wings



# Gravitational redshift?

If gas motion remains virial down to the inner edge of the BLR, then there is a simple relationship between the centroid at 0 intensity and the FWZI, or better $FWZI_{corr}(H\beta)=FWZI_{corr}(H\beta) - 2c(0/4)$:

.

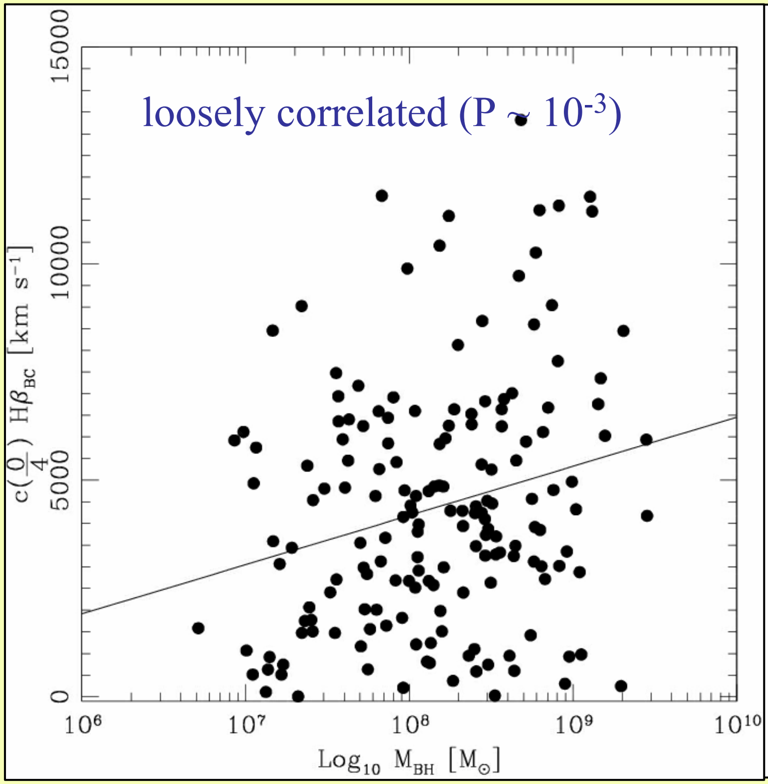
$$2c\left(\frac{0}{4}\right)=\Delta z_{\rm grav}\approx\frac{3}{2}\frac{GM_{\rm BH}}{c^2 r_{\rm BLR,min}}$$

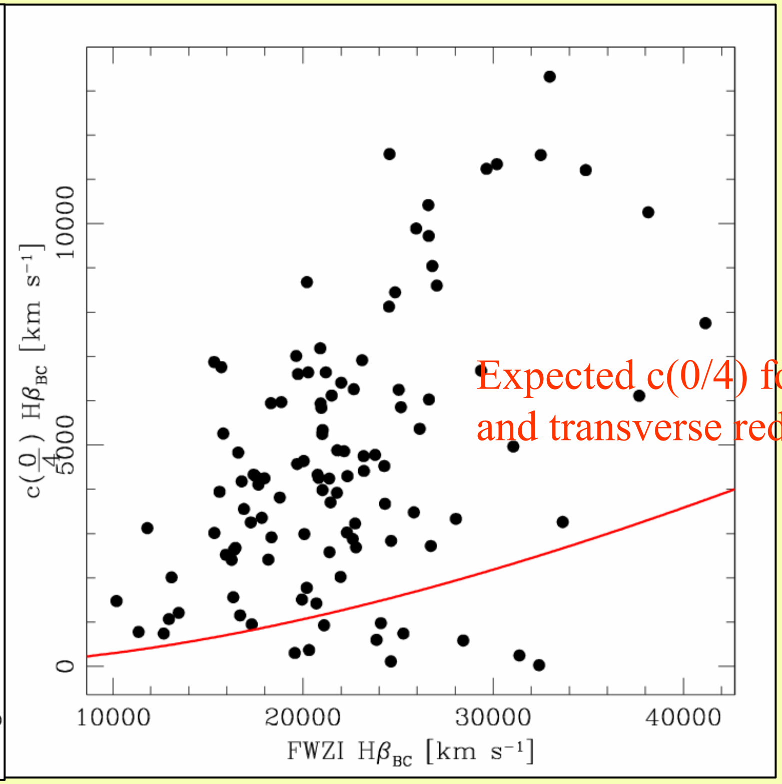
$$\frac{M_{\rm BH}}{r_{\rm BLR,min}} = f\,\frac{FWZI^2_{\rm corr}}{G}$$

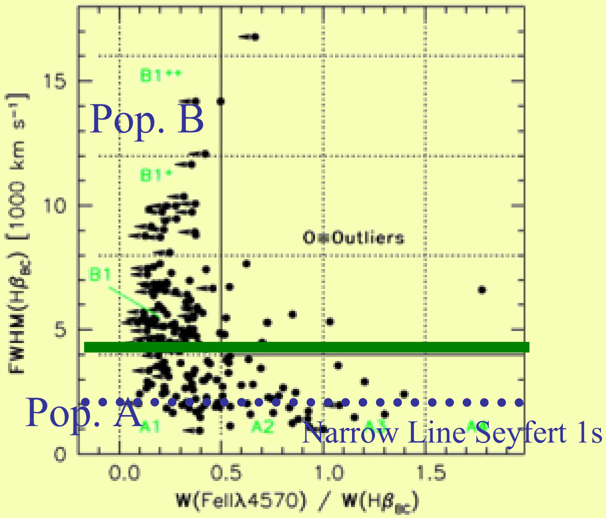
Amplitude of redward asymmetry depends on M but gravitational redshift seems to be statistically inadequate.

Maybe in a few sources gravitational redshift dominates the shift of the line centroids.

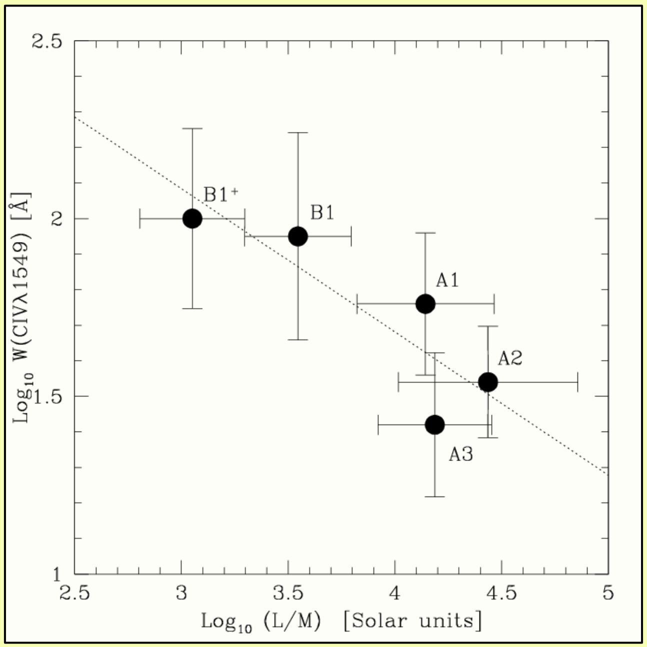
(Kollatschny et al. 2004)

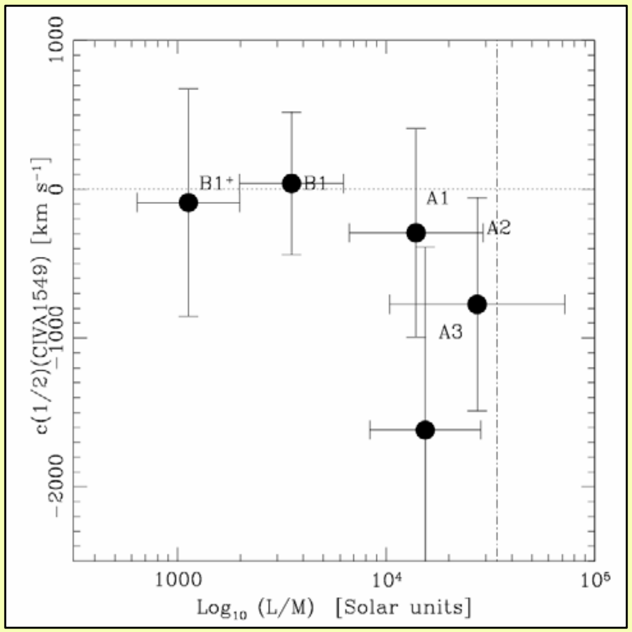





The Eddington ratio affects strongly also high ionization lines like CIV




L/M-dependent “Baldwin effect”, i.e., lower ionization in Pop. A

Large blueshifys are confined to Population A sources

# Orientation

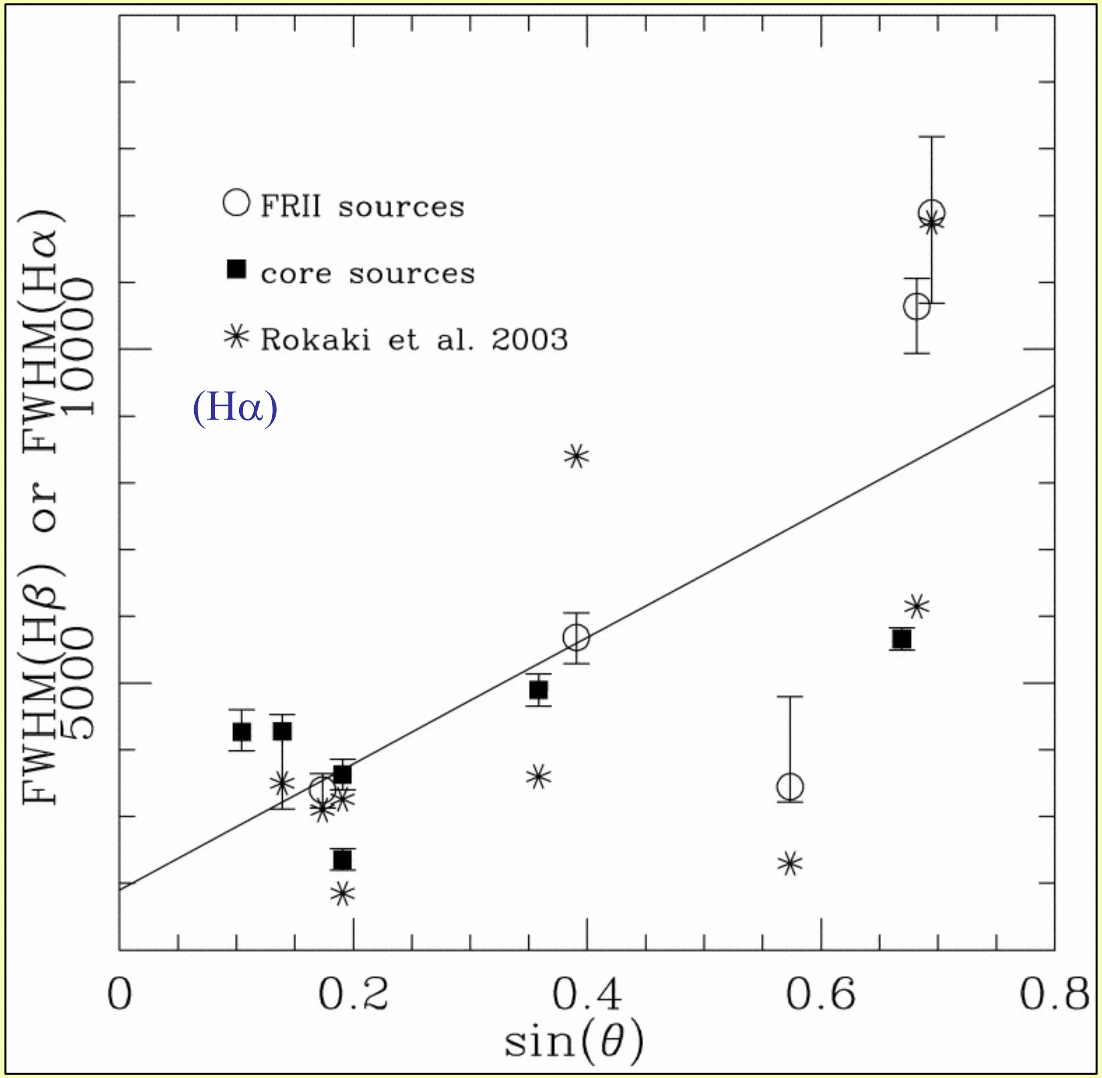
θ: angle between the line of sight and the jet axis

θ is estimated equalling the observed X-ray flux at 1KeV to the flux expected from the synchrotron self-Compton Process.
(following Ghisellini et al. 1993)

➯ Doppler factor, and Lorentz factor, from the apparent velocity if the source is superluminal.

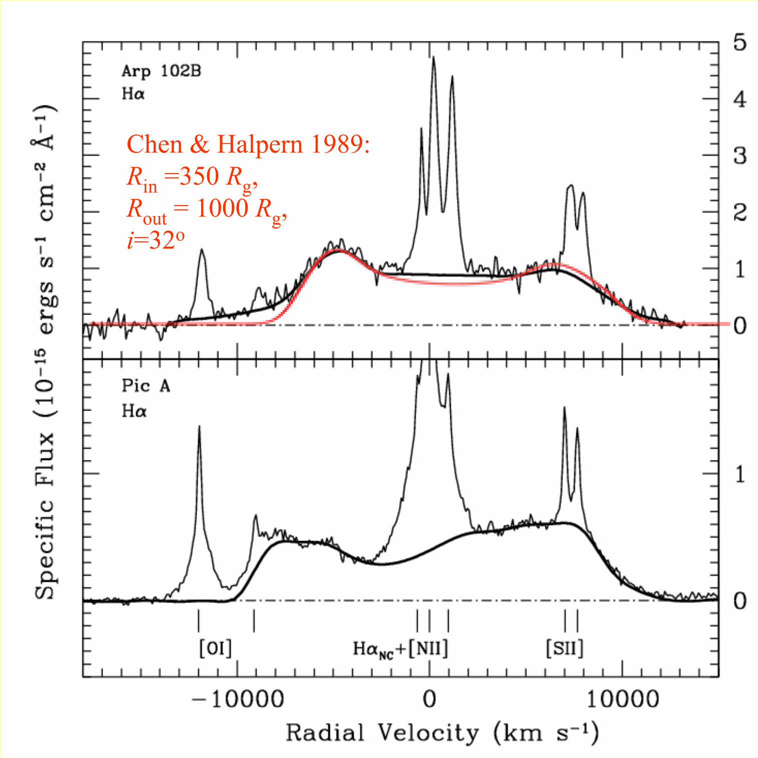
<u>Orientation matters</u>, affecting the FWHM($H\beta_{BC}$) by a factor ≈ 2

(Sulentic et al. 2003; see also Collin et al. 2006)




Method limited to superluminal sources

# LIL VBC: accretion disk?




Major issues:

Few (~ 2% in the SDSS), very broad sources (FWHM ~ 6 times the average FWHM) (Strateva et al. 2003, 2007).

Old criticism based on line profile shape for the wide majority of AGN is still standing (Sulentic et al., 1990, 2000)

Most double-peaked profiles require non-axisymmetric or warped disks.

Energy budget problem: external "illumination" needed (e.g., Strateva et al. 2007, papers by S. Collin, A. Dumont et al.)

Eddington ratios are much lower than those of typical type-1 AGN: < 0.02 in 90% of DP sources (Wu & Liu 2004): AD "bared"?

Two component models for the LILs: disk (VBLR) + spherical (Popovič et al. 2004): successful for 12 AGNs, Pop. A and Pop. B.

Wider sample, E1-organized is needed (in preparation…)

# Concluding…

*Several BLR  physical and kinematical  properties seem to be mainly governed by Eddington ratio. It was not so clear 10 years ago.*

*The BLR seems to be transparent to radio loudness. LIL properties are rather similar over a very wide range of luminosity, even at very high z.*

*Observations until now constrain a semi-qualitative sketch of the BLR structure and dynamics. An accretion disk wind suits the high ionization findings for Pop. A.*

*High-resolution spectra suggest that the LILs of a few Seyfert nuclei are emitted in a continuous flow… the accretion disk?*

*How does the  viewing angle affect observed  BLR parameters?*

*A thorough optical/UV spectrophotometric analysis that includes FeII requires great improvements in S/N and dispersion.*

*UV data are not easy to come… WSO/UV for the future?*