

Quasar emission lines as virial broadening estimators

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with the “extreme team”

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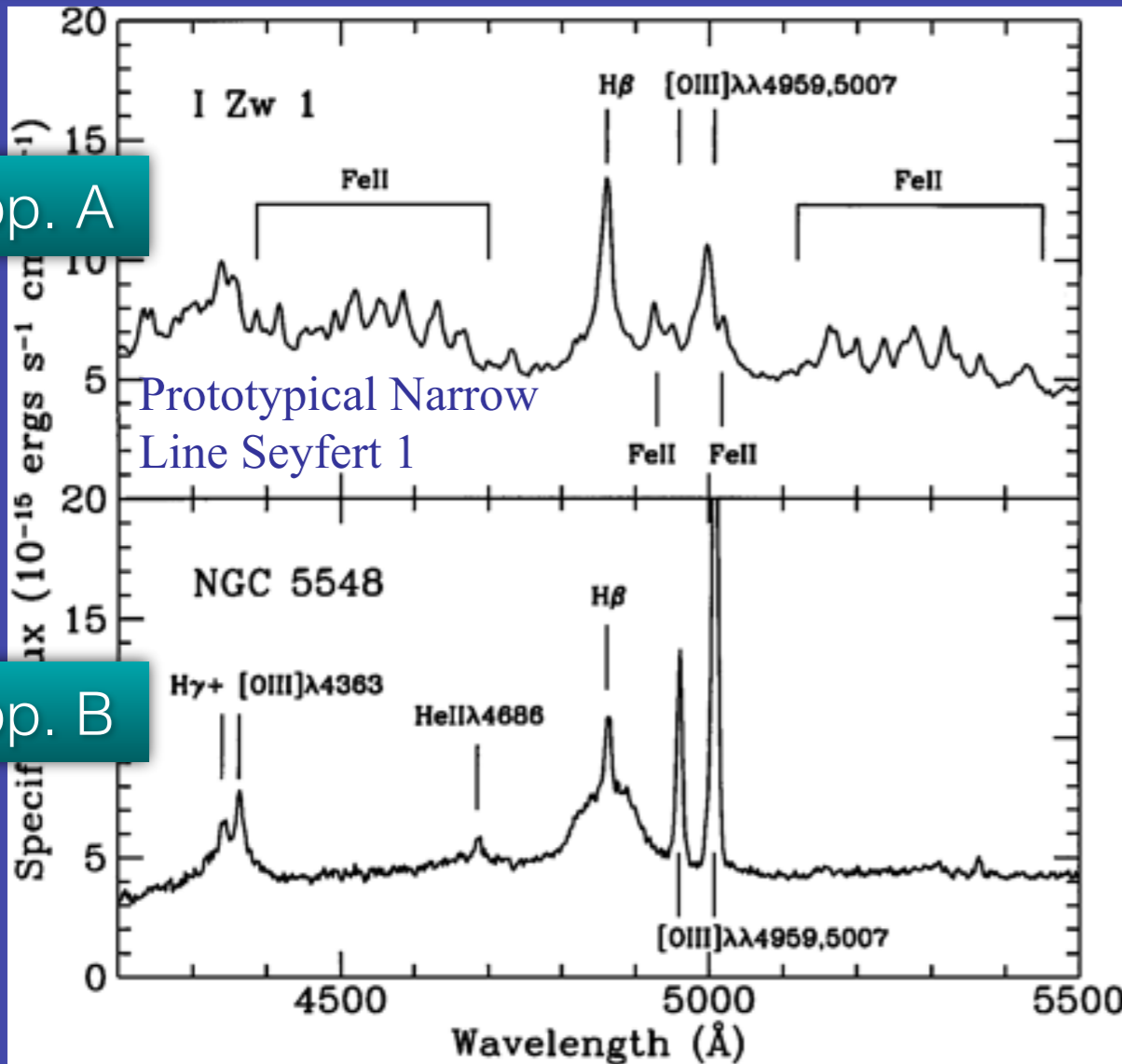
**Introduction: a main sequence (MS) for type-1
(unobscured) quasars**

An extreme (“tip”) of the MS

Cosmological applications?

The Main Sequence — Organizing quasar diversity

Quasar spectra show a wide range of line profiles, line shifts, line intensities → differences in dynamical conditions and ionization levels of the broad line region (BLR)

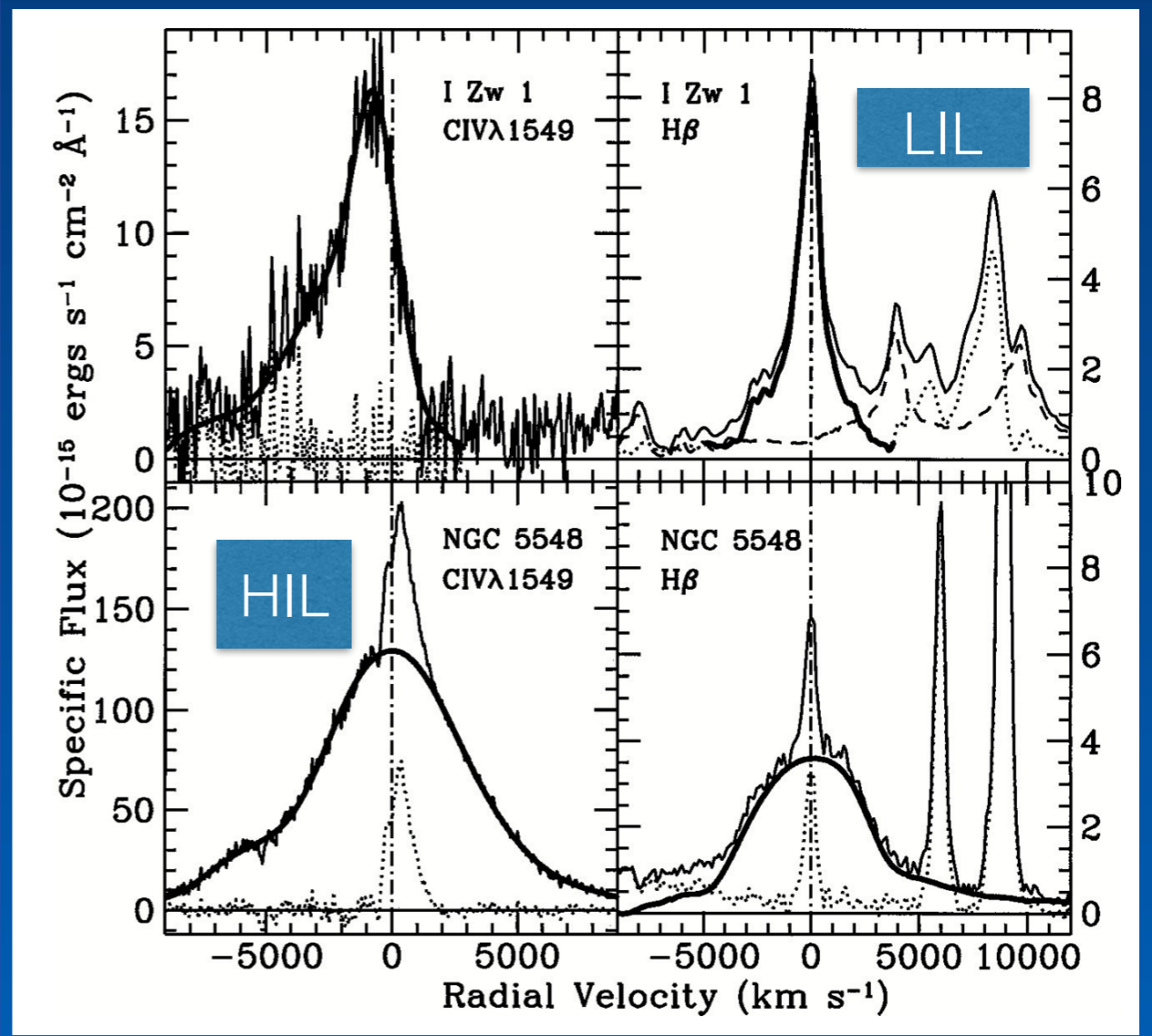


Pop. A

Prototypical Narrow Line Seyfert 1

Pop. B

Hβ spectral range

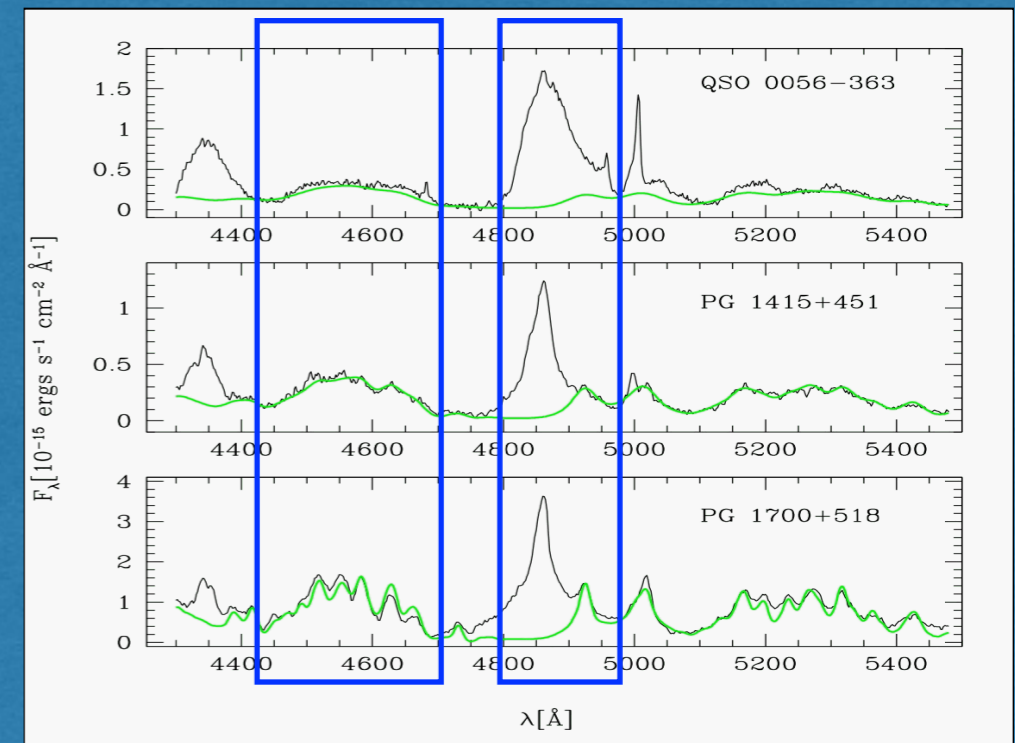
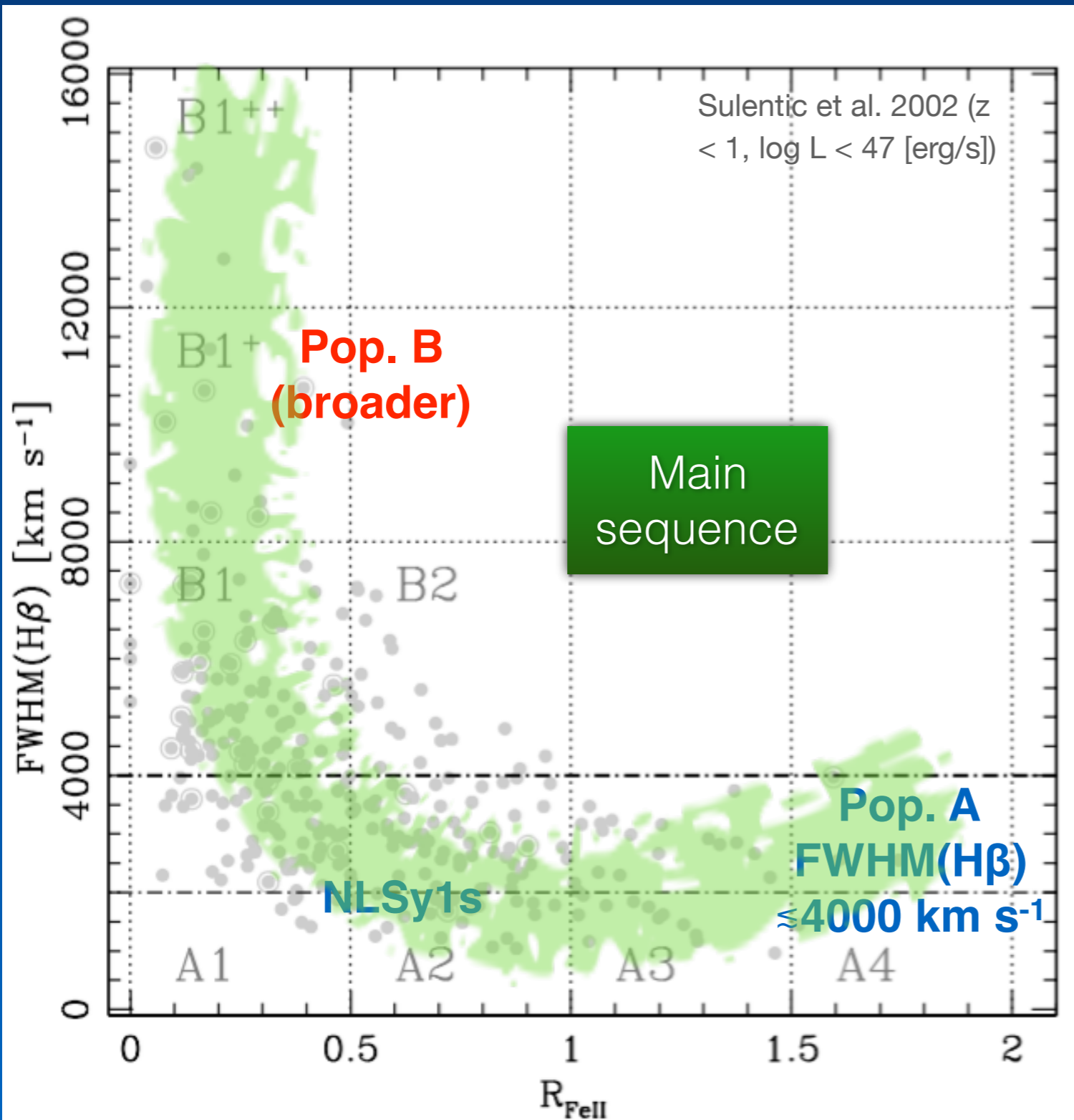


CIV and Hβ (high and low ionization lines)

I Zw 1 and NGC are the prototypes of two different quasar populations

The Main Sequence — Organizing quasar diversity

A main sequence (MS) for quasars organizing quasar diversity



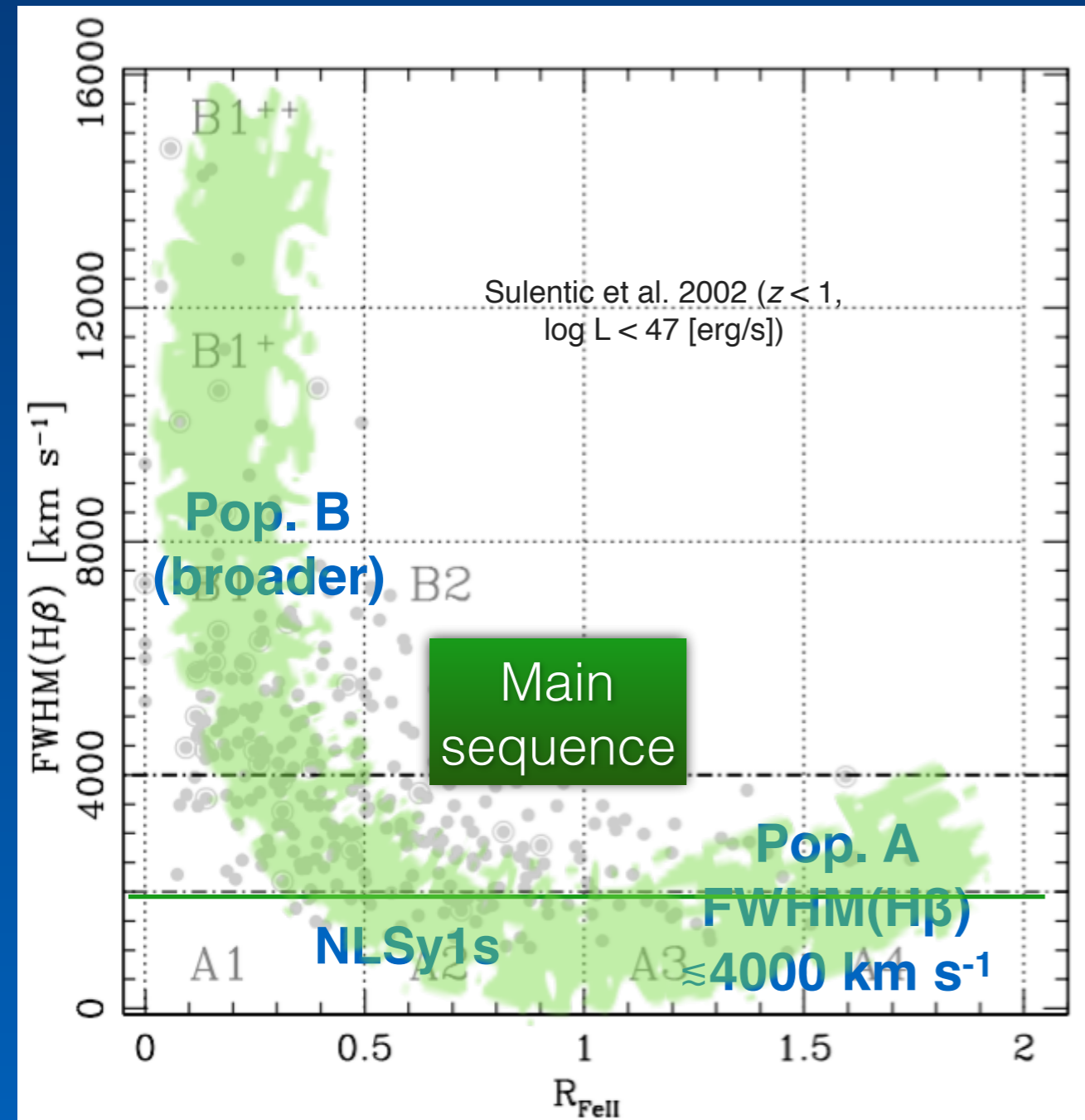
$$R_{\text{FeII}} = \frac{I(\text{FeII}\lambda 4570)}{I(\text{H}\beta)} \approx \frac{W(\text{FeII}\lambda 4570)}{W(\text{H}\beta)}$$

FeII emission can dominate the thermal balance of the BLR

FeII emission is self-similar but intensity with respect to H β changes from object to objects

R_{FeII} is a descriptor of the LIL-BLR physical conditions

The quasar Eigenvector 1: a Main Sequence (MS) for quasars



Eigenvector 1: Originally defined by a Principal Component Analysis of PG quasars; since 1992, the E1 MS has been found in increasingly larger samples.

E1 MS first associated with the anti-correlation between strength of Fe II λ 4570 (or [O III] 5007 peak intensity) and width of H β , but several multifrequency parameters related to the accretion process and the accompanying outflows are also correlated.

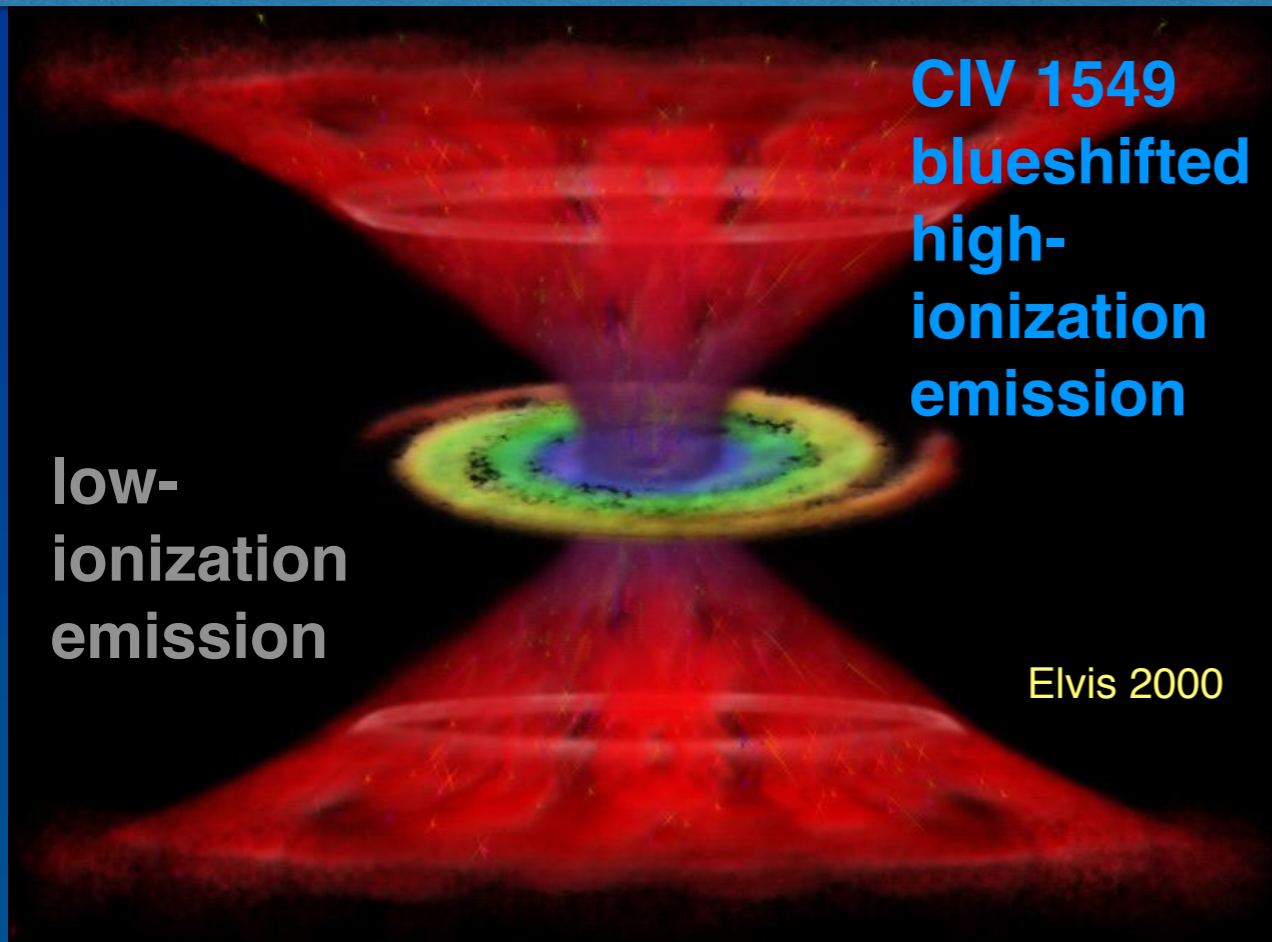
The E1 sequence is probably due to a combination of effects dependent on Eddington ratio, viewing angle, and metal content (more detail in Swayamtrupta Panda's talk).

The Main Sequence — Organizing quasar diversity

$L > 10^{47}$ erg s⁻¹: extremely high amplitude blueshifts in CIV 1549 profiles of Pop. A quasars

Virialized: symmetric and unshifted with respect to rest frame

A virialized system emitting mainly LILs coexists with outflowing gas in Pop. A sources, even at the highest luminosity



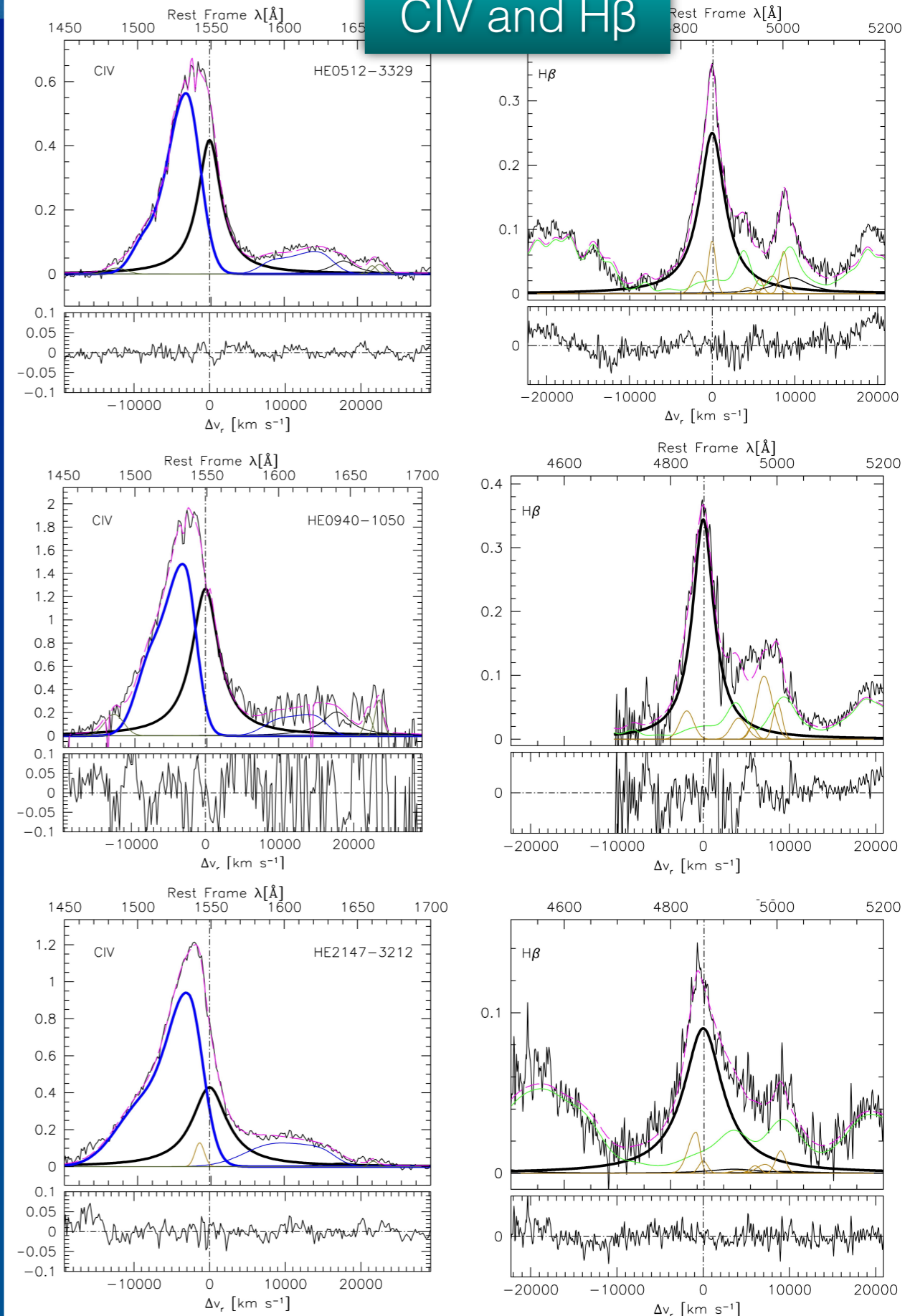
CIV 1549 blueshifted high-ionization emission

low-ionization emission

Elvis 2000

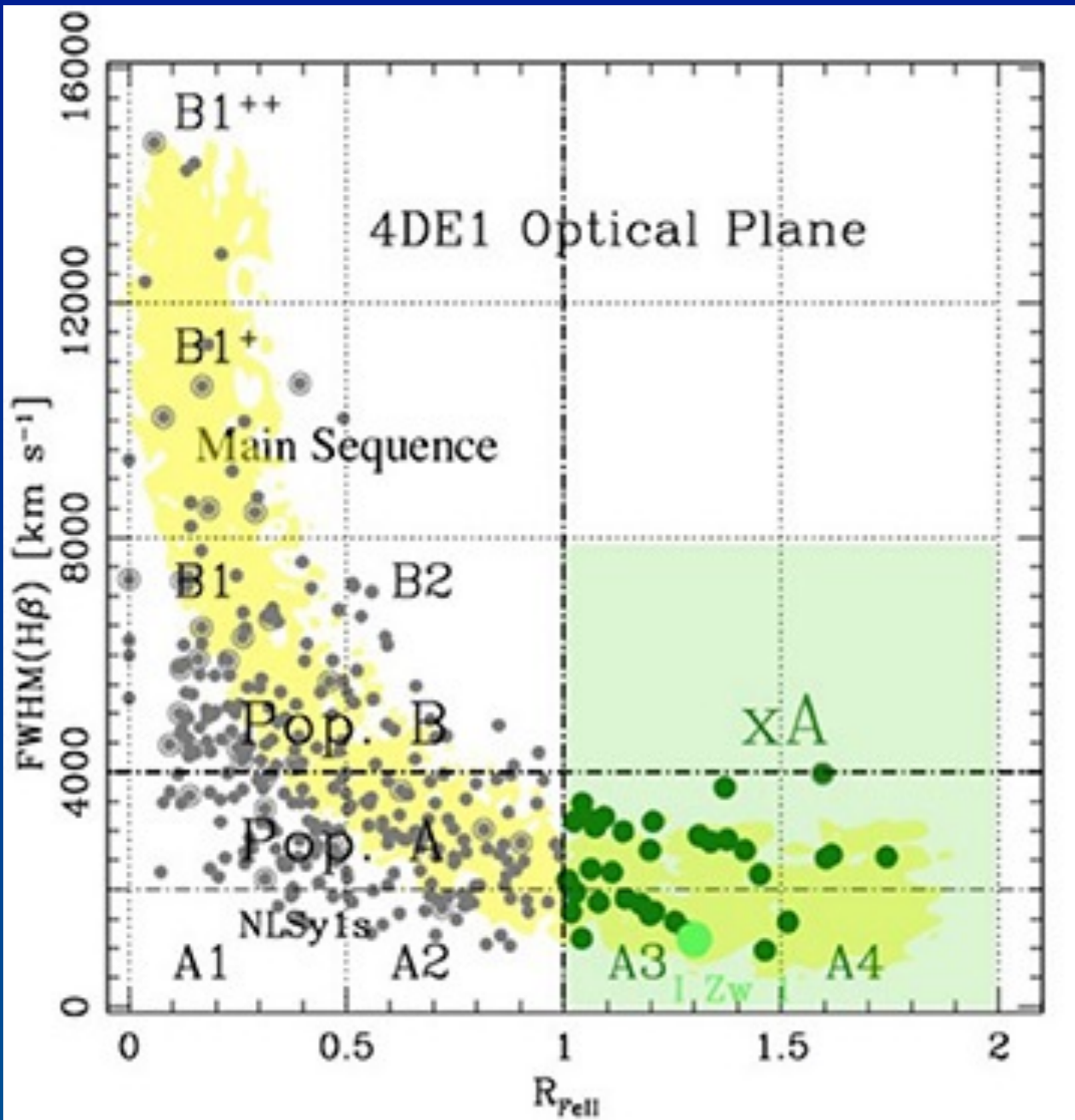
Sulentic et al. 2017; Vietri et al. 2017; Coatman et al 2016

CIV and H β



The “high R_{FeII} end” of the quasar MS
(extreme Population A, x_A , at $R_{\text{Fe}} \gtrsim 1$)

Extreme Population A – Selection and physical conditions



The MS allows for the definition of spectral types, and 2 populations: A (FWHM H β < 4000 km/s) and B

Pop. A includes the Narrow Line Seyfert 1 (NLSy1s)

Gradient of R_{FeII} in Pop. A Spectral type within Pop. A are defined by R_{FeII} ranges;

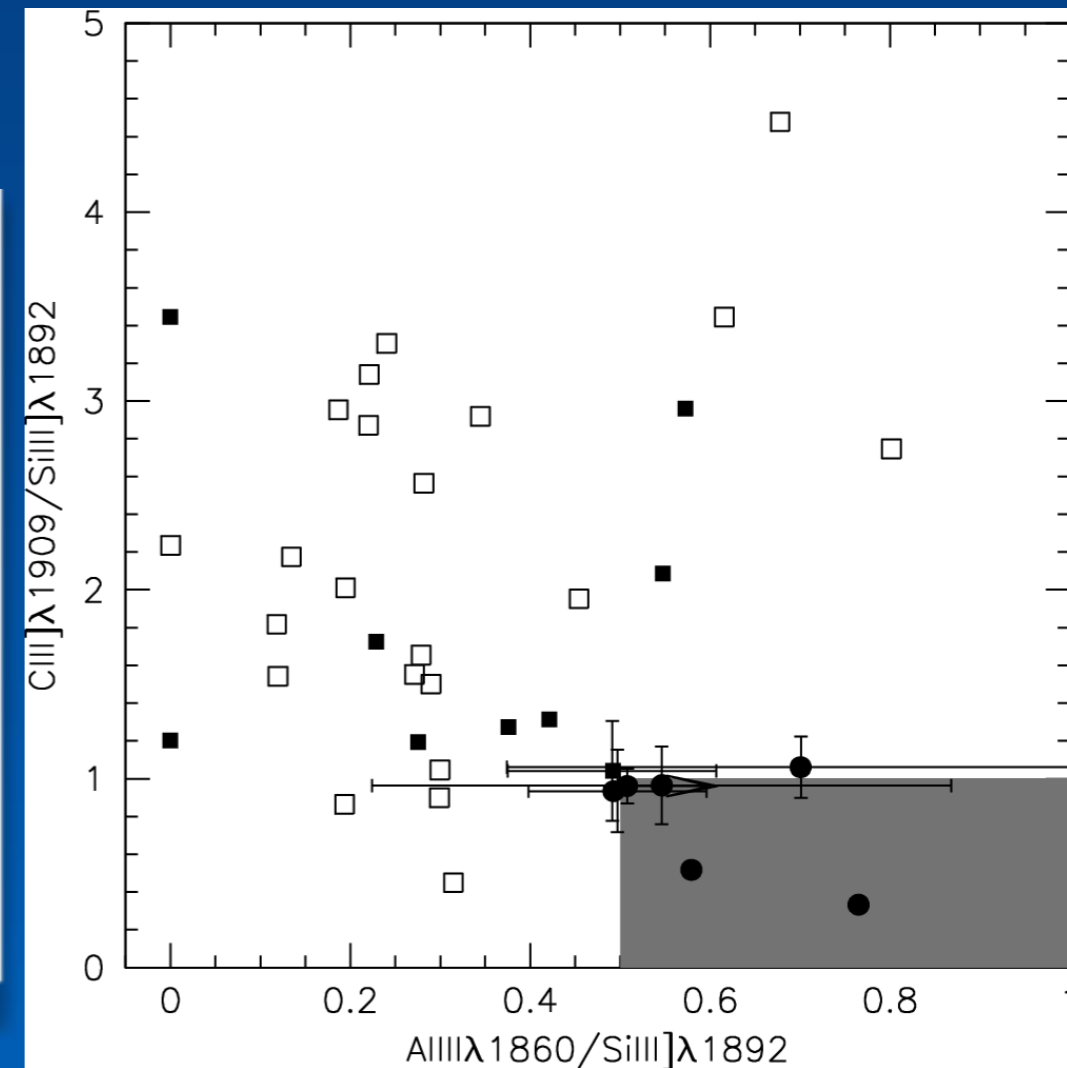
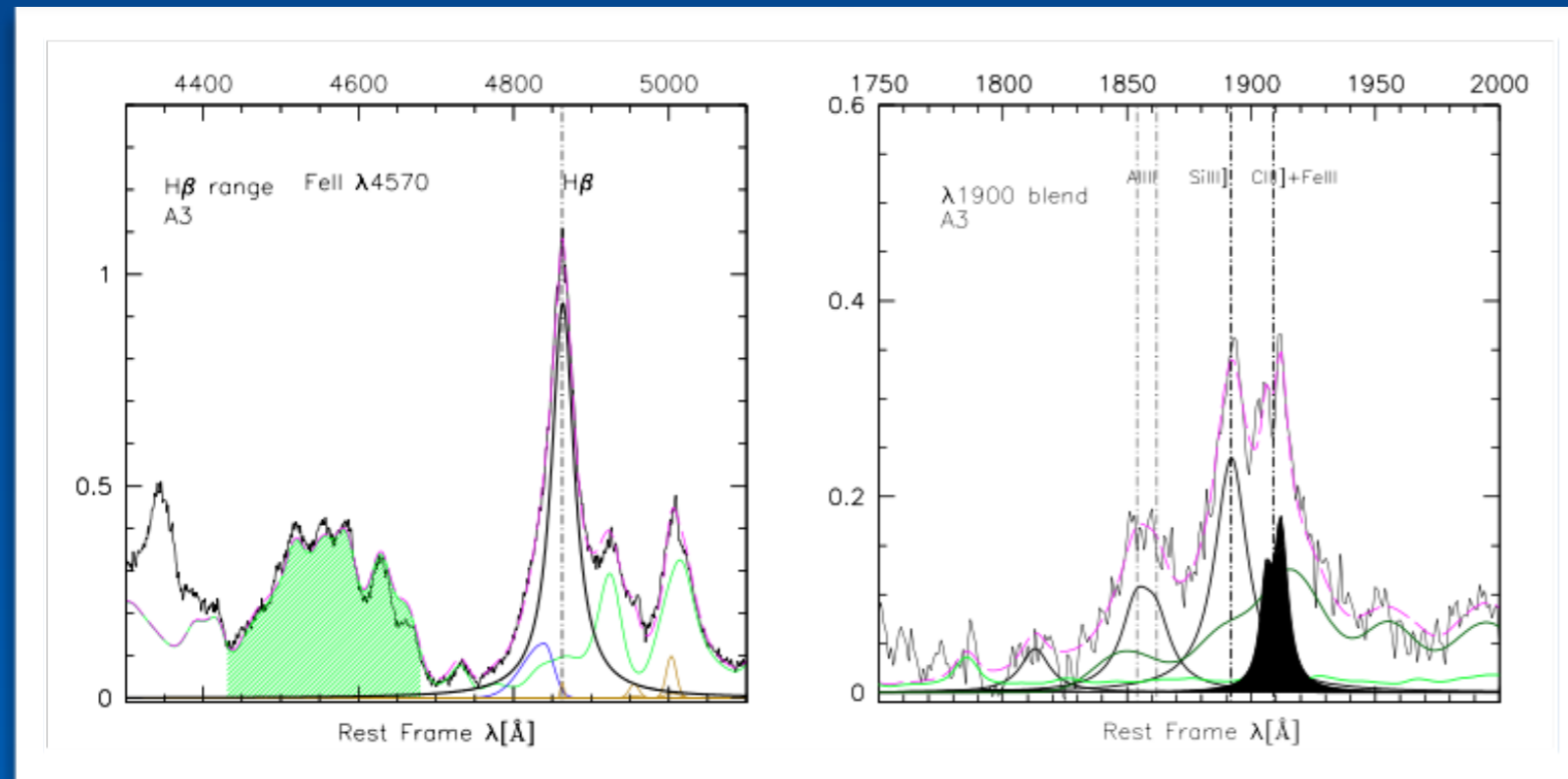
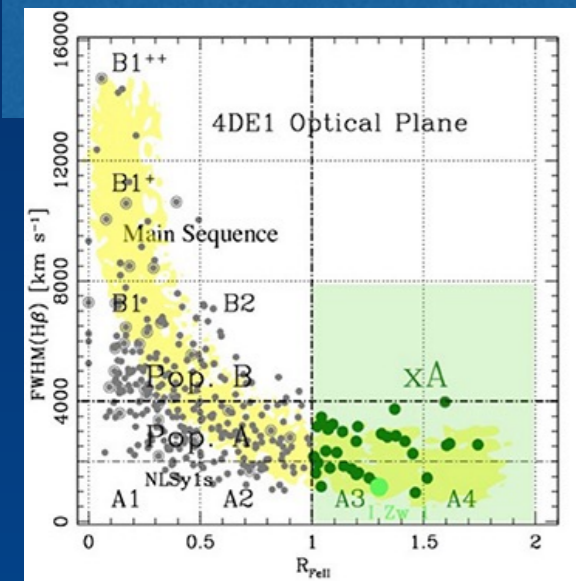
Extreme Population A (xA) quasars satisfy R_{FeII} > 1; ~ 10% of quasars in low-z, optically selected samples

Extreme Population A — Selection and physical conditions

Extreme Pop. A quasars (xA)

Simple selection criteria from diagnostic line ratios

- 1) $R_{\text{FeII}} = \text{FeII}\lambda 4570 \text{ blend}/\text{H}\beta > 1.0$
- 2) $\text{UV AIII}\lambda 1860/\text{SiIII]}\lambda 1892 > 0.5$ & $\text{SiIII]}\lambda 1892/\text{CIII]}\lambda 1909 > 1$

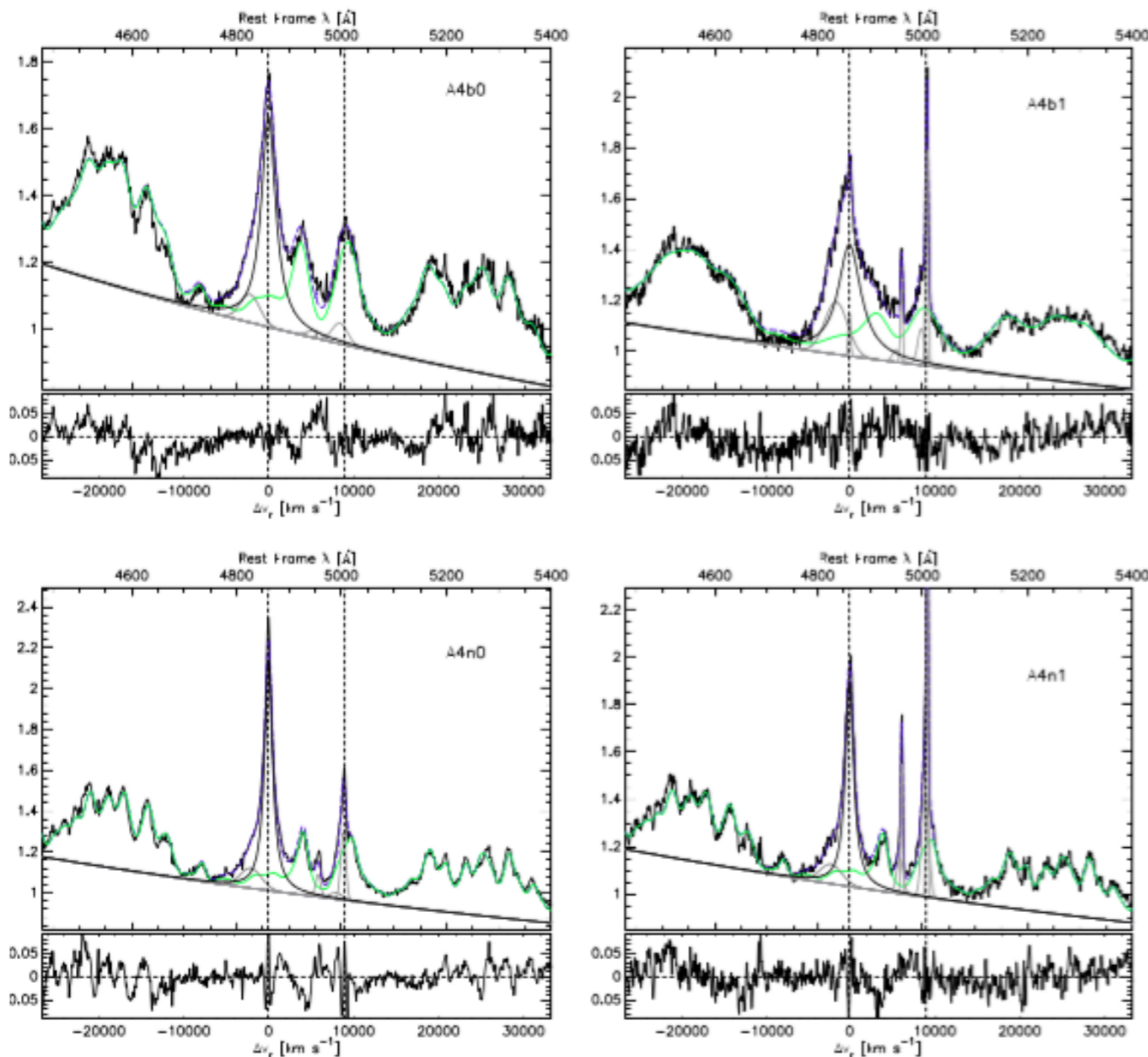


UV and optical selection criteria are equivalent

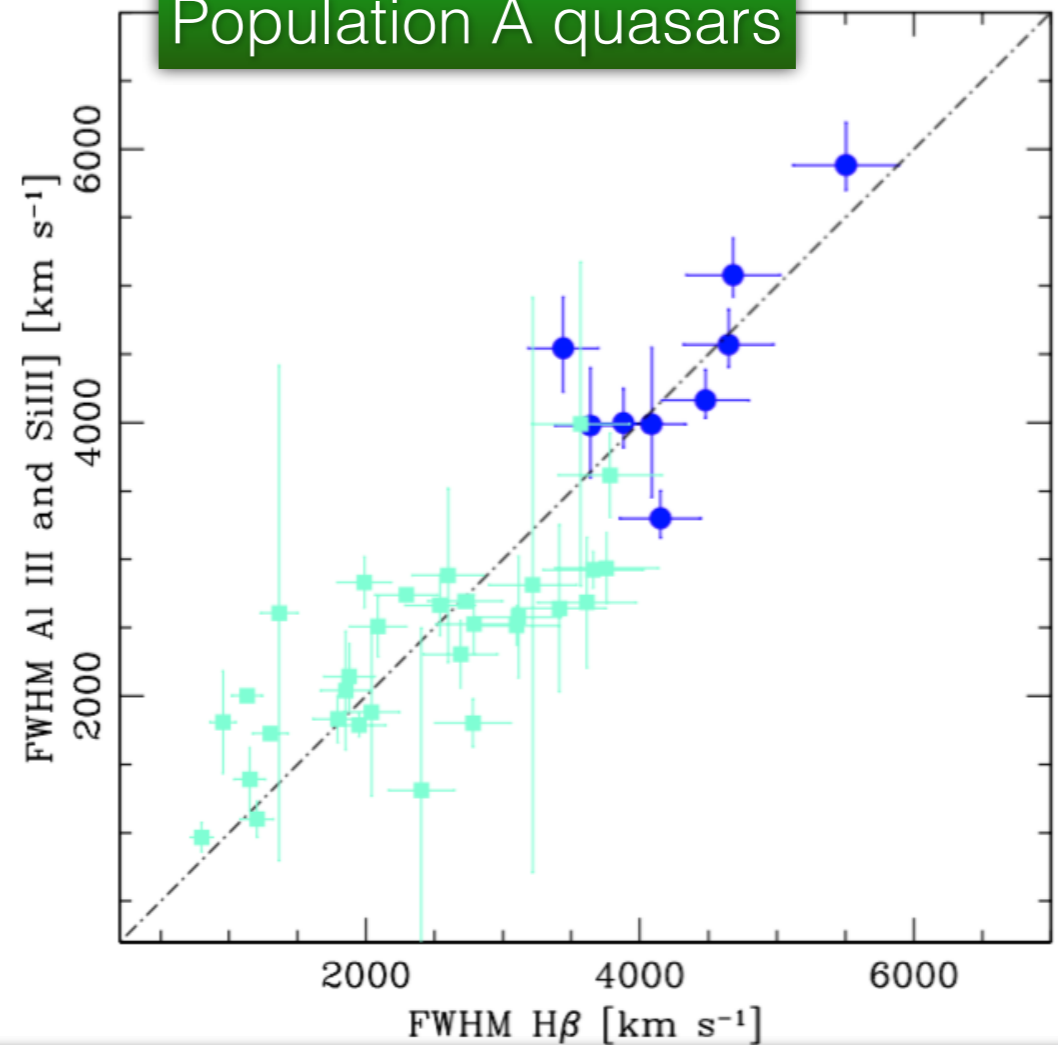
Extreme Population A — Selection and physical conditions

xA spectra show distinctively strong FeII emission and Lorentzian Balmer line profiles

**$\text{FWHM}(\text{H}\beta) \sim \text{FWHM}(\text{AlIII } 1860)$
AlIII 1860 virial broadening estimator equivalent to $\text{H}\beta$**



Population A quasars



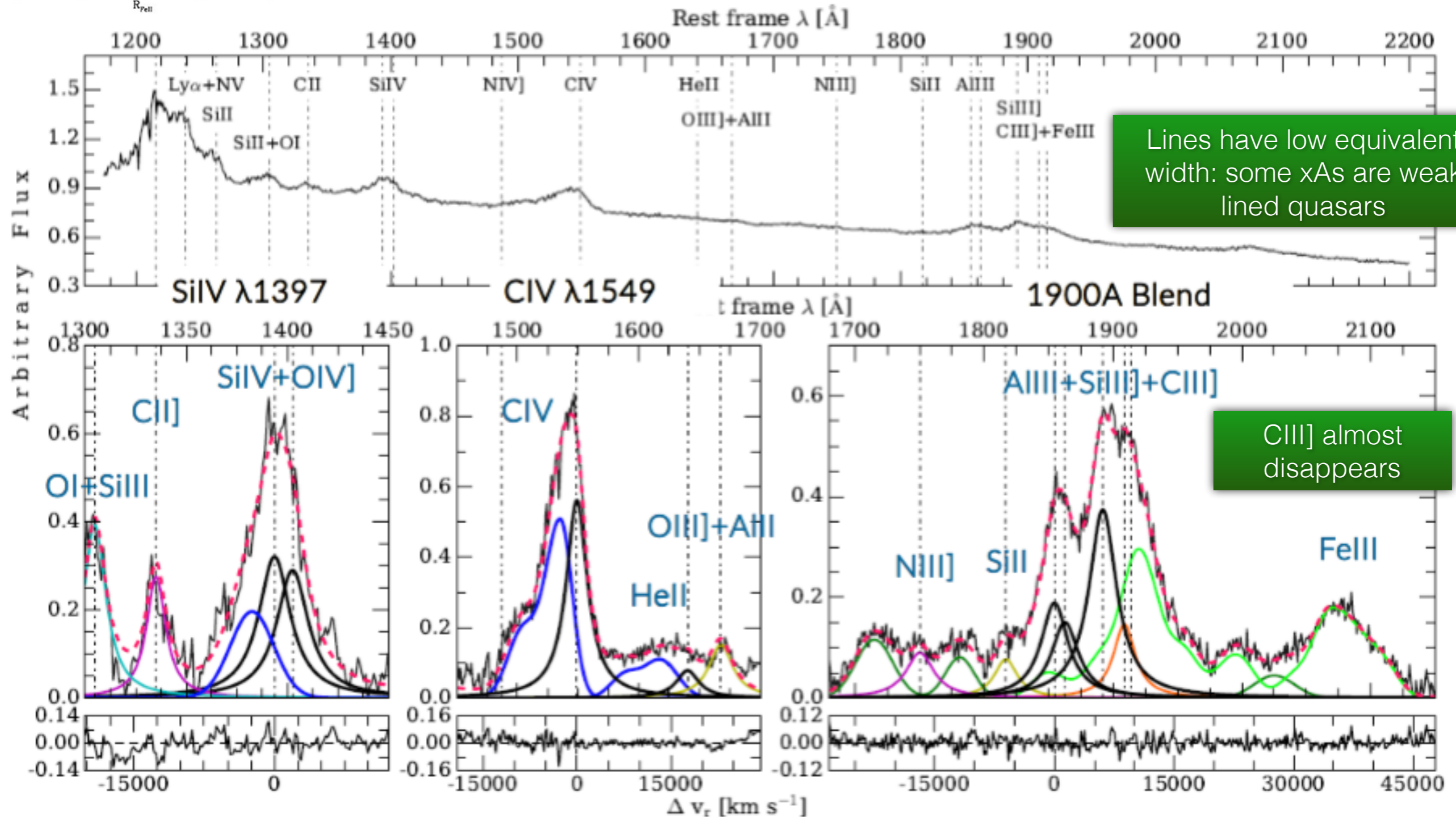
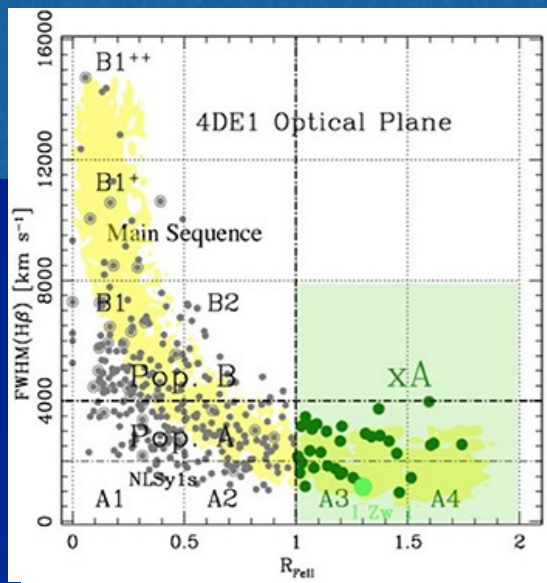
Allows for the consideration of xA quasars at high z (>1.2)

Extreme Population A — Selection and physical conditions

The UV spectrum of xA quasars at $z \sim 2$

Symmetric low-ionization and blueshifted high-ionization lines even at the highest luminosity

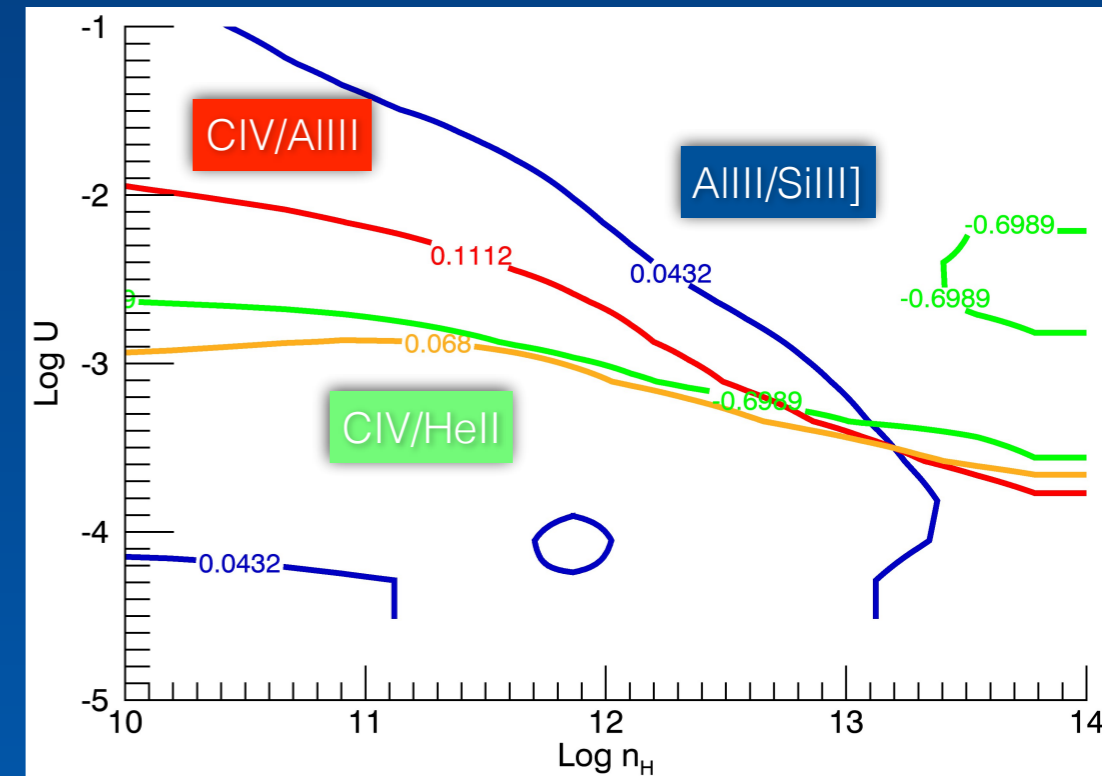
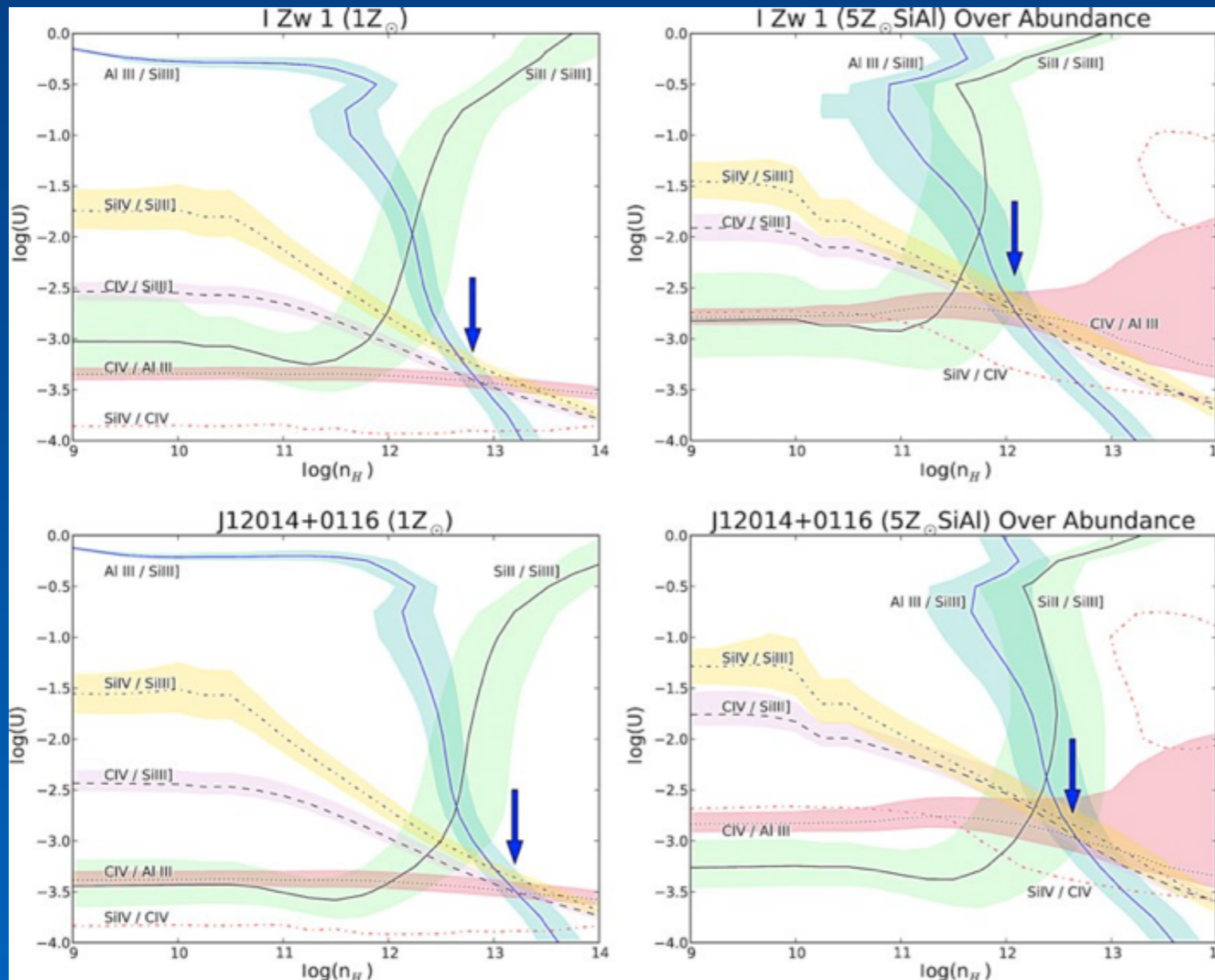
Martínez-Aldama et al. 2018, and reference therein



Extreme Population A — Selection and physical conditions

Extreme values for density
(high, $n > 10^{12-13} \text{ cm}^{-3}$), ionization
(high, $U \sim 10^{-3}$)

Extreme values of
metallicity ($Z > 20 Z_{\odot}$)



Plane ionization parameter versus density from arrays of CLOUDY simulations

Emitting region a dense compact remnant of the LI-BLR?

(Negrete et al. 2012; Martínez-Aldama et al. 2018; Sniegowska et al. 2019 in preparation)

Extreme Population A ($R_{\text{Fe}} \gtrsim 1$): implications for Cosmology?

xA: Marziani & Sulentic 2014 (MS14); Negrete et al. 2018; Martínez-Aldama et al. 2018; related to “Super-Eddington” accreting massive black holes (SEAMBHs): Wang et al. 2013; 2014; Du et al. 2016; Czerny et al. 2018 for a review; Czerny et al. 2013; Risaliti & Lusso 2015, and La Franca et al. 2014 for alternative methods.

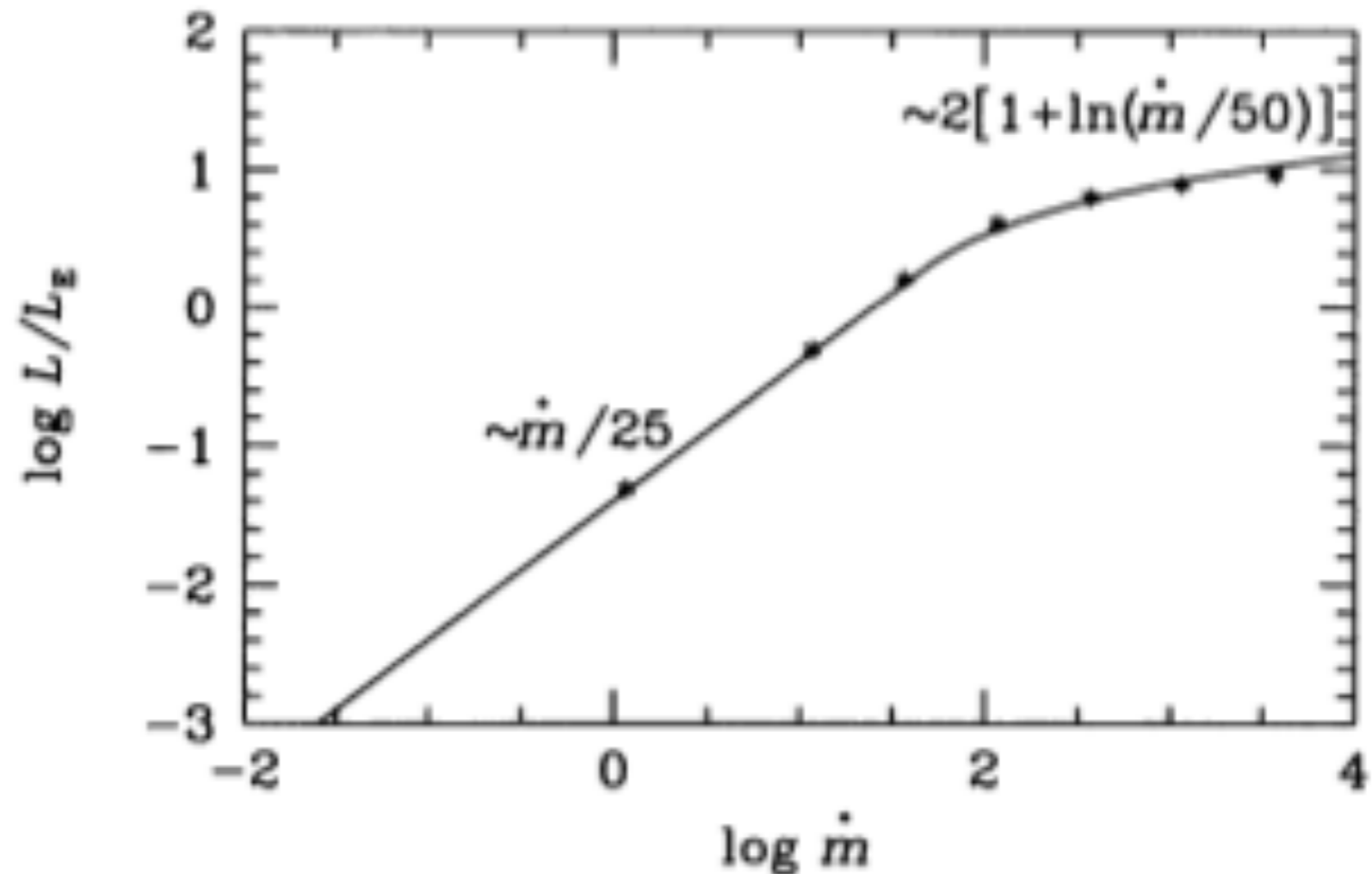
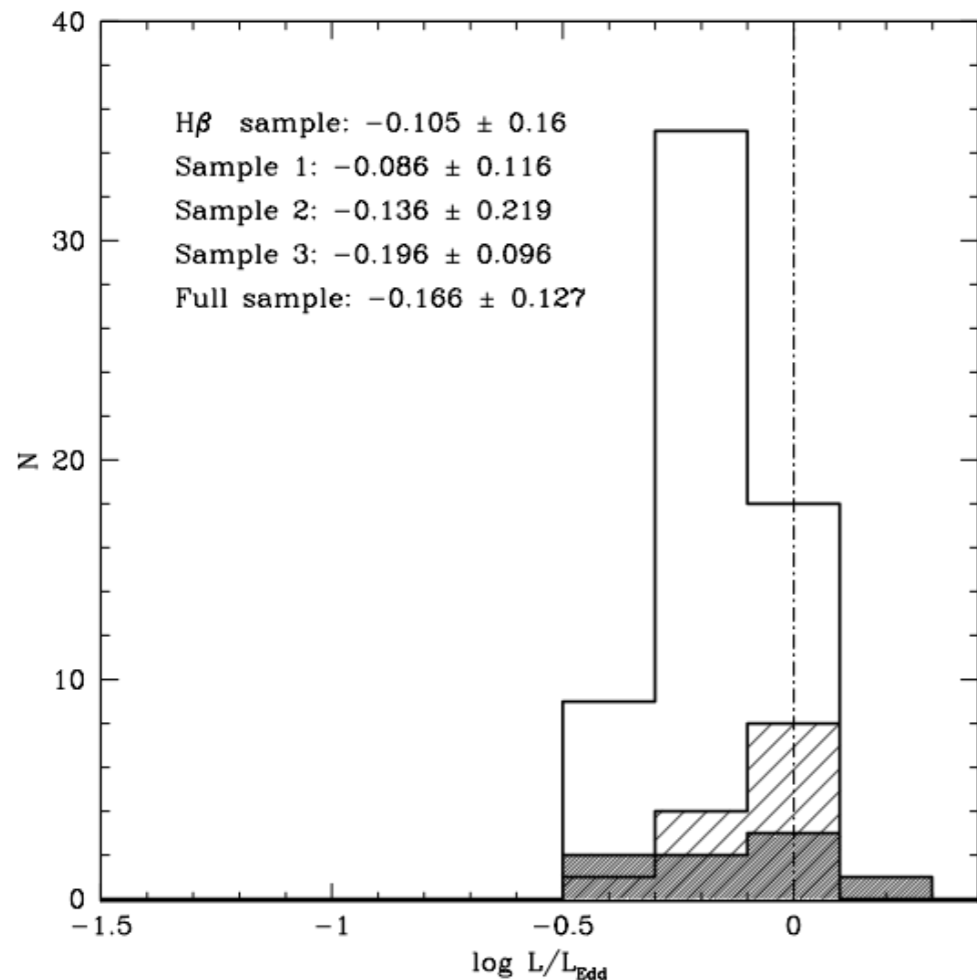
Extreme Population A: cosmological applications?

**xA quasars:
Extreme L/L_{Edd}
along the MS with
small dispersion**

**Accretion disk theory: low radiative
efficiency at high accretion rate;
 L/L_{Edd} saturates toward a limiting
values**

$$L = \eta L_{\text{Edd}} = \text{const} \eta M_{\text{BH}}$$

$$L/L_{\text{Edd}} \rightarrow \text{const. for } \dot{m} \gg 1$$



Extreme Population A: cosmological applications?

Eddington standard candles

1. xA quasars radiate close to Eddington limit $\eta \sim 1$

$$L = \eta L_{\text{Edd}} = \text{const} \eta M_{\text{BH}}$$

2. Assuming **virial motions** of the low-ion. BLR,
 $L \propto \eta M_{\text{BH}} \propto \eta r_{\text{BLR}} (\delta v)^2$

$$M_{\text{BH}} = \frac{f r (\delta v)^2}{G}$$

geometry dynamics

r_{BLR}

FWHM σ, FWZI

3. xA quasars have similar BLR physical parameters (n_{H} and U), implying that the BLR radius rigorously scales with L $r_{\text{BLR}} \propto (L n_{\text{H}} U)^{1/2}$

4. If we know a **virial broadening estimator** δv (in practice, the FWHM of a low-ionization line), we can derive a z-independent

$$\text{“virial luminosity” } L_{\text{vir}} \propto \eta^2 (n_{\text{H}} U)^{-1} (\delta v)^4$$

Extreme Population A: cosmological applications?

“Virial luminosity”

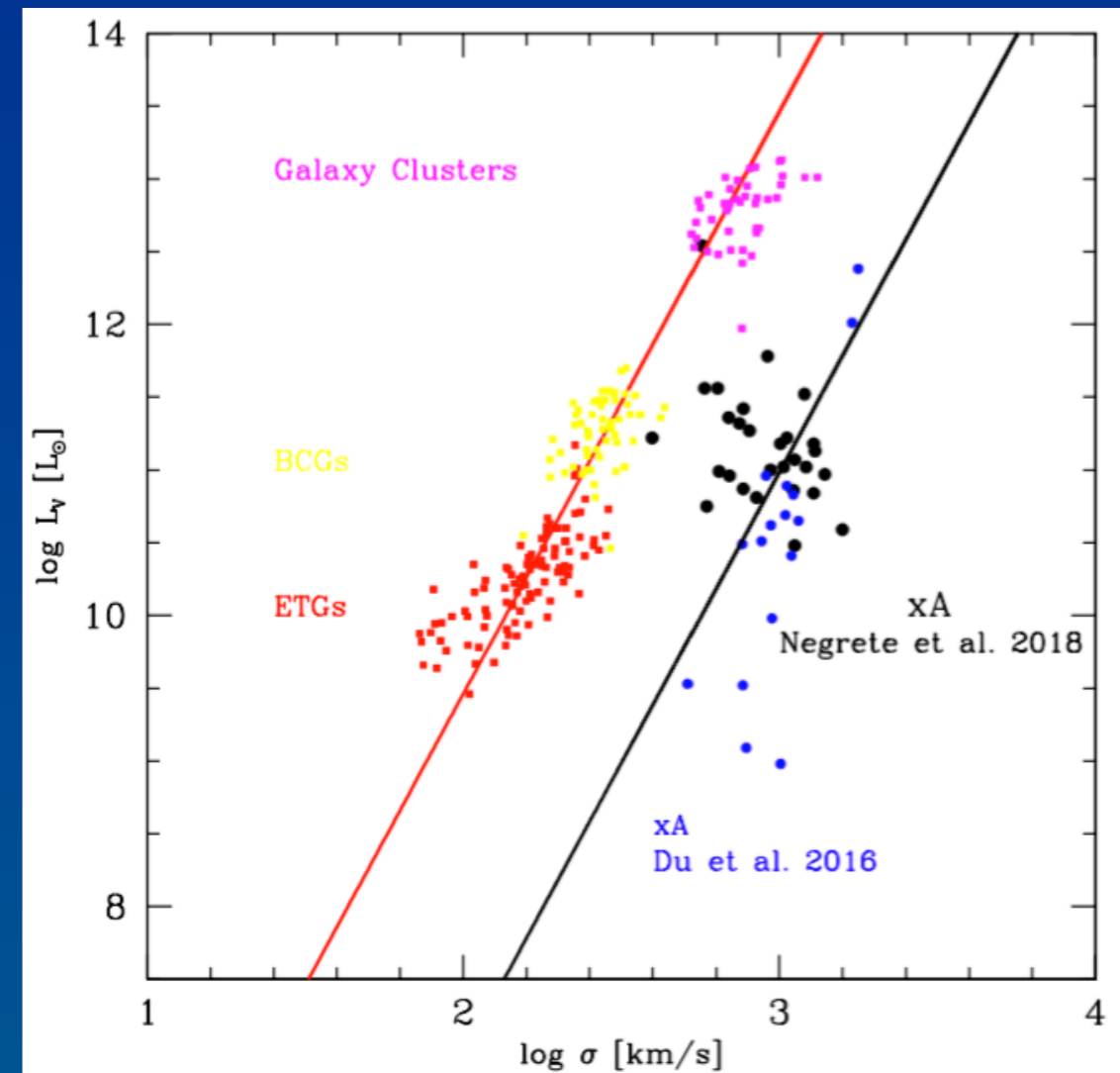
$$L \approx 7.8 \cdot 10^{44} \frac{\eta_1^2 \kappa_{0.5} f_2^2}{\bar{\nu}_{i2.42} \cdot 10^{16}} \frac{1}{(nU)^{9.6}} \delta v_{1000}^4 \text{ erg s}^{-1}$$

fraction of ionizing luminosity

average frequency of ionizing photons

Analogous to the Tully-Fisher and the early formulation of the Faber Jackson laws for early-type galaxies; galaxies and even clusters of galaxies are virialized systems that show an overall consistency with an $L \propto \sigma^4$ law

Applicable to xA quasars ($L/L_{\text{Edd}} = \eta \Rightarrow 1$) over a wide range of luminosity and redshift



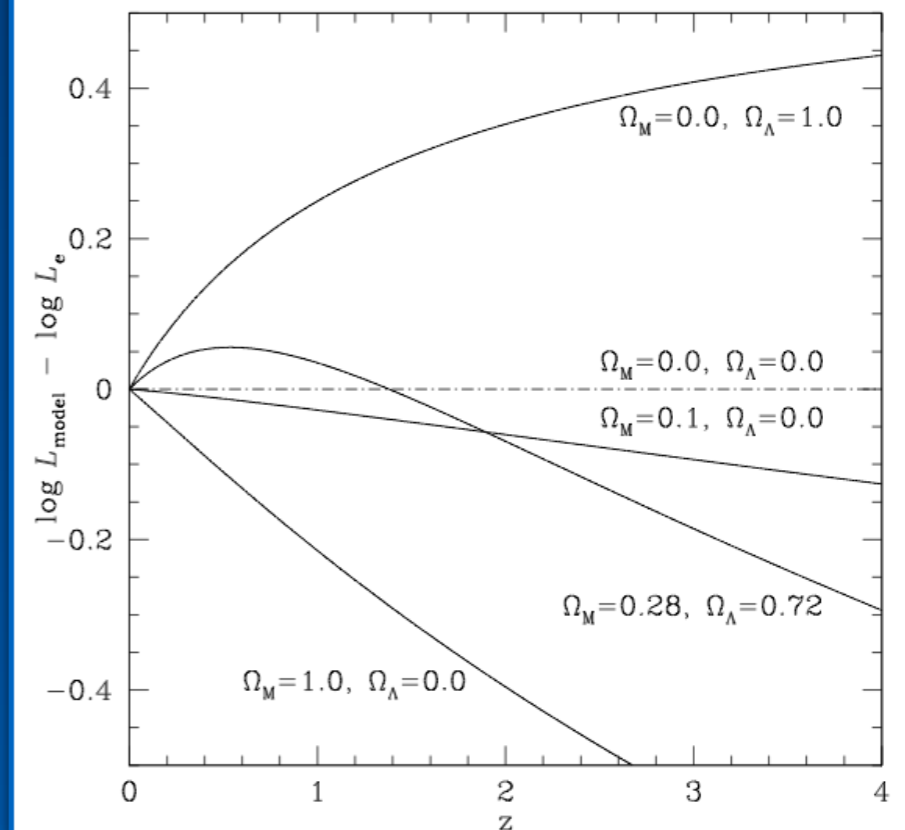
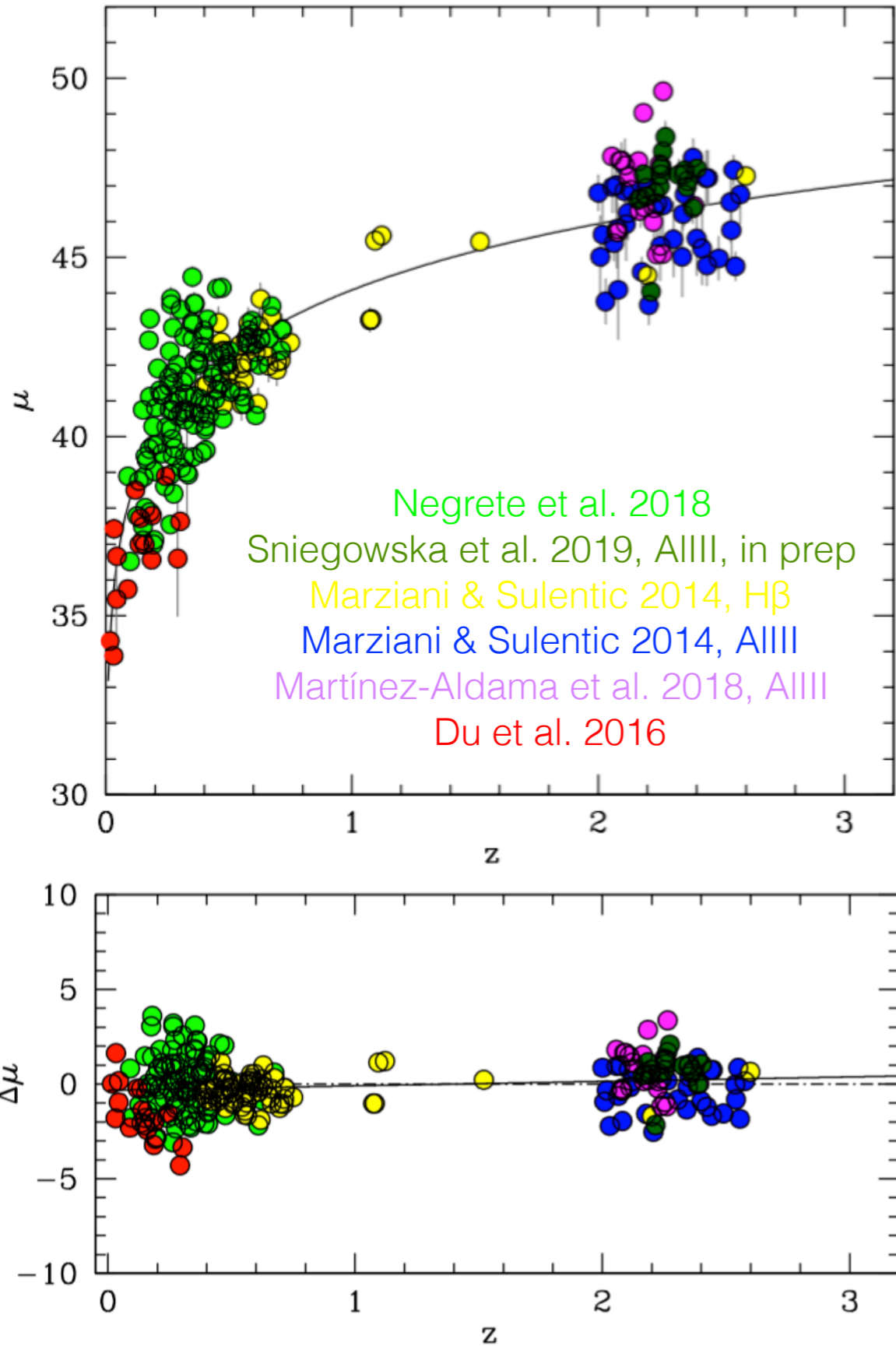
Extreme Population A: cosmological applications?

A Hubble Diagram for quasars: consistent with concordance Λ CDM

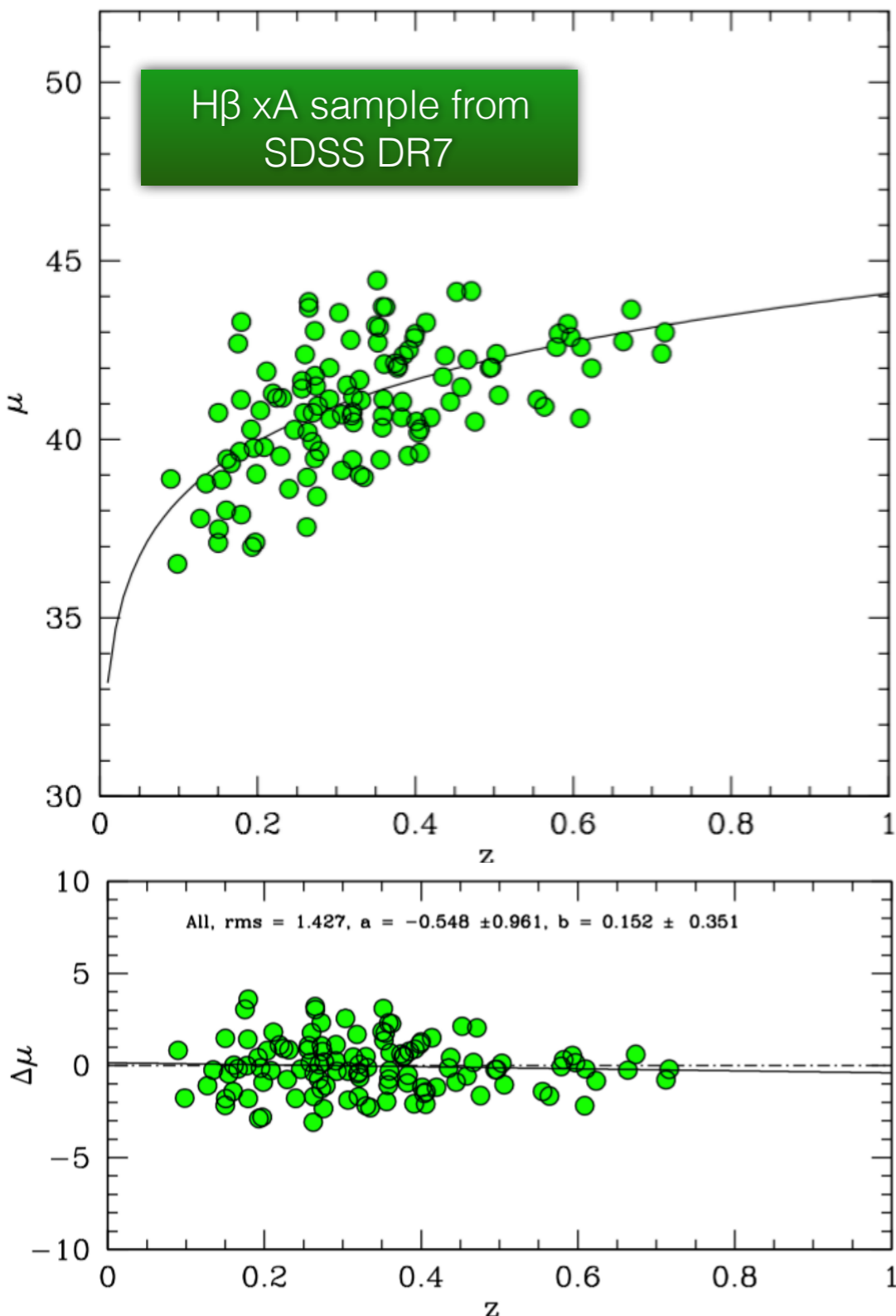
Significant scatter, $\sigma_{\Delta\mu} \sim 1.1 - 1.3$ mag

Data already rule out extreme Universes
($\Omega_{\Lambda}=1, \Omega_M=0$) or the Einstein-de Sitter
Universe

Data already
provide
significant
constraints on
 Ω_M
($0.19^{+0.17}_{-0.08}$):
the redshift
range 2 - 3 is
highly
sensitive to
 Ω_M

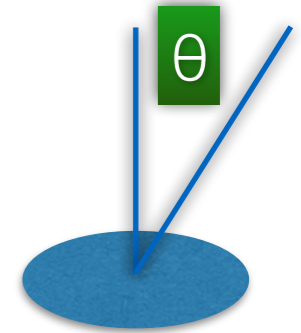


Extreme Population A: cosmological applications?

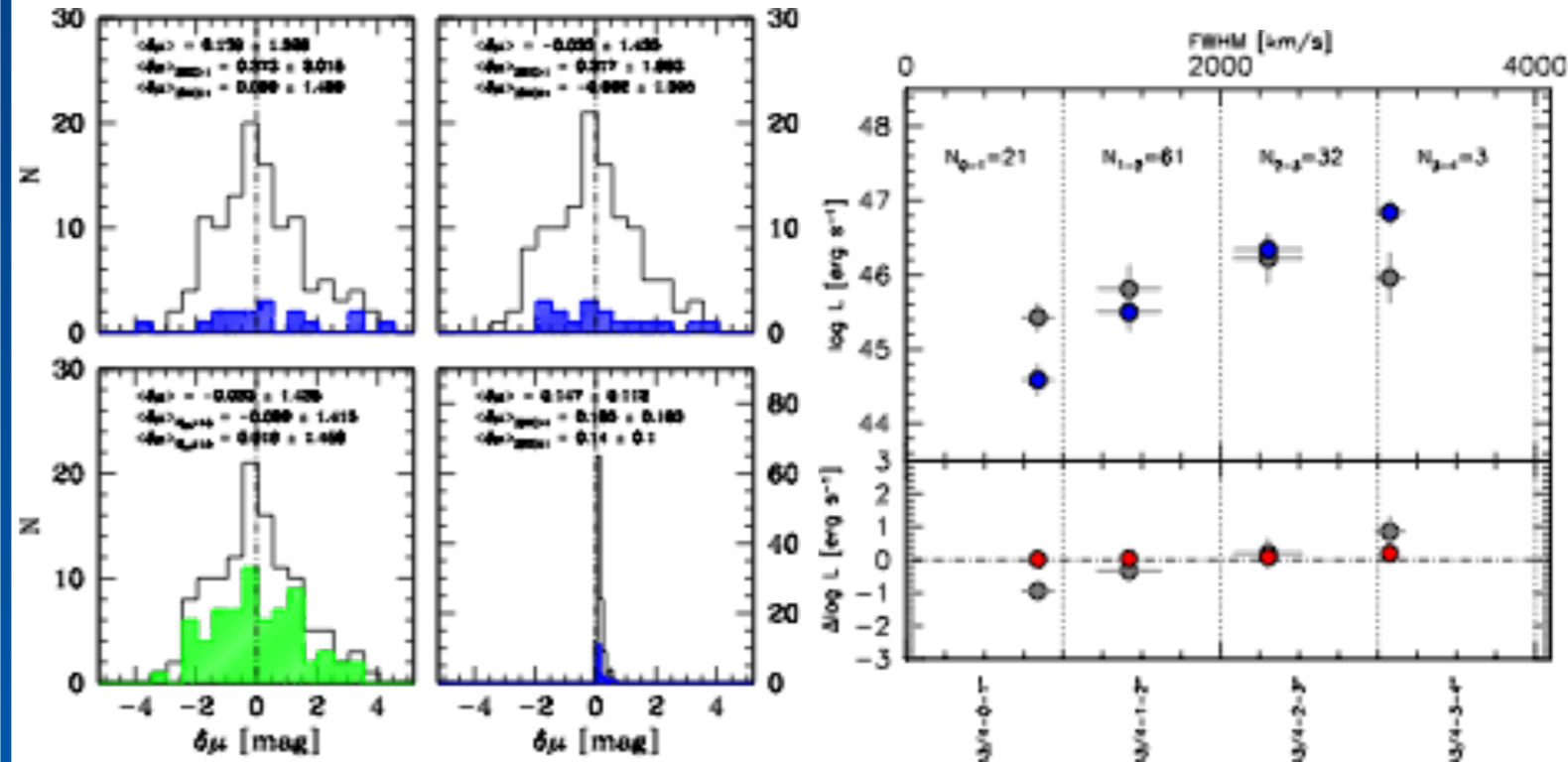


$$\delta\mu = \mu^{\text{vir}} - \mu^z = 2.5 \log L(\text{FWHM}) - 2.5 \log L(z, H_0, \Omega_M, \Omega_\Lambda).$$

Orientation dependent form factor
Highly flattened system



$$f_s = \frac{1}{4 \left[\frac{1}{3} \left(\frac{\delta v_{\text{iso}}}{\delta v_K} \right)^2 + \sin^2 \theta \right]}, \quad M_{\text{BH}} = f_s \frac{r \text{FWHM}^2}{G}$$



$$\delta \log L = \log 16 \mathcal{L}_0^* \delta v_K^4 \left[\frac{\kappa^2}{3} + \sin^2 \theta \right]^2 - \delta \log L \rightarrow \theta.$$

Difference between virial and concordance L estimate

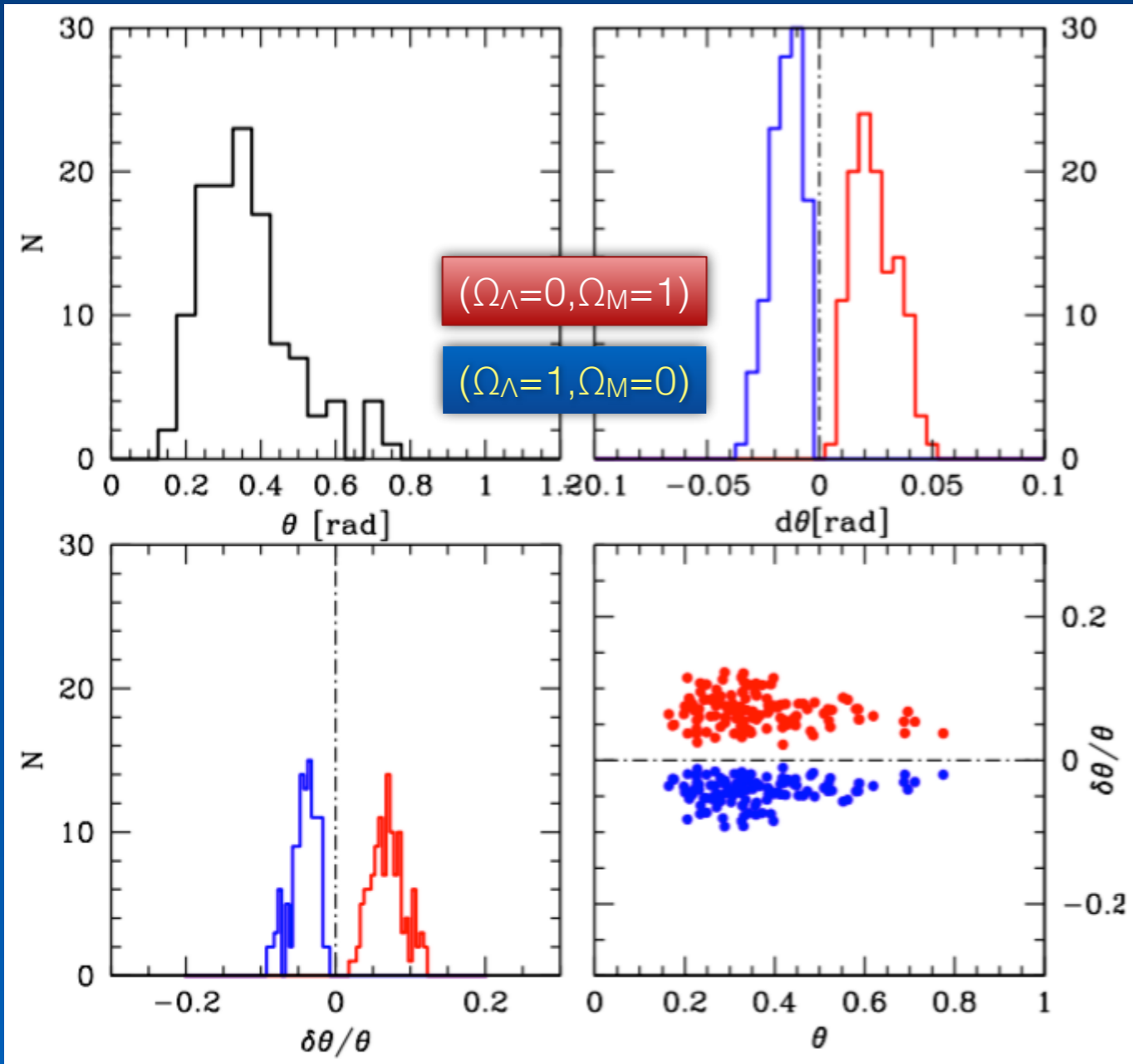
$$\log \left[\frac{L_0(z, H_0, \Omega_s)}{2} \cos \theta \frac{(1 + \beta \cos \theta)}{1 + \beta} + \frac{L_0(z, H_0, \Omega_s)}{2} \right],$$

Orientation accounts for most of the scatter if lines are emitted in a flattened system ($\kappa \sim 0.1$).

Negrete et al. 2018; cf. Afanasiev, Popovic, et al. 2018 from spectropolarimetry)

Extreme Population A: cosmological applications?

Make θ estimates independent from the cosmology



The assumption of extreme cosmologies yield modest differences in θ estimates, $d\theta < 0.05$ rad.

Randomization and de-correlation should make the estimate of the viewing angle independent from the cosmology and strongly reduce the scatter in the Hubble diagram.

A full Bayesian analysis is in progress.

Work to improve the accuracy of black hole mass and Eddington ratio using θ is in progress.

Conclusion

The MS offer contextualization of quasar observational and physical properties.

Extreme Population A (xA) quasars at the high R_{FeII} end of the MS appear to radiate at extreme L/L_{Edd} . Low ionization lines are apparently emitted in a highly-flattened, virialized BLR.

xA quasars show a relatively high prevalence (10%) and are easily recognizable. They might be suitable as “Eddington standard candles” especially if orientation effects can be accounted for.

