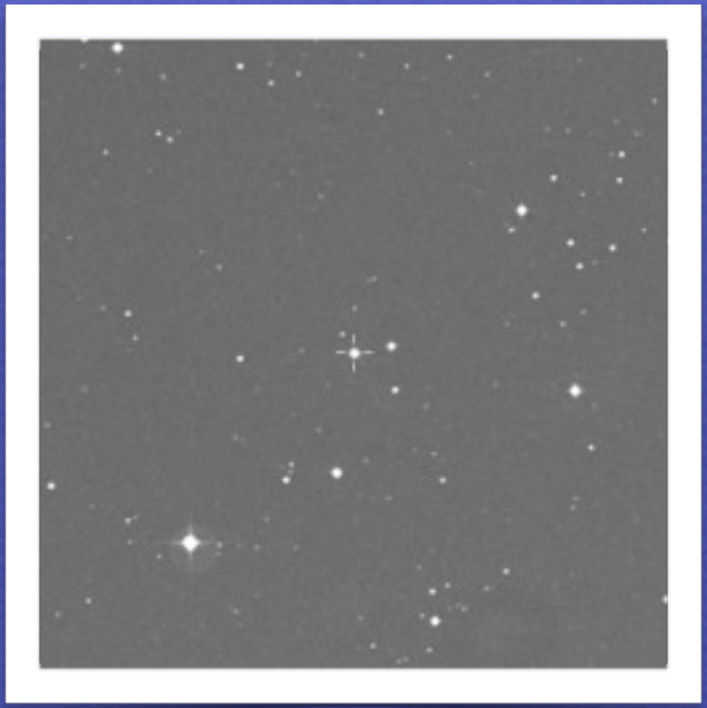
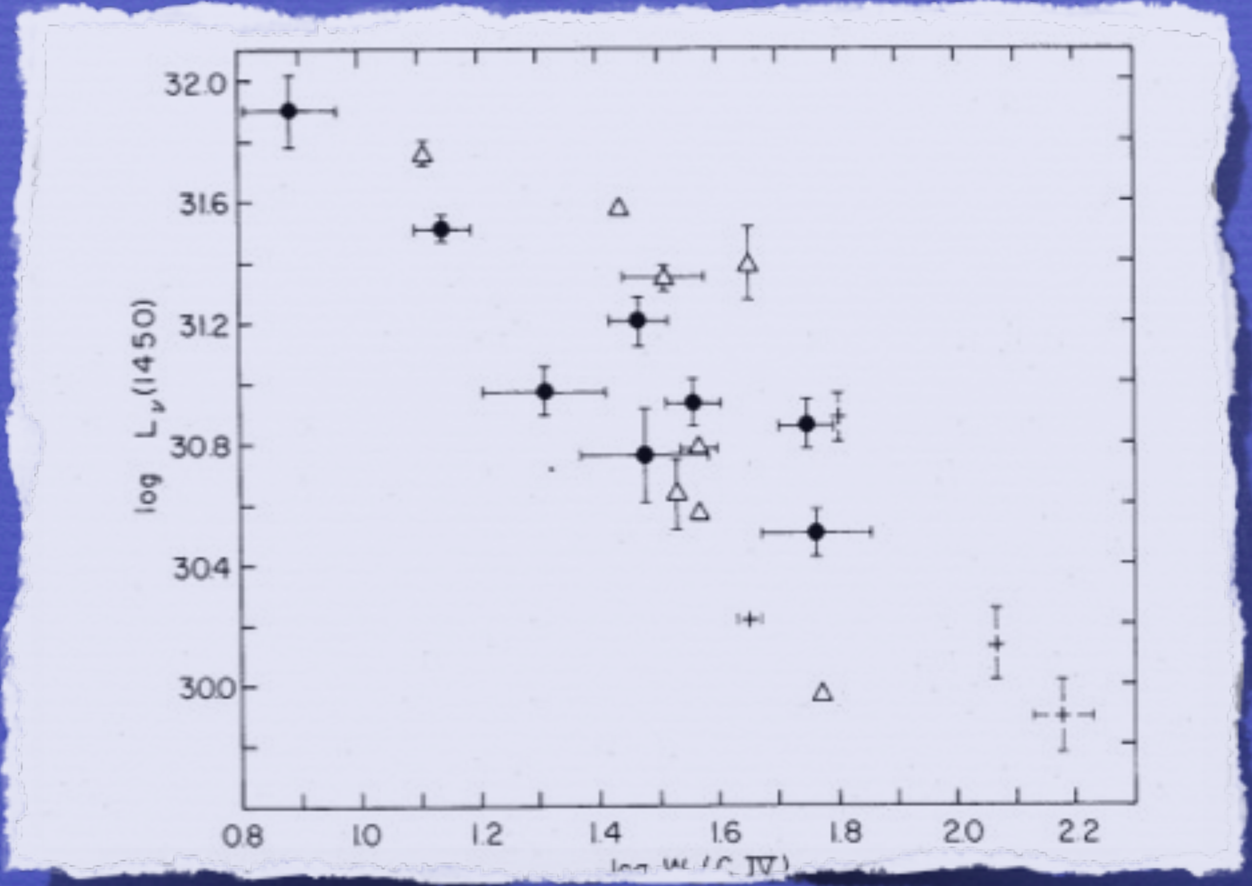
Quasars
and their emission lines as cosmological probes





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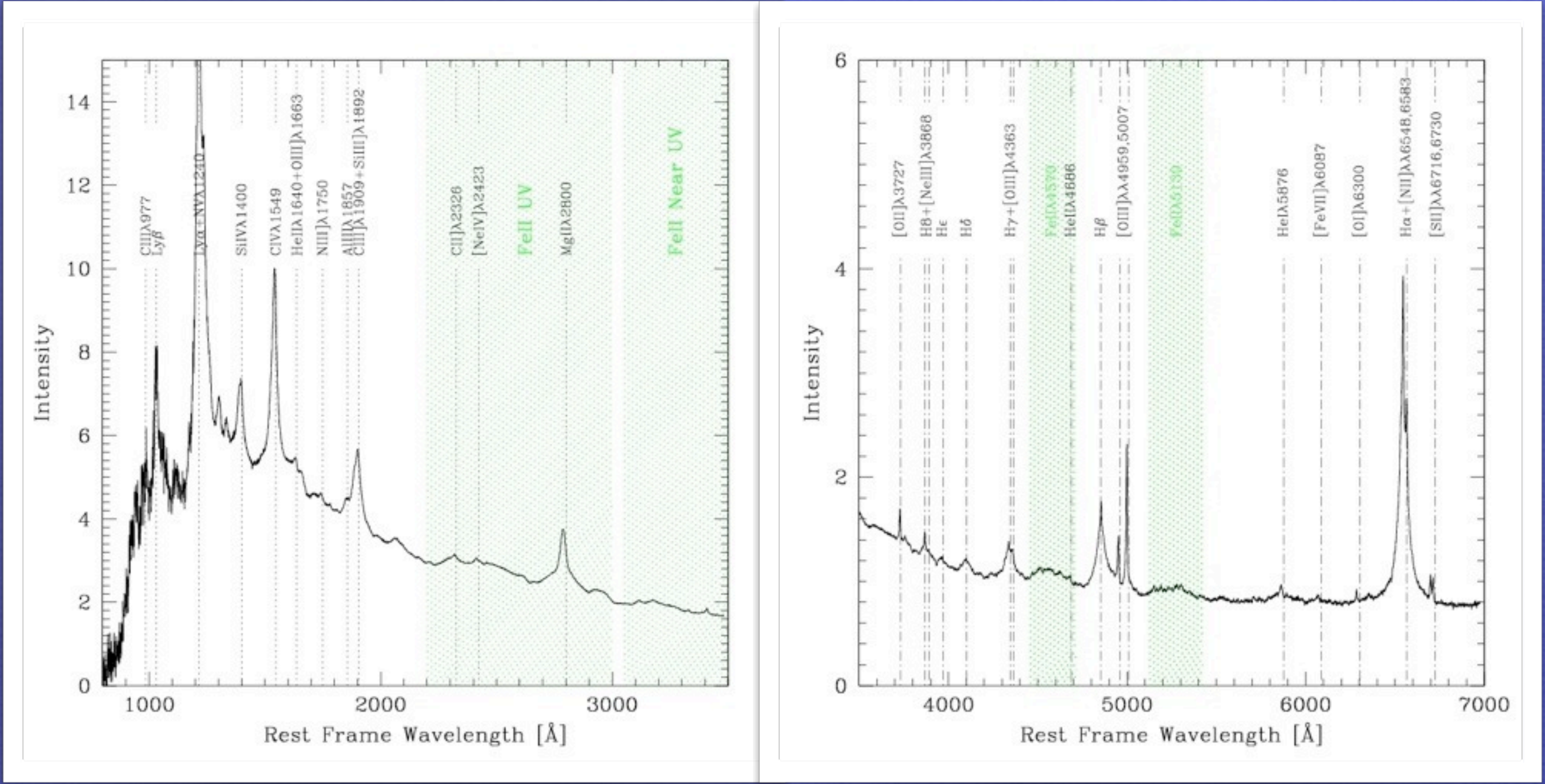


The composite quasar spectrum from the Sloan DSS (Van den Berk et al. 2001; Marziani et al. 2006)

Distinctive emission line spectrum with prominent lines and continuum raising toward UV

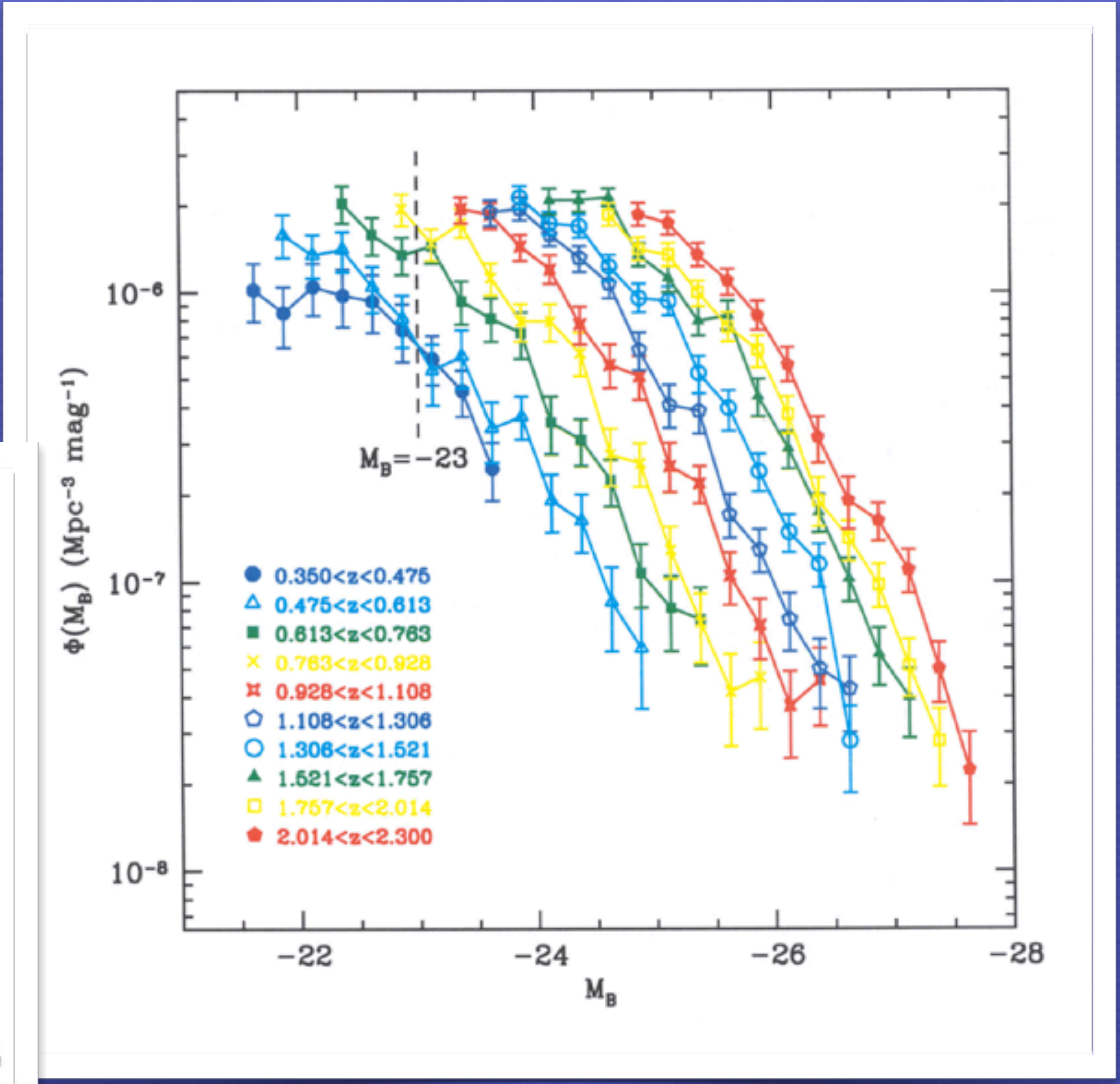
Broad (FWHM > 1000 km s^{-1}), low ionization (< 20 eV; Hβ, FeII,MgIIλ2800) and high ionization lines

Why have quasars never been successfully used as cosmological probes?

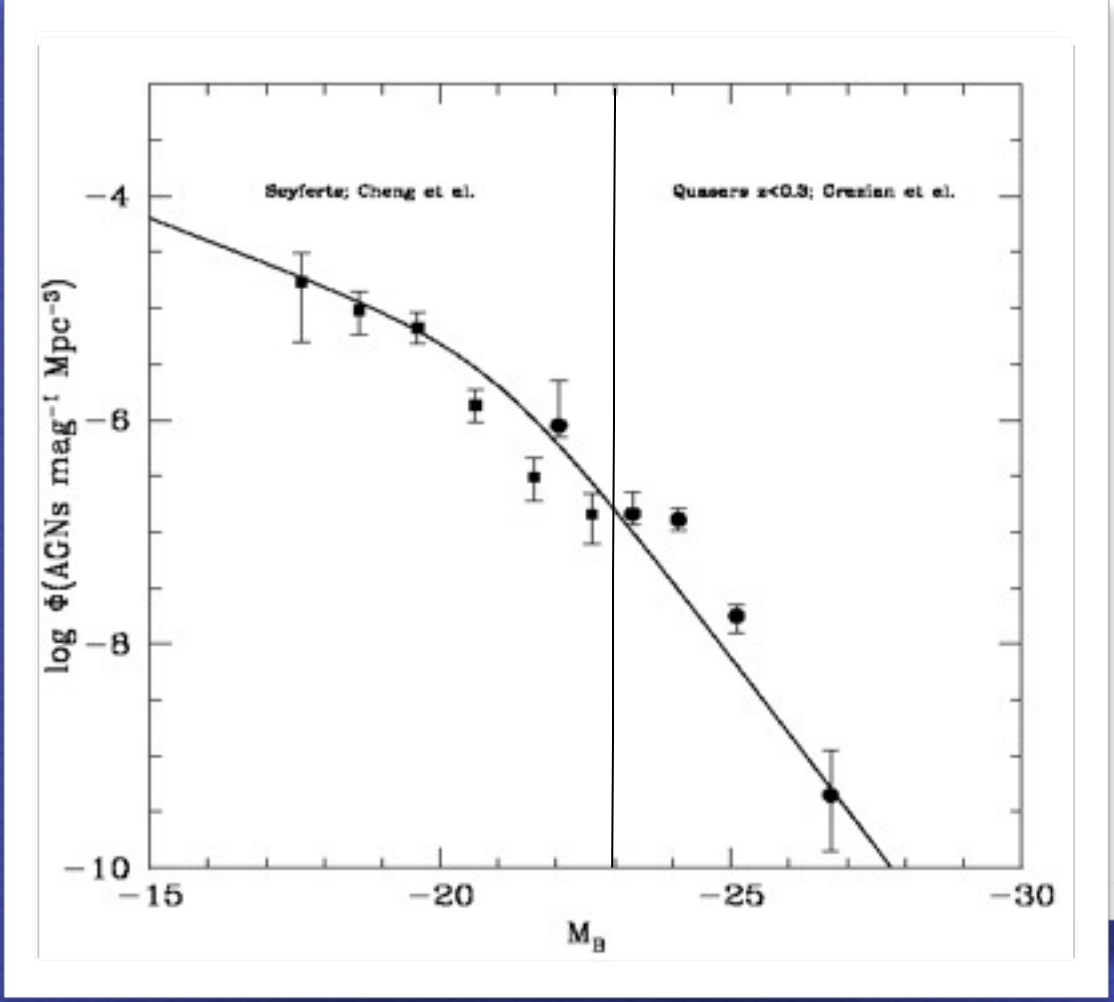
1. Quasars are plentiful
2. very luminous $L > 10^{48}$ erg s^{-1}
3. observed in an extremely broad range of redshift $0 < z < 7$
4. relatively stable

Broad (FWHM > 1000 km s^{-1}), low ionization (< 20 eV; Hβ, FeII,MgIIλ2800) and high ionization lines

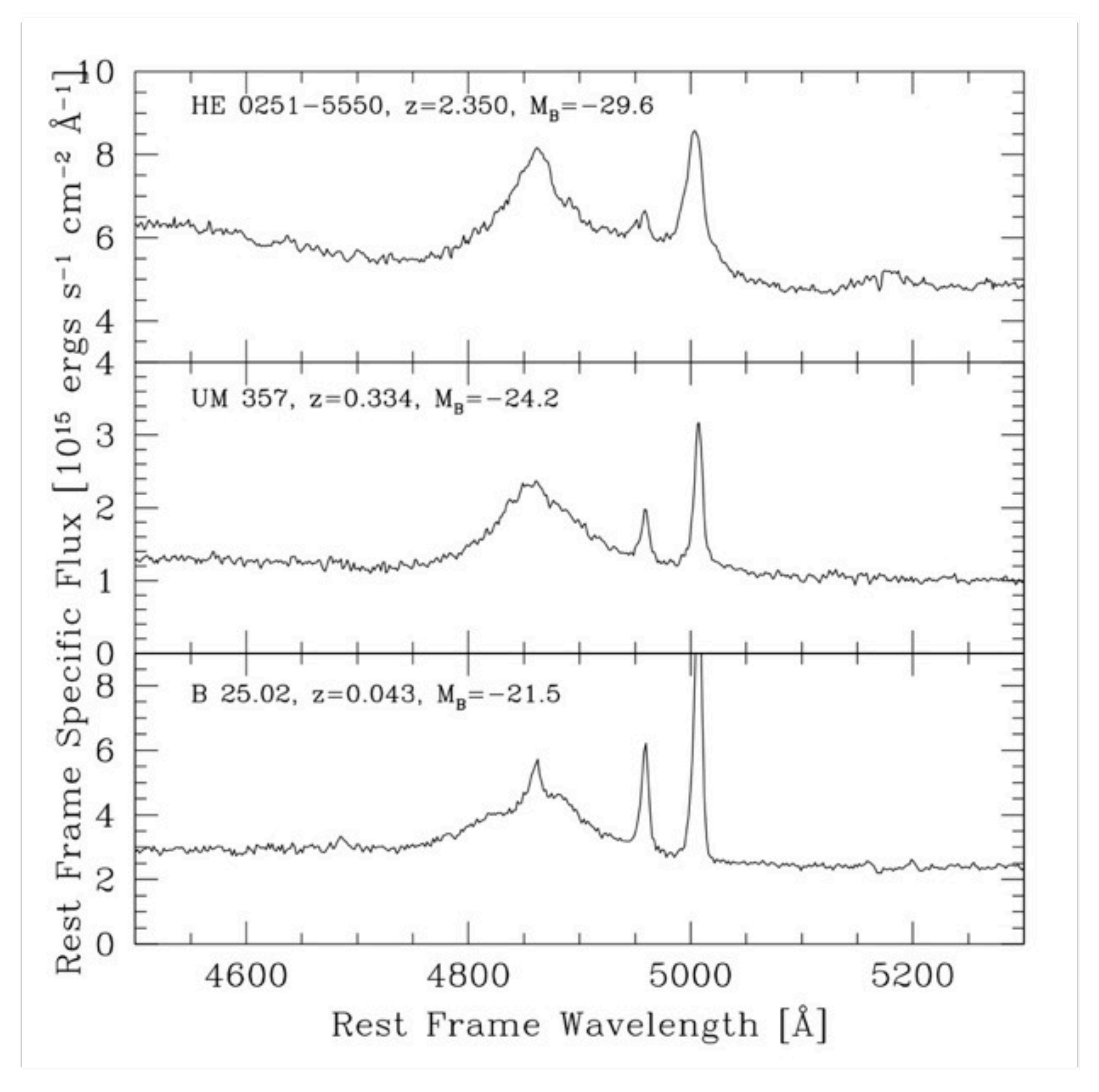
They are also sources with an evolving luminosity function, open-ended at low L



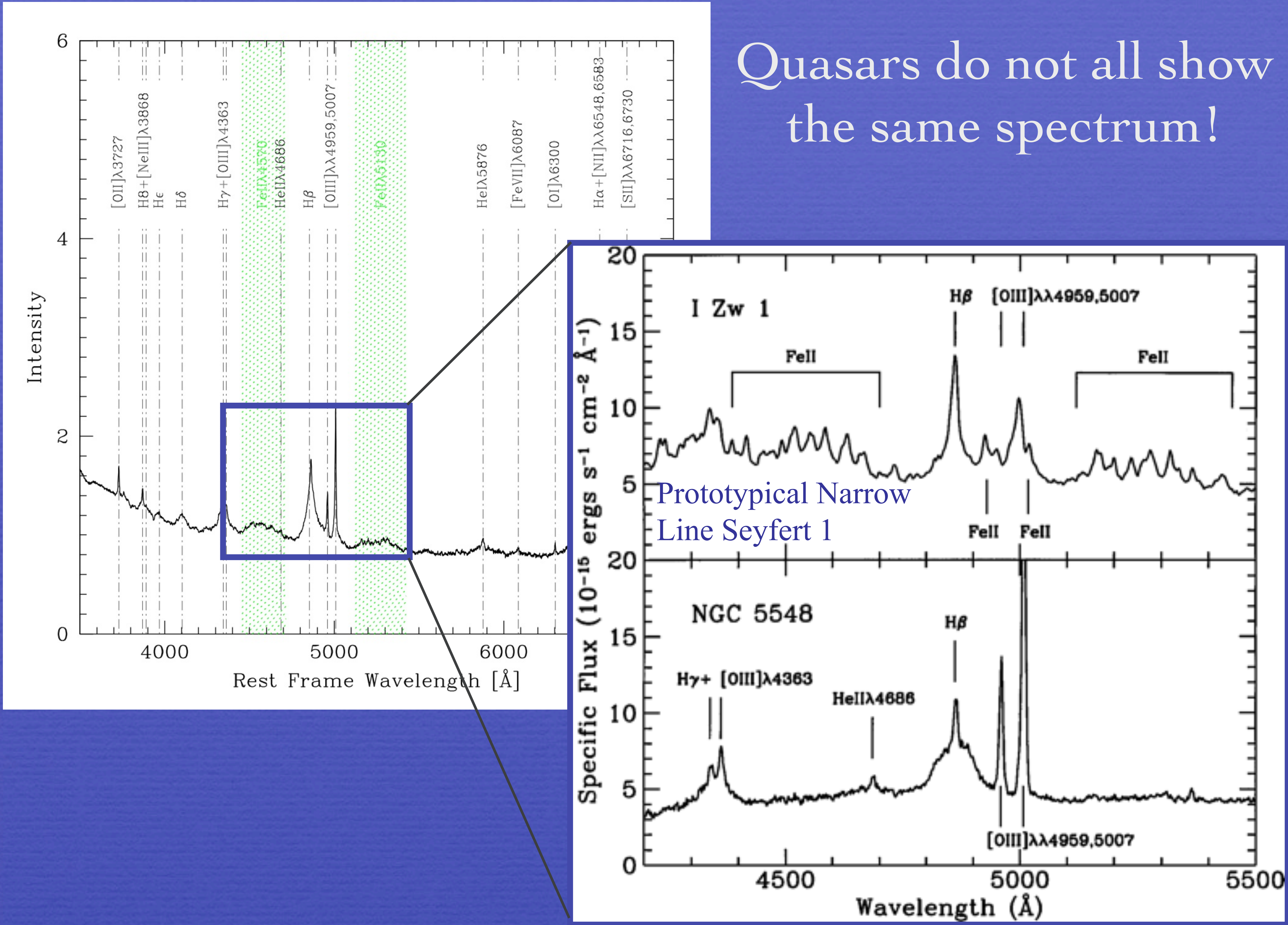
2dF; Boyle et al. 2001



Quasar spectral properties do not show *strong* signs of dependence on luminosity

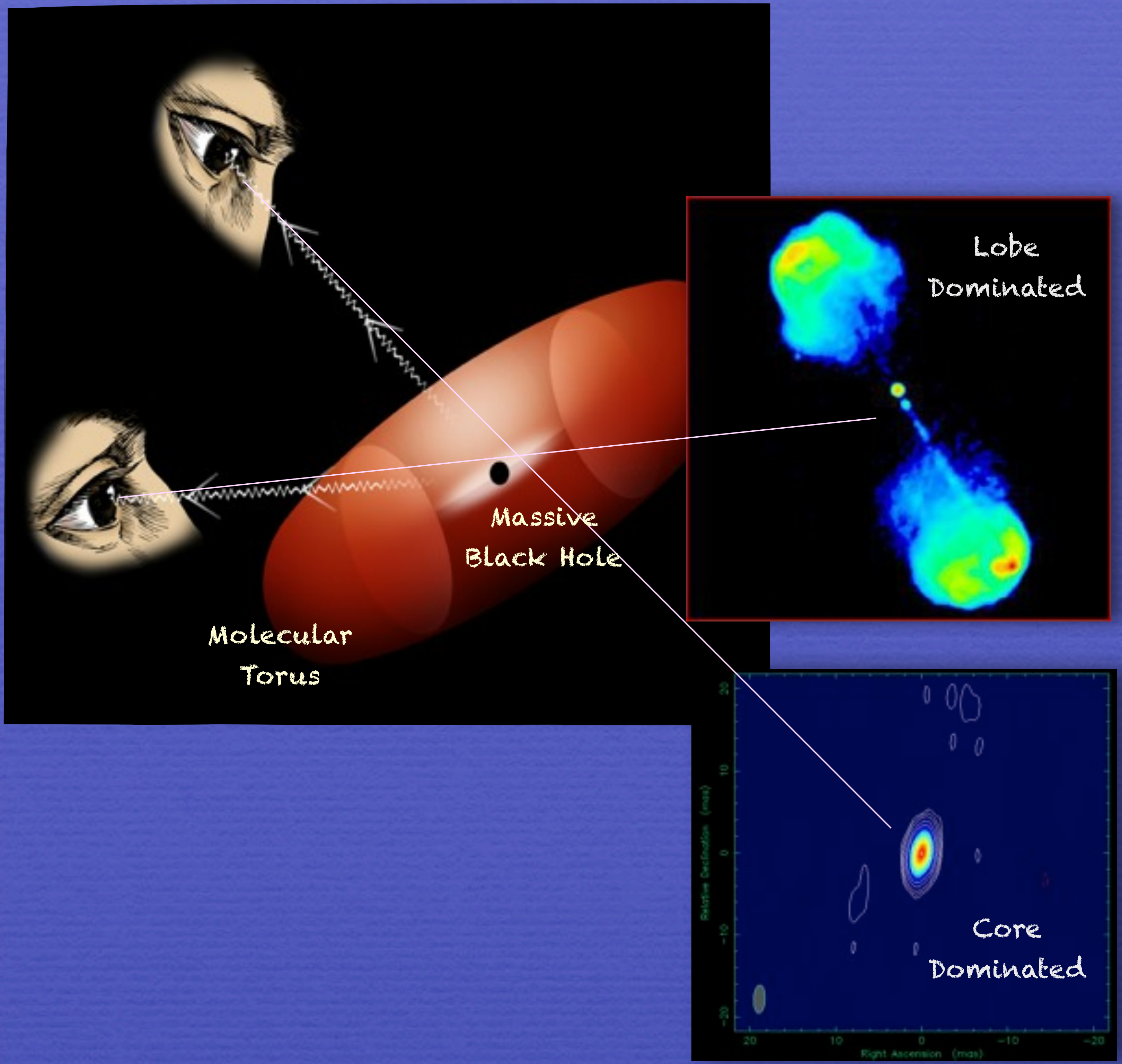


Quasars do not all show the same spectrum!



Prototypical Narrow Line Seyfert 1

Quasars are anisotropic sources



Relativistic beaming in Radio-Loud sources

Obscuring material co-axial with the accretion disk?

Beaming and orientation effects on

1) optical/UV spectroscopic properties is concerned

2) radio-quiet AGN

3) width of emission lines

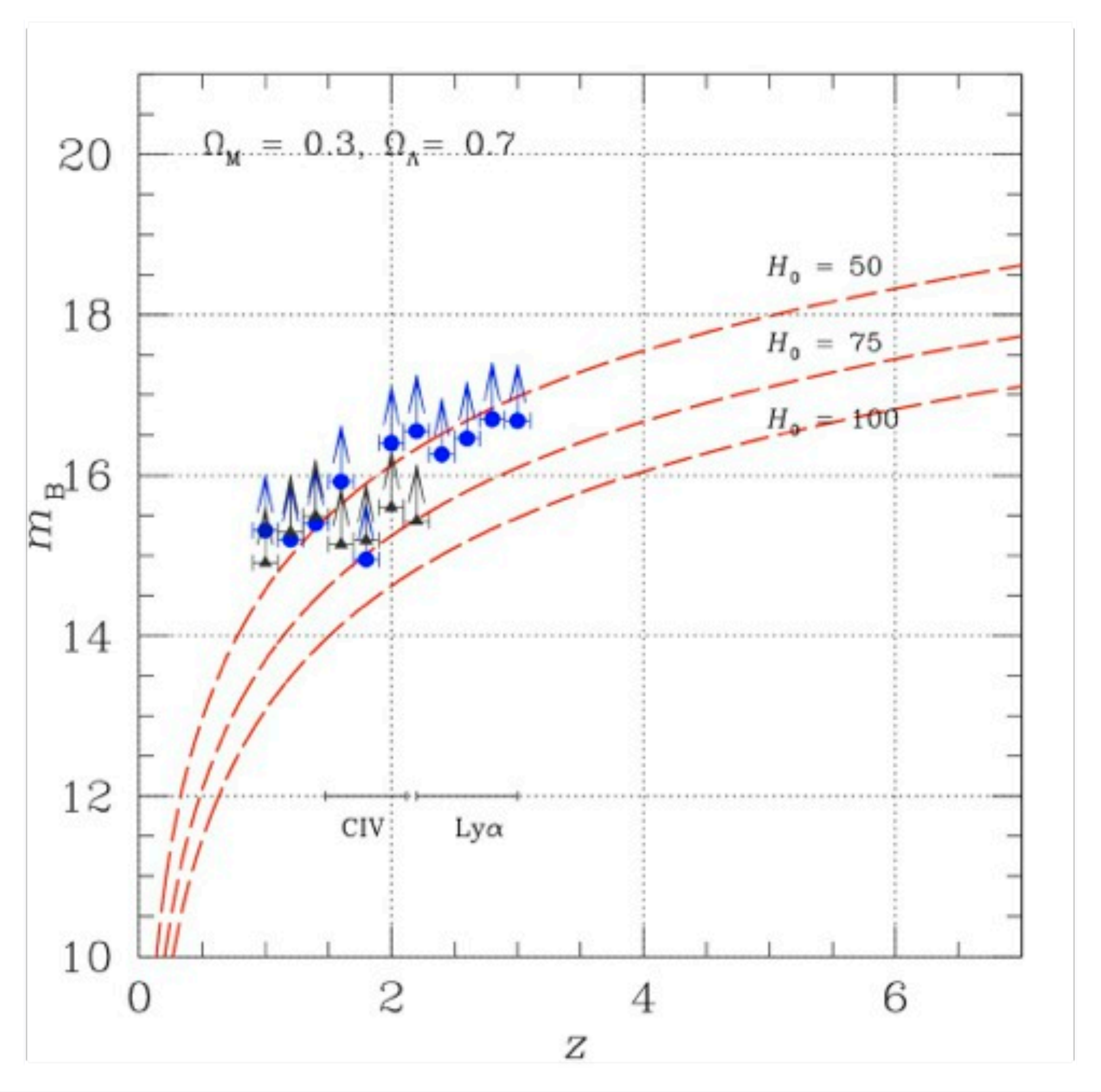
not yet fully understood

Can Quasars tell us anything on the geometry of the Universe?

Hubble diagram for the brightest quasars

Curves predict the apparent magnitude of a quasar of "maximum" mass radiating at Eddington limit

$H_0 \sim 60\text{-}70 \text{ km s}^{-1} \text{ Mpc}^{-1}$



Bartelmann et al. 2009

Several approaches were devised to exploit quasars for cosmology:

Correlations with Luminosity

the Baldwin Effect

Time delay methods (present and future)

Broad Line Region reverberation
[accretion disk reverberation]
[Gravitational lenses]

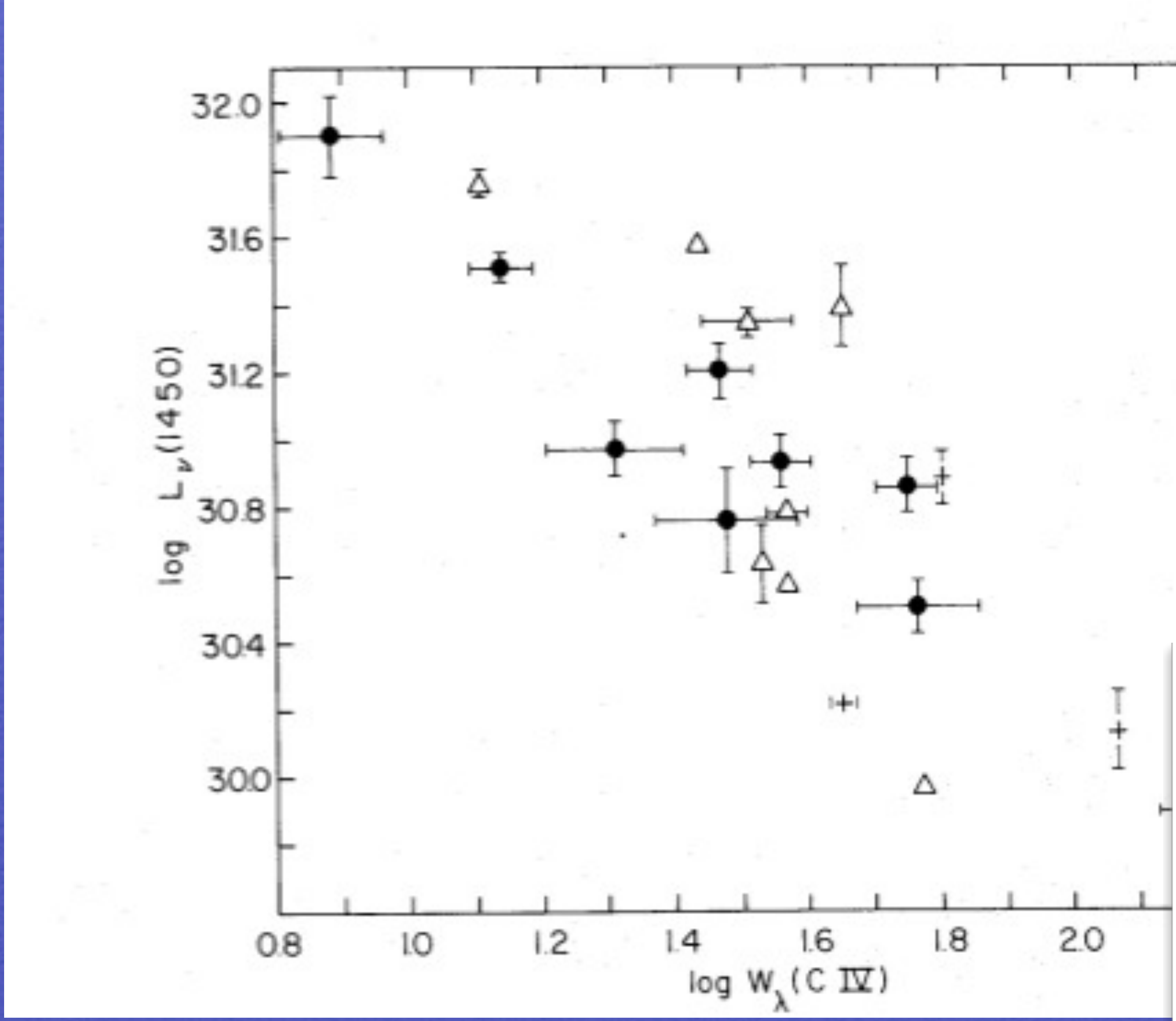
"Eddington standard candles"

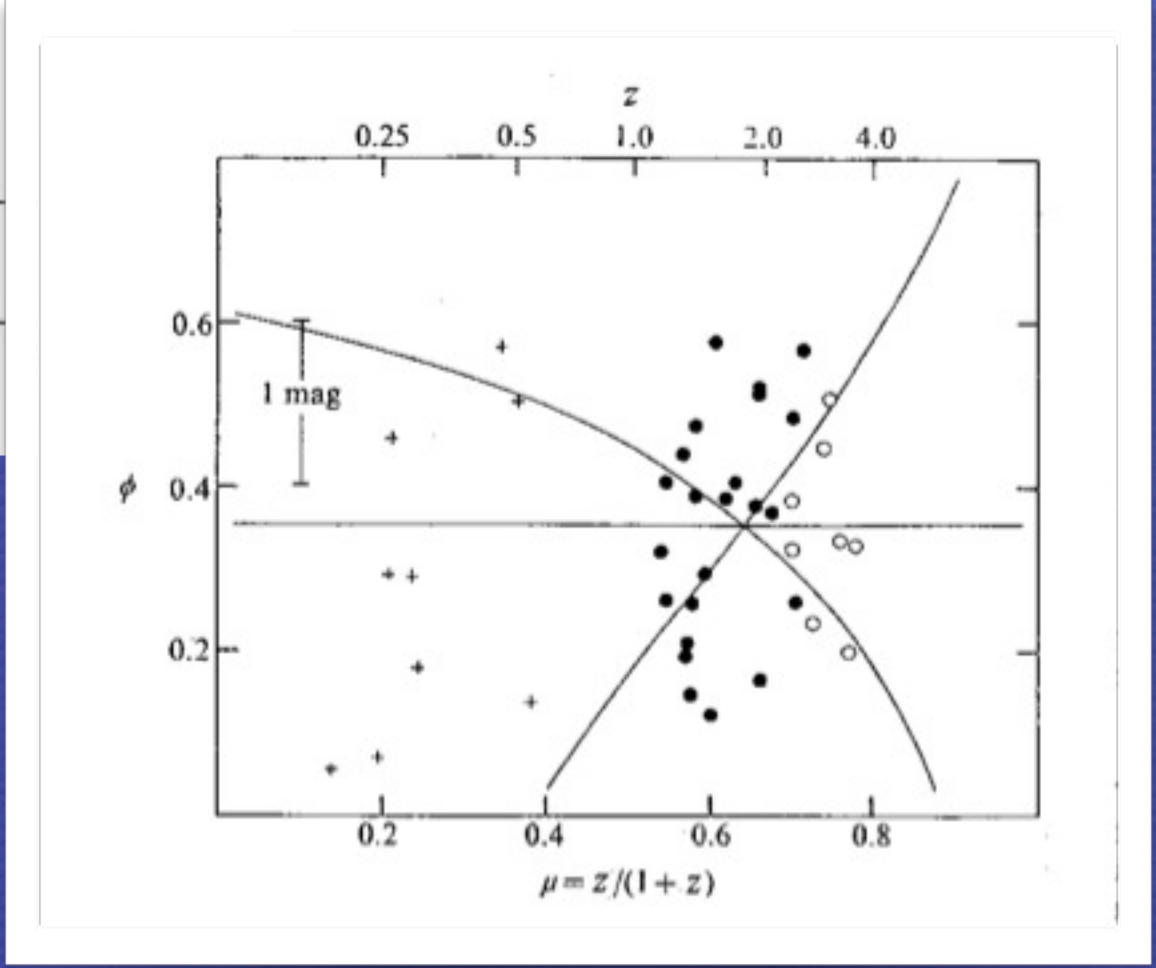
super-Eddington accreting massive black holes (SEAMBHs)
xA sources in 4D "eigenvector 1" space

Other methods

PCA, line widths, etc.
Baryon acoustic oscillations in the Lyα forest of BOSS quasars (Busca et al. 2013)

The Baldwin effect



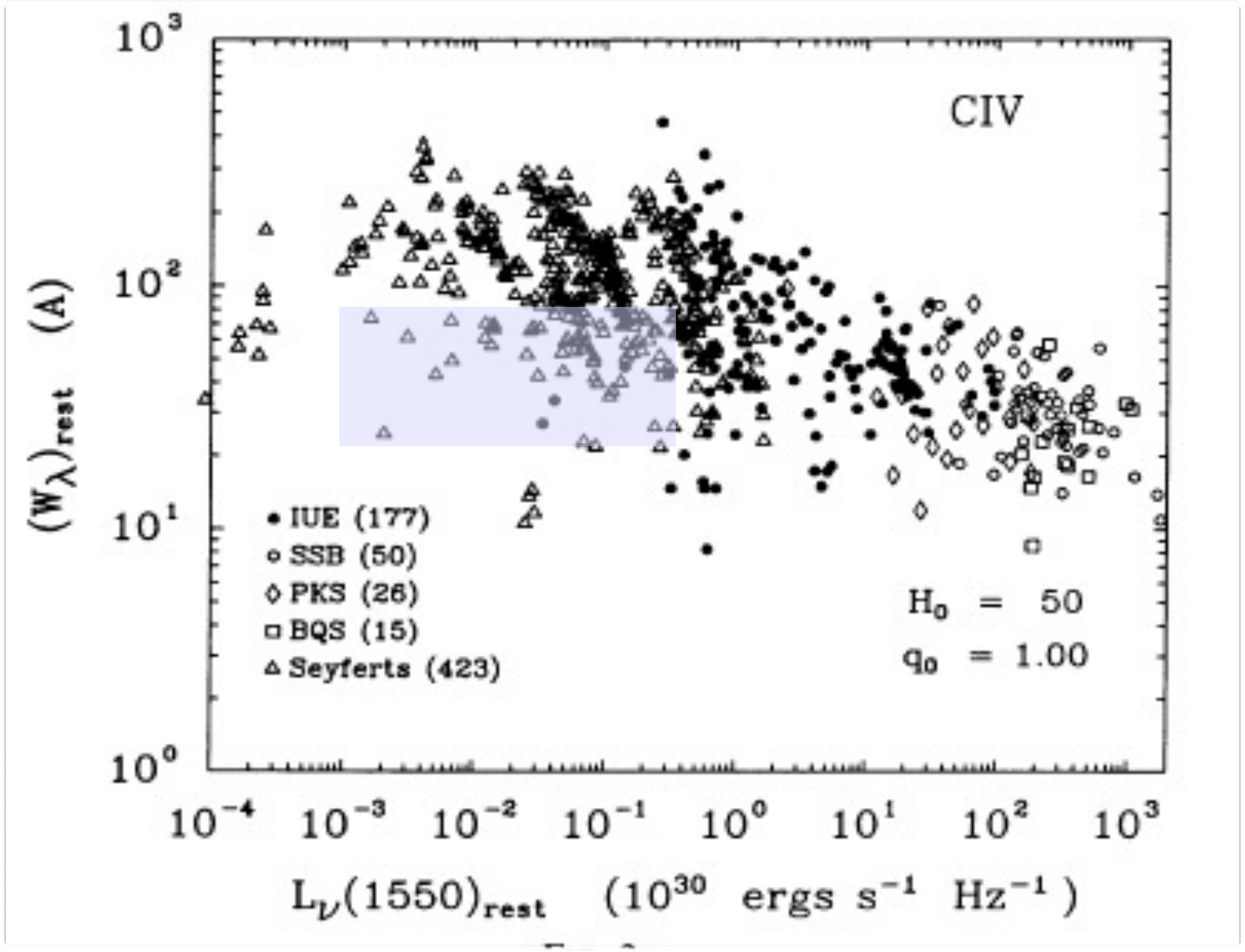


Baldwin et al. (1977,1978)

… already some tentative inferences from a modified Hubble diagram

The Baldwin effect: a more modern assessment

(see Sulentic et al., 2000, ARAA 38,521 for a synopsis up to mid-1999)



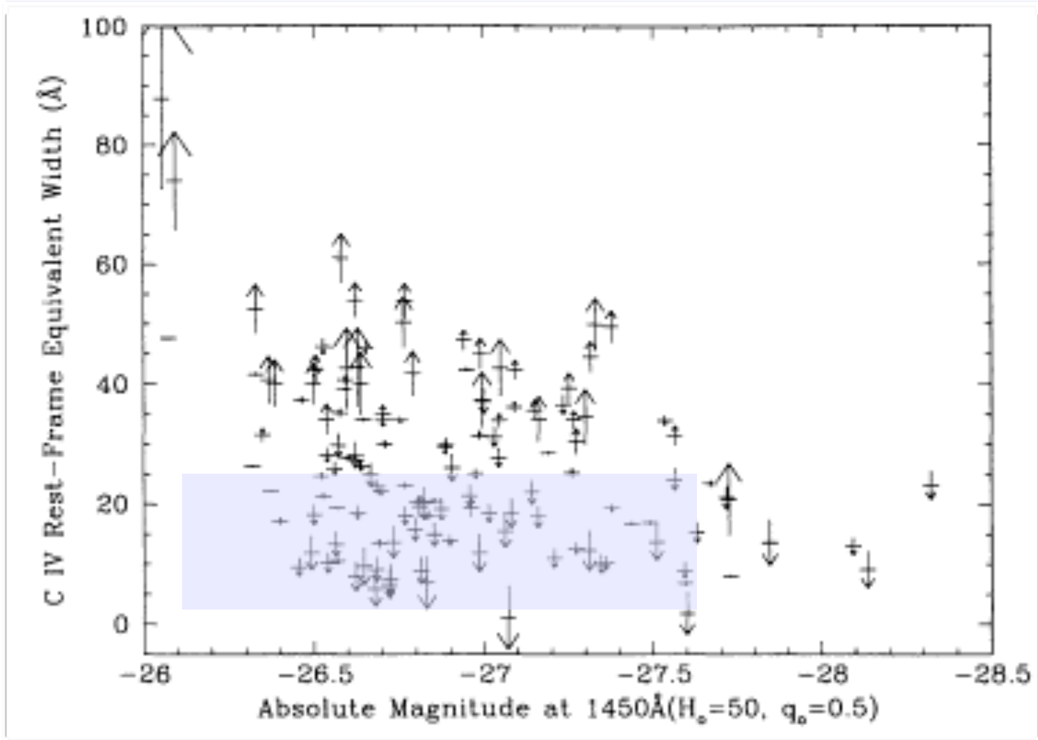
Kinney et. al. 1990

Weak Anticorrelation

(Dietrich et al. 2002; Croom et al. 2002; Xu et al. 2009, Bian et al. 2012)

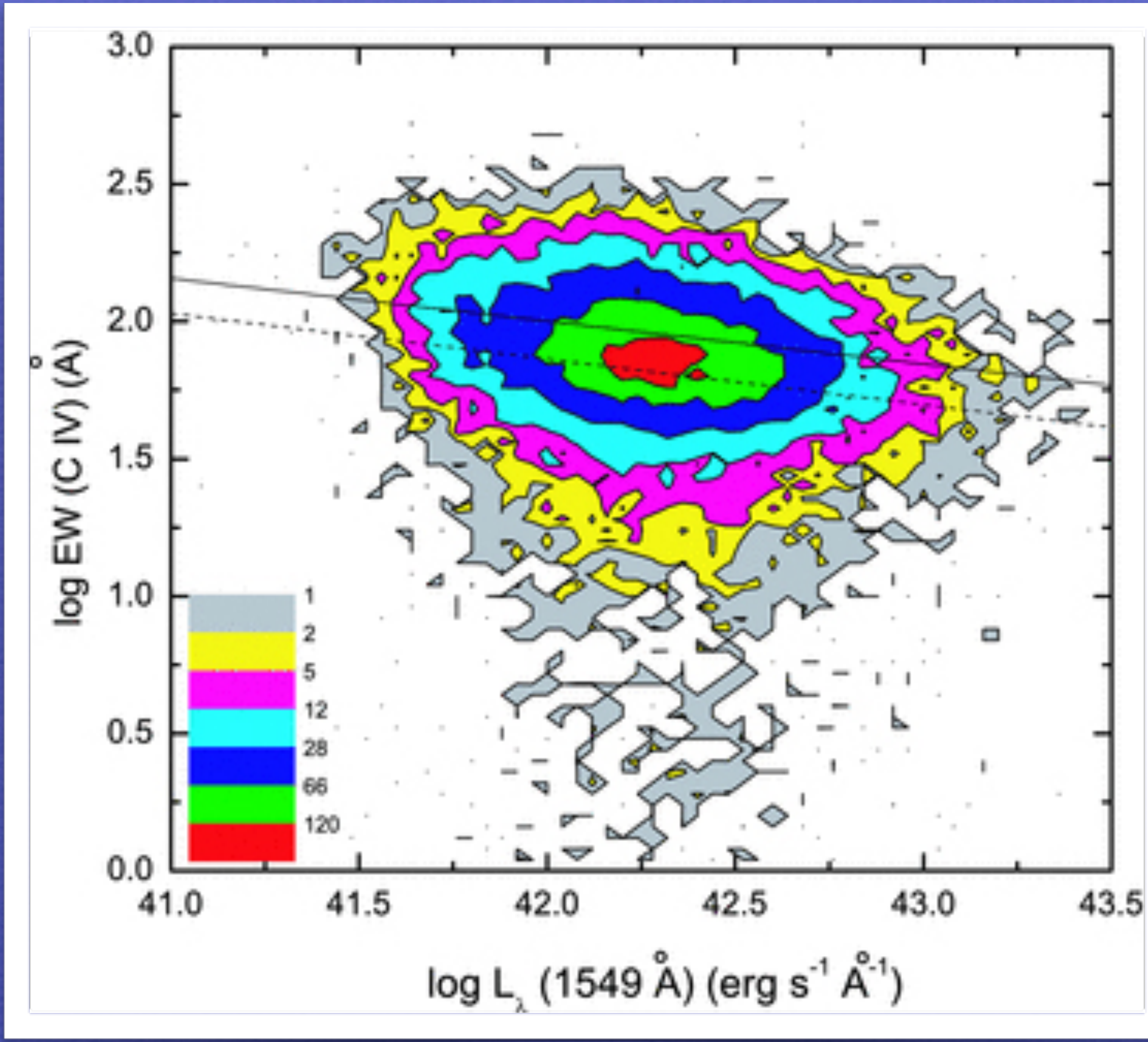
The cosmological expectations raised by the original Baldwin Effect did not live up to the dispersion

NLSy1



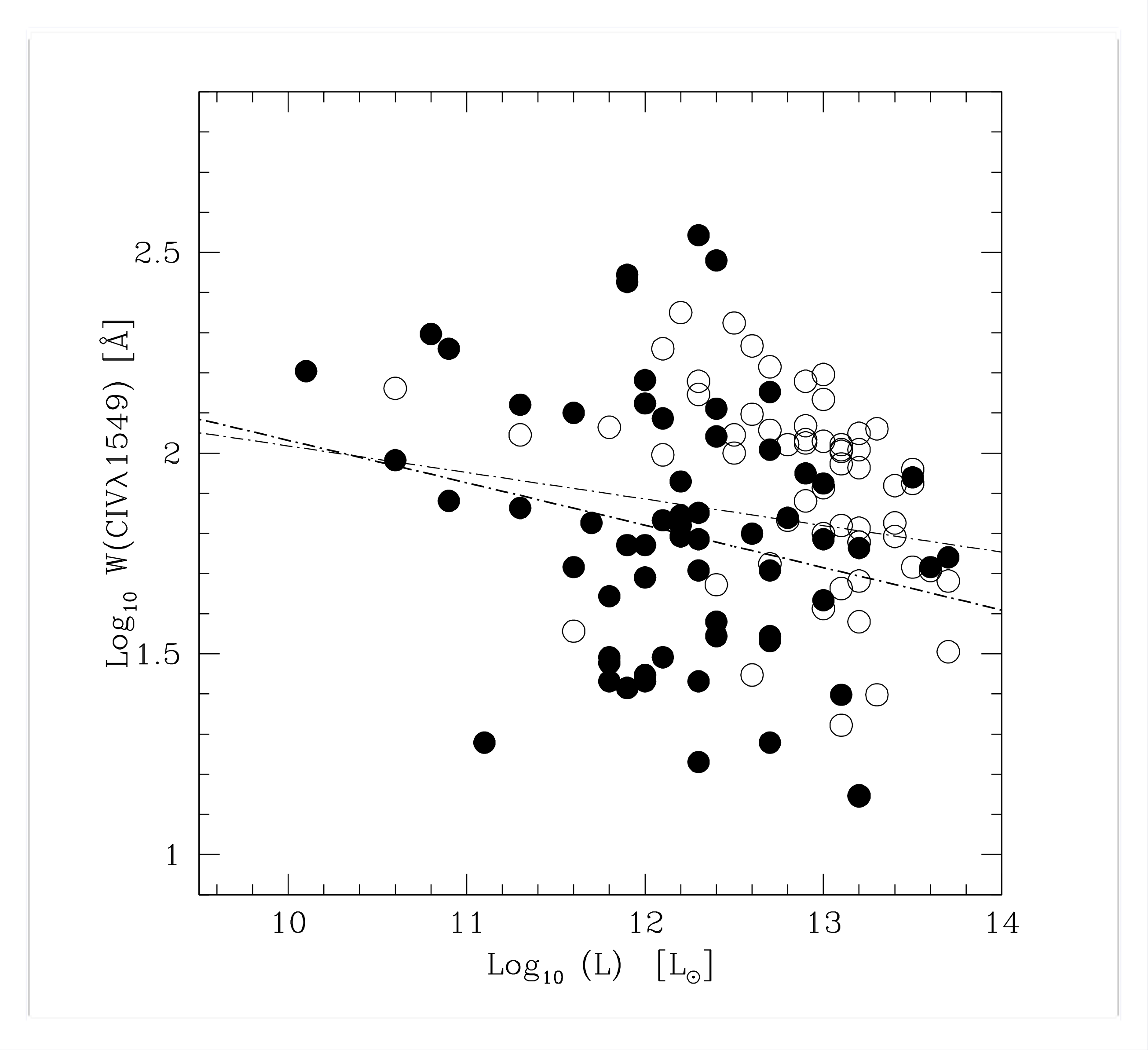
Brotherton & Francis 1999

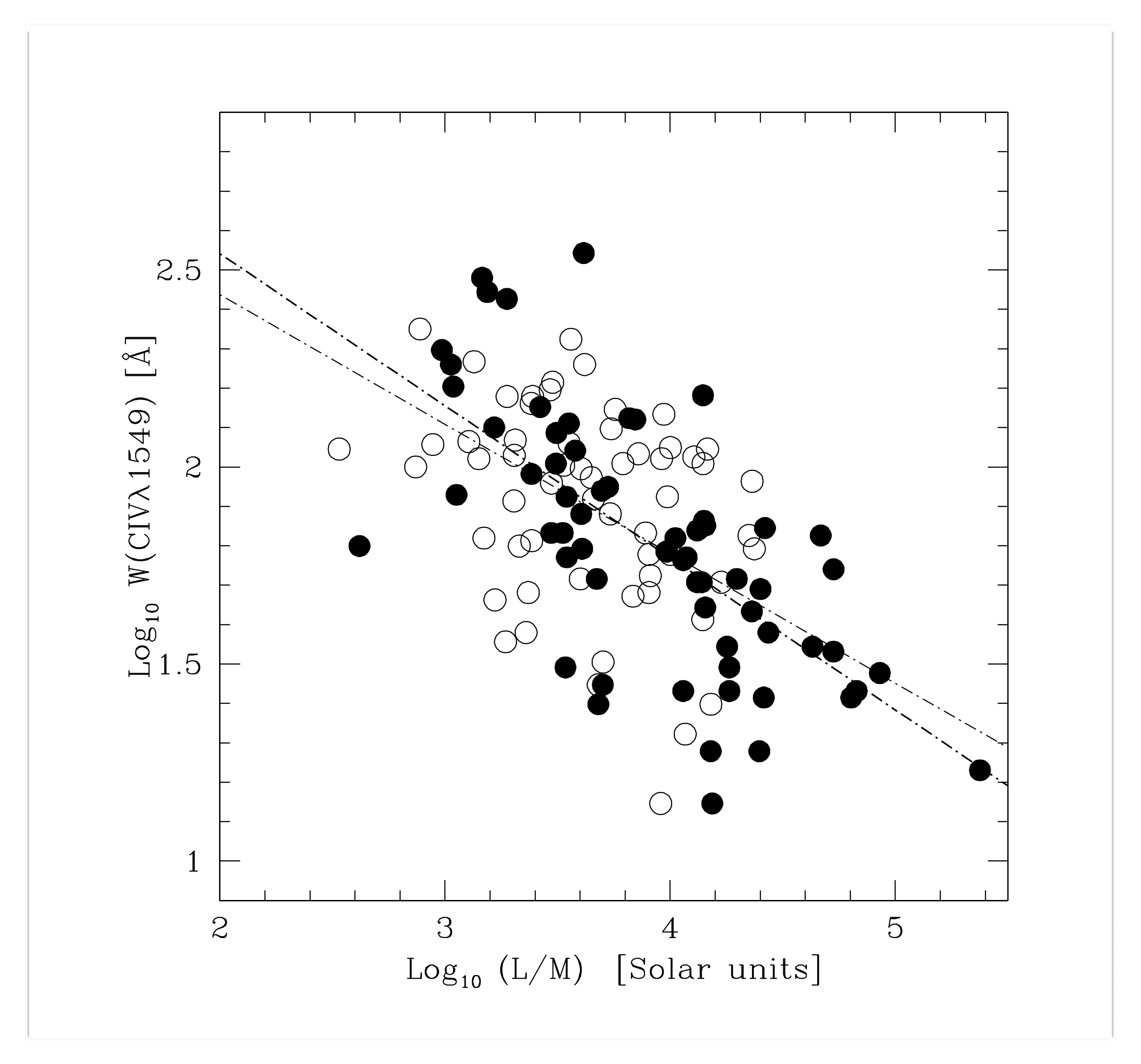
The Baldwin effect confirmed by recent SDSS-based studies



Xu et al. 2008; c.f. Bian et al. 2012

What is the origin of the Baldwin effect? Is there any hope to use it for cosmology?





Baldwin effect: dependence on Eddington ratio is stronger

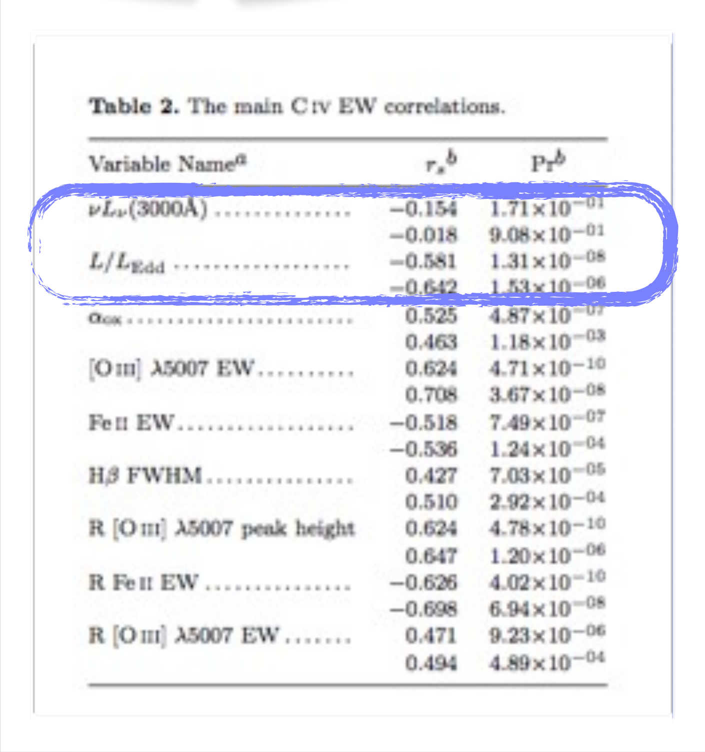
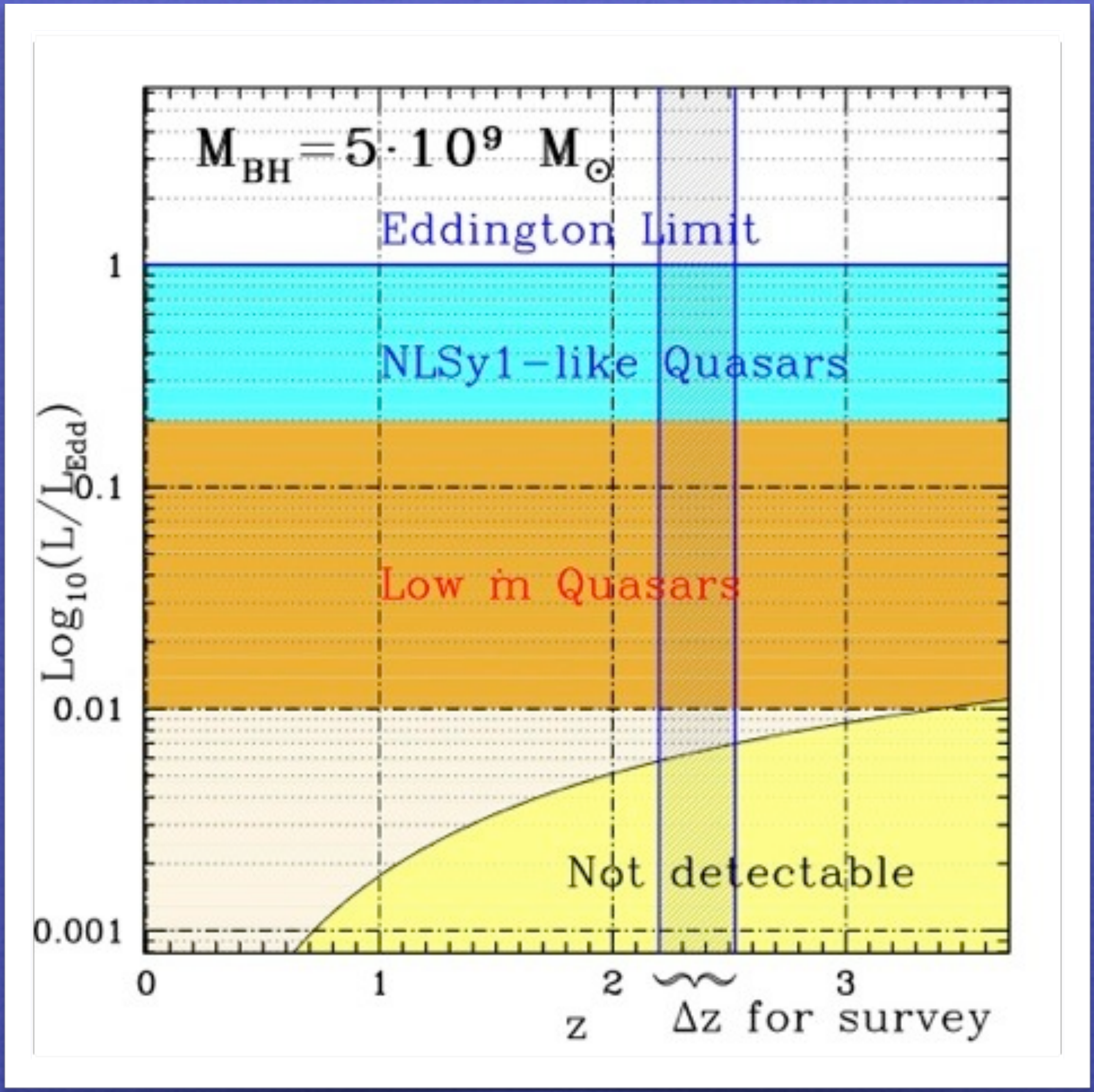


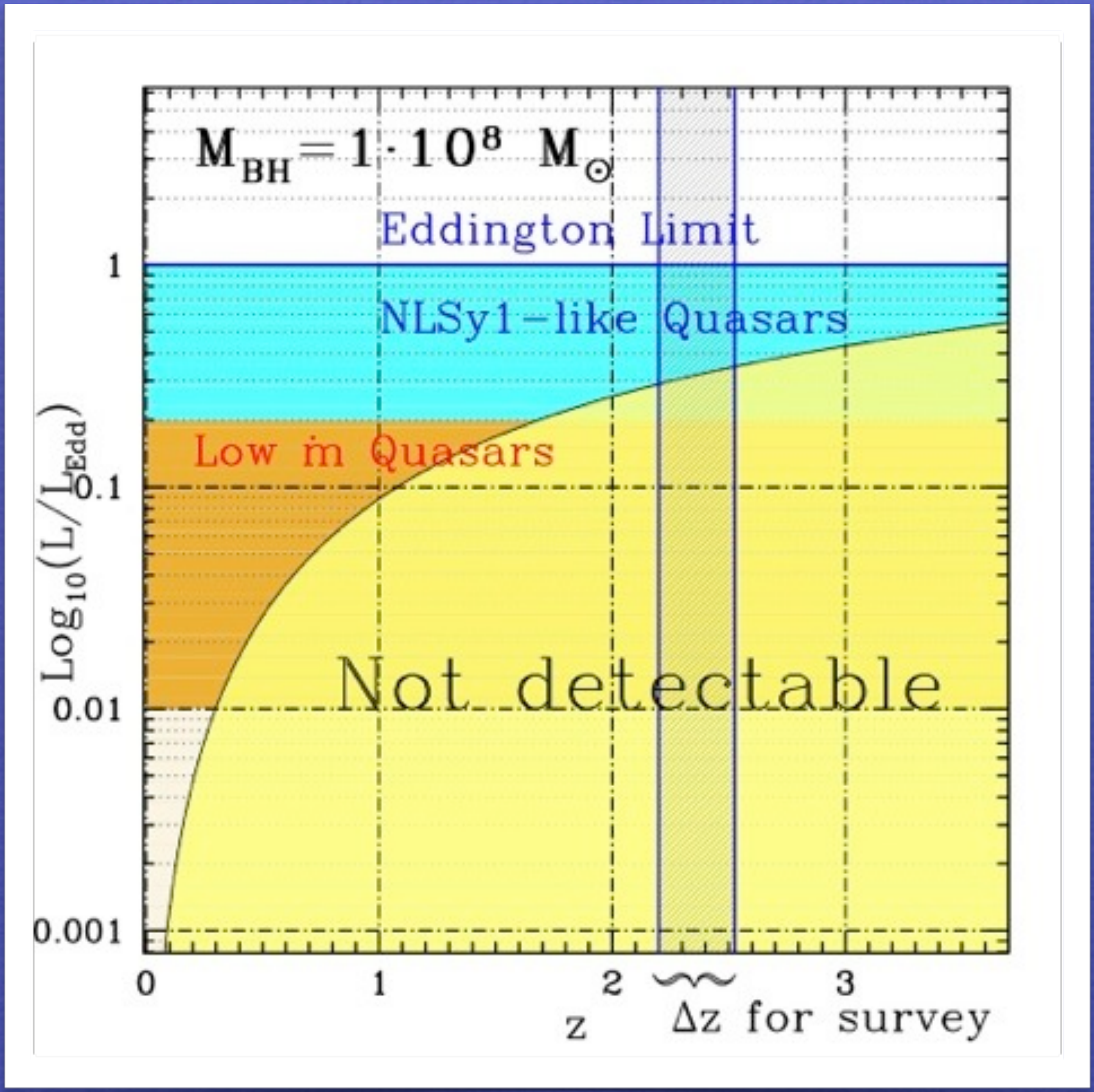
Table 2. The main C IV EW correlations.

Variable Name^a	$r_s{}^b$	Pr^b
νL_ν(3000Å)	−0.154	1.71×10^{-01}
	−0.018	9.08×10^{-01}
$L/L_{\rm Edd}$	−0.581	1.31×10^{-08}
	−0.642	1.53×10^{-06}
$\alpha_{\rm ox}$	0.525	4.87×10^{-07}
	0.463	1.18×10^{-03}
[O III] λ5007 EW	0.624	4.71×10^{-10}
	0.708	3.67×10^{-08}
Fe II EW	−0.518	7.49×10^{-07}
	−0.536	1.24×10^{-04}
Hβ FWHM	0.427	7.03×10^{-05}
	0.510	2.92×10^{-04}
R [O III] λ5007 peak height	0.624	4.78×10^{-10}
	0.647	1.20×10^{-06}
R Fe II EW	−0.626	4.02×10^{-10}
	−0.698	6.94×10^{-08}
R [O III] λ5007 EW	0.471	9.23×10^{-06}
	0.494	4.89×10^{-04}

Bachev et al. 2004; Baskin & Laor 2005; Sulentic et al. 2007; Marziani et al. 2008

Selection effects on a flux limited sample





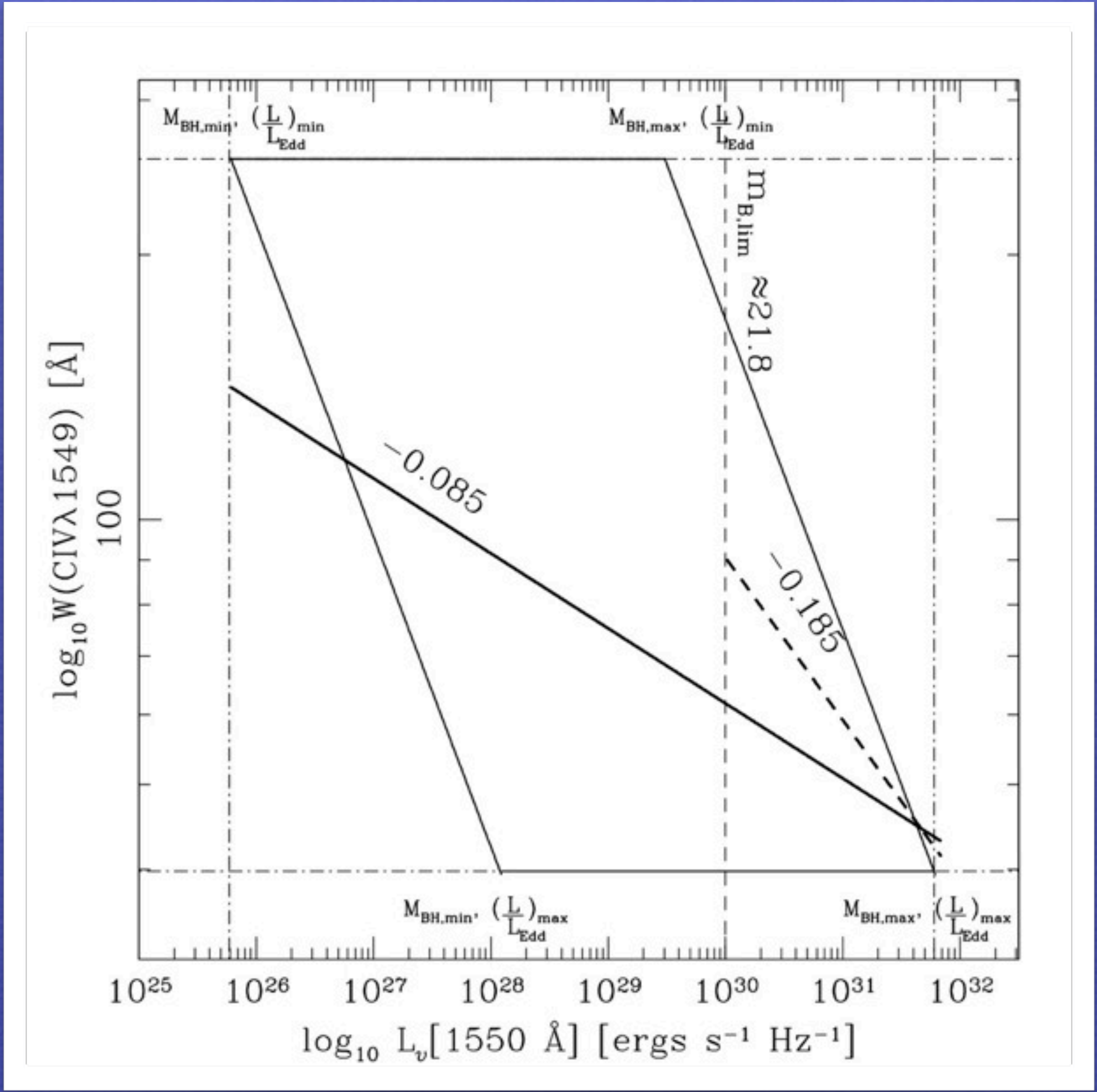
Spectral evolution results (the “Baldwin effect”) could be mainly due to selection effects

“Theoretical” BE plane W(CIVλ1549) vs L_ν

The expected Baldwin effect slope computed assuming:

- An *L/M* distribution as observed for low-z quasars;
- The relation *L/M*-W(CIVλ1549) derived for low-*z* quasars

A slight anti-correlation is expected in a volume limited sample at a fixed *z*; it becomes steeper if a flux-limit is introduced. Eddington ratio evolution enhances the effect.



(Marziani et al. 2008)

1) Any linear size that can be used as a standard ruler?

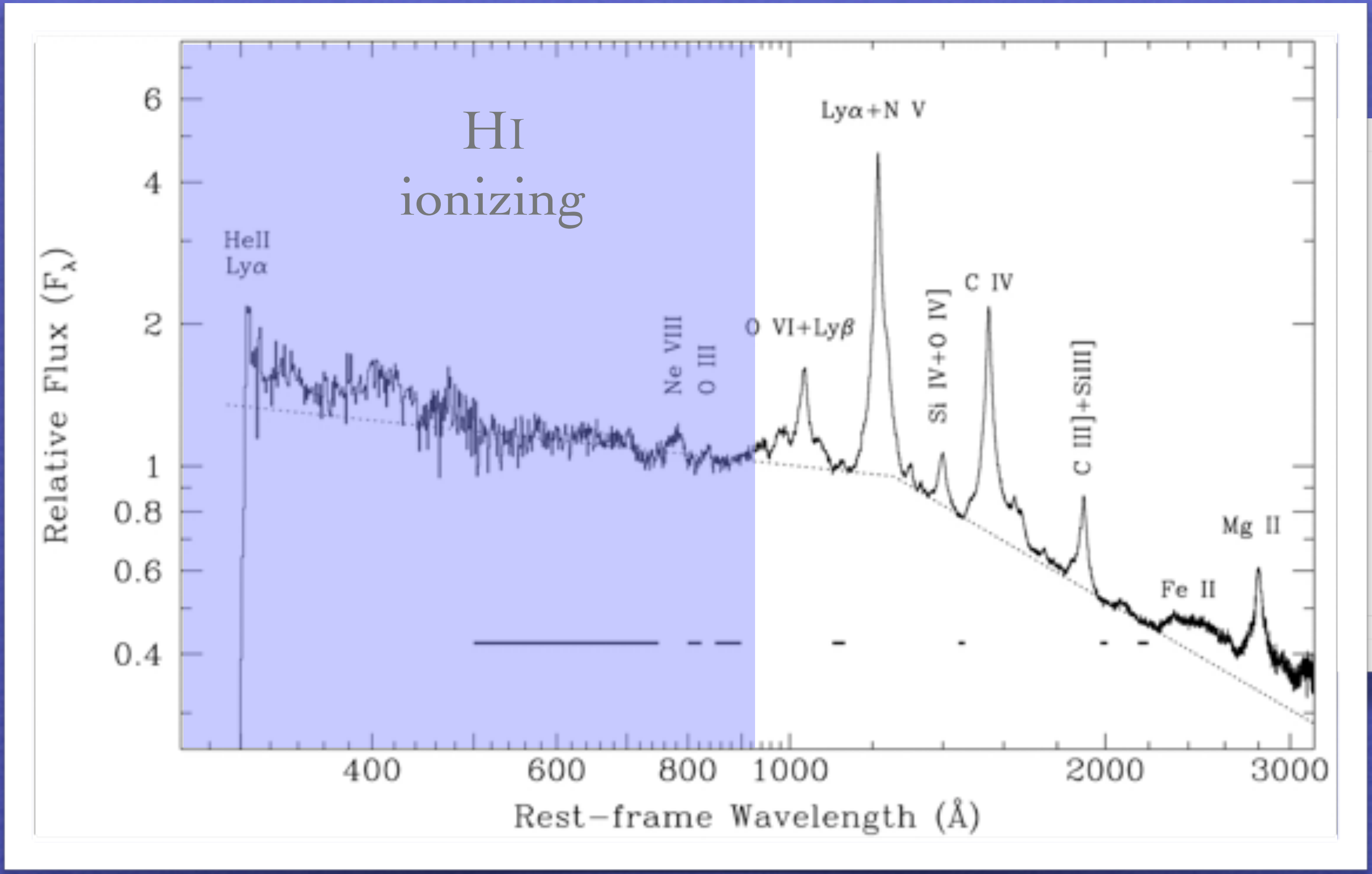
2) Accretion onto a massive compact object

Accretion rate (L_{bol}): dependences too weak and affected by selection effects;

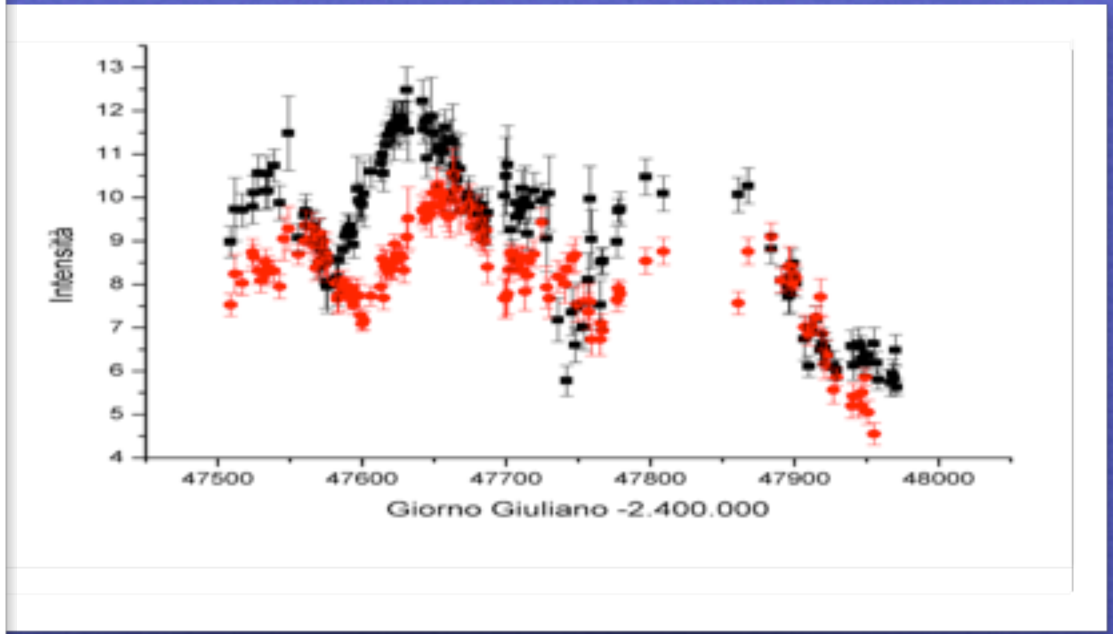
an almost self similar phenomenon over an extremely wide range of black hole mass (M_{BH});

Eddington ratio ($L_{\mathrm{bol}}/M_{\mathrm{BH}}$).

Line luminosity due to photoionization by FUV continuum
Lines respond to continuum luminosity change



Telfer et al. 2002



B. Peterson & the International AGN Watch

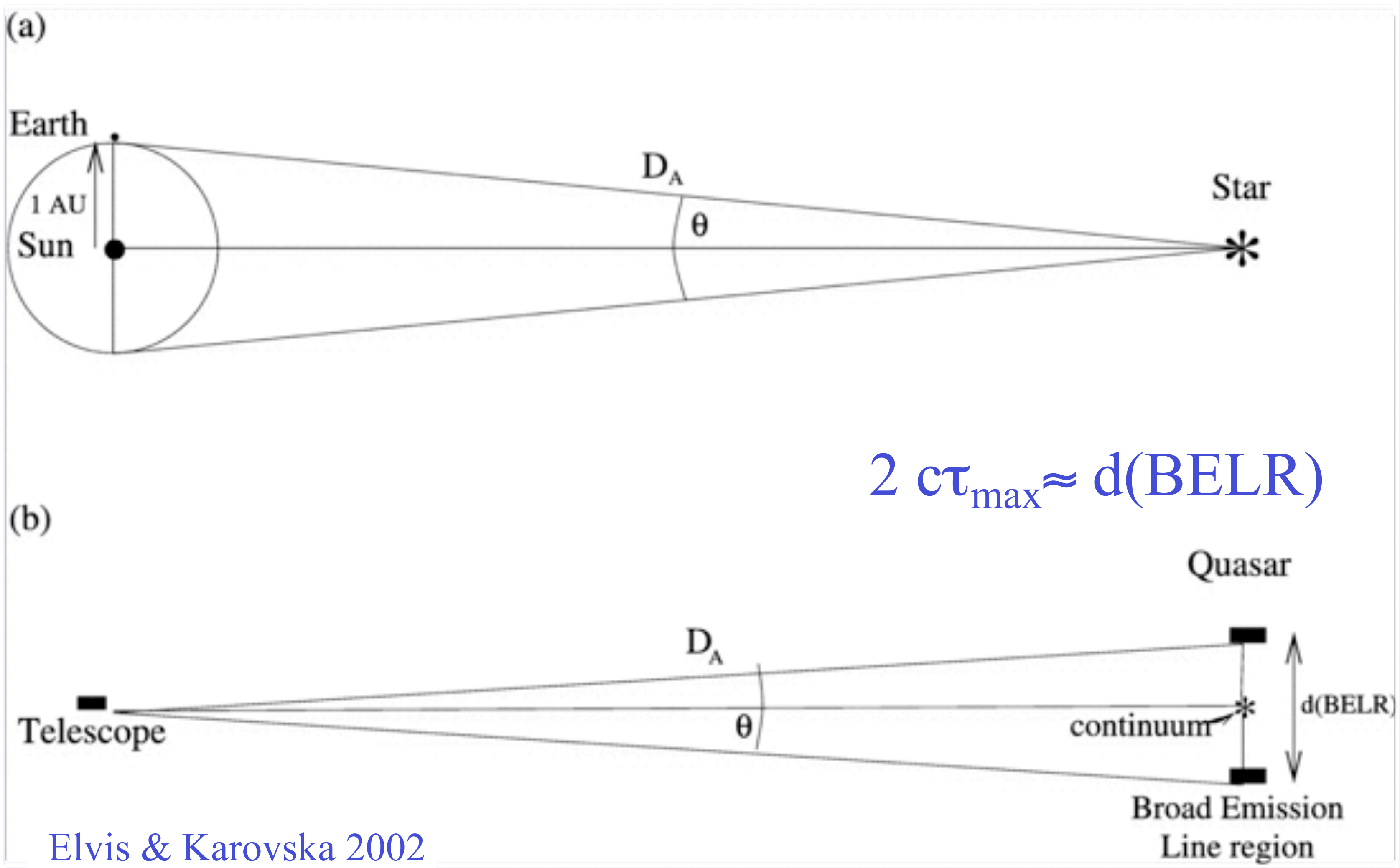
Emitting region distance r_{BLR} from central continuum source

Peak or (centroid) of the cross-correlation function between line and continuum

$$\mathrm{CCF}(\tau) = \int \mathcal{L}(t)\mathcal{C}(t+\tau)dt$$

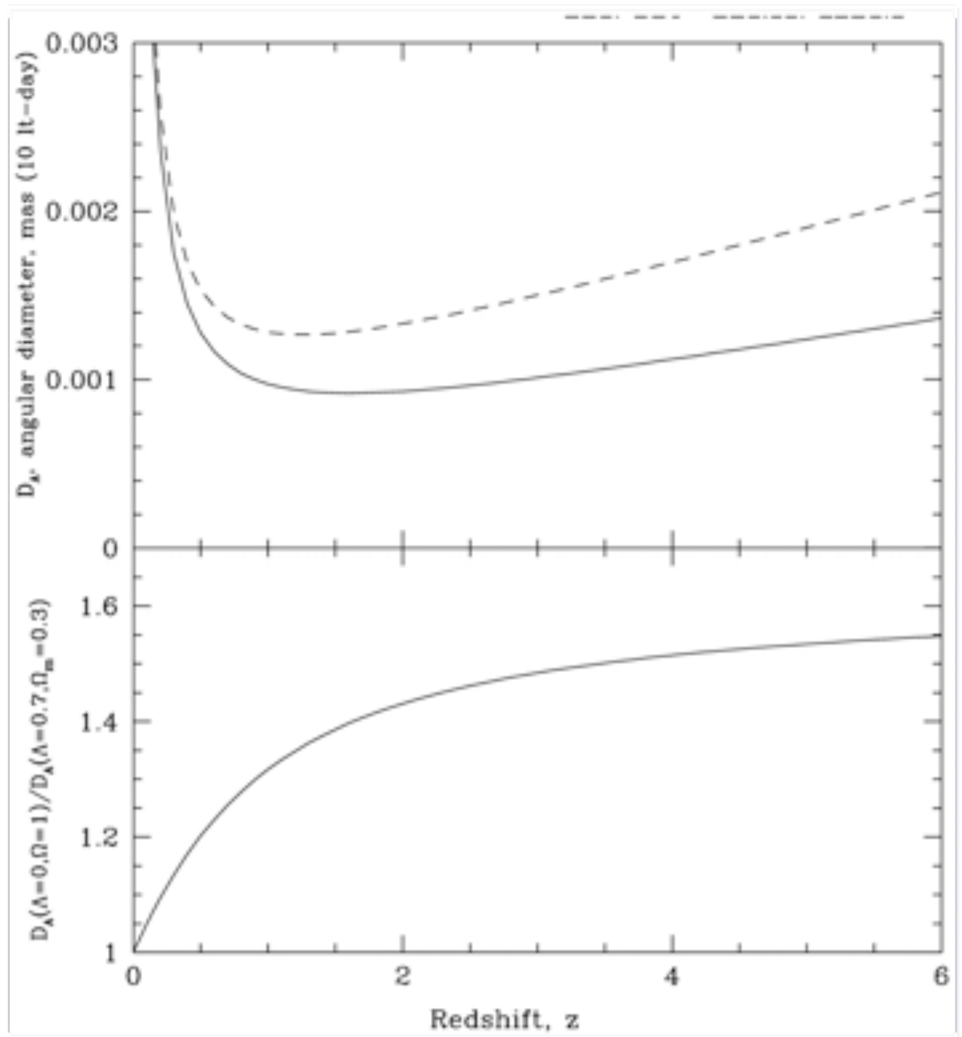
$r_{\mathrm{BLR}} = c\tau_{\mathrm{H}\beta}$from H$\beta$ available for ~60 low-z AGN as of early 2013

(Kaspi et al. 2005, Bentz. et al. 2009; 2013)



$2\, c\tau_{max} \approx d(\mathrm{BELR})$

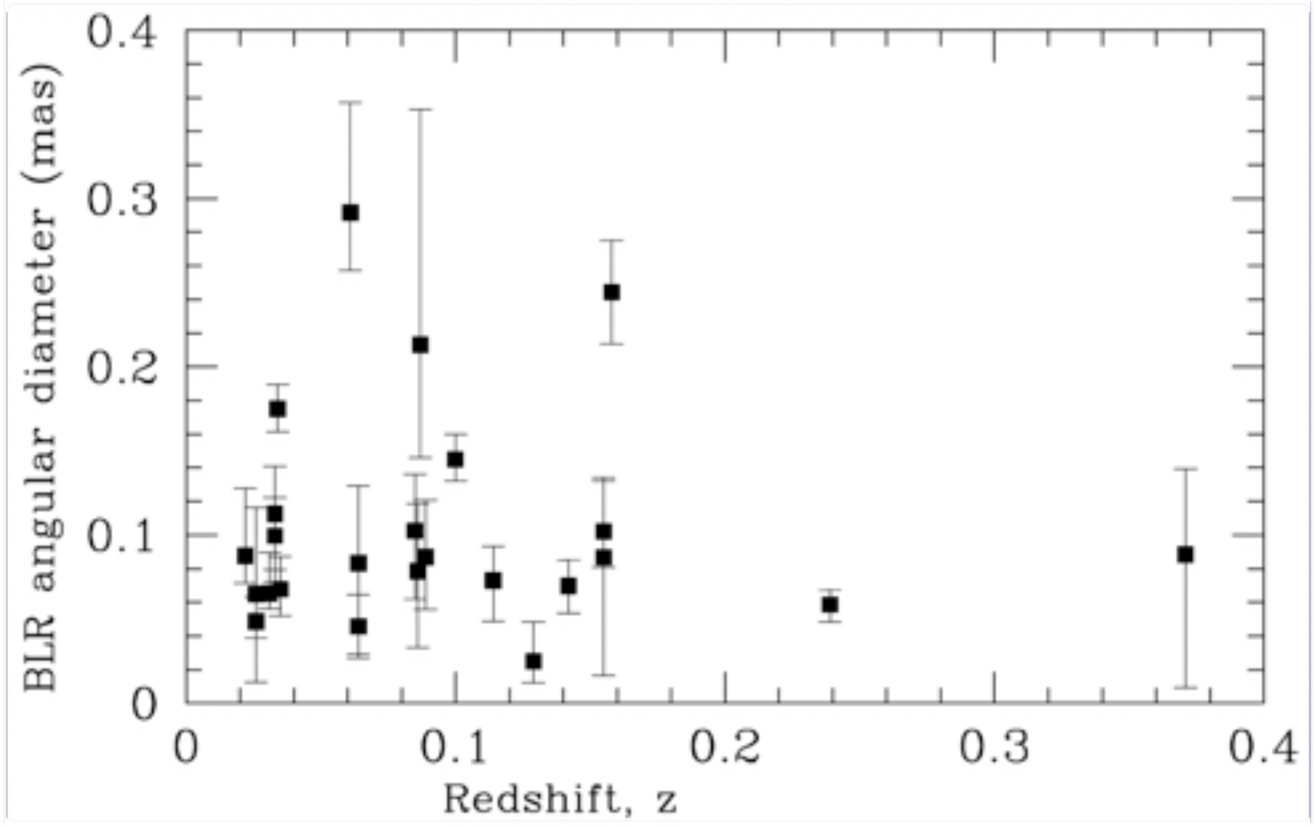
Elvis & Karovska 2002



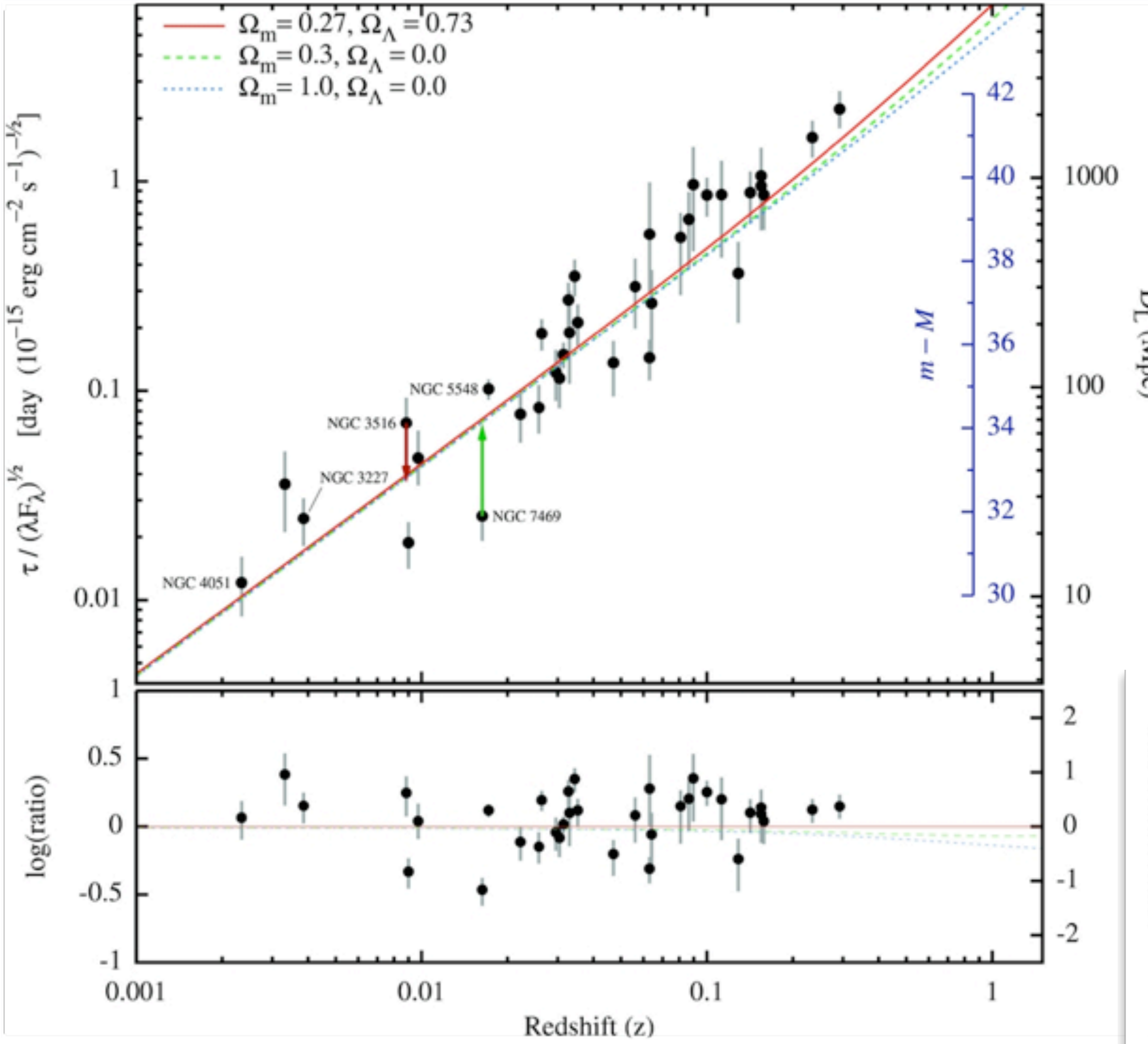
In an ideal world…

$R_{\rm BLR}$ from rev. mapping measurements;
angular size measurements
(i.e., resolved images of the BLR
solve for cosmology)

$$\theta'' = \frac{c\tau}{d_{\rm A}(H_0, \Omega_{\rm M}, \Omega_\Lambda)}$$



cτ from reverberation as a standard ruler

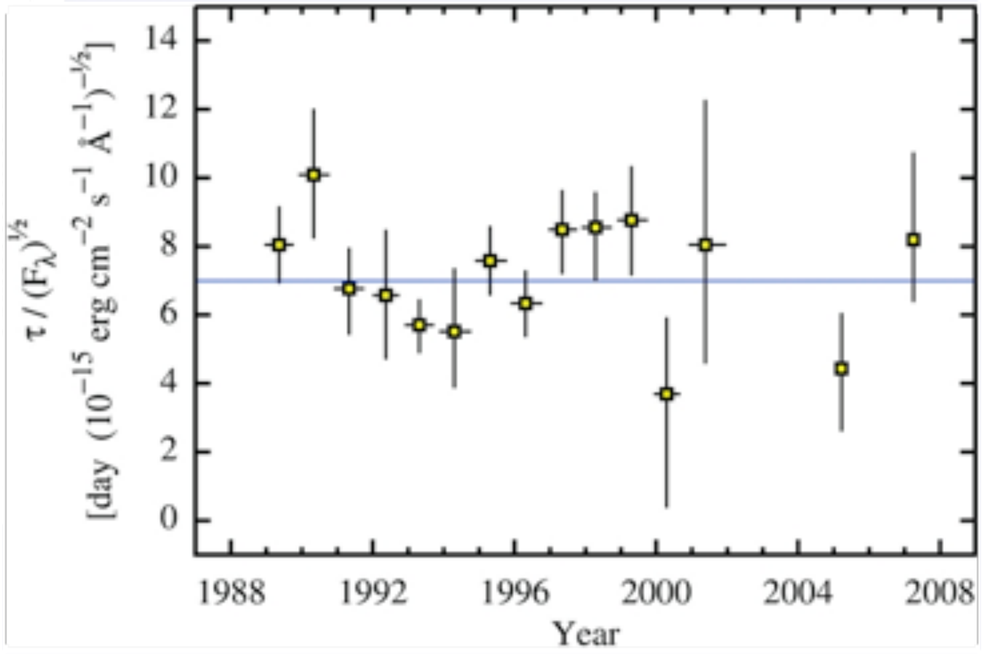


Watson et al. 2011

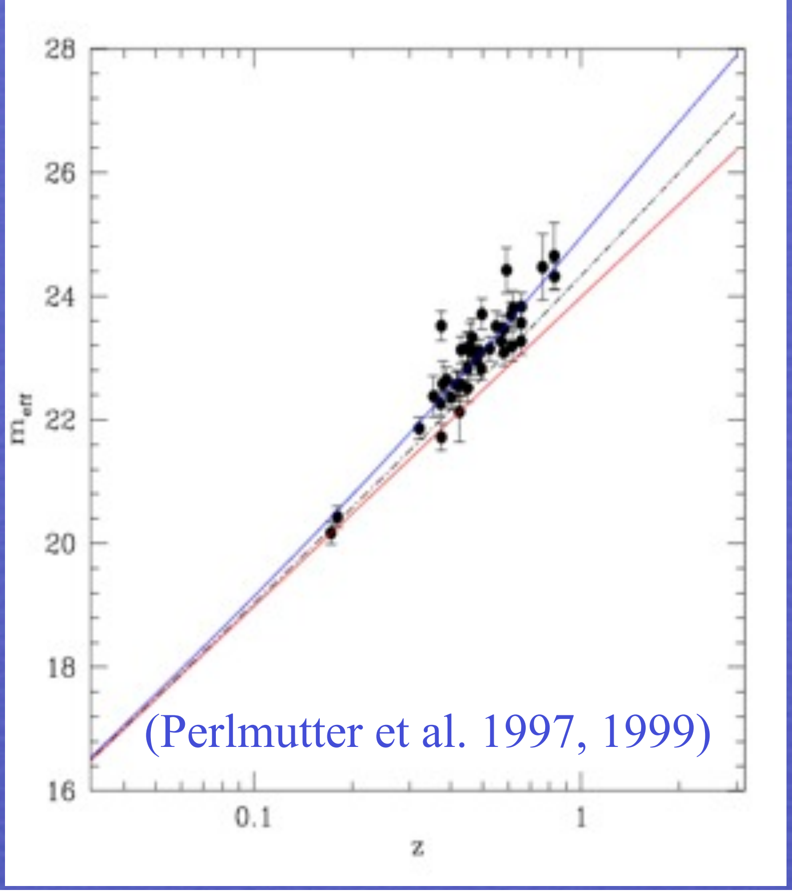
Great promise with photometric reverberation

$$\tau \propto \sqrt{L}$$

$$\frac{\tau}{\sqrt{\lambda f_\lambda}} \propto d_{\rm L}$$



A parenthesis: 1997 - 2013, Supernovae, CMB, etc.

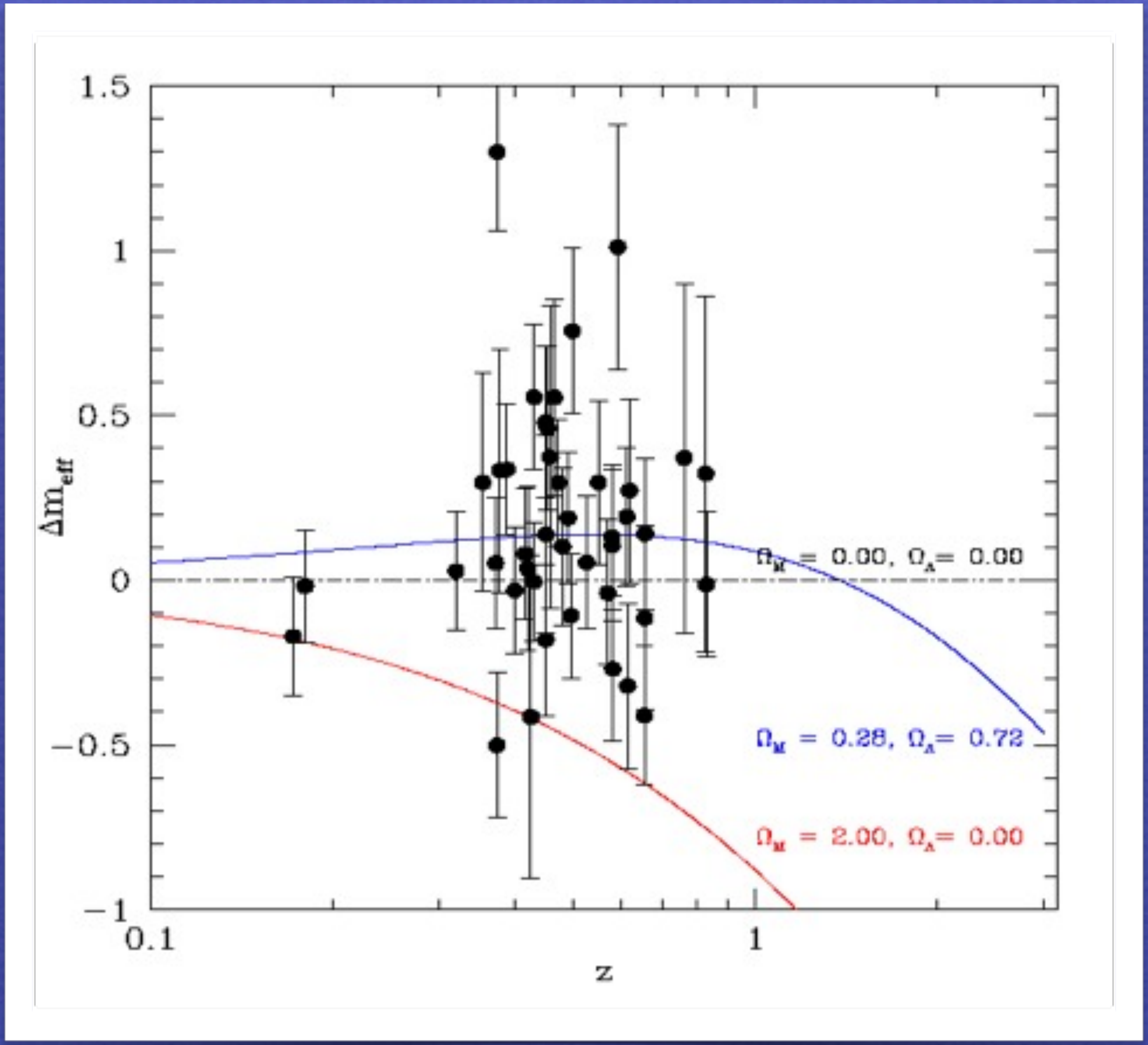


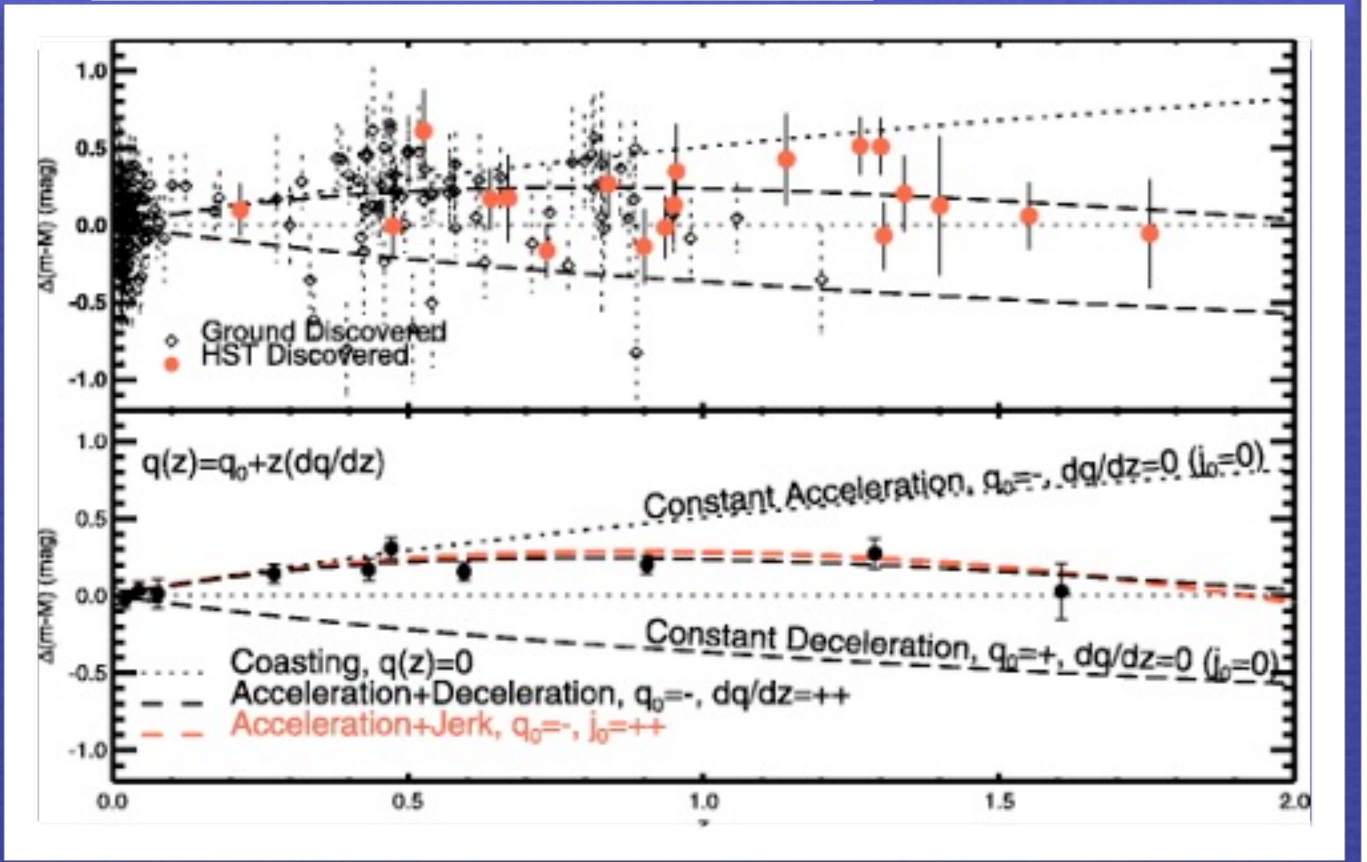
(Perlmutter et al. 1997, 1999)

10-15 years
ago
(1998-2003)
....only few
Supernovae
at z>1

Hubble diagram with type Ia Supernovae

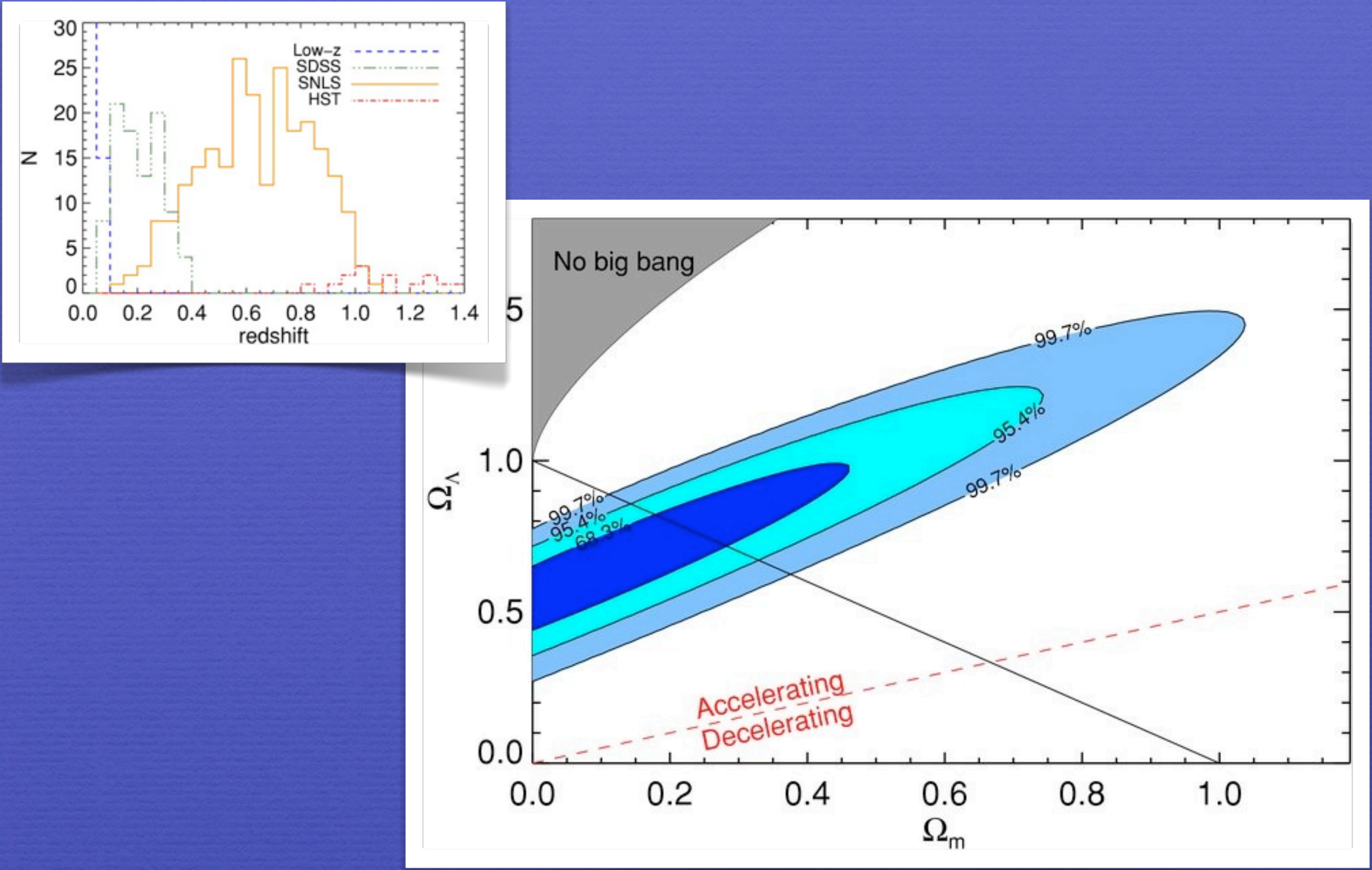
Supernova Cosmology Project





Riess et al. 2004

Supernova Legacy Survey: where we are now



Conley et al. 2011

WMAP 9 yr and Planck combined results

Hinshaw et al. 2013

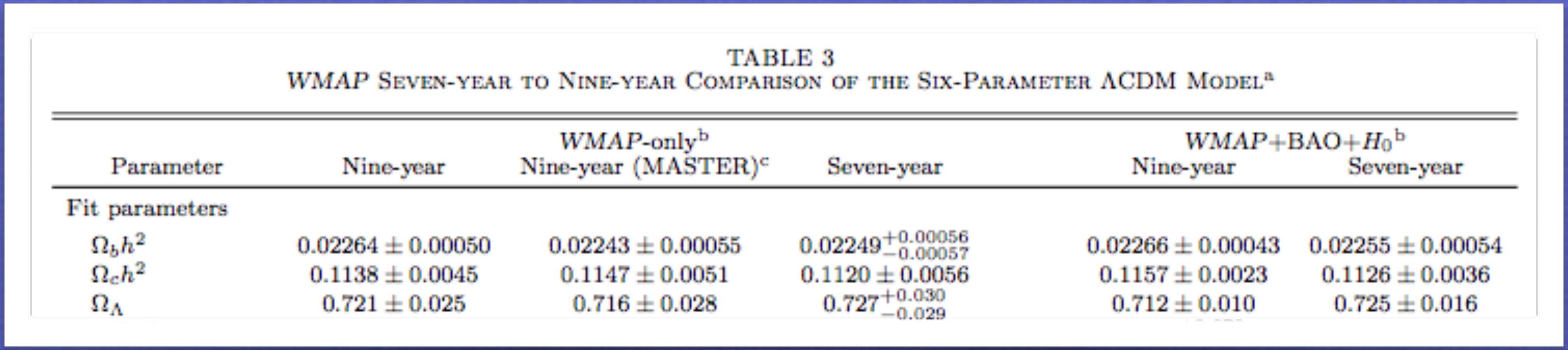
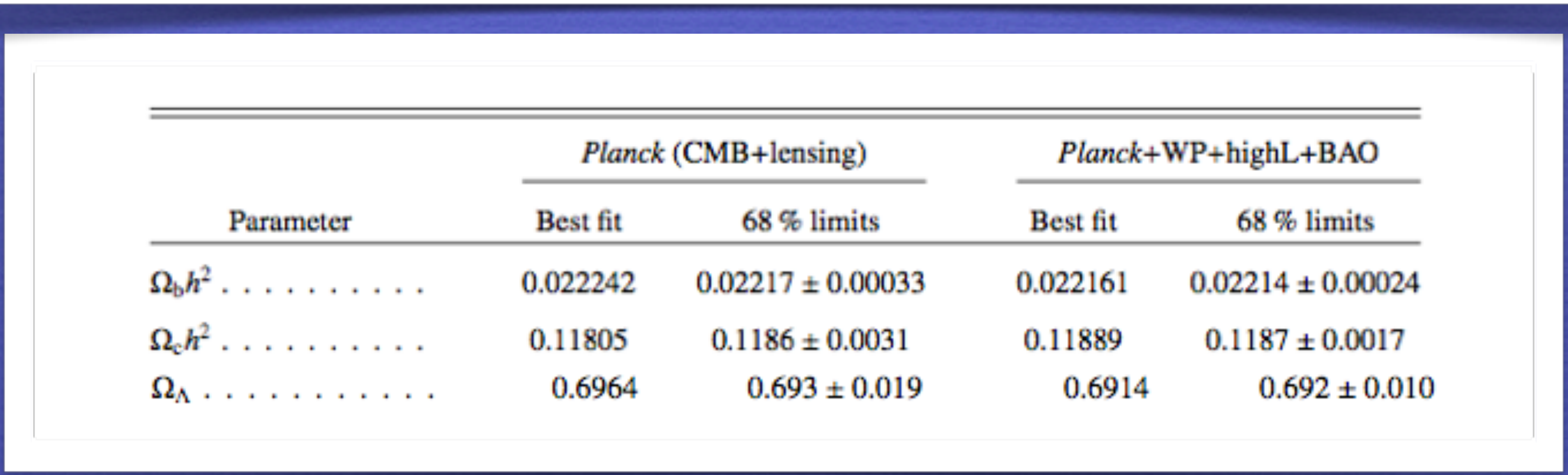


TABLE 3
WMAP SEVEN-YEAR TO NINE-YEAR COMPARISON OF THE SIX-PARAMETER ΛCDM MODEL[a]

Parameter	*WMAP*-only[b] Nine-year	*WMAP*-only[b] Nine-year (MASTER)[c]	*WMAP*-only[b] Seven-year	*WMAP*+BAO+H_0[b] Nine-year	*WMAP*+BAO+H_0[b] Seven-year
Fit parameters					
$\Omega_b h^2$	0.02264 ± 0.00050	0.02243 ± 0.00055	$0.02249^{+0.00056}_{-0.00057}$	0.02266 ± 0.00043	0.02255 ± 0.00054
$\Omega_c h^2$	0.1138 ± 0.0045	0.1147 ± 0.0051	0.1120 ± 0.0056	0.1157 ± 0.0023	0.1126 ± 0.0036
Ω_Λ	0.721 ± 0.025	0.716 ± 0.028	$0.727^{+0.030}_{-0.029}$	0.712 ± 0.010	0.725 ± 0.016



Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010

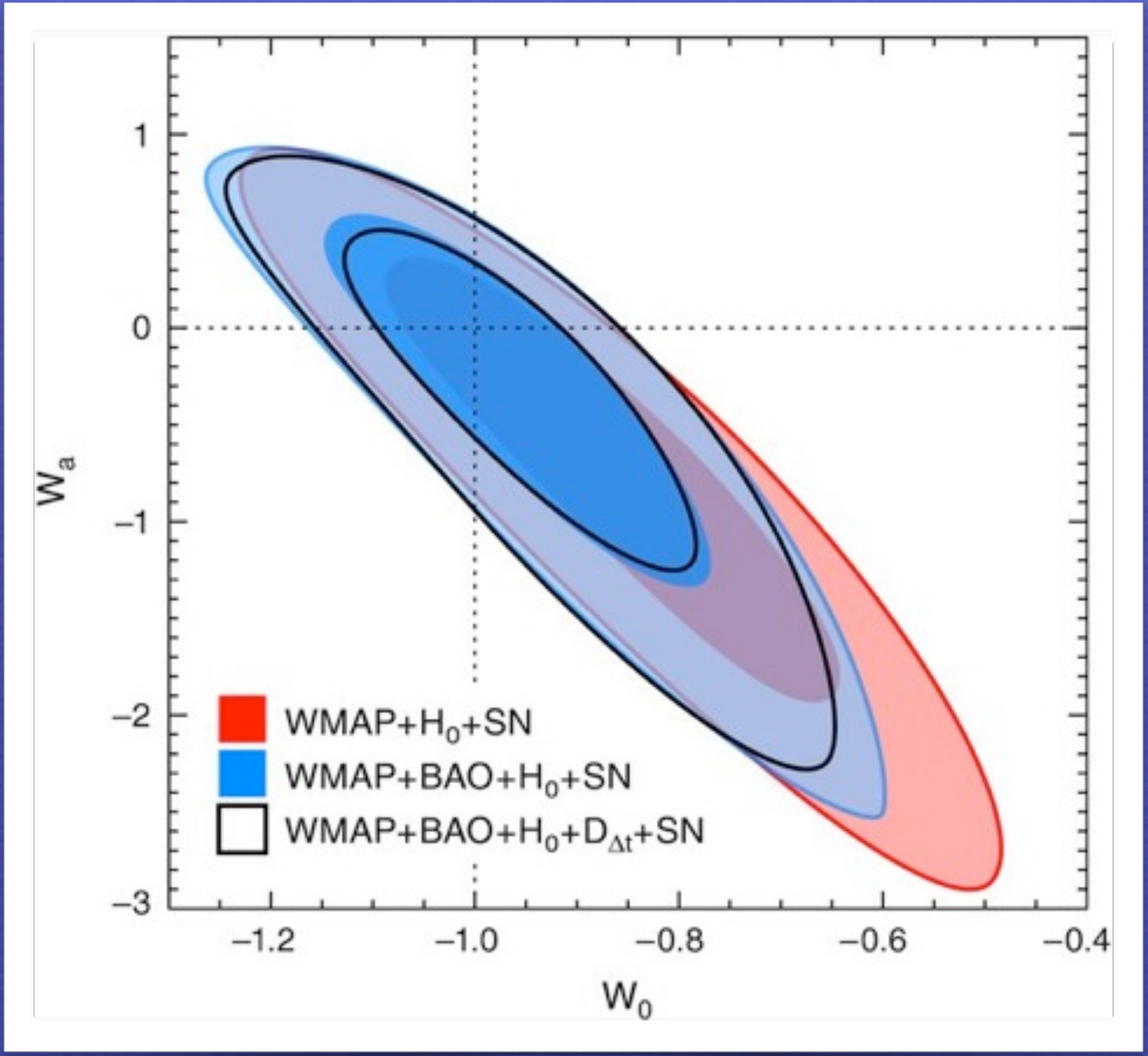
Ade et al. 2013

Is the acceleration of the Universe still an issue?

Dark energy: evolution of the equation of state?

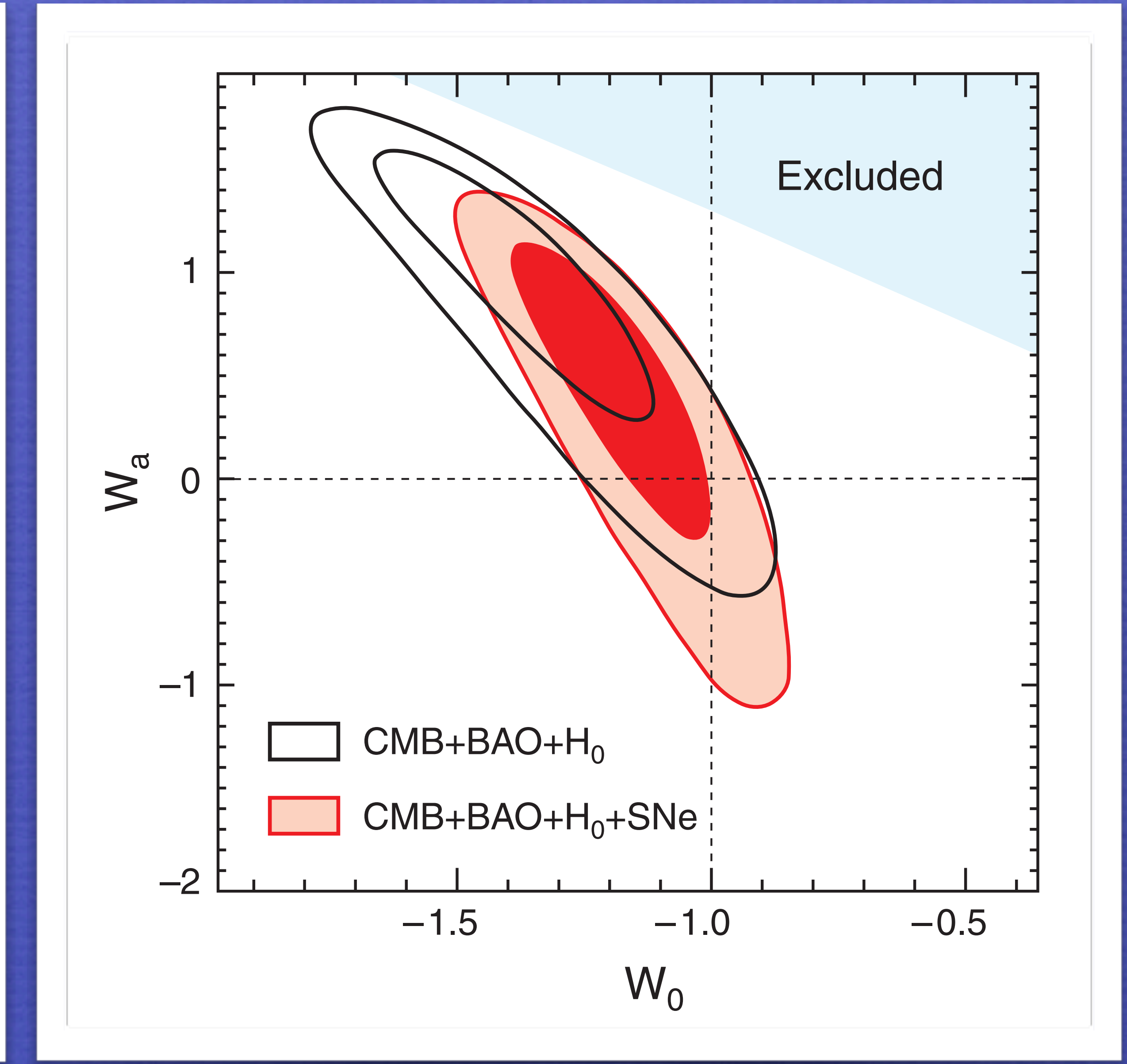
$$\frac{P}{\rho} = w(a) = w_0 + w_{\mathrm{a}} \frac{z}{1+z}$$

7 year WMAP



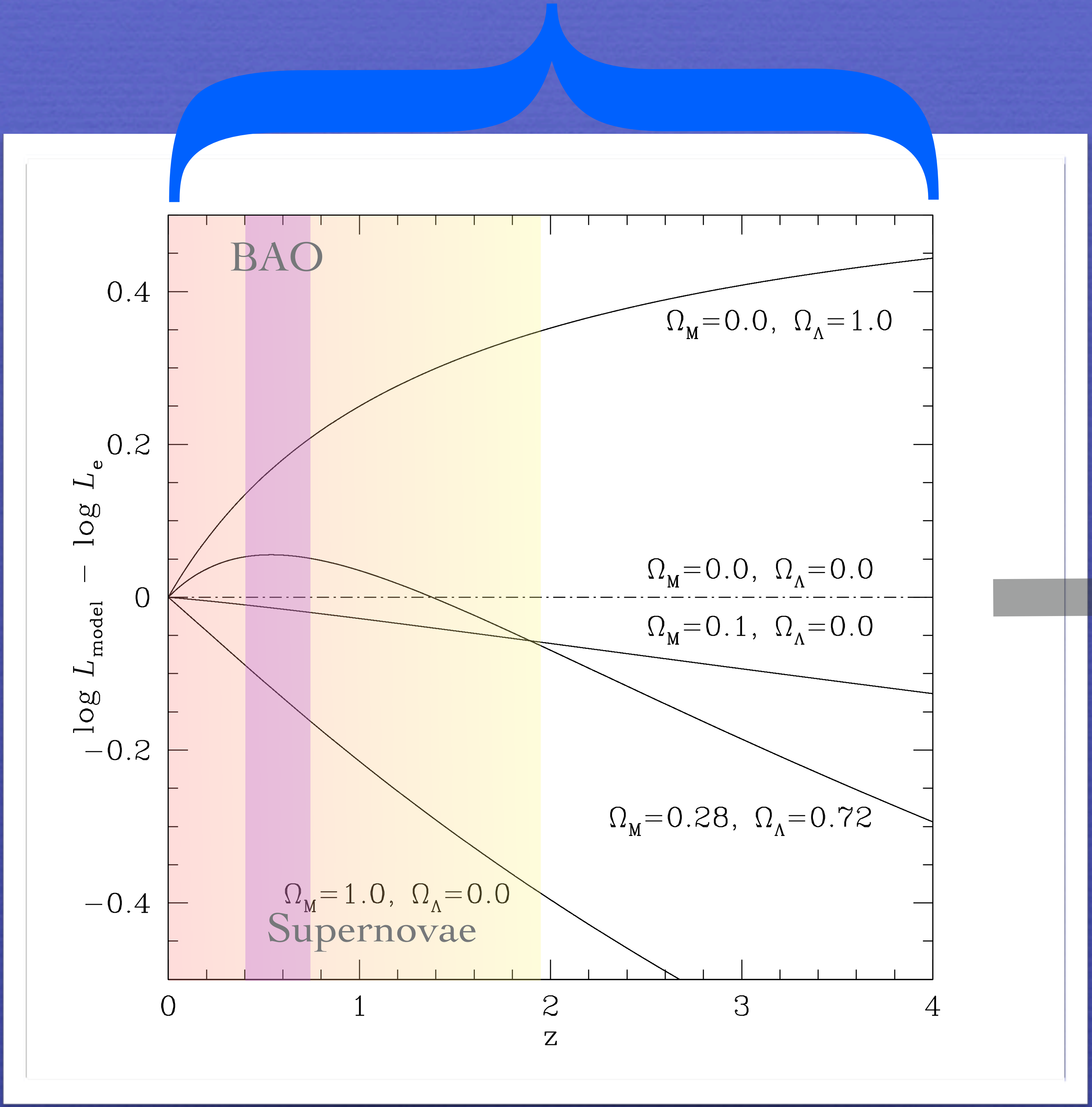
Komatsu et al. 2011

9 year WMAP



Hinshaw et al. 2012

Quasar data could cover almost uniformly the range between 0 and 4



CMB
z~1000

The 4D Eigenvector 1 Space

Observed parameter	Physical parameter	Accretion interpretation
R_{FeII}=I(FeII)/I(Hβ)	Ionization degree Z	L/L_{Edd}
FWHM(Hβ)	velocity field of low-ionization gas	L/L_{Edd}, M_{BH}, orientation
CIVλ1549 Shift	velocity field of high-ionization gas	L/L_{Edd}, orientation
Γ_{soft} (0.2-2 KeV)	Continuum emission	L/L_{Edd}

Optical plane of 4DE1

Wang et al. 1996; Boller et al. 1996; Sulentic et al. 2000, Grupe 2004; Kuraszkiewicz et al. 2008

4D E1: soft-X photon index Γ_{soft}

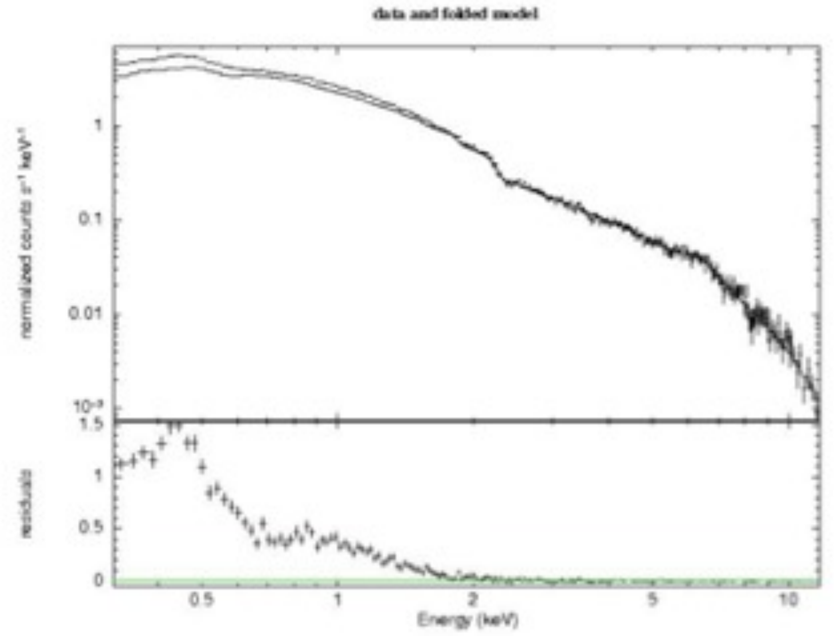
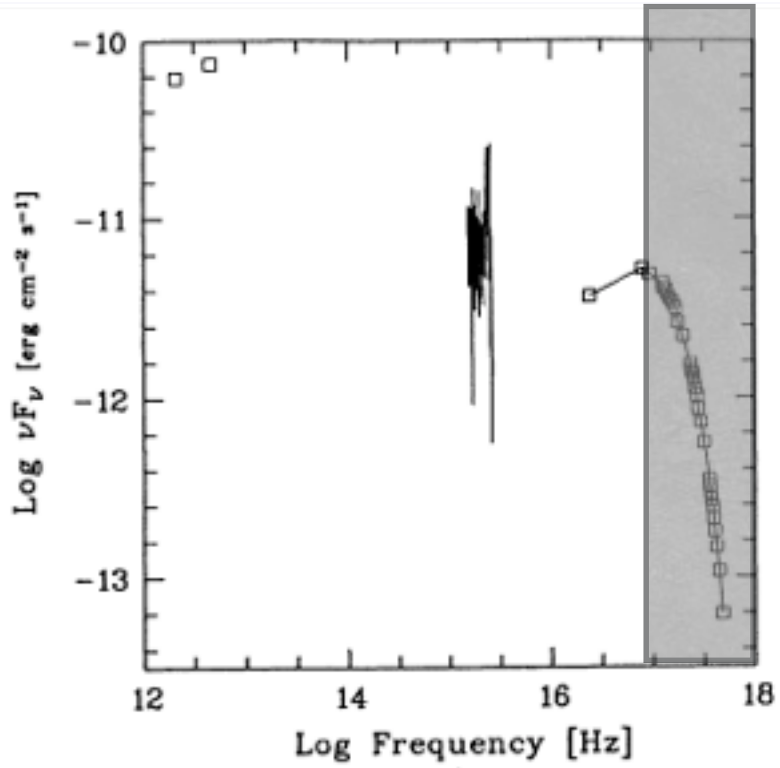
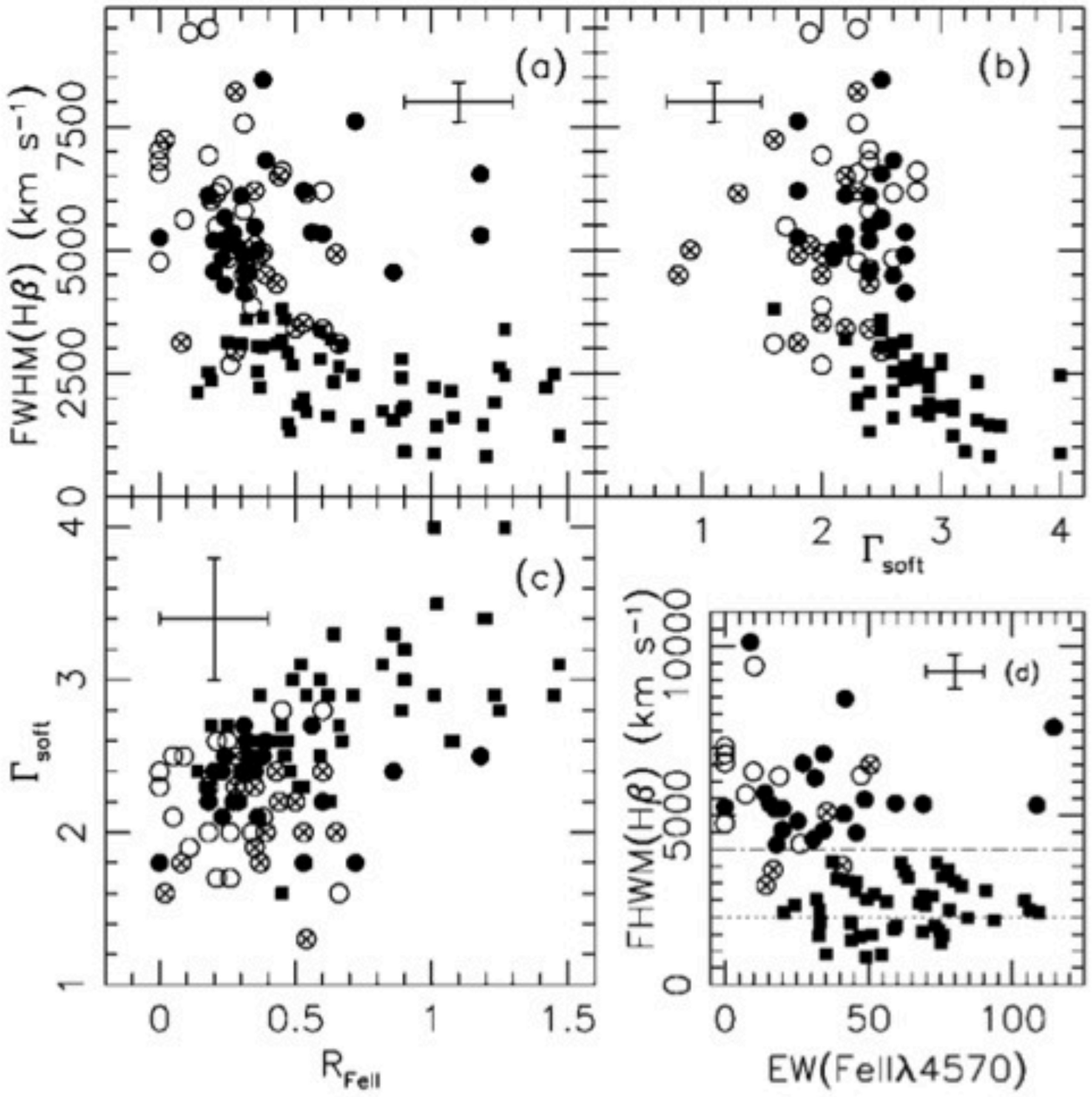
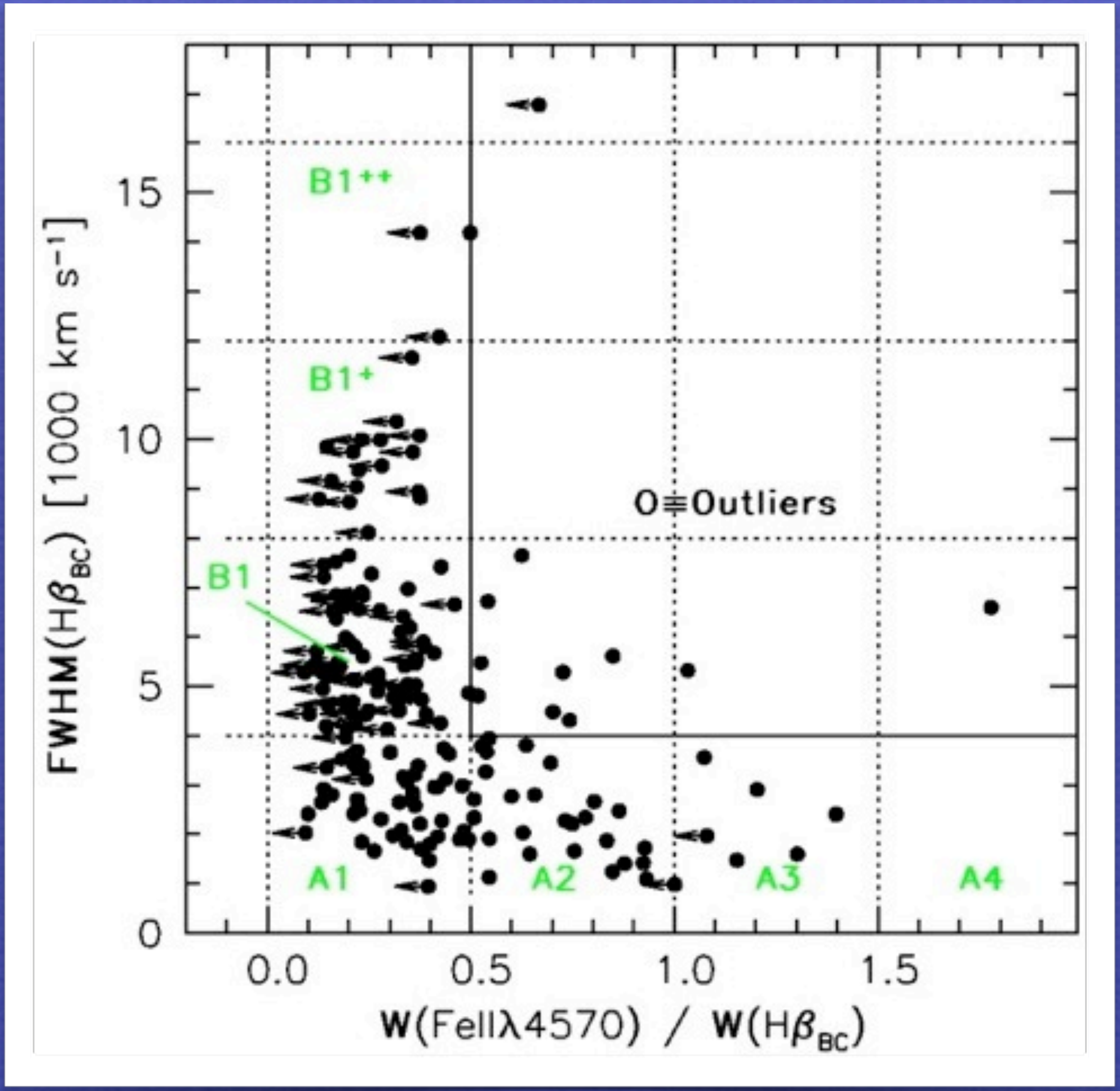


Fig. 2. Spectra with a power law fitted in the 2–12 keV band, showing the soft excess residuals below 2 keV.

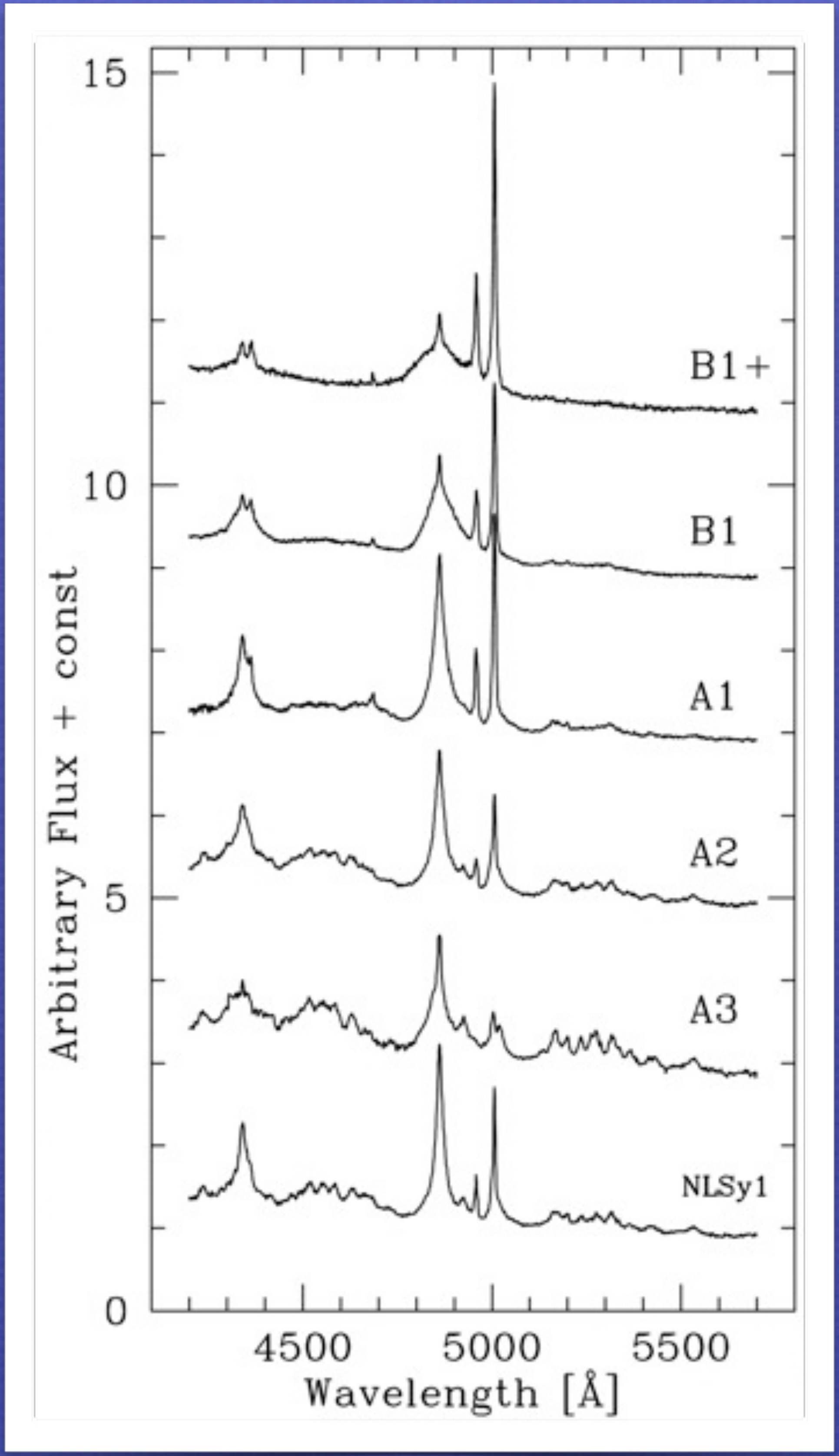




Optical plane of Eigenvector 1: Spectral types in bins to account for quasars' diverse properties



Sulentic et al. 2002



Eddington standard candles

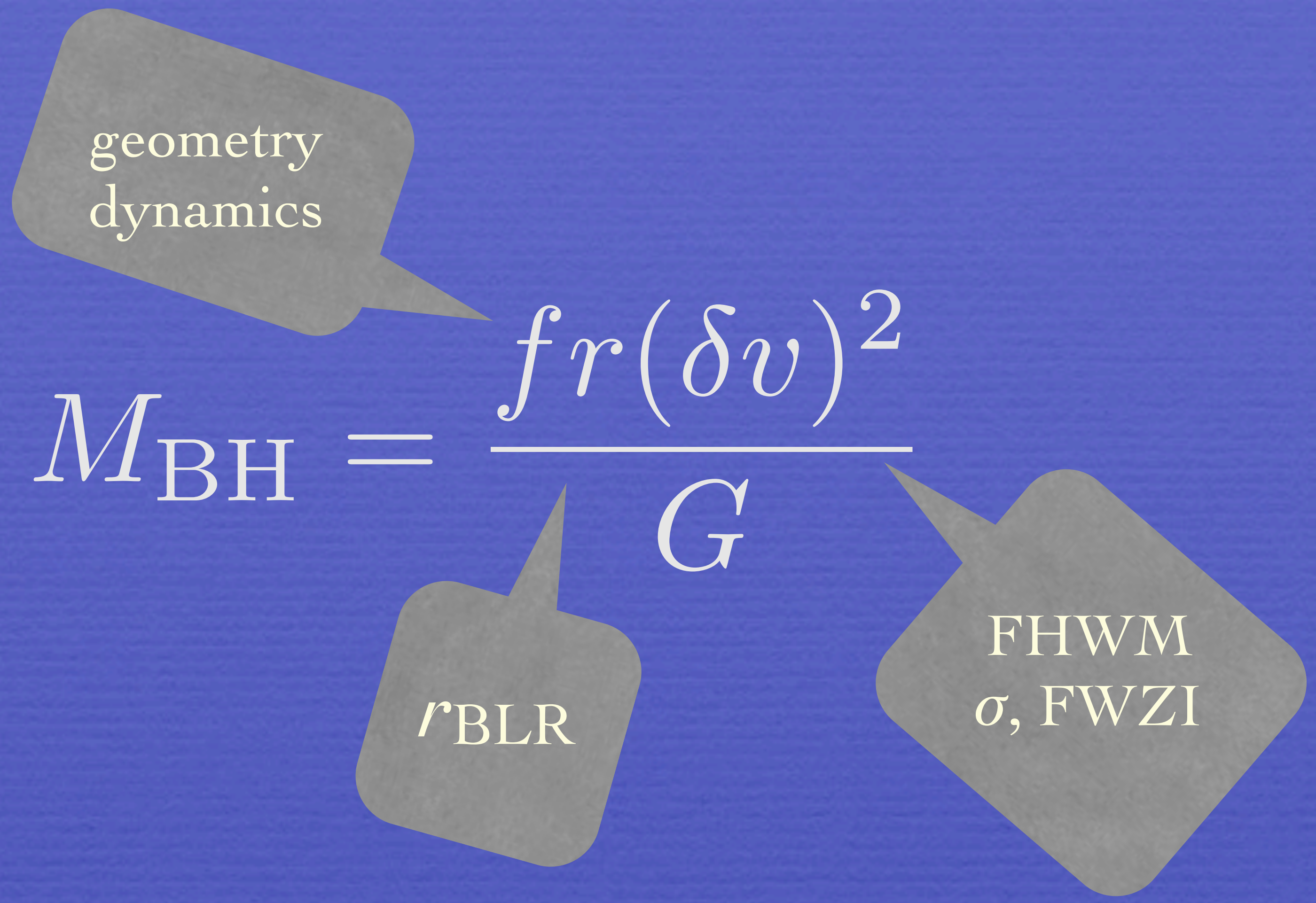
$$L = \eta L_{\rm Edd} = {\rm const}\,\eta M_{\rm BH}$$

Two main issues:

1) definition of a sample with ``known'' $L/L_{\rm Edd}$ ($\eta \Rightarrow 1$);

2) can any method based on $L/L_{\rm Edd}$ estimates be applied in practice to actual data and give relevant results?

Virial Black Hole Mass



geometry
dynamics

$$M_{\mathrm{BH}} = \frac{fr(\delta v)^2}{G}$$

r_{BLR}

FHWM
σ, FWZI

$$M_{\mathrm{BH}} : \text{if } \delta v = \mathrm{FWHM}, \text{isotropy} : \frac{\sqrt{3}}{2}\mathrm{FWHM} \rightarrow f = 0.75$$

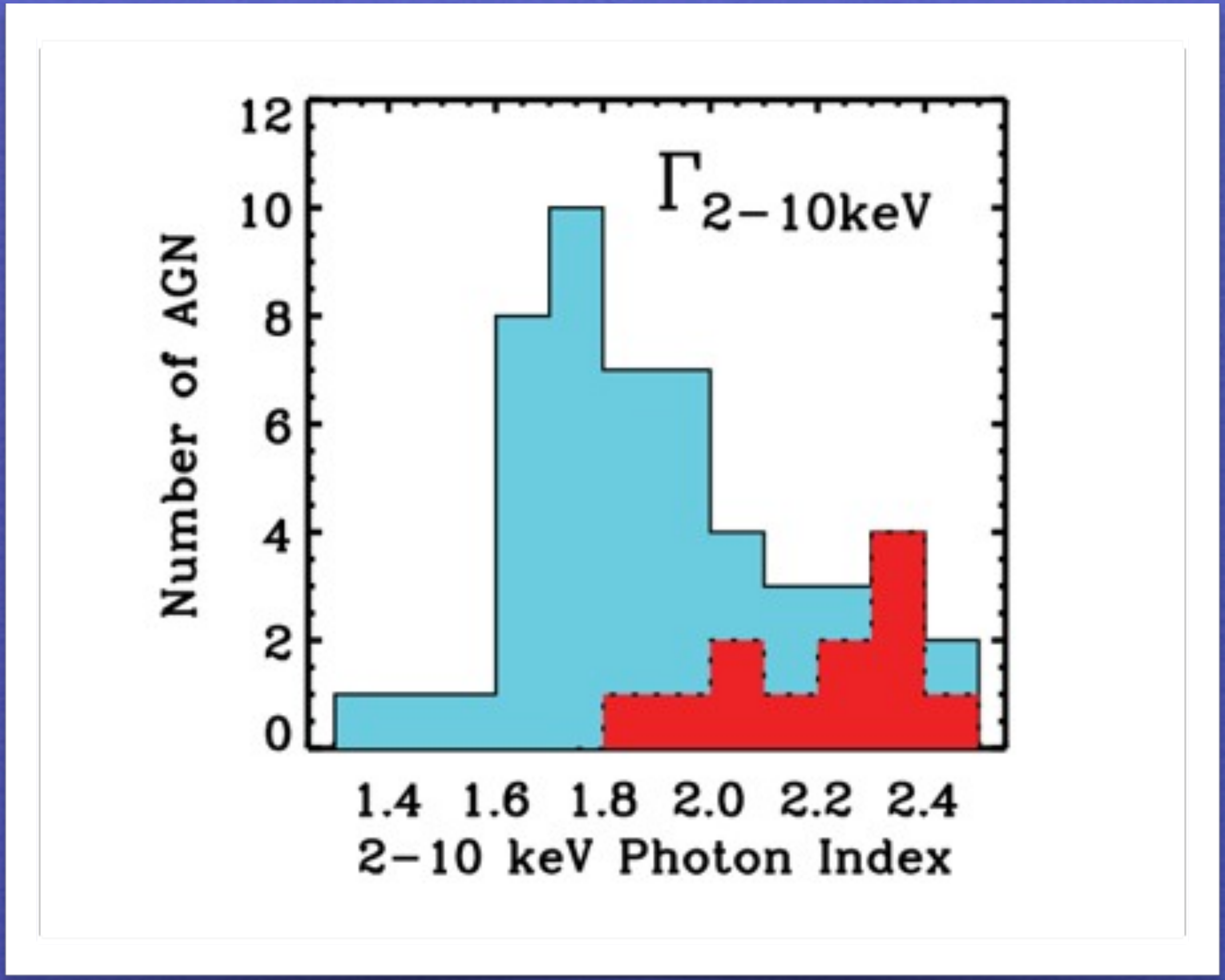
f = 2.0 more appropriate for Pop. A sources

Collin et al. (2006)

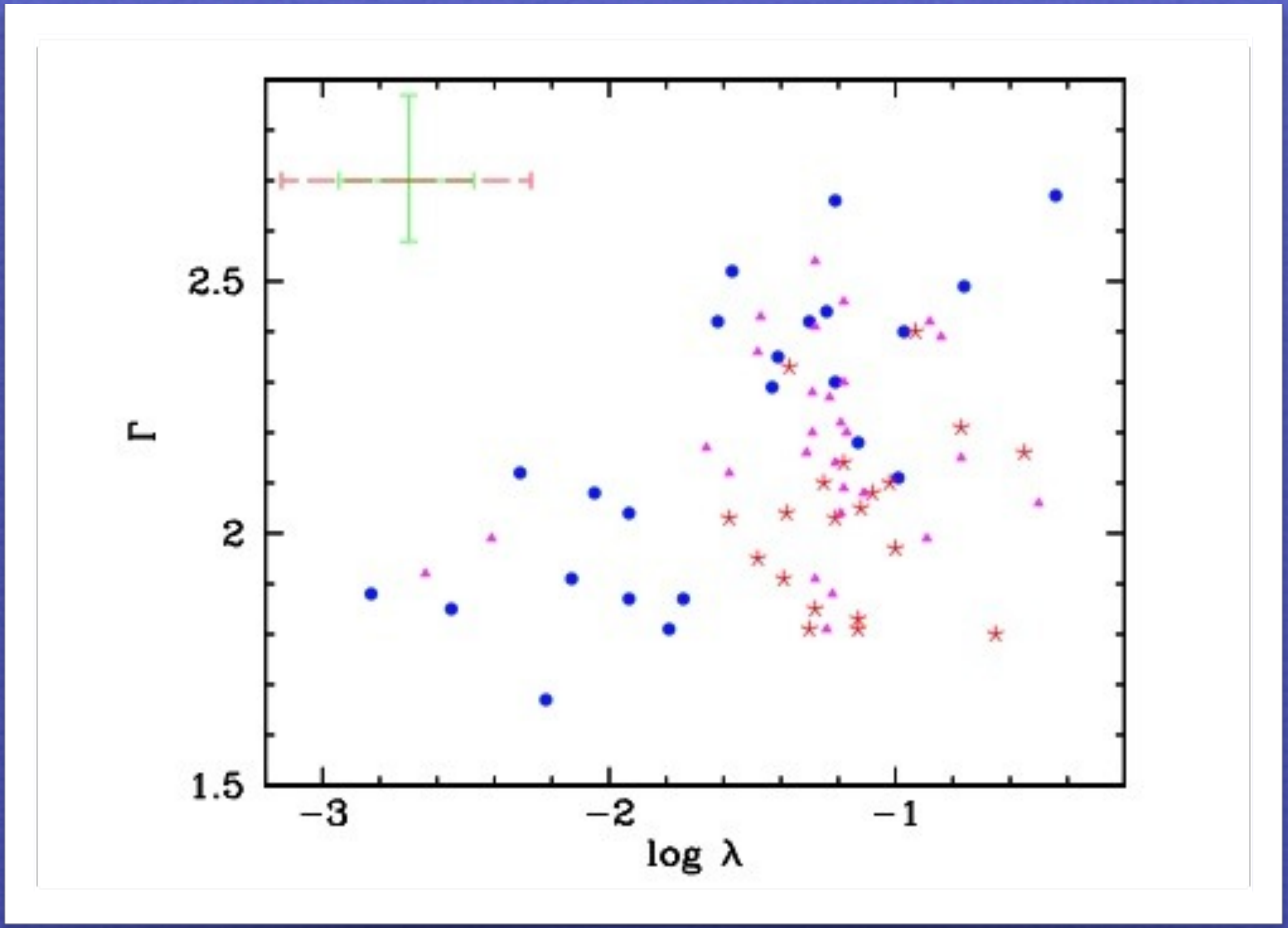
Keplerian velocity field: the BLR dynamics dominated by
the gravity of a central mass; $v \propto r^{-1/2}$

$$\Gamma_{\rm hard} \geq 2$$

A sufficient condition to isolate high accretors (?)



Jin et al. 2012



Fanali et al. 2013

super-Eddington accreting massive black holes (SEAMBHs)

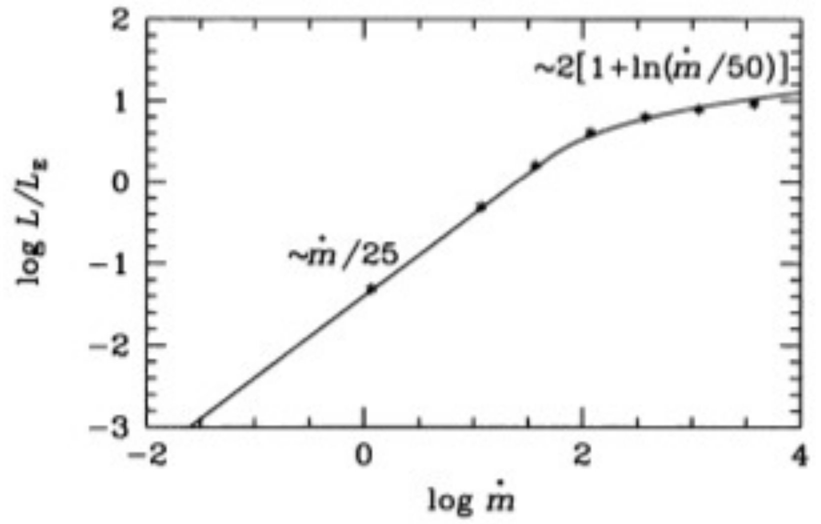
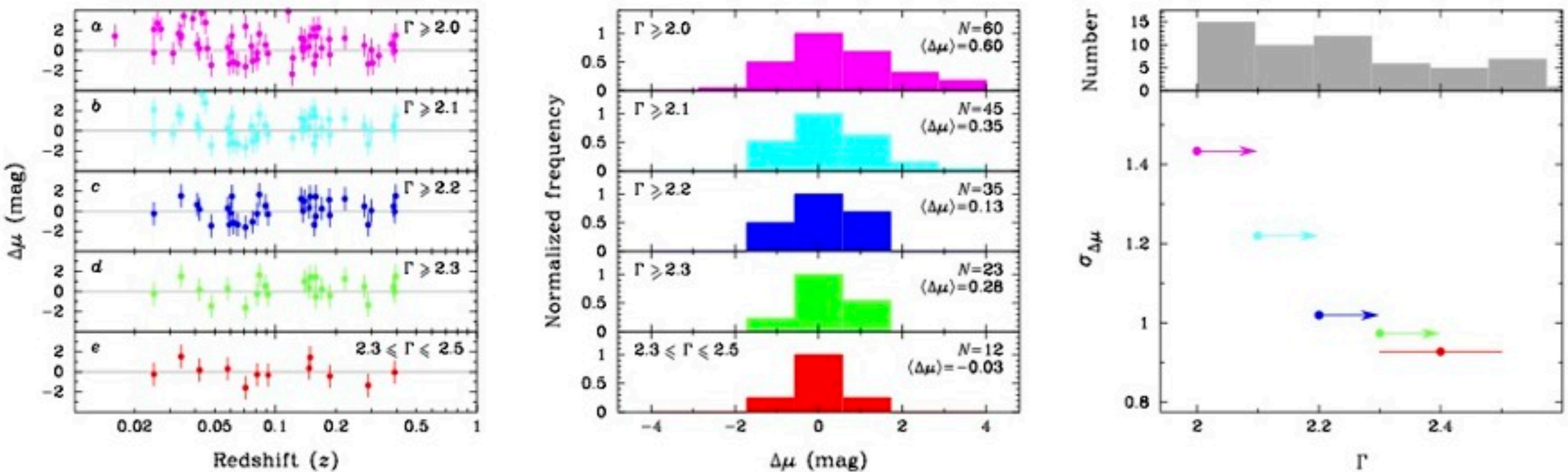


Fig. 2. Disk luminosity as a function of $\dot{m}$. The asterisks denote the calculated luminosities, whereas the solid line shows the fitting formula (8). It is clear that an increase in L is suppressed at $L > 2L_E$.

steepening of hard X-ray continuum in an advection-dominated accretion scenario

$$L = L_0(1 + \mathrm{const} \ln \dot{m}) M_{BH}$$

Mineshige et al. 2000



$\sigma_{\min} \approx 0.95$ mag

Wang et al. 2013

The distance of the BLR from the central photoionzing continuum source

ionization parameter

$$U = \frac{\int_{\nu_0}^{+\infty} \frac{L_\nu}{h\nu} d\nu}{4\pi r_{\mathrm{BLR}} n_{\mathrm{e}} c}$$

$$r_{\mathrm{BLR}} = \left(\frac{\int_{\nu_0}^{+\infty} \frac{L_\nu}{h\nu} d\nu}{4\pi U n_{\mathrm{e}} c} \right)^{\frac{1}{2}}$$

$$r_{\mathrm{BLR}} = \underbrace{\frac{1}{(4\pi c)^{\frac{1}{2}}}}_{\text{const.}} \underbrace{(U n_{\mathrm{e}})^{-\frac{1}{2}}}_{\text{diagnostics}} \left(\underbrace{\int_{\nu_0}^{+\infty} \frac{L_\nu}{h\nu} d\nu}_{\#\ \text{ionizing photons}} \right)^{\frac{1}{2}}$$

Relation for luminosity not dependent on z

assuming the Eddington ratio is known,
and that the virial relation applies with $r_{\rm BLR} \propto L^{0.5}$

$$\frac{L}{L_{\rm Edd}} = \eta \qquad\qquad L = \eta L_{\rm Edd} = \mathrm{const}\,\eta M_{\rm BH}$$

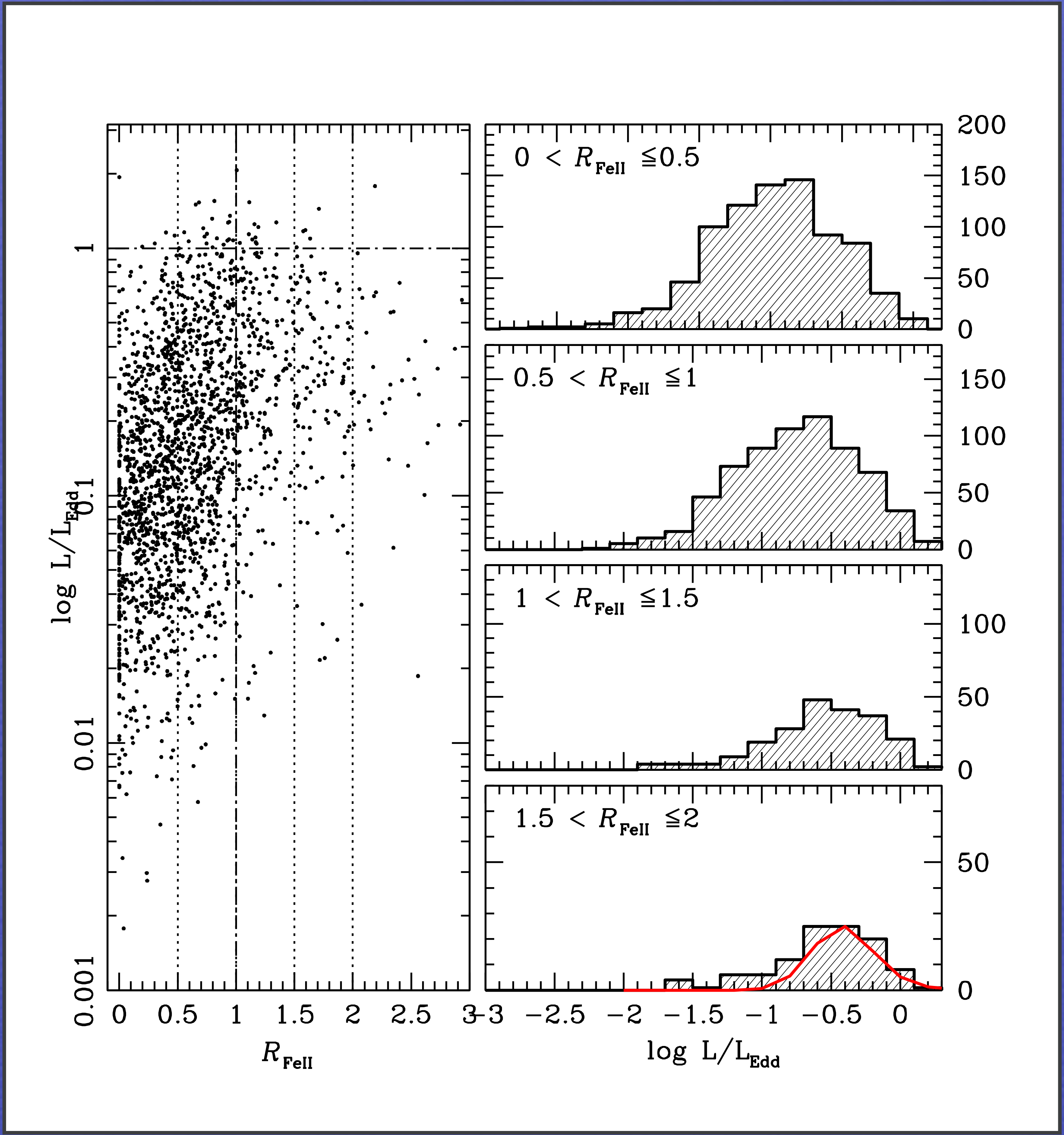
fraction of ionizing luminosity

$$L \approx 7.8\ 10^{44}\, \frac{\eta_1^2 \kappa_{0.5} f_2^2}{\bar{\nu}_{\rm i\, 2.42\ 10^{16}}} \frac{1}{(nU)_{9.6}} v_{1000}^4 \quad \mathrm{erg\ s}^{-1}$$

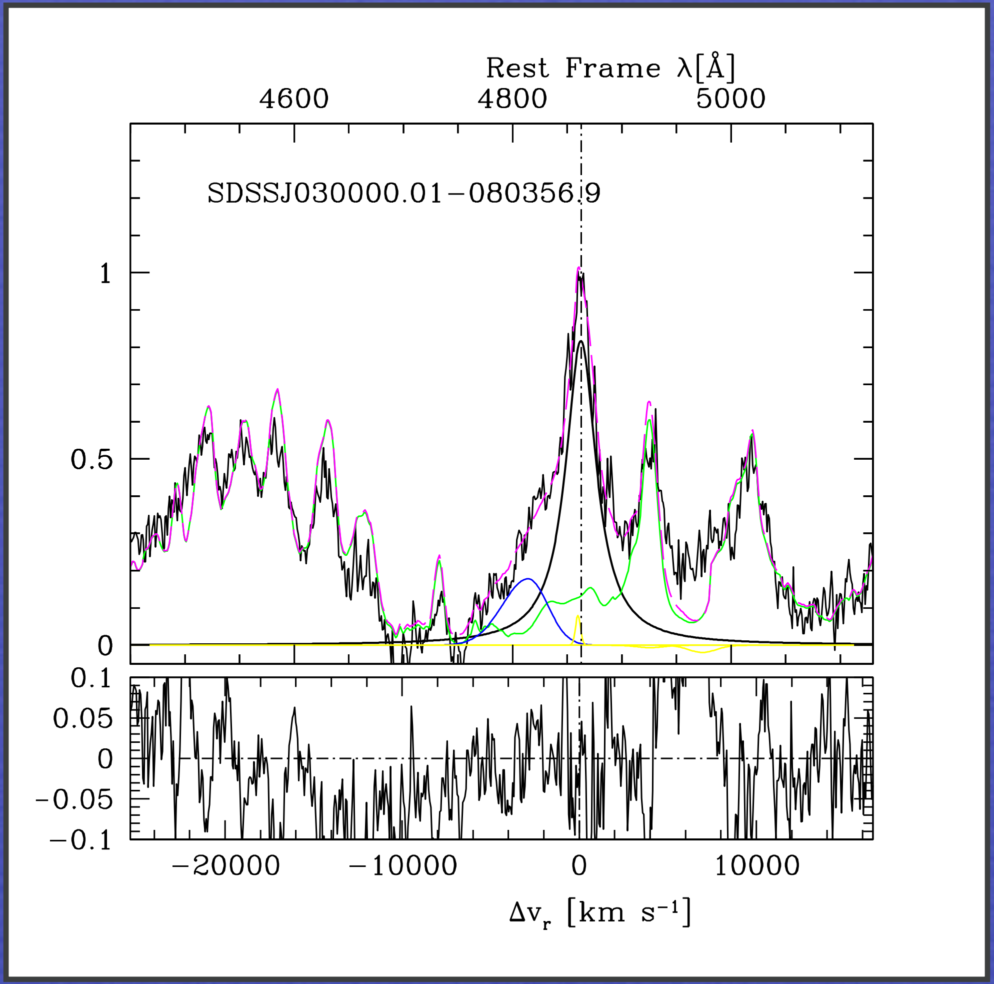
average frequency of ionizing photons

cf Marziani et al. 2003; Teerikorpi 2005

Defining a sample L/L$_{\mathrm{Edd}}$ ⇒ 1: A preliminary analysis



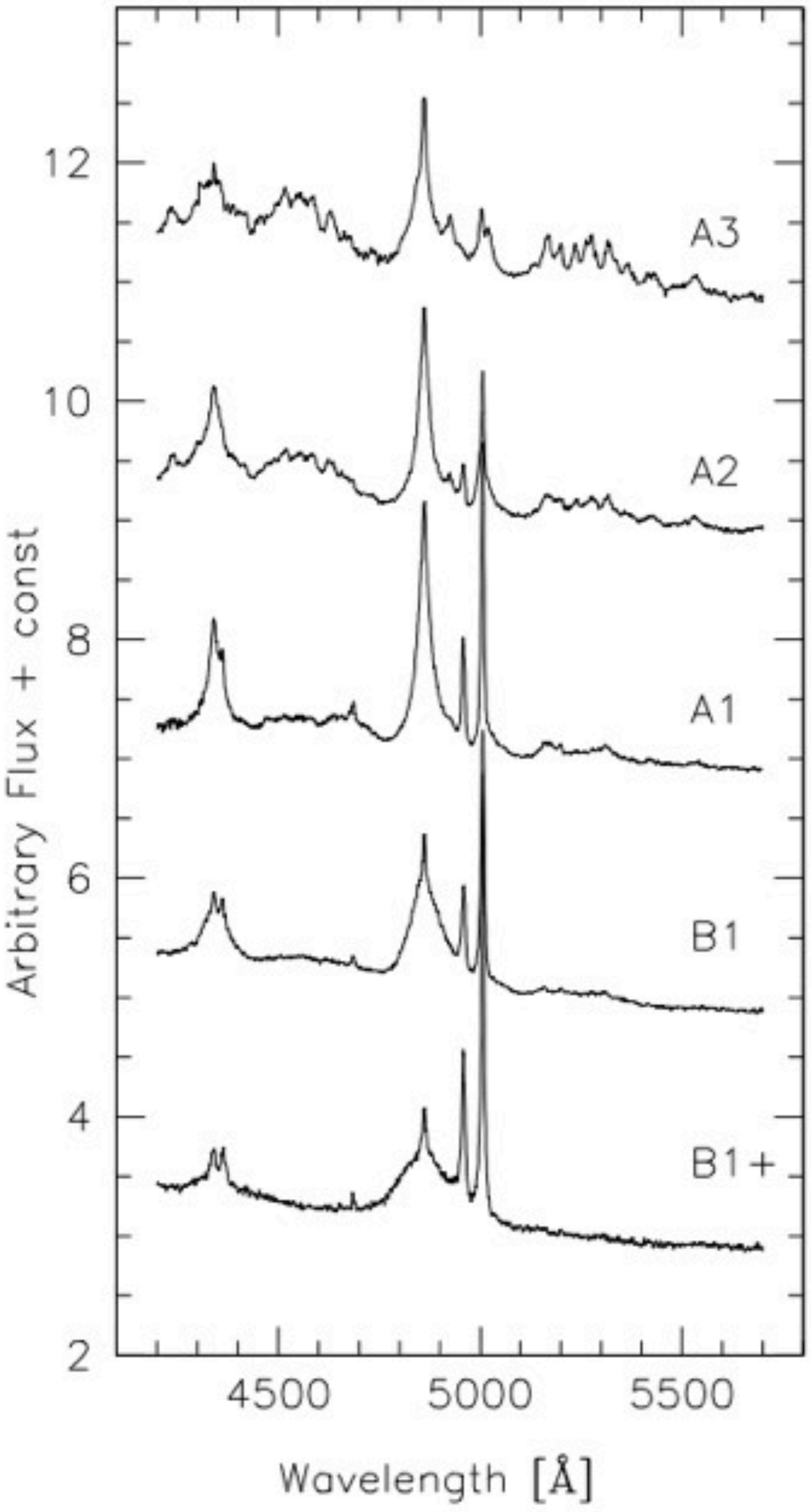
Careful consideration of the line profile is needed to compute M$_{\mathrm{BH}}$ and L/L$_{\mathrm{Edd}}$: asymmetry ⇒ non-virial motion

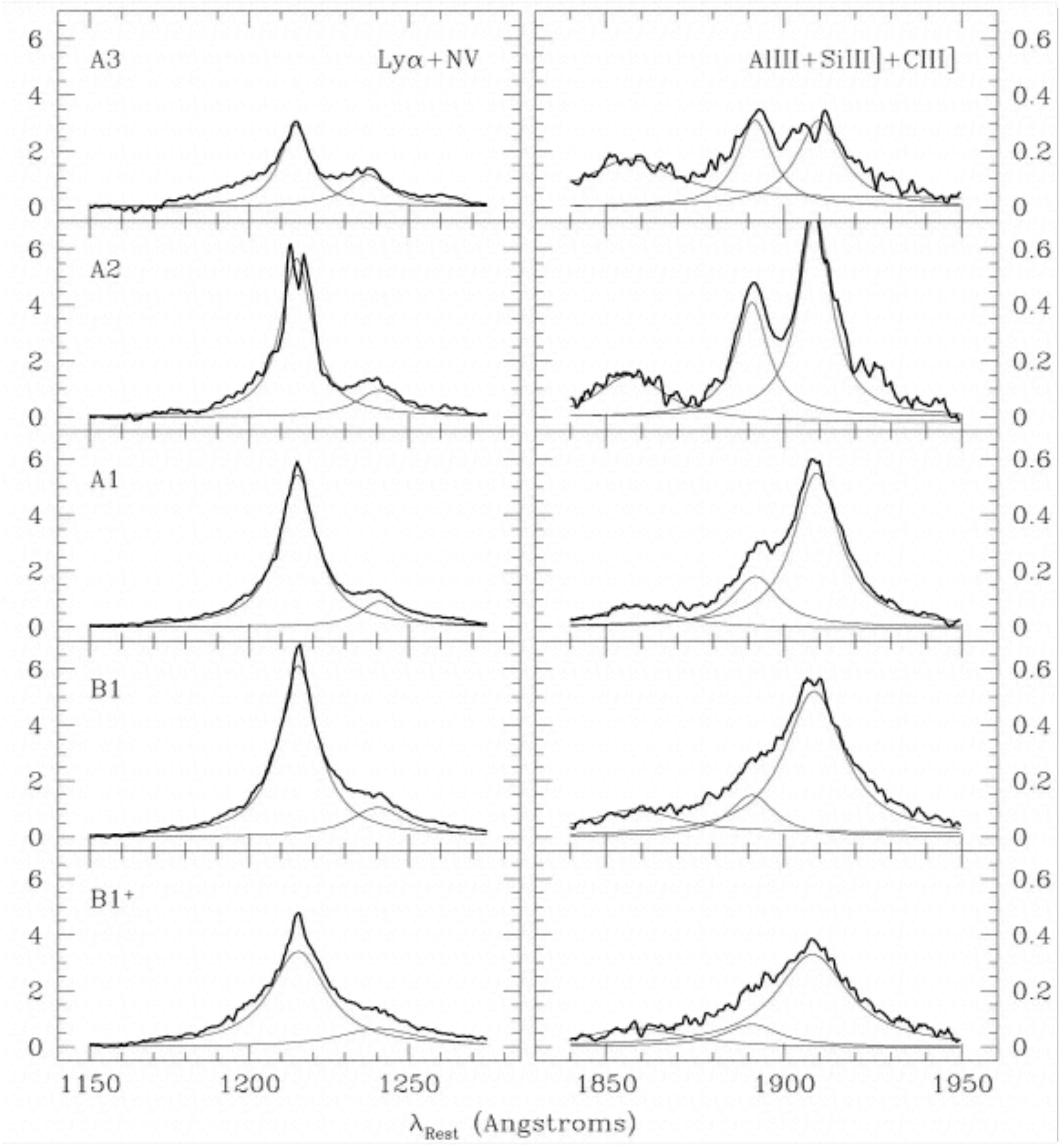


Data from Shen et al 2011

Optical and UV spectral systematic changes along E1

Bachev et al. 2004; Negrete et al. 2012



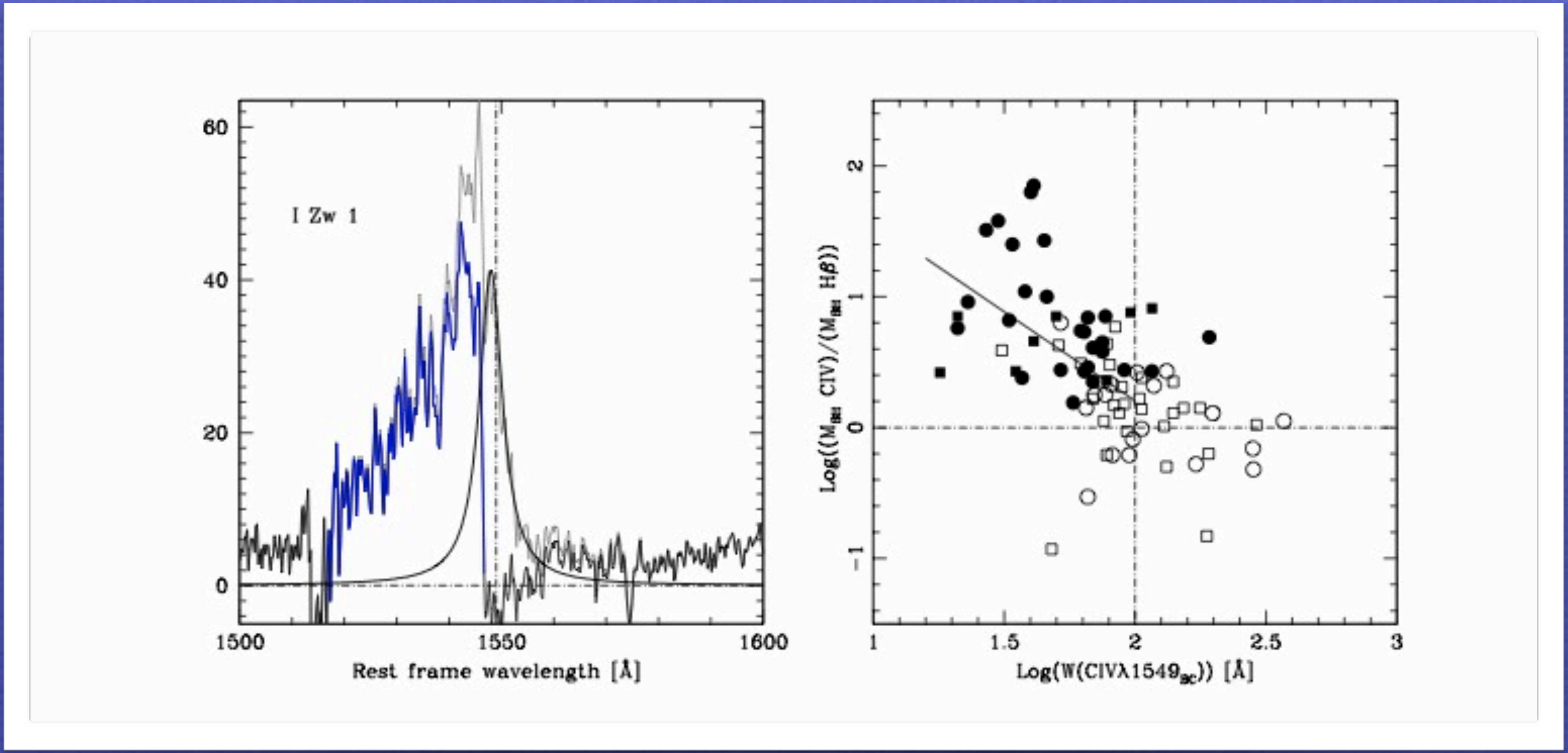


BROAD COMPONENT

emitting all LILs, low ionization, high density, large N_c

presumed VIRIAL component whose width
can be used for M_{BH} computations

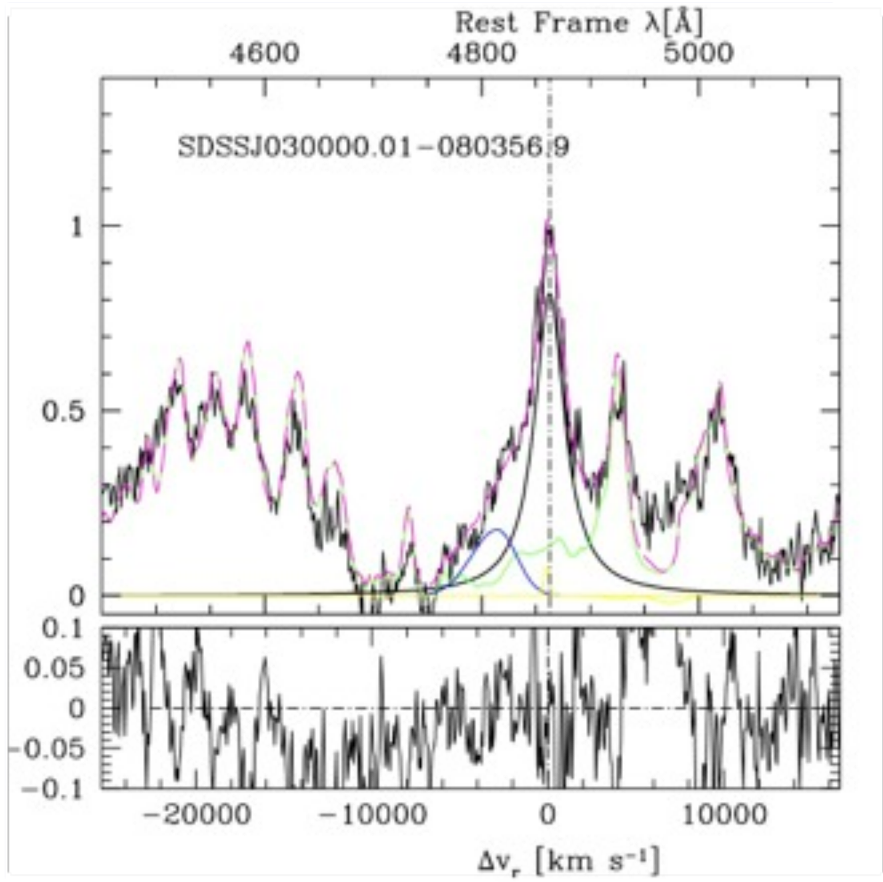
Including non virial components:

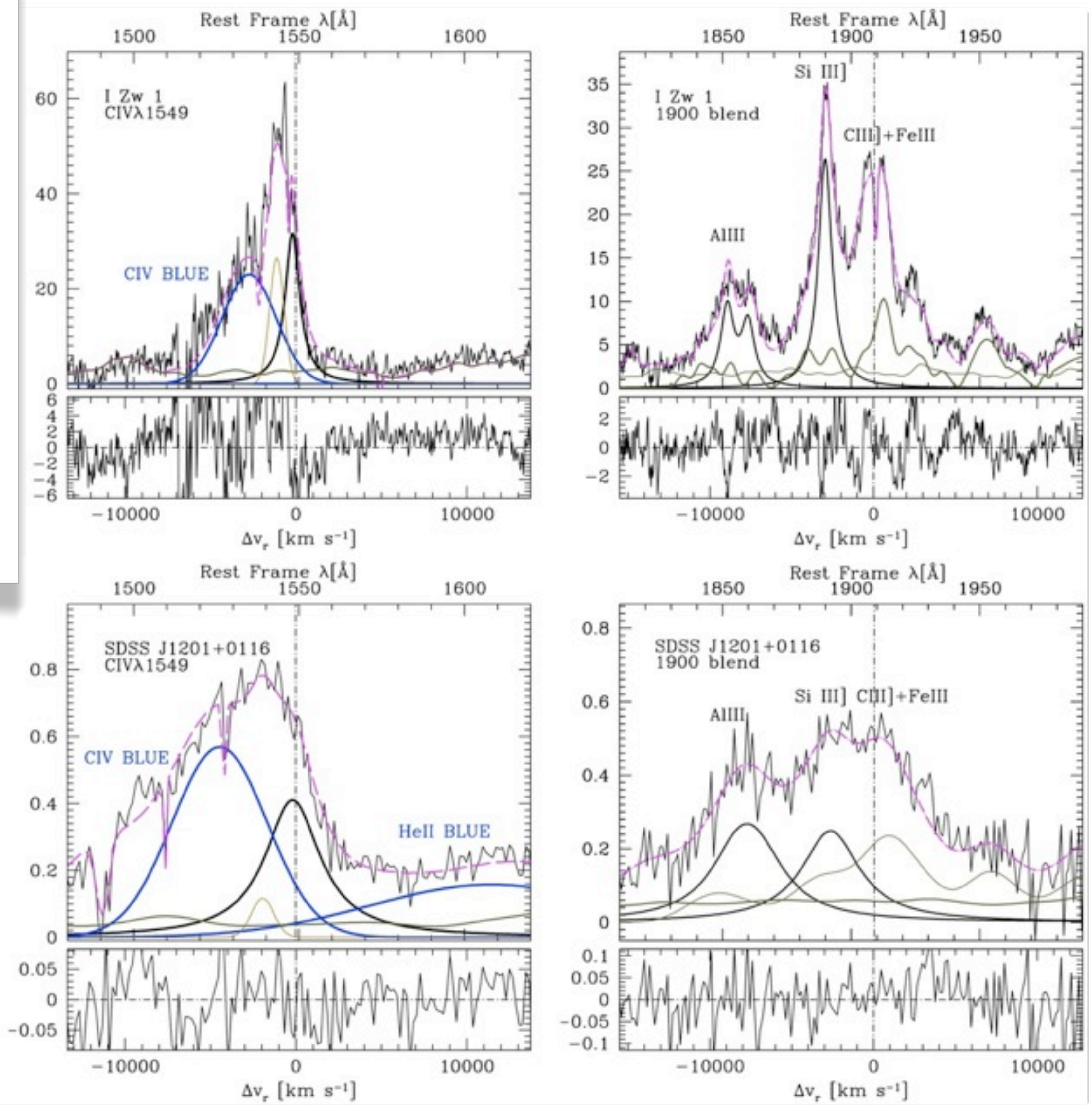


Sulentic et al. 2007

Black hole mass overestimates ⇒ L/L_{Edd} underestimates

The targets: high luminosity equivalents of NLSy1s





Analysis of the UV intermediate ionization lines in extreme Pop. A (xA) sources

(Negrete et al. 2012)

Sample selection criteria based on emission line ratios:

1) optical $R_{\mathrm{FeII}} > 1.0$

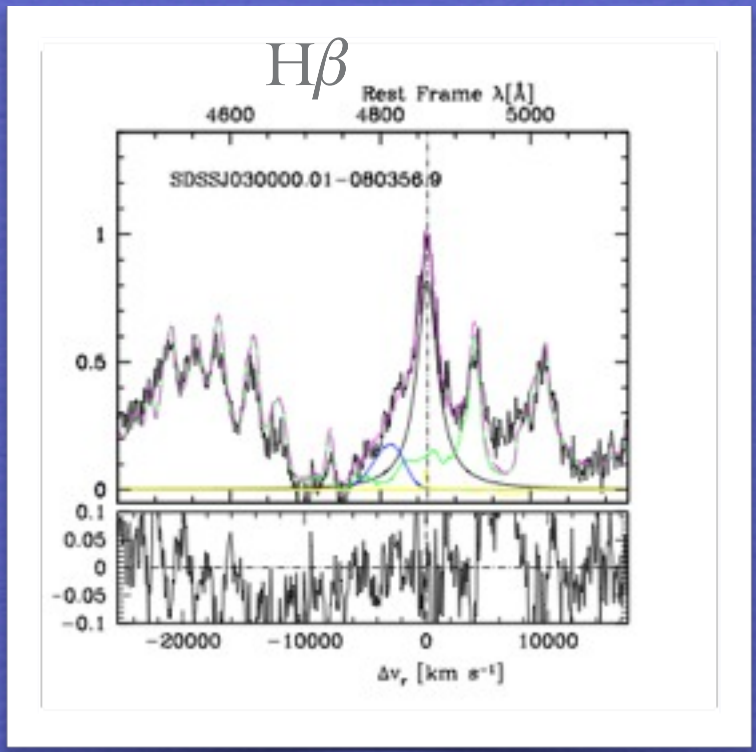
2) UV AlIII λ1860/SiIII]λ1892>0.5

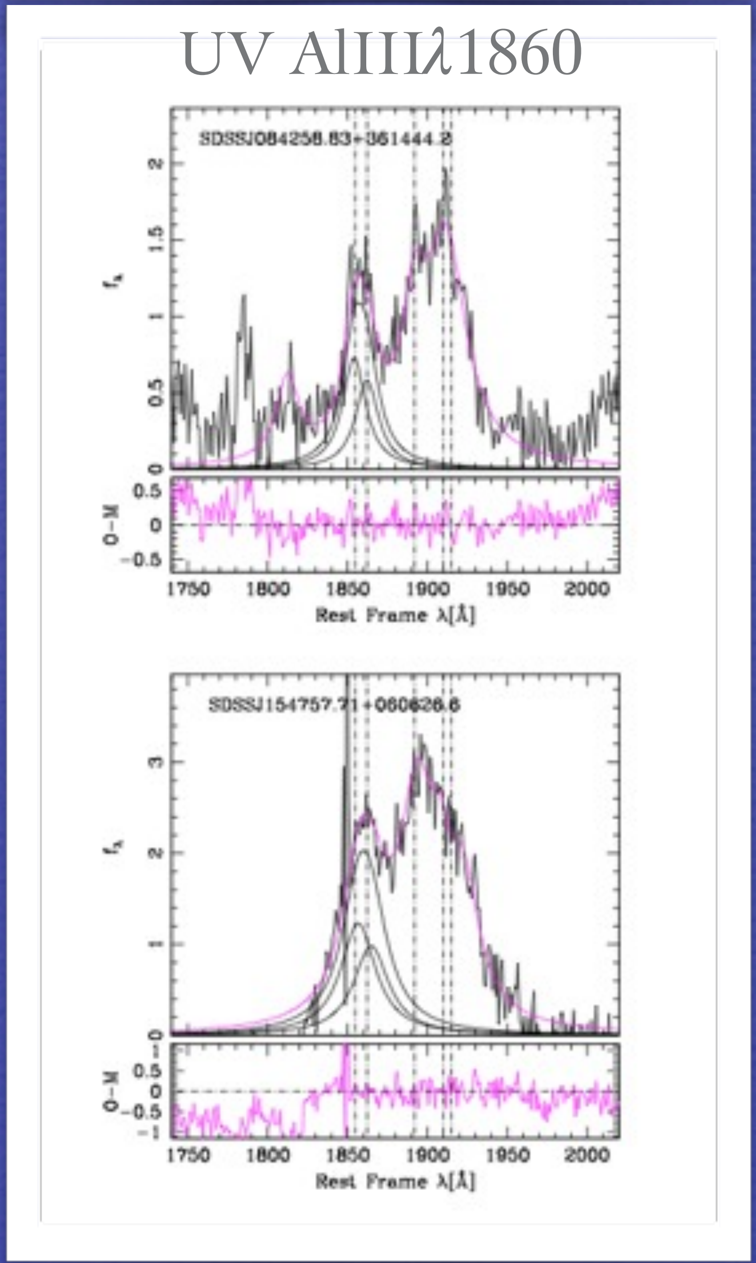
No broad line width selection criterion

3 preliminary quasar samples:

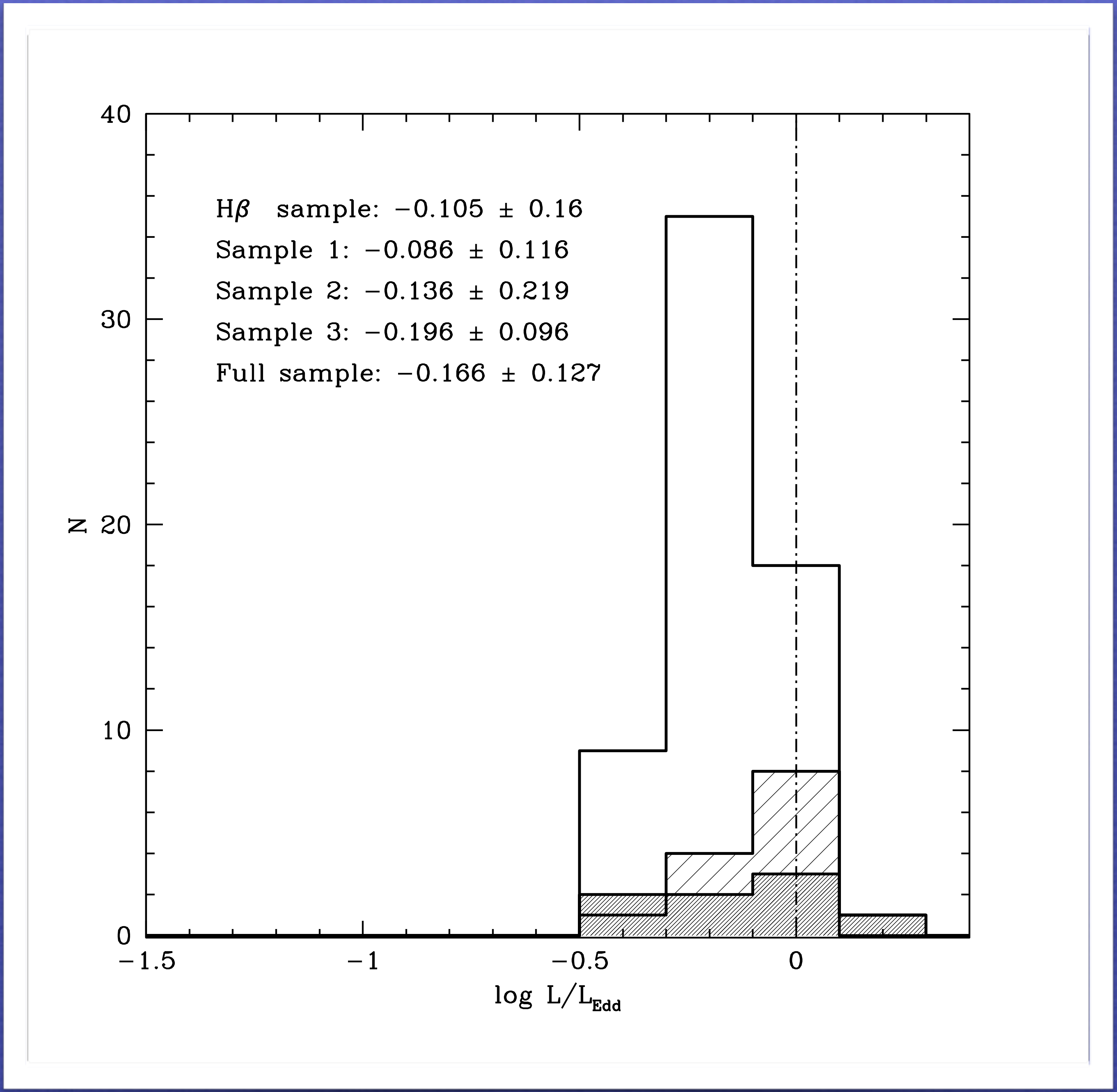
1. Hβ SDSS; $0.4 < z < 0.75$
2. Hβ VLT ISAAC; $0.9 < z < 1.5$
3. SDSS UV AlIIIλ1860; $2 < z < 2.6$

62 sources in total





Dispersion in L/L_{Edd} and a posteriori verification:



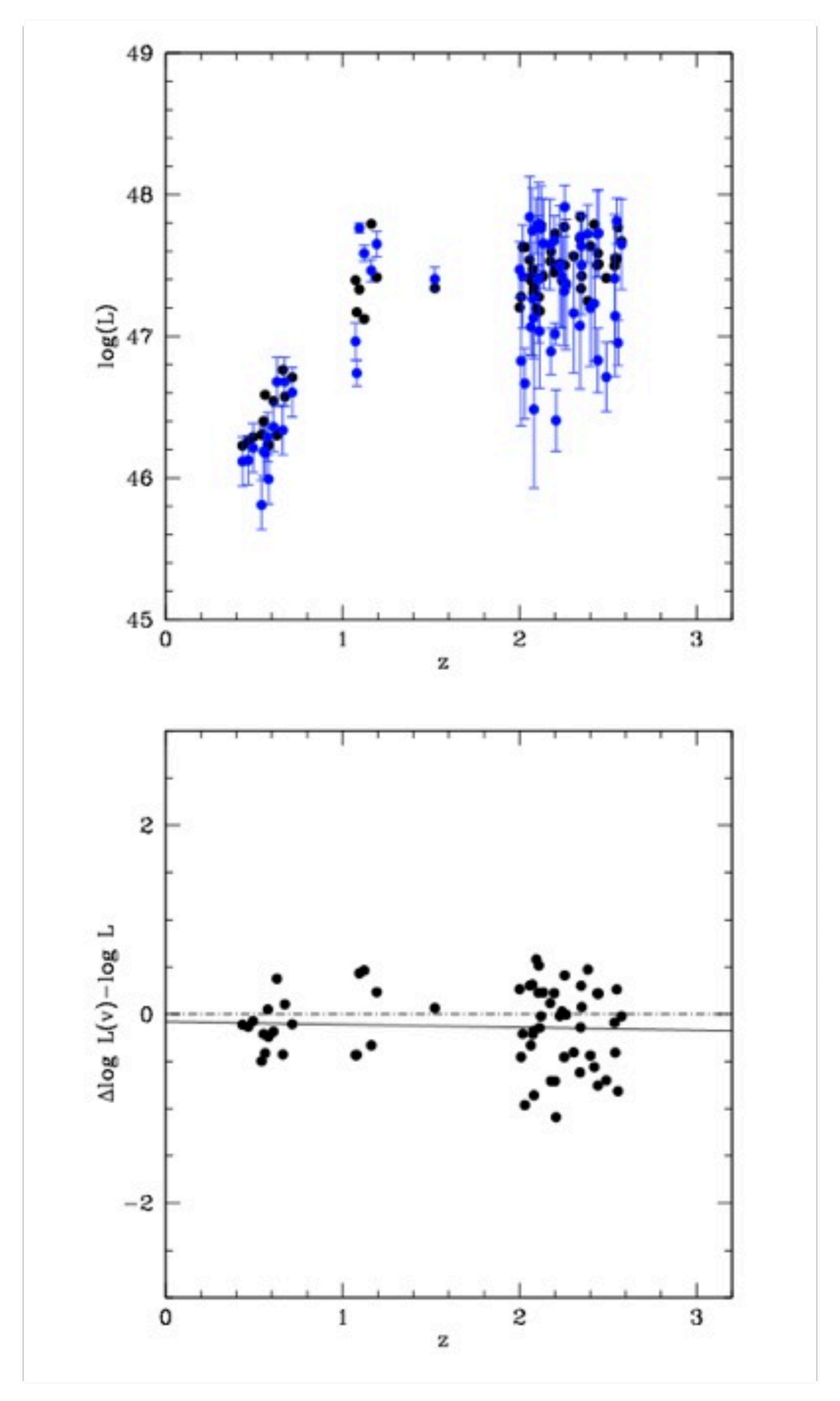
Results: comparing “virial luminosity” $L(v)$ and luminosity $L(z)$ estimated from z

$$L = 4\pi d^2(z, \Omega_{\mathrm{M}}, \Omega_{\Lambda})(\lambda f_{\lambda}) \cdot 10^{\mathrm{B.C.}}$$

$$\Delta = \Delta \log L(z) = \log L(v) - \log L(z)$$

$$\Delta \log L(z) = \overline{\Delta \log L} + \zeta(z)$$

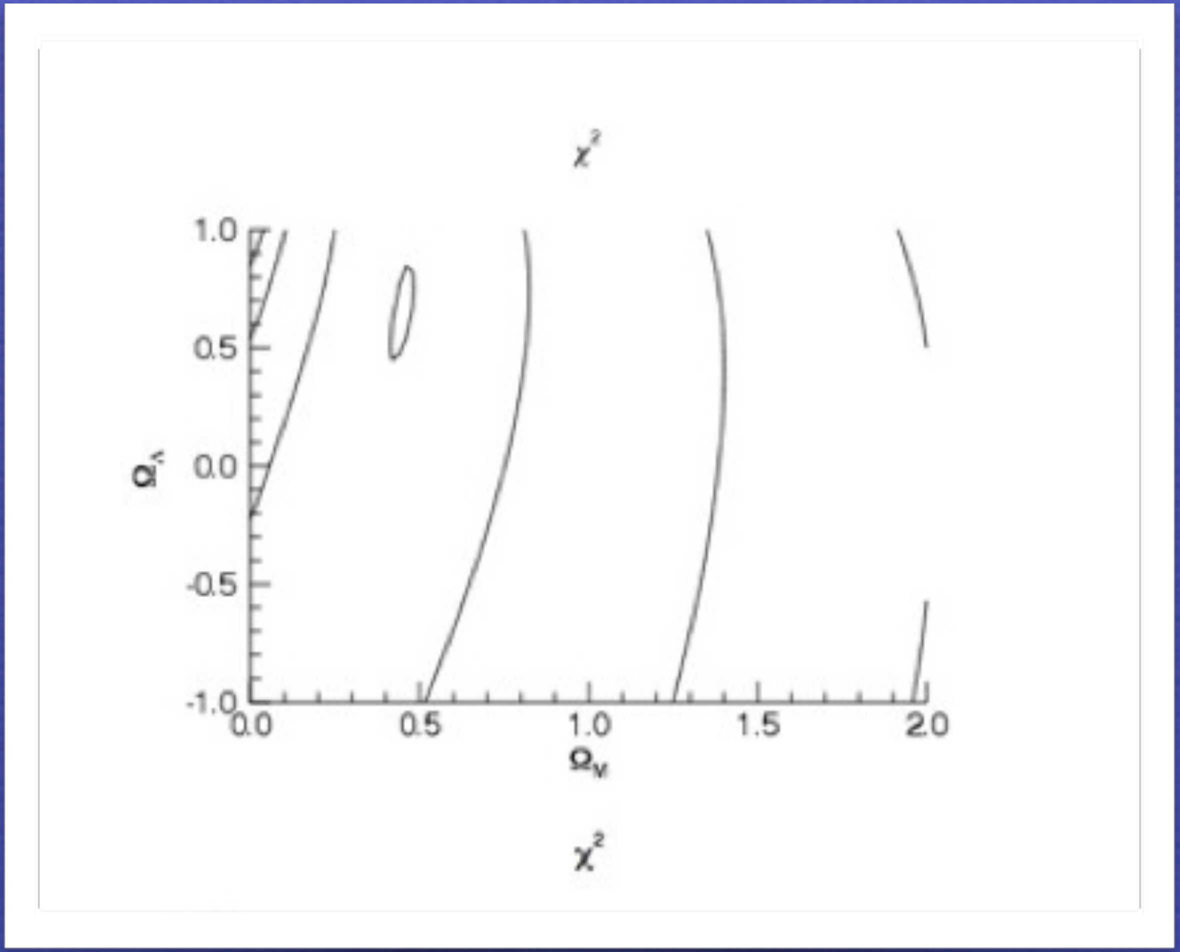
$$\Delta \log L(z) = a + b \cdot z$$

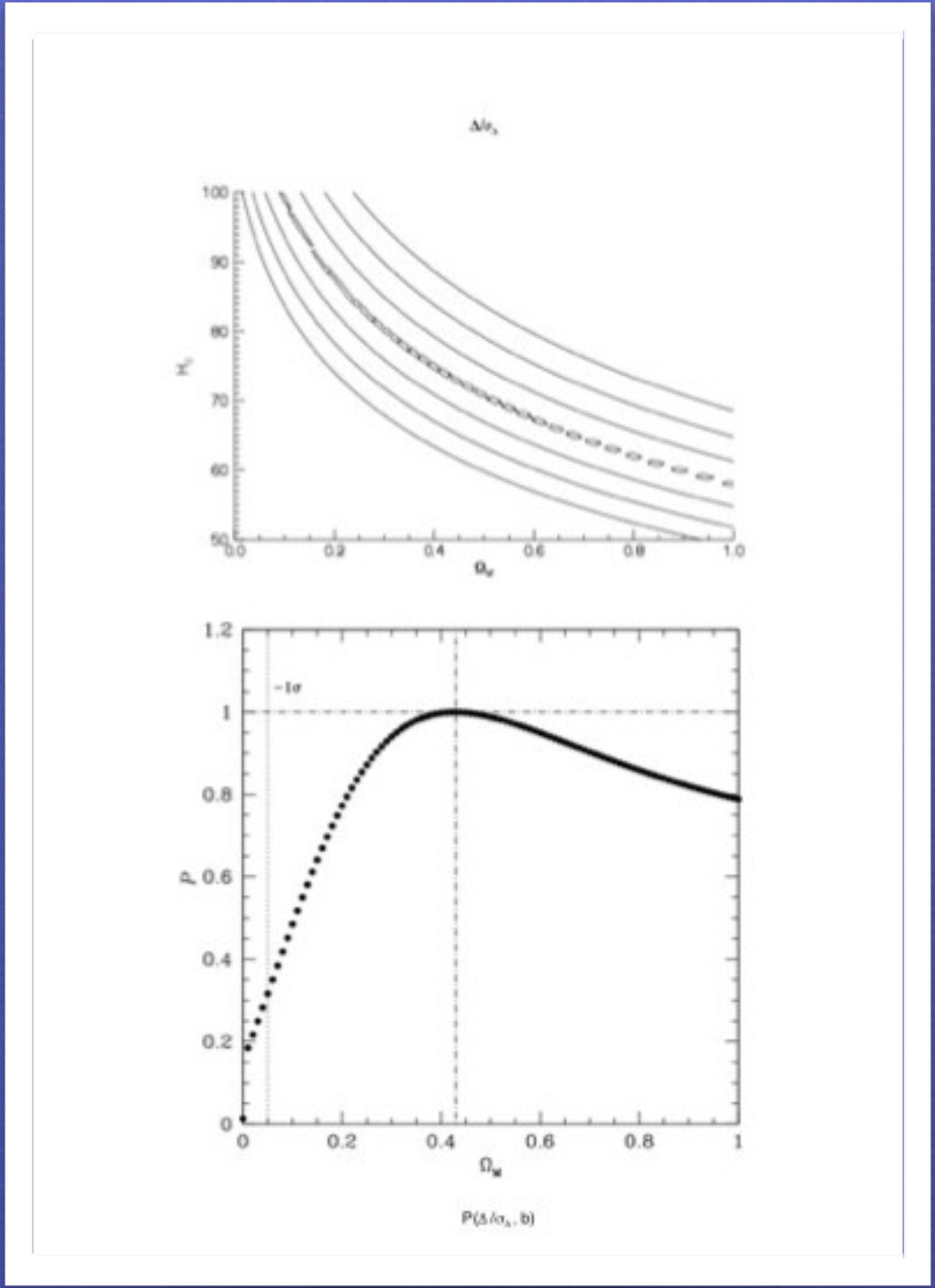


Results for samples 1,2,3: n = 62, rms(log$L$)=0.4

$$\Omega_{\mathrm{M}} \approx 0.30 \pm 0.06(1\sigma)$$

assuming H_0 and $\Omega_{\mathrm{M}} + \Omega_\Lambda = 1.0$





Results on some relevant models

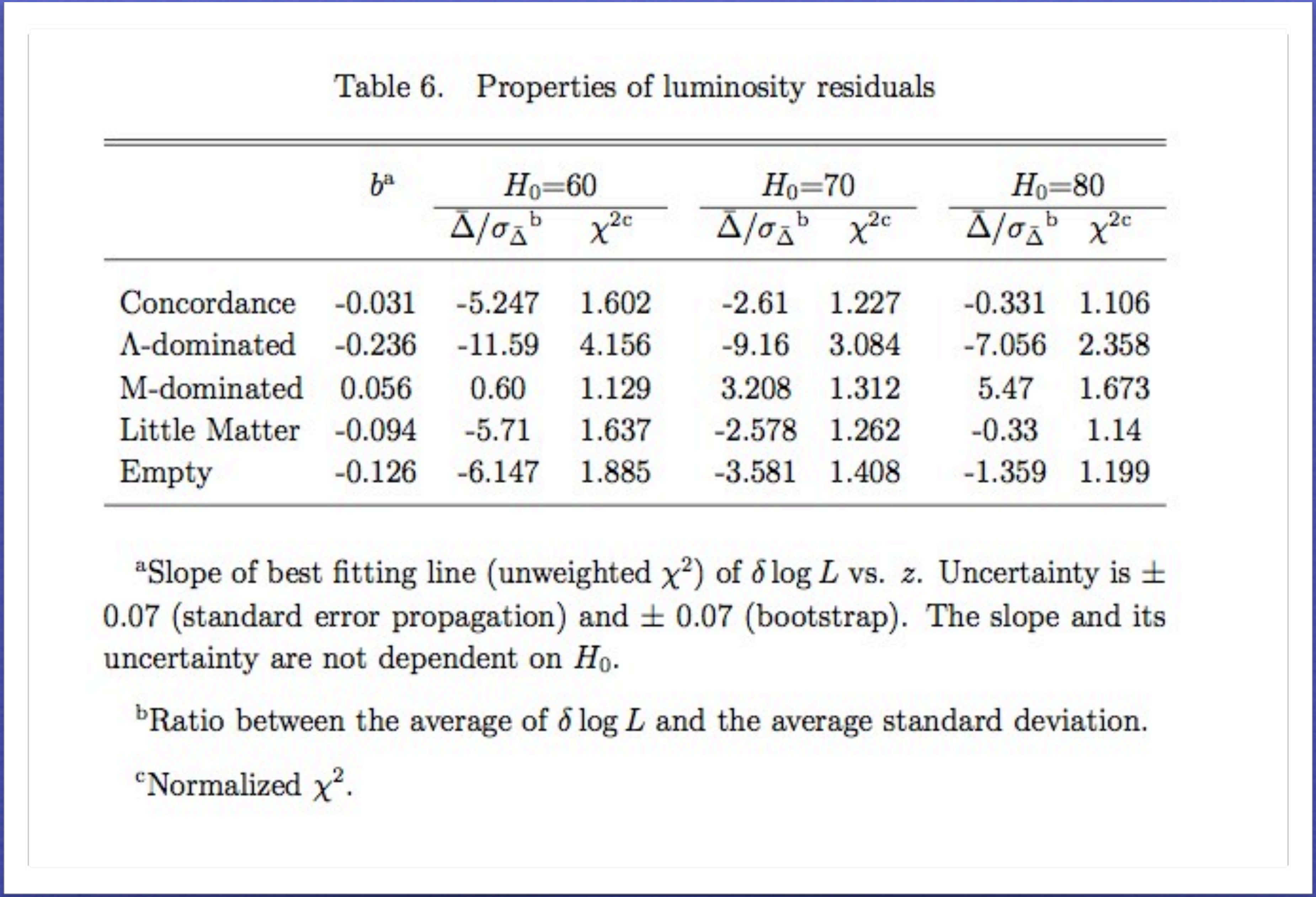


Table 6. Properties of luminosity residuals

	b^{a}	H_0=60		H_0=70		H_0=80	
		$\bar{\Delta}/\sigma_{\bar{\Delta}}{}^{b}$	χ^{2c}	$\bar{\Delta}/\sigma_{\bar{\Delta}}{}^{b}$	χ^{2c}	$\bar{\Delta}/\sigma_{\bar{\Delta}}{}^{b}$	χ^{2c}
Concordance	-0.031	-5.247	1.602	-2.61	1.227	-0.331	1.106
Λ-dominated	-0.236	-11.59	4.156	-9.16	3.084	-7.056	2.358
M-dominated	0.056	0.60	1.129	3.208	1.312	5.47	1.673
Little Matter	-0.094	-5.71	1.637	-2.578	1.262	-0.33	1.14
Empty	-0.126	-6.147	1.885	-3.581	1.408	-1.359	1.199

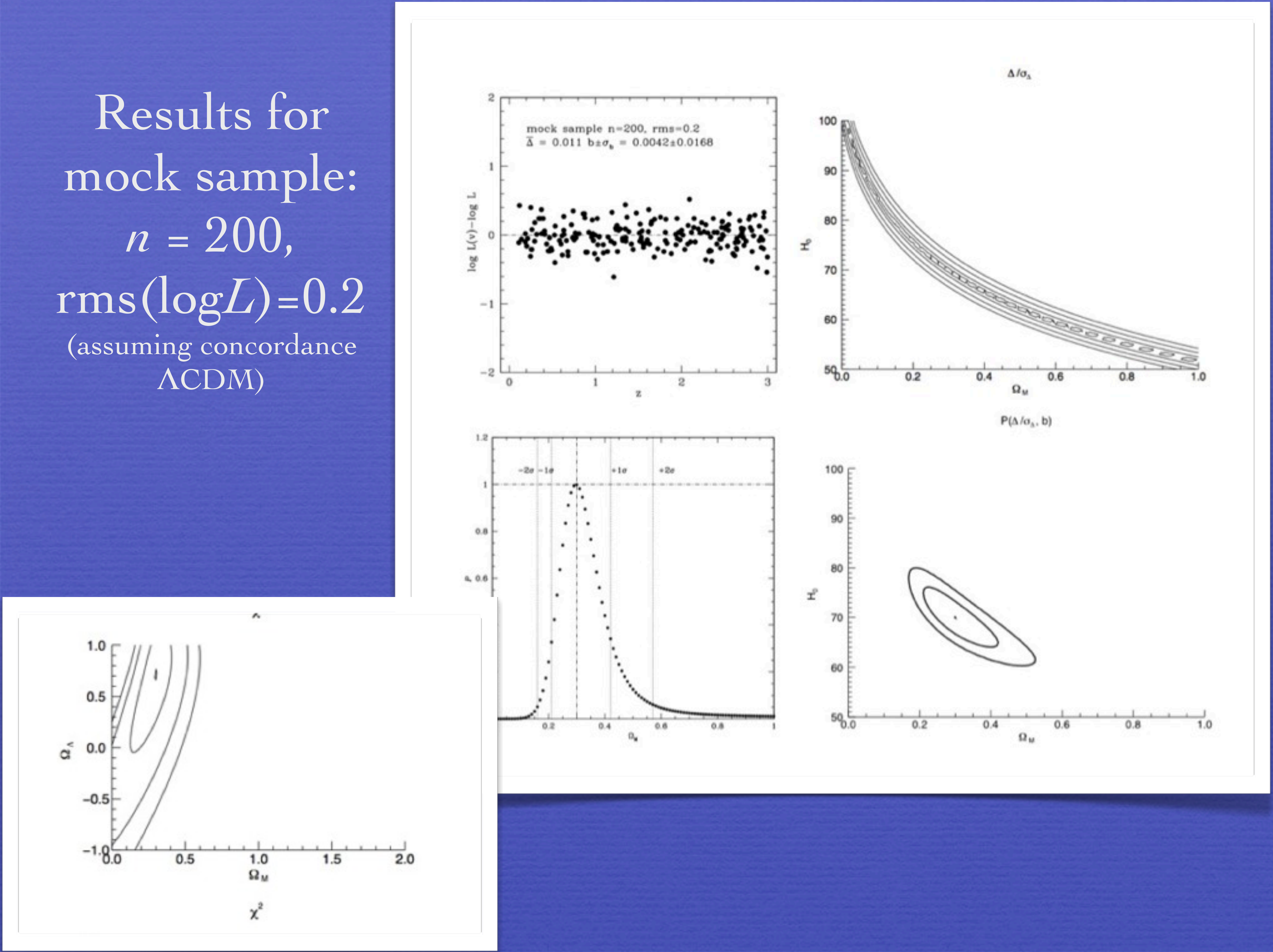
[a] Slope of best fitting line (unweighted χ^2) of $\delta \log L$ vs. z. Uncertainty is ± 0.07 (standard error propagation) and ± 0.07 (bootstrap). The slope and its uncertainty are not dependent on H_0.

[b] Ratio between the average of $\delta \log L$ and the average standard deviation.

[c] Normalized χ^2.

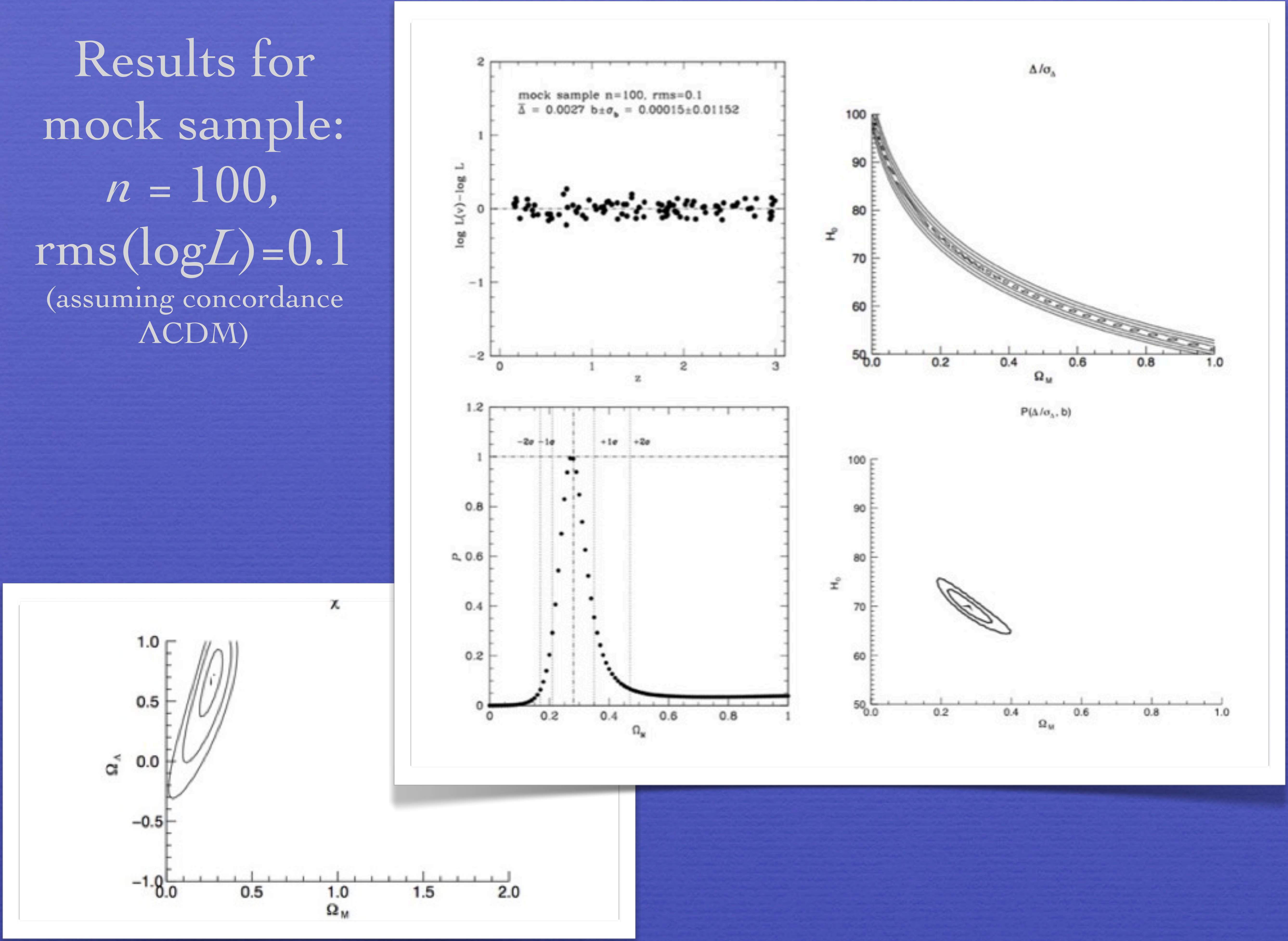
Results for mock sample: n = 200, rms(log$L$)=0.2

(assuming concordance ΛCDM)



Results for mock sample: n = 100, rms(log$L$)=0.1

(assuming concordance ΛCDM)



A simplified error budget for statistical errors

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

$$L = 4\pi d^2(z, \Omega_{\mathrm{M}}, \Omega_{\Lambda})(\lambda f_{\lambda}) \cdot 10^{\mathrm{B.C.}}$$

Main source of statistical error: FWHM measurement errors

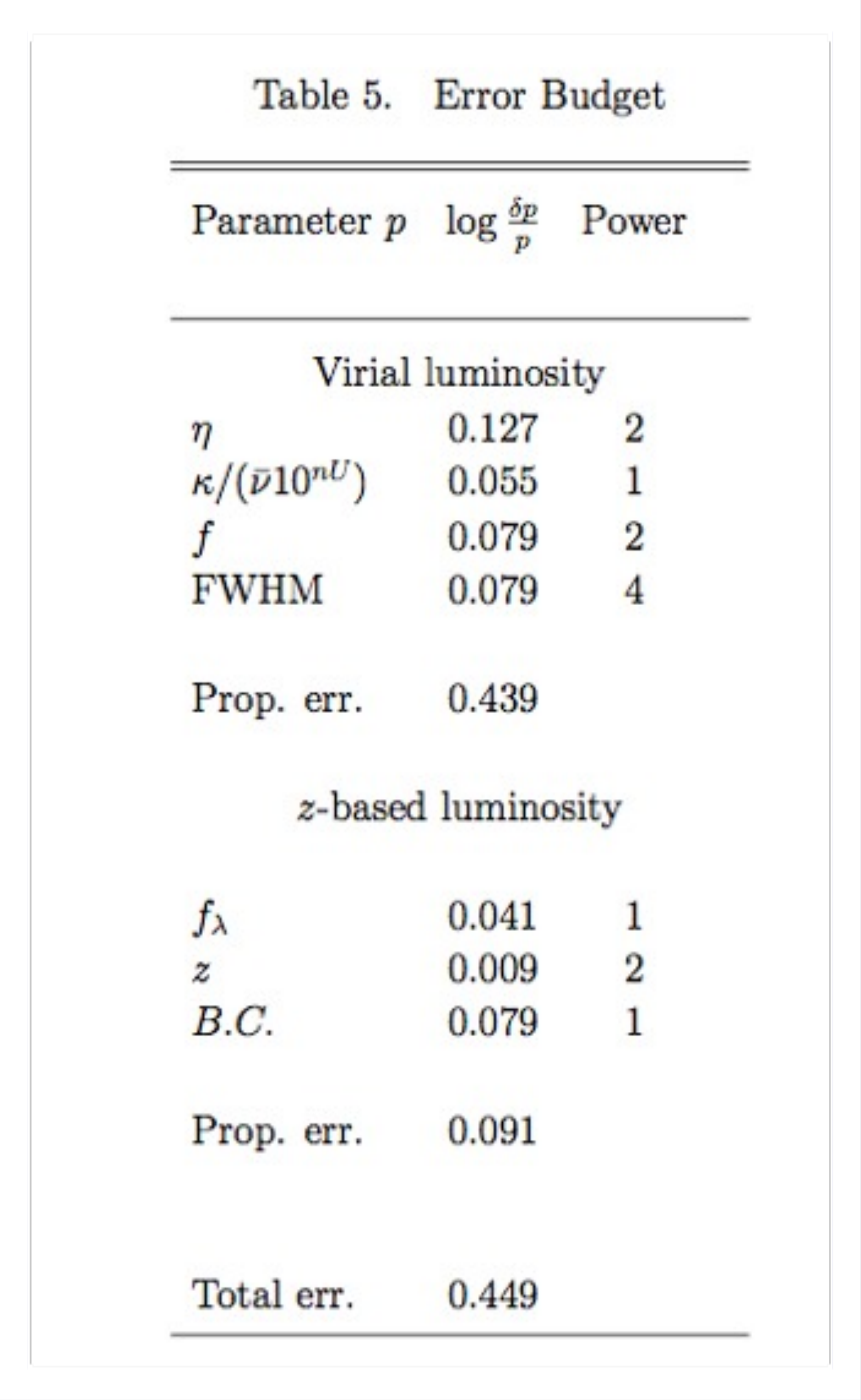
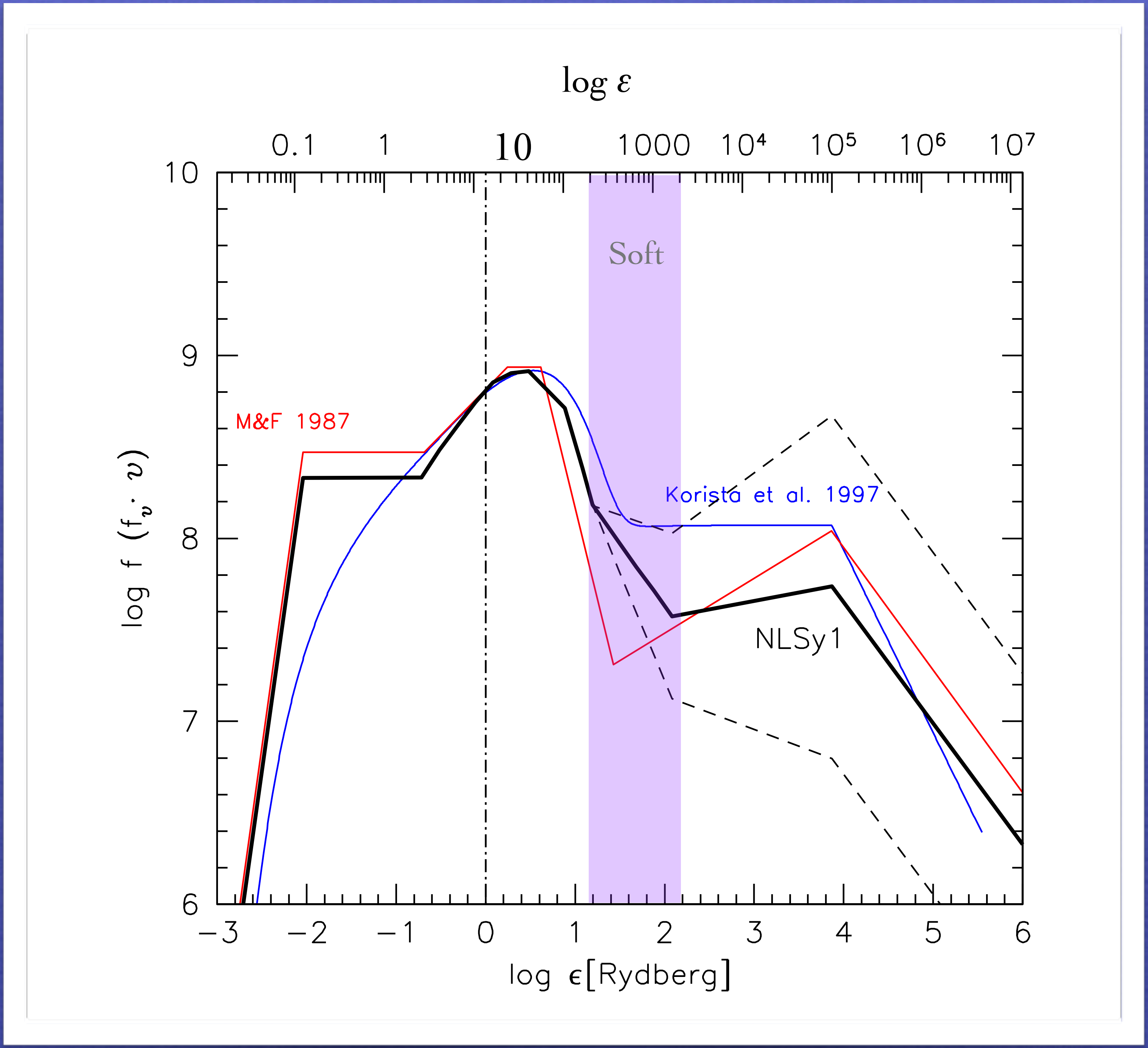


Table 5. Error Budget

Parameter p	$\log \frac{\delta p}{p}$	Power
	Virial luminosity	
η	0.127	2
$\kappa/(\bar{\nu}10^{nU})$	0.055	1
f	0.079	2
FWHM	0.079	4
Prop. err.	0.439	
	z-based luminosity	
f_λ	0.041	1
z	0.009	2
$B.C.$	0.079	1
Prop. err.	0.091	
Total err.	0.449	

Constraining the continuum of xA sources



NLSy1 SEDs: optical/UV/soft X Grupe et al. 2010; hard X: Panessa et al. 2011

Statistical errors

can be reduced to rms ≈ 0.3

Efforts should be oriented toward obtaining a larger sample ($\gtrsim$300 sources)

Systematic errors

1) increasing $R_{\rm FeII}$ and AlIII λ1860/SiII]λ 1892
2) bolometric correction dependent on L

an analysis is possible only on a larger sample of real data

Conclusions

Quasars potential for cosmographic studies has not been exploited yet

Most promising methods involve the identification of “Eddington standard candles”

“Eddington standard candles” could cover a range of distances where the metric of the Universe has not been “charted” as yet

The potential may extend to the physics of accelerated expansion…