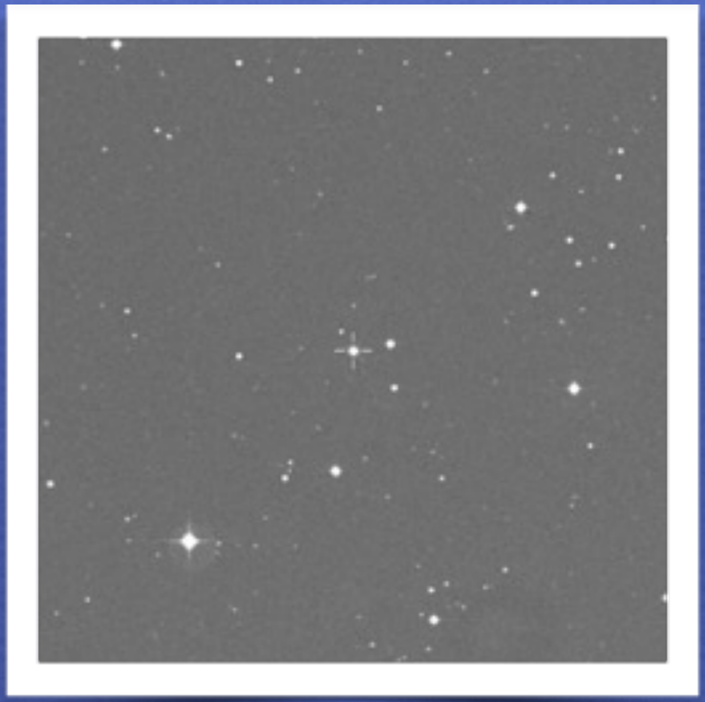
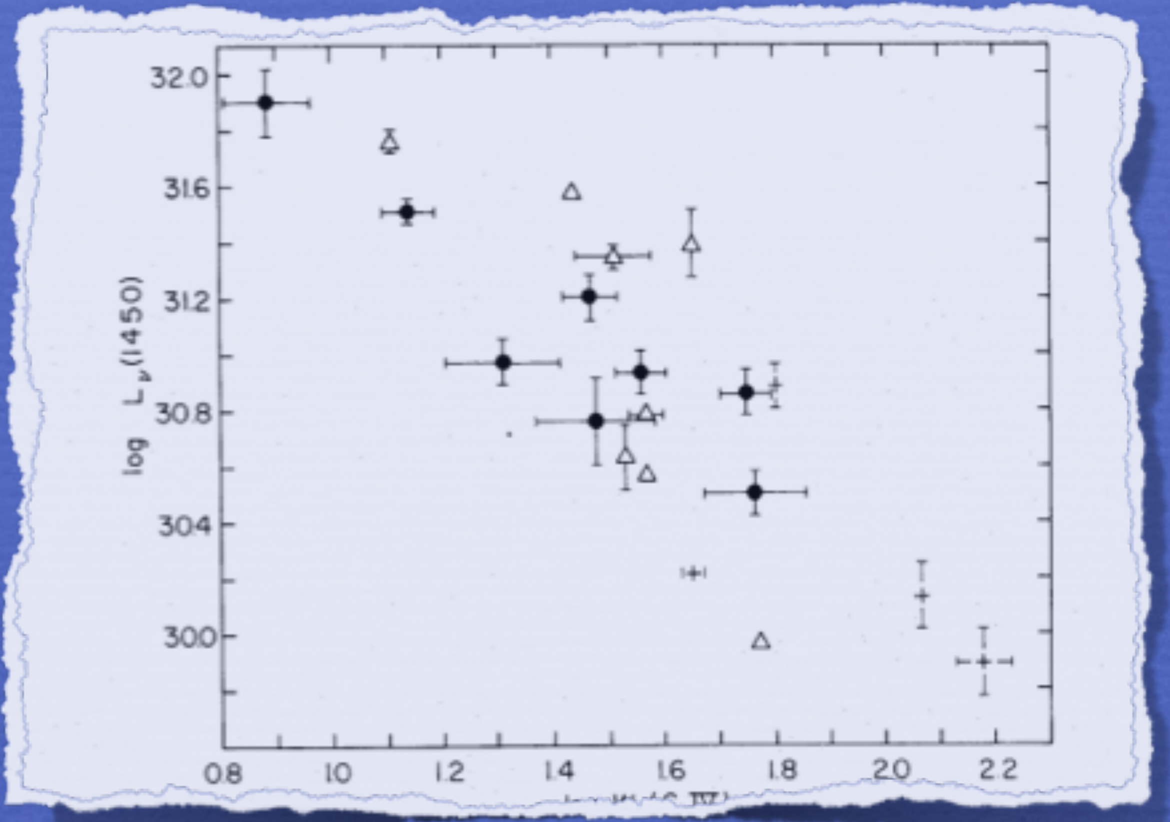
Quasars at Extremely High Accretion Rates: Potential Distance Indicators?





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Why have quasars never been successfully used as cosmological probes?

1. Type 1 quasars are plentiful (~10^5)

2. can be very luminous, bolometric luminosity $L > 10^{48}$ erg s^{-1}

3. observed in an extremely broad range of redshift $0 < z < 7$

4. relatively stable, especially if RQ (90% of all quasars) (Zamfir et al. 2008)

Why have quasars never been successfully used as cosmological probes?

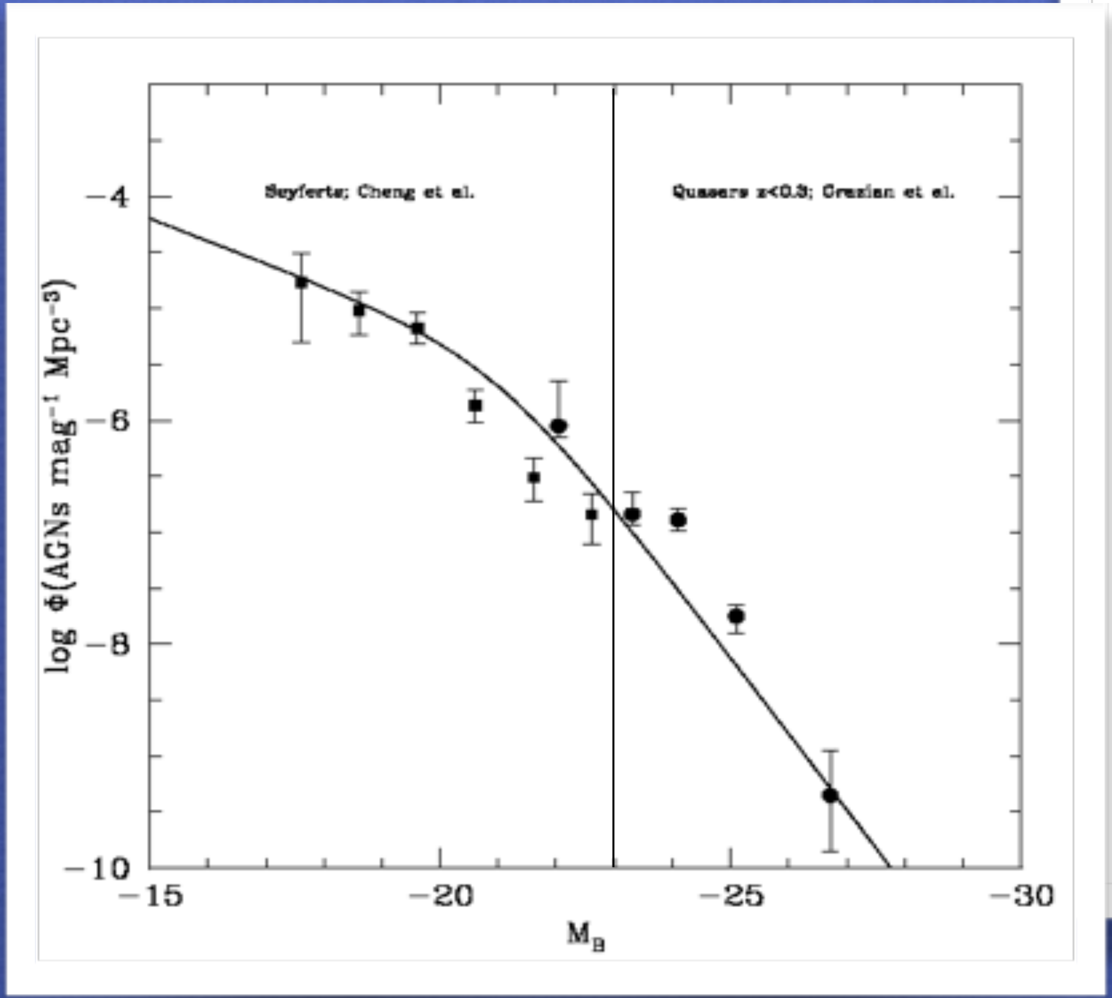
Quasars are sources with an evolving luminosity function, open-ended at low L

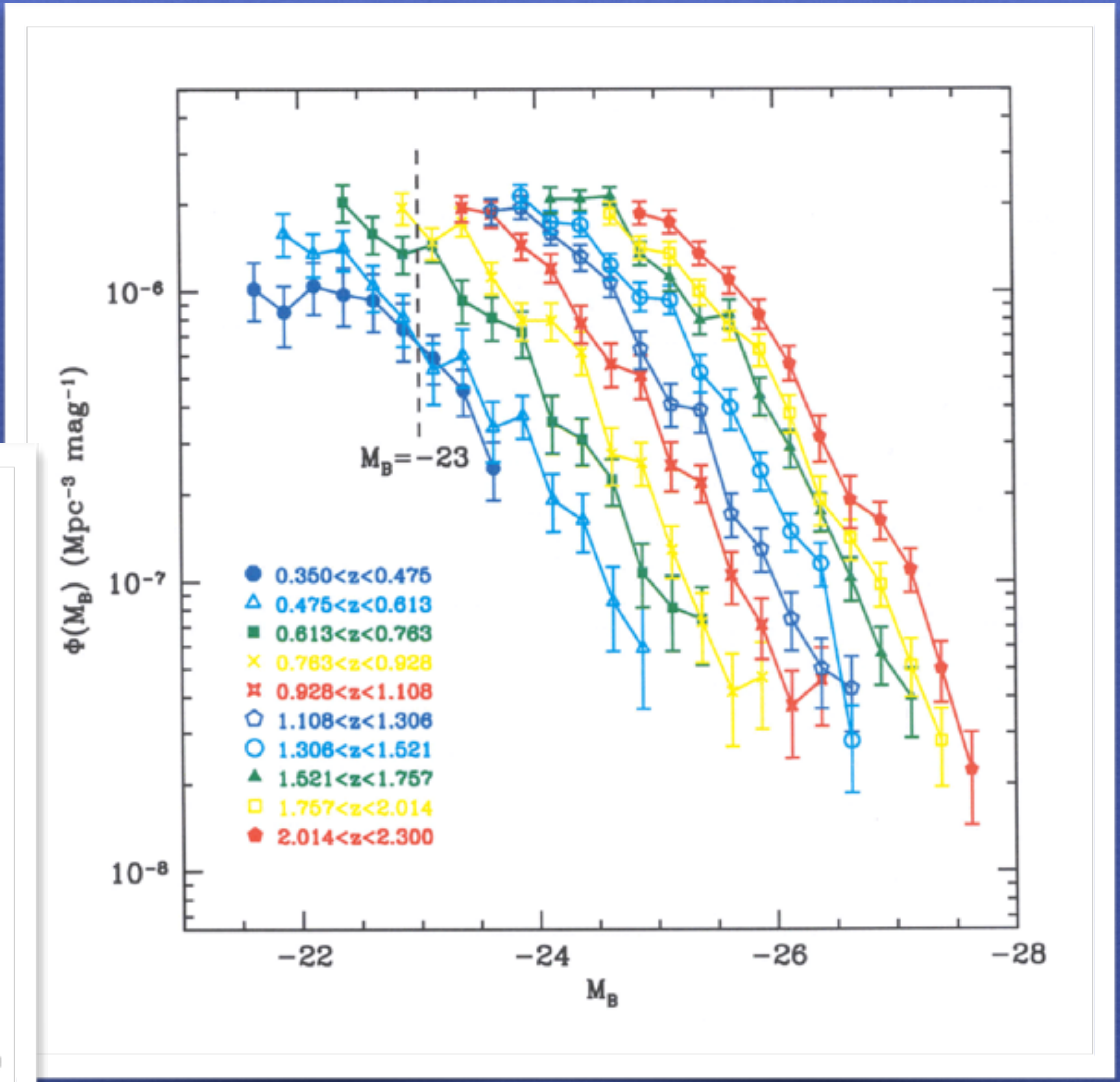
Quasar spectral properties do not show *strong* signs of dependence on luminosity

Quasars are anisotropic sources

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

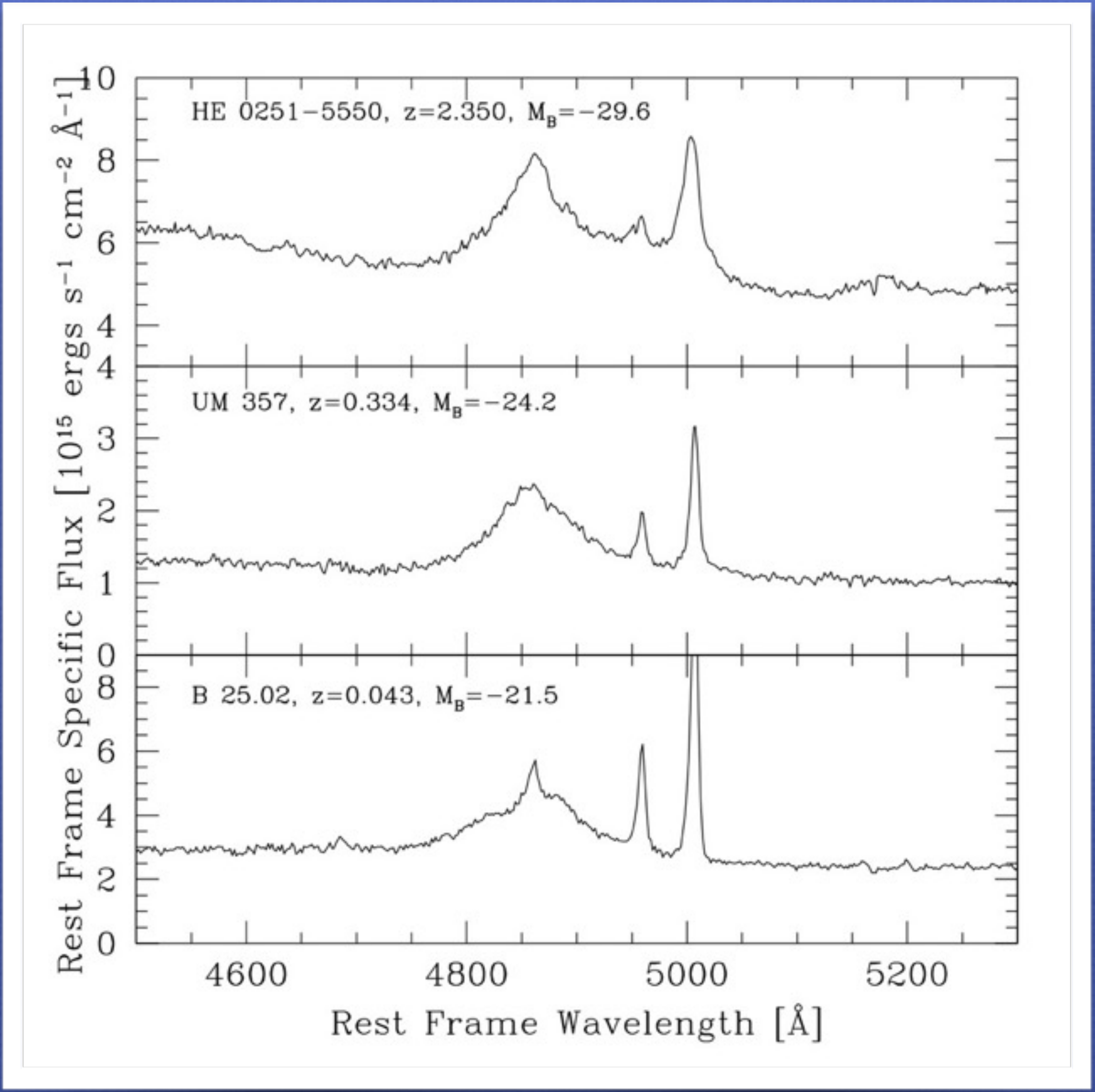
Quasars are sources with an evolving luminosity function, open-ended at low *L*

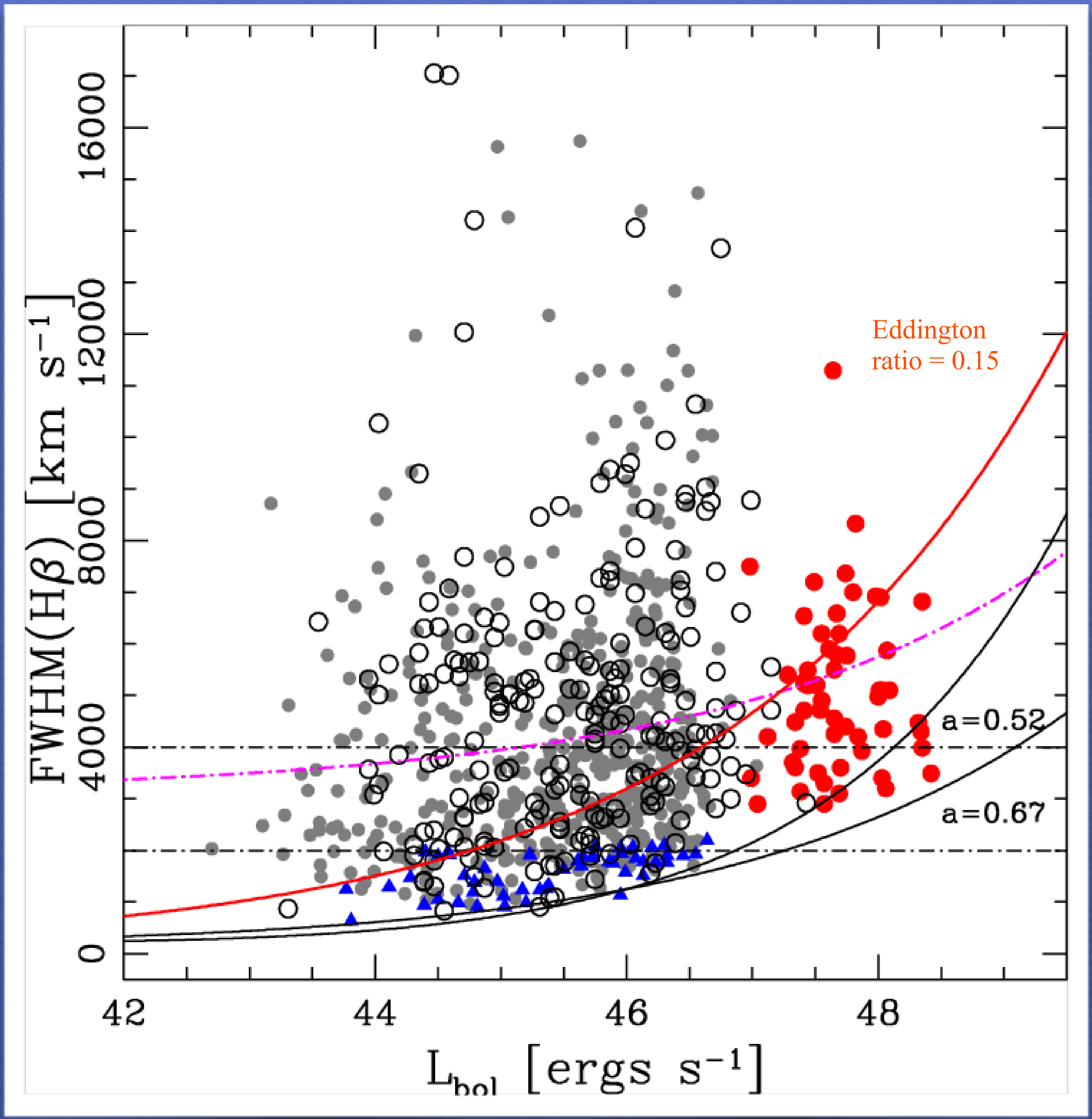




2dF; Boyle et al. 2001

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





Minimum FWHM(Hβ) consistent with virial assumption and maximum luminosity ad Eddington Limit

The Pop. A limit is luminosity dependent

Curves assume virial relationship with $r \propto L^a$

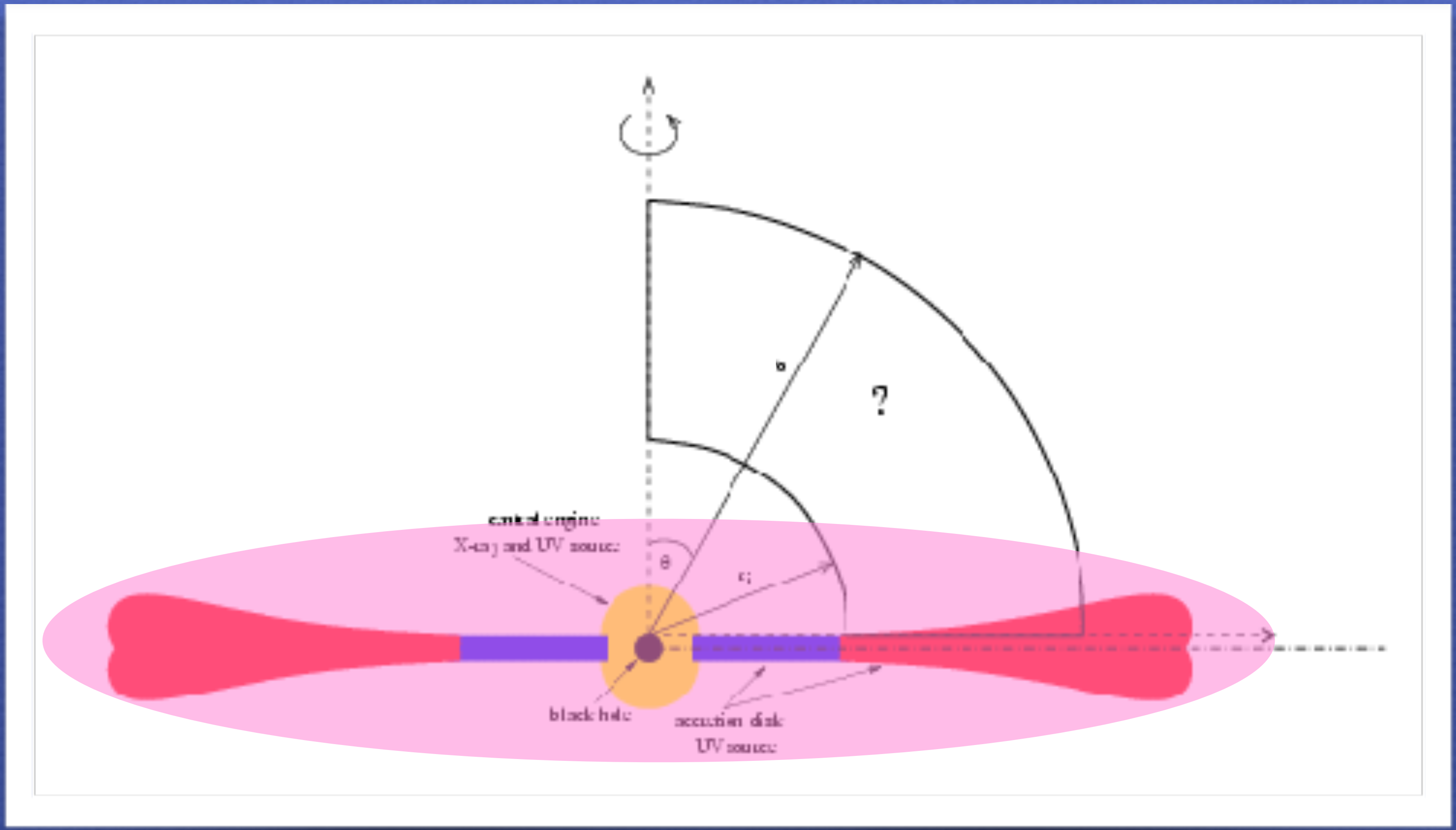
Marziani et al. 2009

Quasars are anisotropic sources

In radio-quiet quasars, thermal emission from an optically thick accretion disk is anisotropic.

Orientation effects are expected on optical/UV emission continuum, and emission line width

They are not yet well constrained/understood

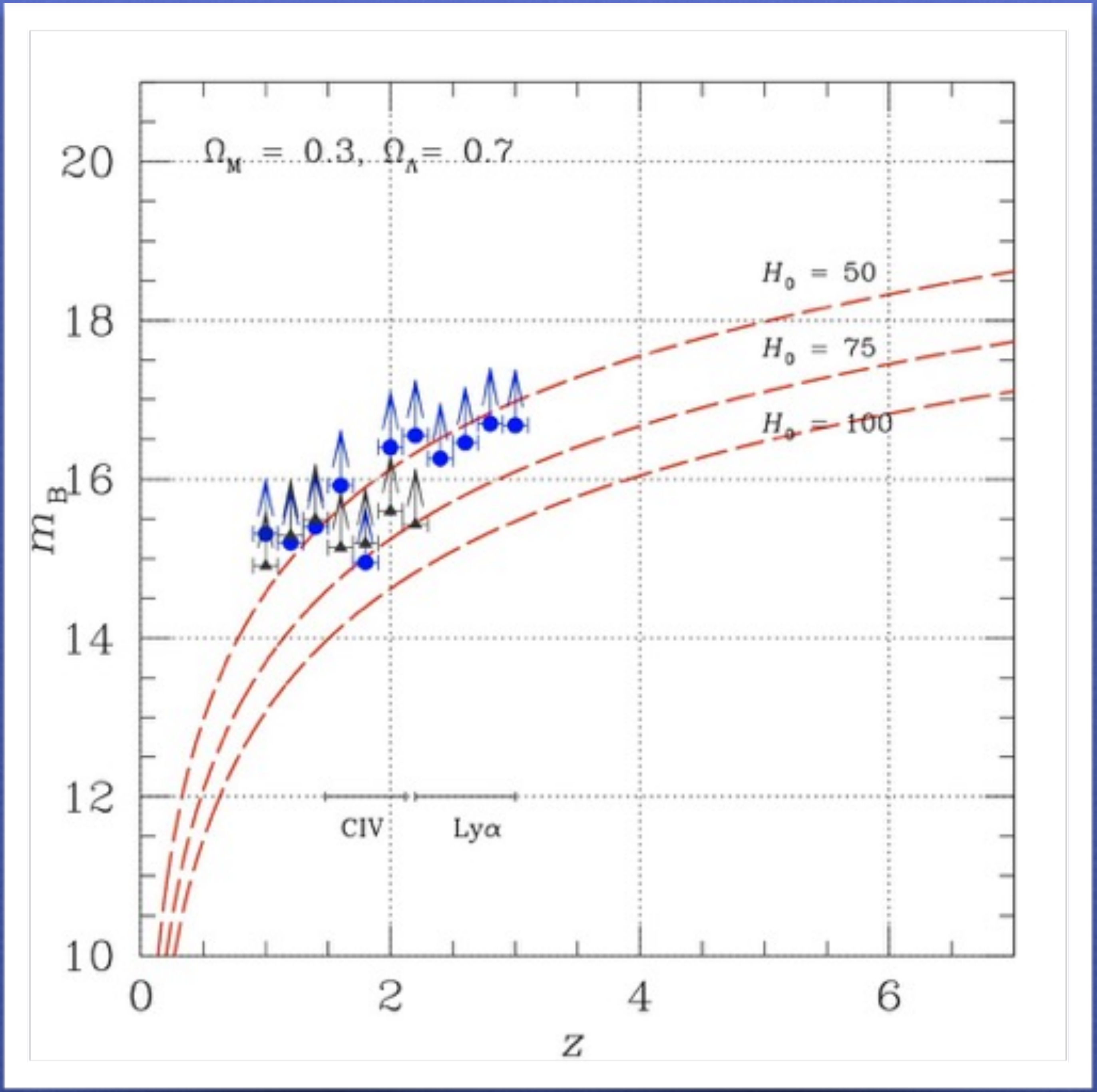


Can Quasars tell us anything on the geometry of the Universe?

Hubble diagram for the brightest quasars

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

H_0 ~60-70 km s^{-1} Mpc^{-1}



Bartelmann et al. 2009

Several approaches were devised
to exploit quasars for cosmology:

Correlations with Luminosity

the “Baldwin Effect”: too weak a correlation
(Xu et al. 2008; Marziani et al. 2008, Bian et al. 2012)

Time delay methods (present and future)

Broad Line Region reverberation
accretion disk reverberation
(Karowska et al.2004)

“Eddington standard candles”

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

Other methods

not based on quasar intrinsic properties
Baryon acoustic oscillations in the Lyα forest of BOSS quasars (Busca et al. 2013)

Eddington standard candles

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

Two main issues:

1) definition of a sample with "known" $L/L_{\rm Edd}$ ($\eta \Rightarrow 1$); following the 4DE1 approach

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

Defining a sample of Eddington “standard candles”

The main sequence of 4DE1: optical plane

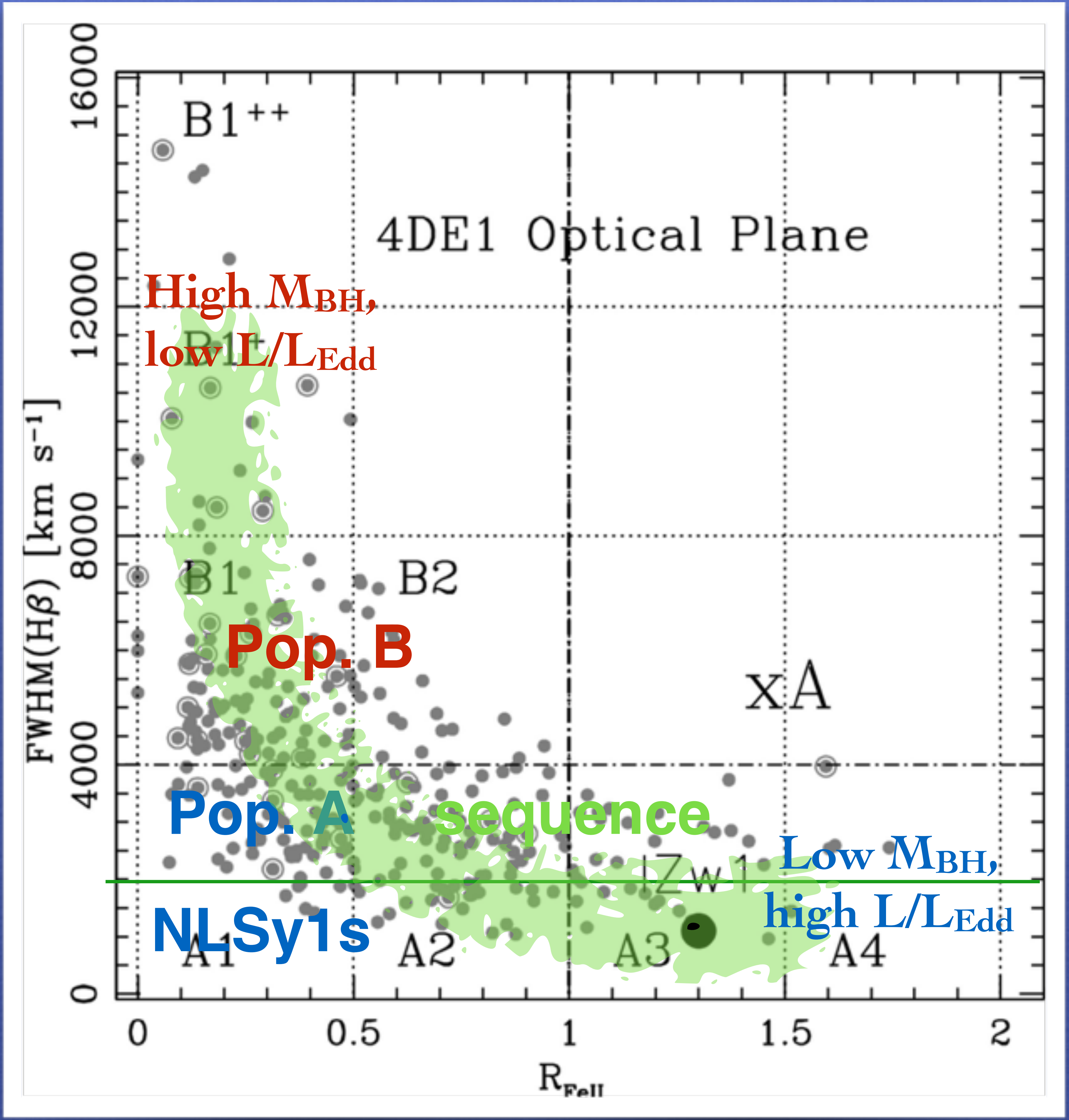
$$R_{\rm FeII} = \frac{I({\rm FeII}\lambda4570)}{I(H\beta)} \approx \frac{W({\rm FeII}\lambda4570)}{W(H\beta)}$$

FWHM(Hβ)

extreme Pop. A sources (xA) radiating at highest Eddington ratio values

Eddington ratio increases toward A3 and A4

Sulentic et al. 2000; Sulentic et al. 2002, c.f. Shen & Ho 2014



The 4DE1 space of Sulentic et al.

width of Hβ

strength of FeIIλ4570
emitting gas

$$R_{\mathrm{FeII}} = \frac{I(\mathrm{FeII}\lambda4570)}{I(H\beta)} \approx \frac{W(\mathrm{FeII}\lambda4570)}{W(H\beta)}$$

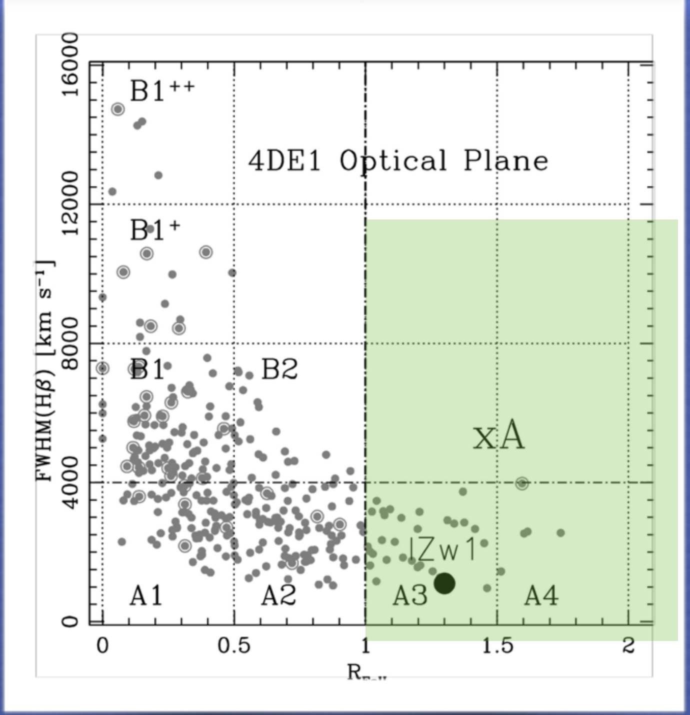
CIVλ1549 line shift
emitting region

soft-X ray photon index
keV: optically thick Comptonized radiation, correlated to Γ
20 keV)

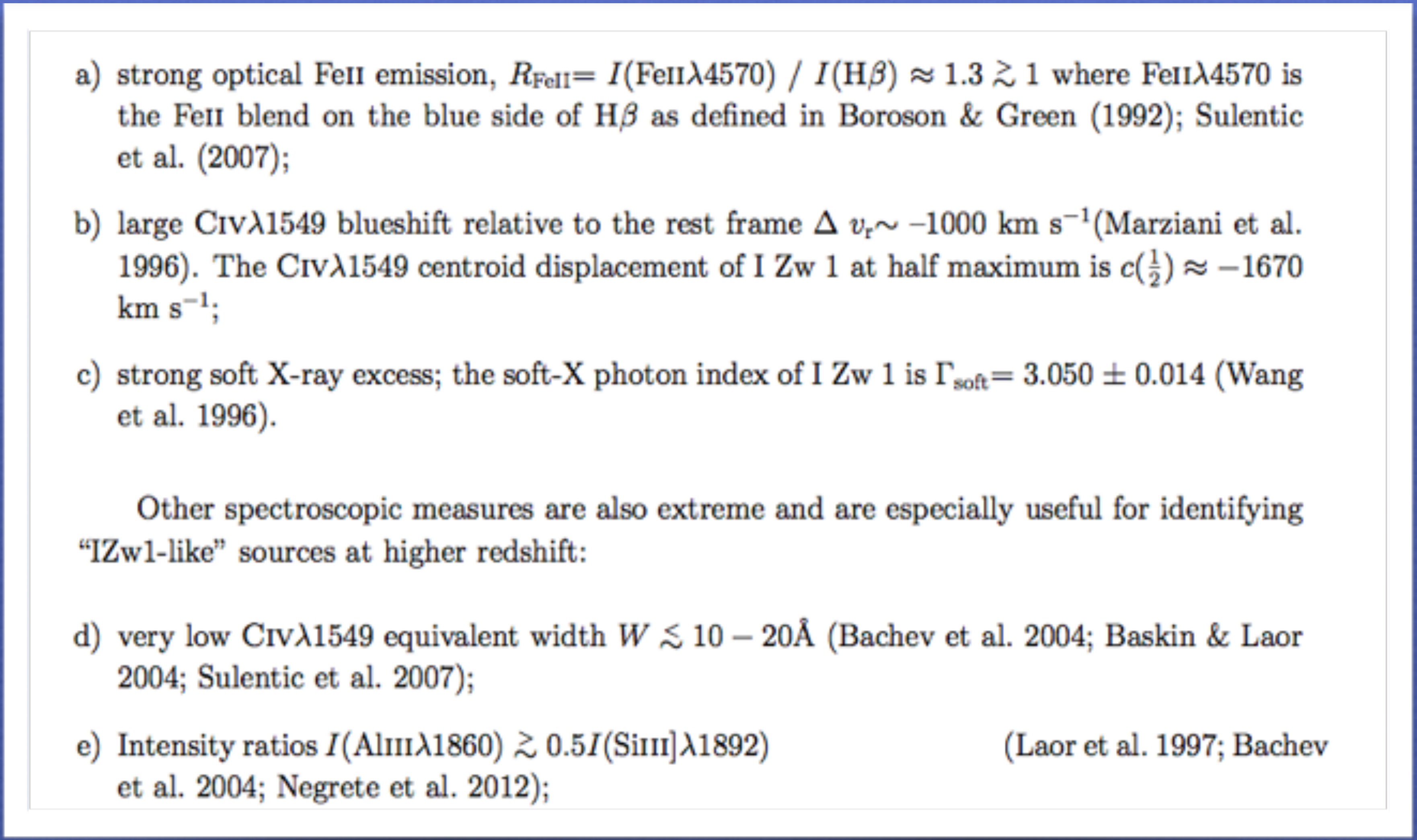
Separation of Population A (FWHM Hβ<4000 km/s) and Population B(roader) sources, associated with a critical Eddington ratio

(Marziani et al. 2003b)

Extreme Population A sources in the 4DE1 context



The prototypical source is NLSy1 I Zw 1



a) strong optical FeII emission, $R_{\rm FeII}$= I(FeIIλ4570) / I(Hβ) $\approx$ 1.3 $\gtrsim$ 1 where FeIIλ4570 is the FeII blend on the blue side of Hβ as defined in Boroson & Green (1992); Sulentic et al. (2007);

b) large CIVλ1549 blueshift relative to the rest frame $\Delta\ v_{\rm r} \sim -1000$ km s^{-1}(Marziani et al. 1996). The CIVλ1549 centroid displacement of I Zw 1 at half maximum is $c(\frac{1}{2}) \approx -1670$ km s^{-1};

c) strong soft X-ray excess; the soft-X photon index of I Zw 1 is $\Gamma_{\rm soft}$= 3.050 $\pm$ 0.014 (Wang et al. 1996).

Other spectroscopic measures are also extreme and are especially useful for identifying "IZw1-like" sources at higher redshift:

d) very low CIVλ1549 equivalent width $W \lesssim 10 - 20$Å (Bachev et al. 2004; Baskin & Laor 2004; Sulentic et al. 2007);

e) Intensity ratios I(AlIIIλ1860) $\gtrsim 0.5 I$(SiIII]λ1892) (Laor et al. 1997; Bachev et al. 2004; Negrete et al. 2012);

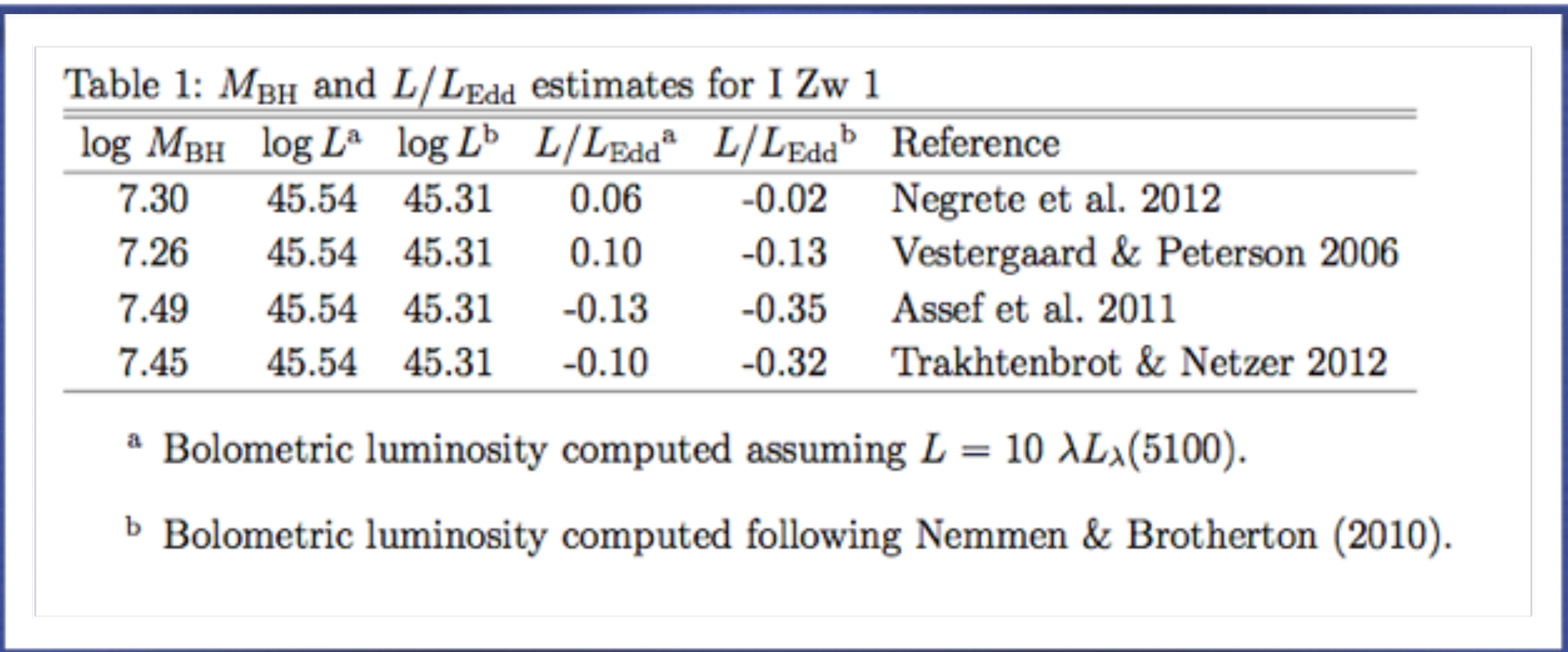
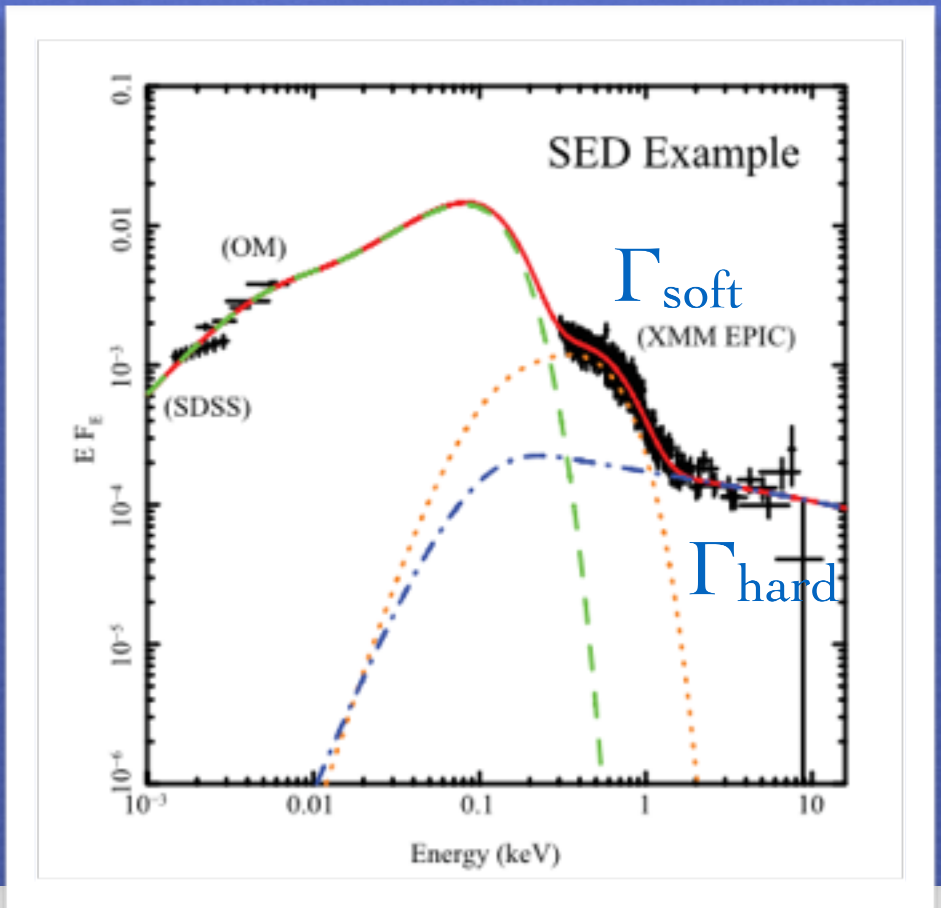


Table 1: $M_{\rm BH}$ and $L/L_{\rm Edd}$ estimates for I Zw 1

log $M_{\rm BH}$	log $L^{\rm a}$	log $L^{\rm b}$	$L/L_{\rm Edd}{}^{\rm a}$	$L/L_{\rm Edd}{}^{\rm b}$	Reference
7.30	45.54	45.31	0.06	-0.02	Negrete et al. 2012
7.26	45.54	45.31	0.10	-0.13	Vestergaard & Peterson 2006
7.49	45.54	45.31	-0.13	-0.35	Assef et al. 2011
7.45	45.54	45.31	-0.10	-0.32	Trakhtenbrot & Netzer 2012

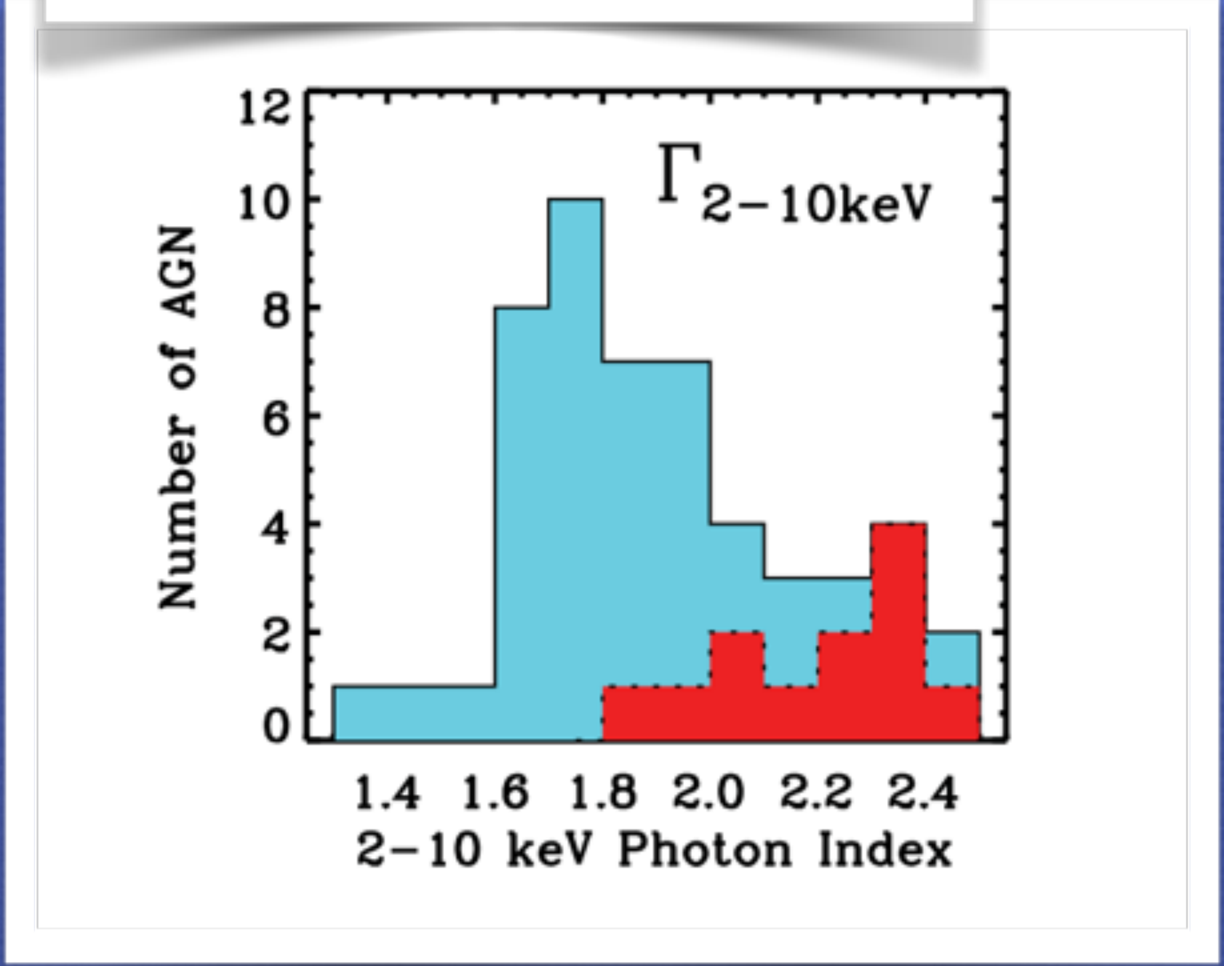
[a] Bolometric luminosity computed assuming $L = 10\ \lambda L_{\lambda}(5100)$.

[b] Bolometric luminosity computed following Nemmen & Brotherton (2010).

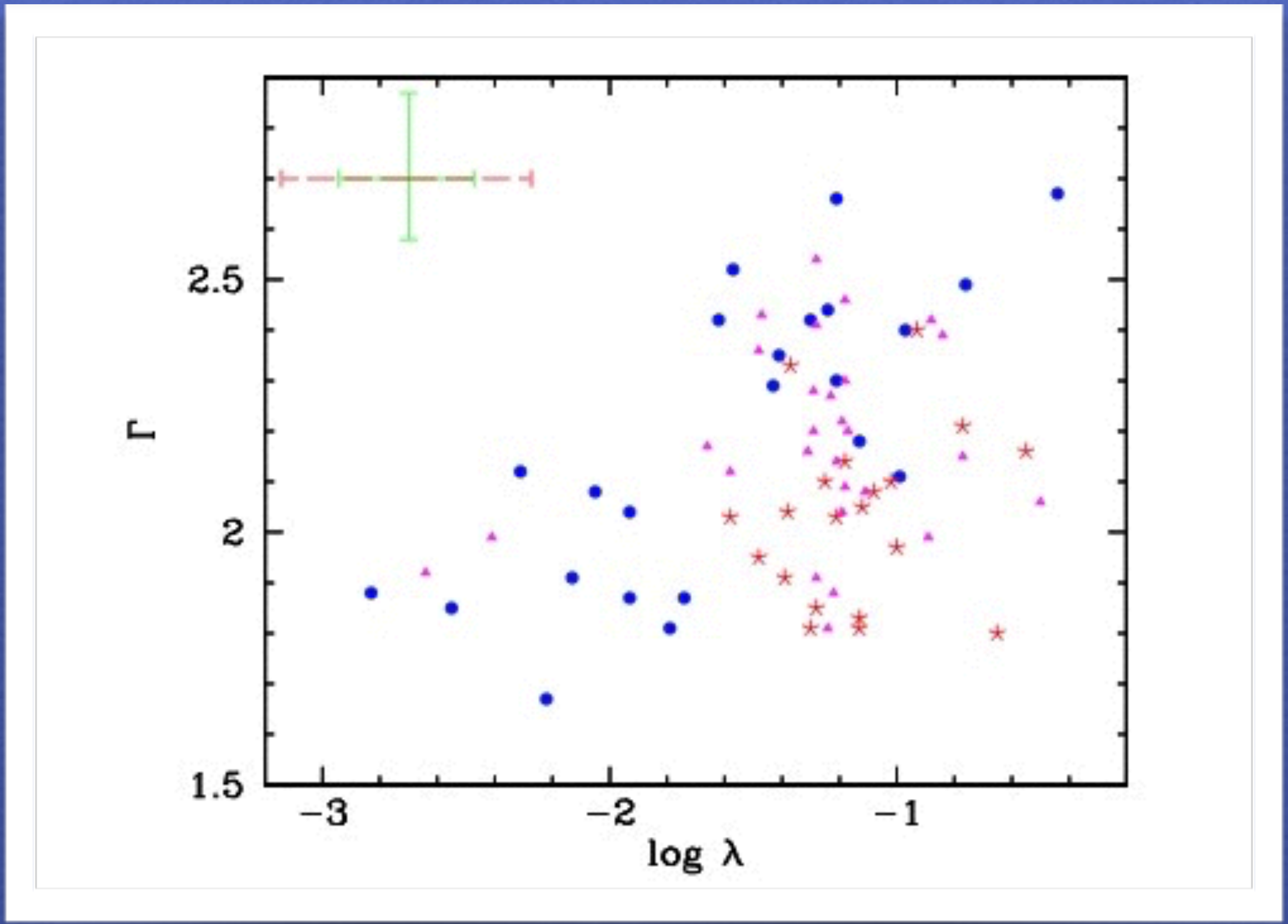


$\Gamma_{\rm hard} \geq 2$

A sufficient condition to isolate high accretors (?)

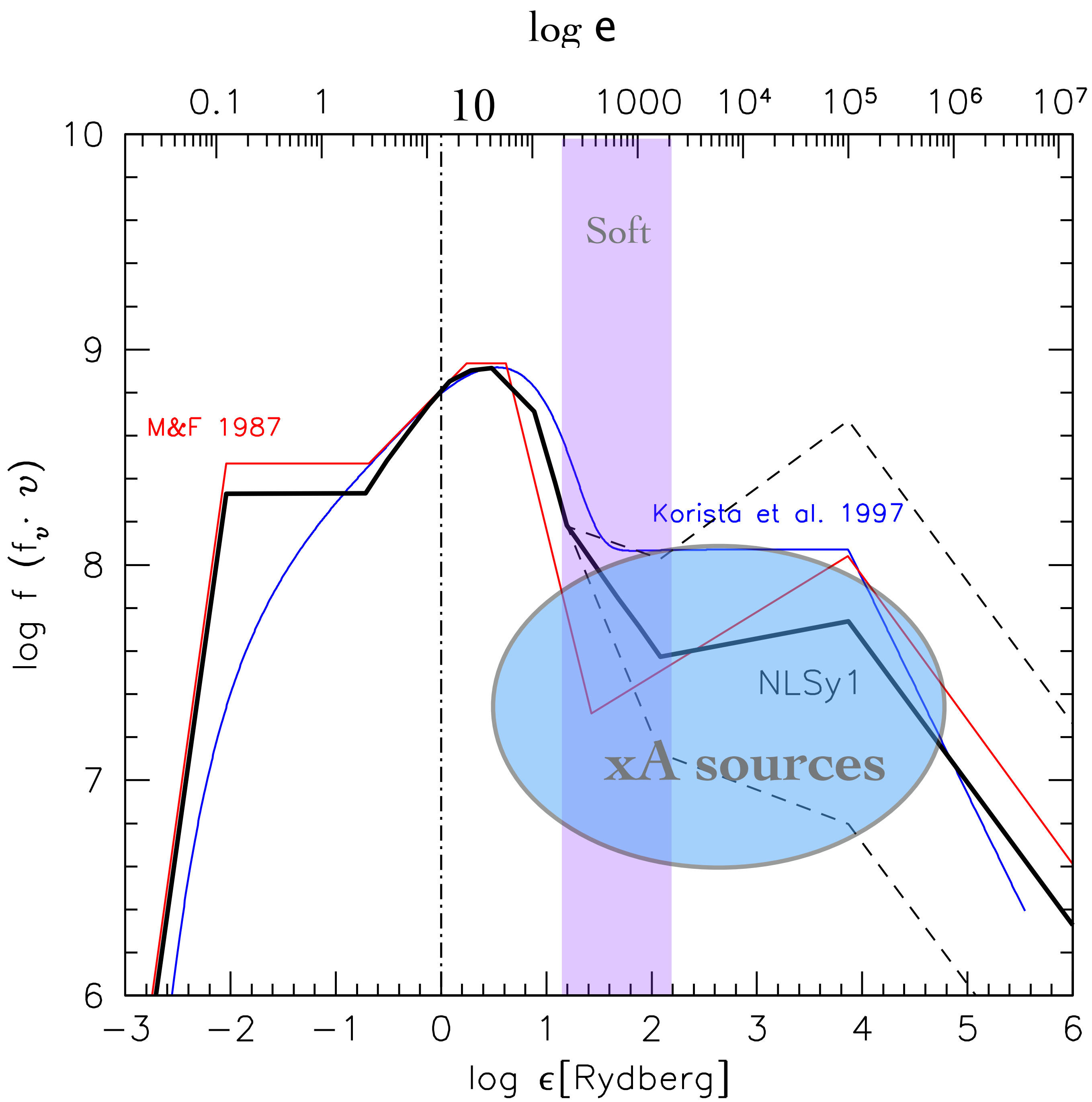


Jin et al. 2012



Fanali et al. 2013

Continuum of xA sources



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

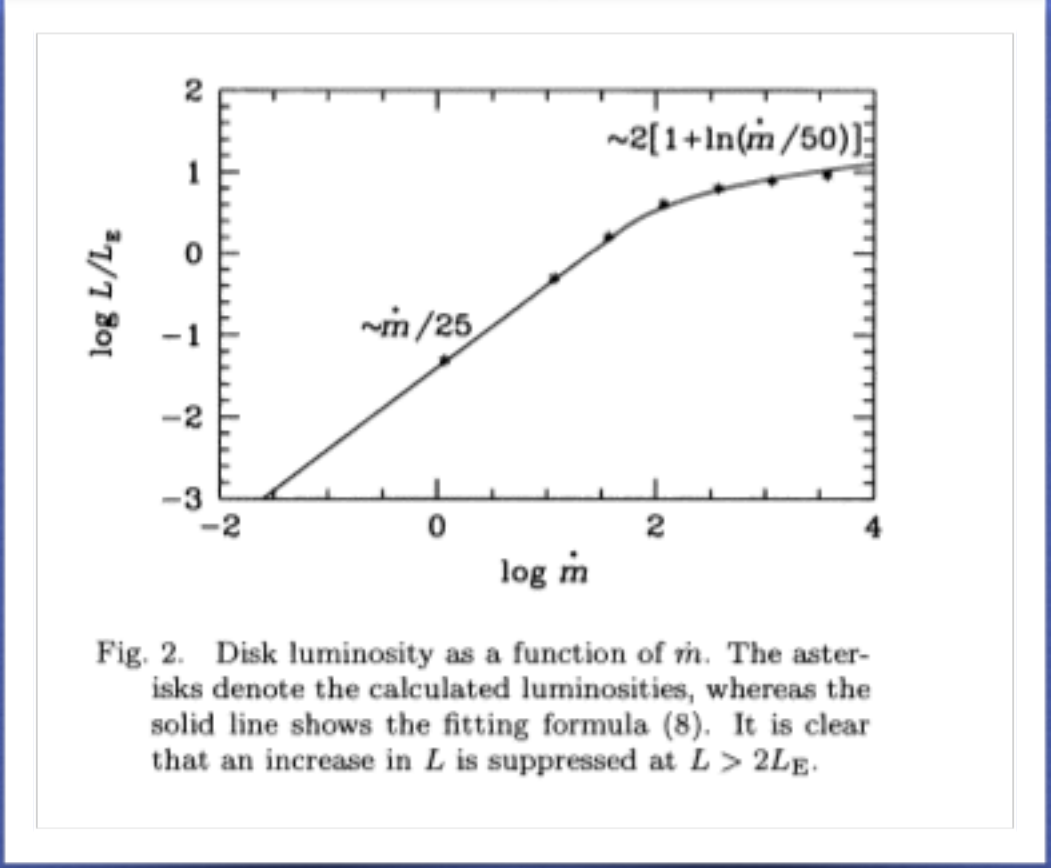


Fig. 2. Disk luminosity as a function of $\dot{m}$. The asterisks denote the calculated luminosities, whereas the solid line shows the fitting formula (8). It is clear that an increase in L is suppressed at $L > 2L_E$.

The luminosity is expected to "saturate" toward a few times the Eddington limit

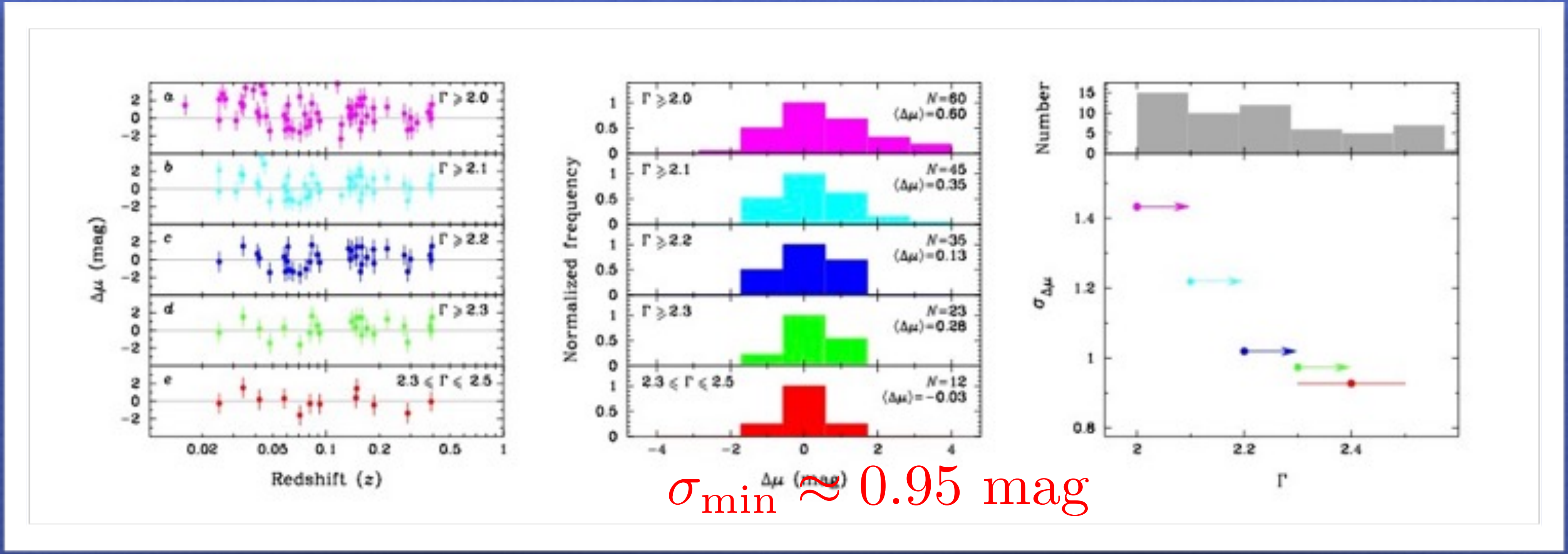
$$L = L_0(1 + \text{const} \ln \dot{m}) M_{BH}$$

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

Szuszkiewicz et al. 1996 Mineshige et al. 2000;
Sadowski et al. 2011; 2013

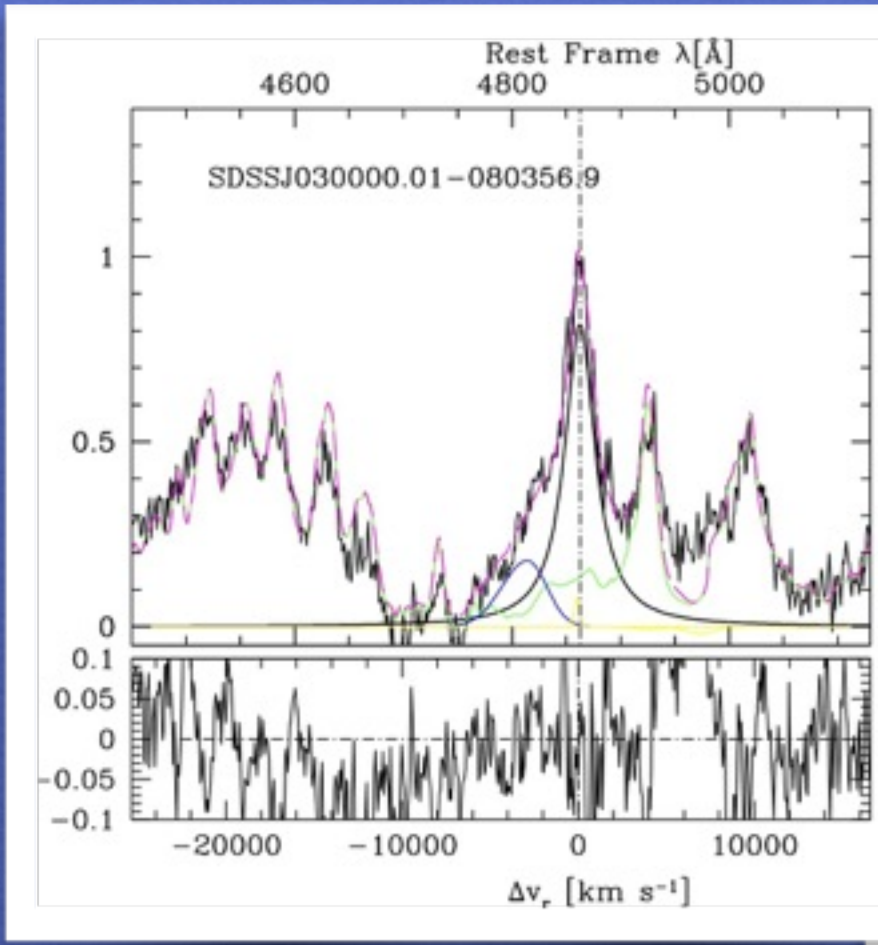
Wang et al. 2013

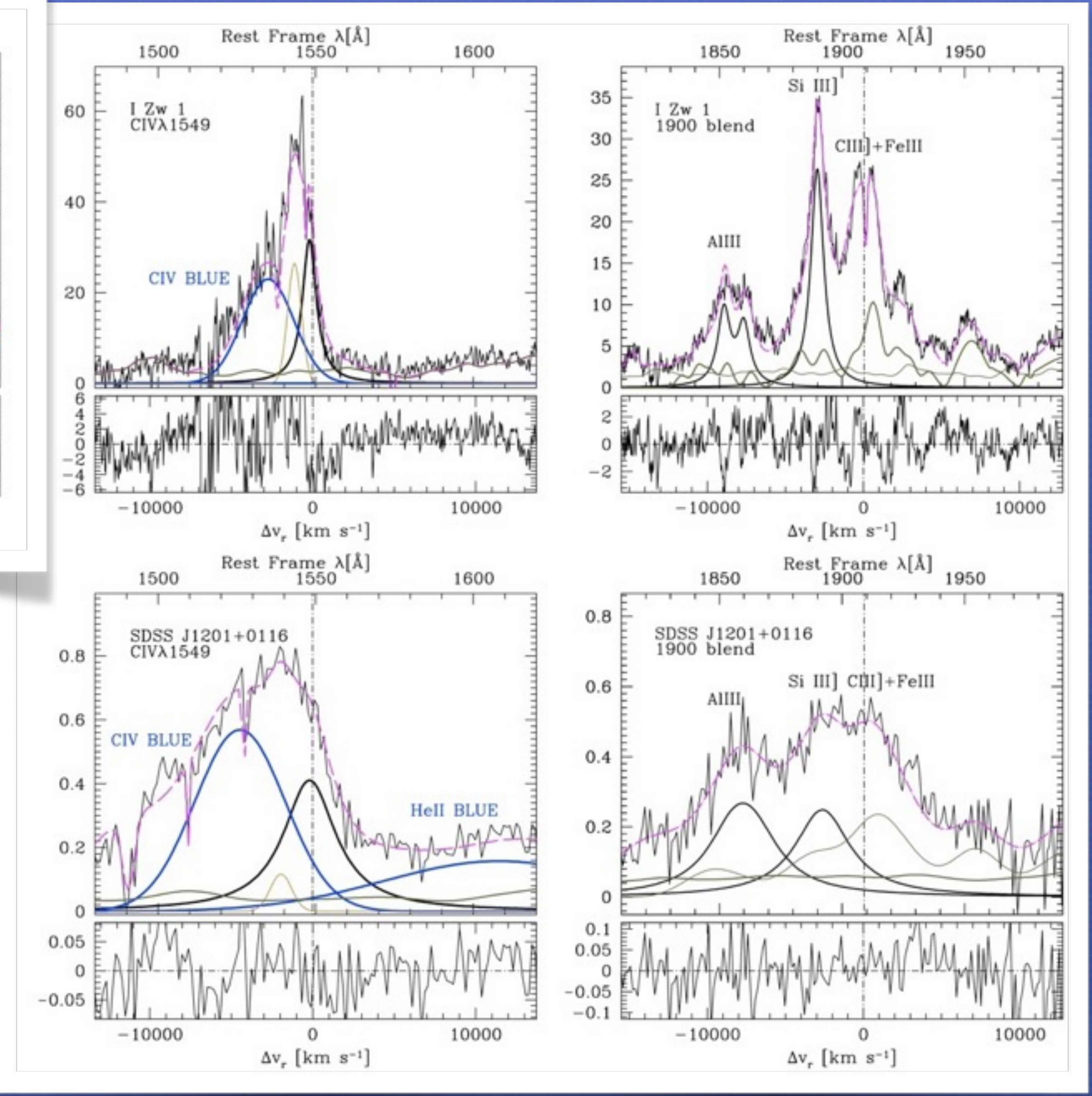
Data available for few sources at low z, with a significant scatter



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

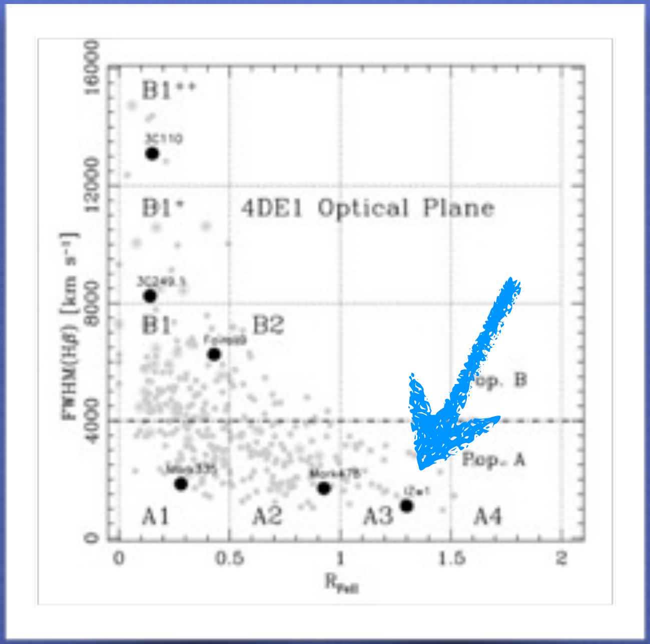
xA sources include high luminosity equivalents of NLSy1s



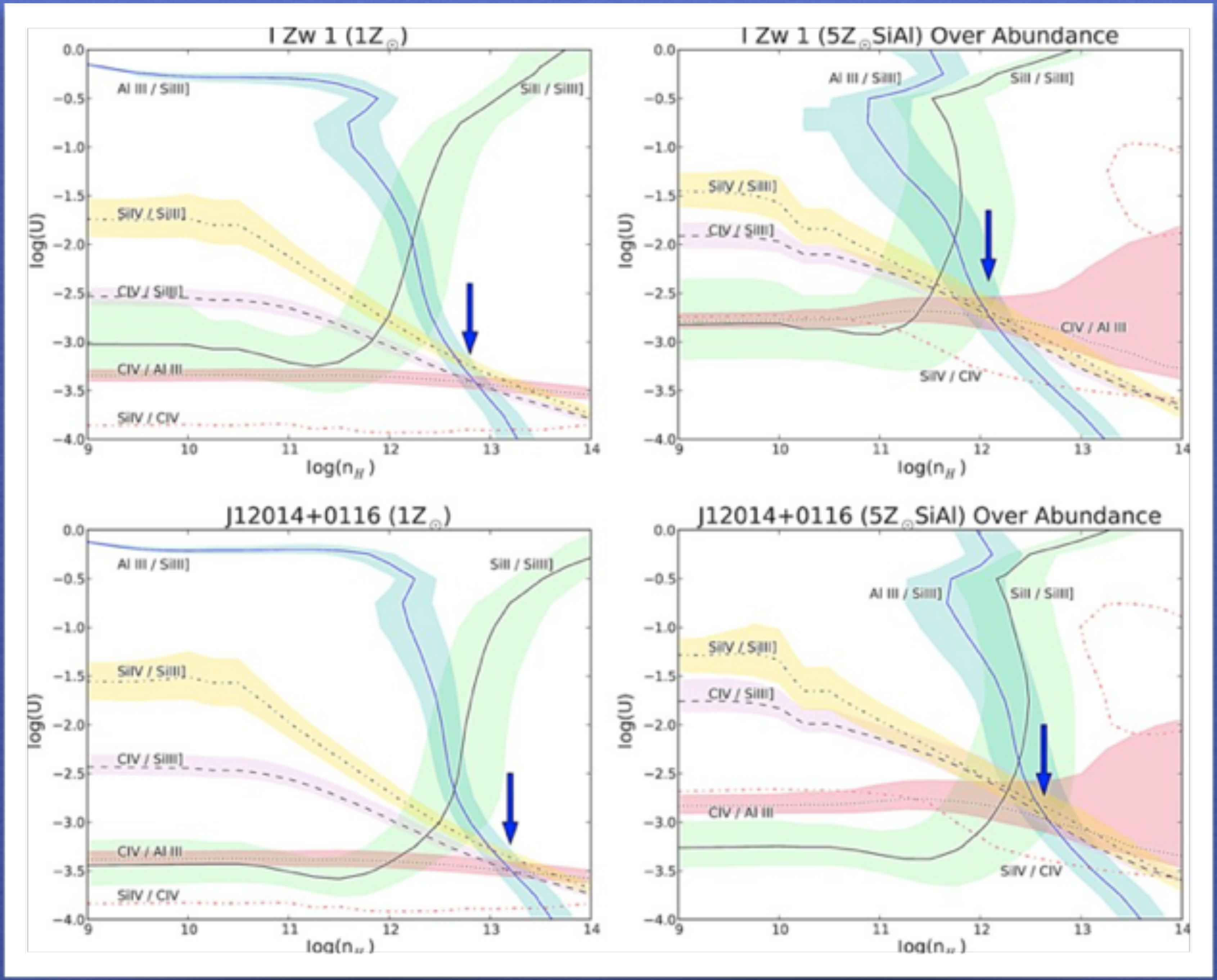


(Negrete et al. 2012)

Extreme A sources



Physical conditions in their broad component: well defined-values for density (high), ionization (high) and metallicity (high)



Plane ionization parameter versus density (Negrete et al. 2012)

A dense BLR remnant?

Merg

l. (2010)
preparation

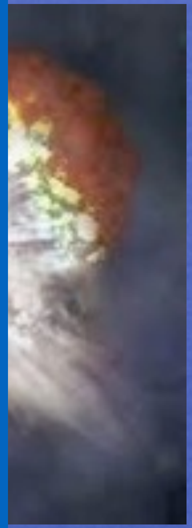
Extreme Population A sources

“wind dominated”: largest CIV blueshift

Eddington ratio close to 1

prominent low ionization spectrum

LIL emitting region: a dense remnant

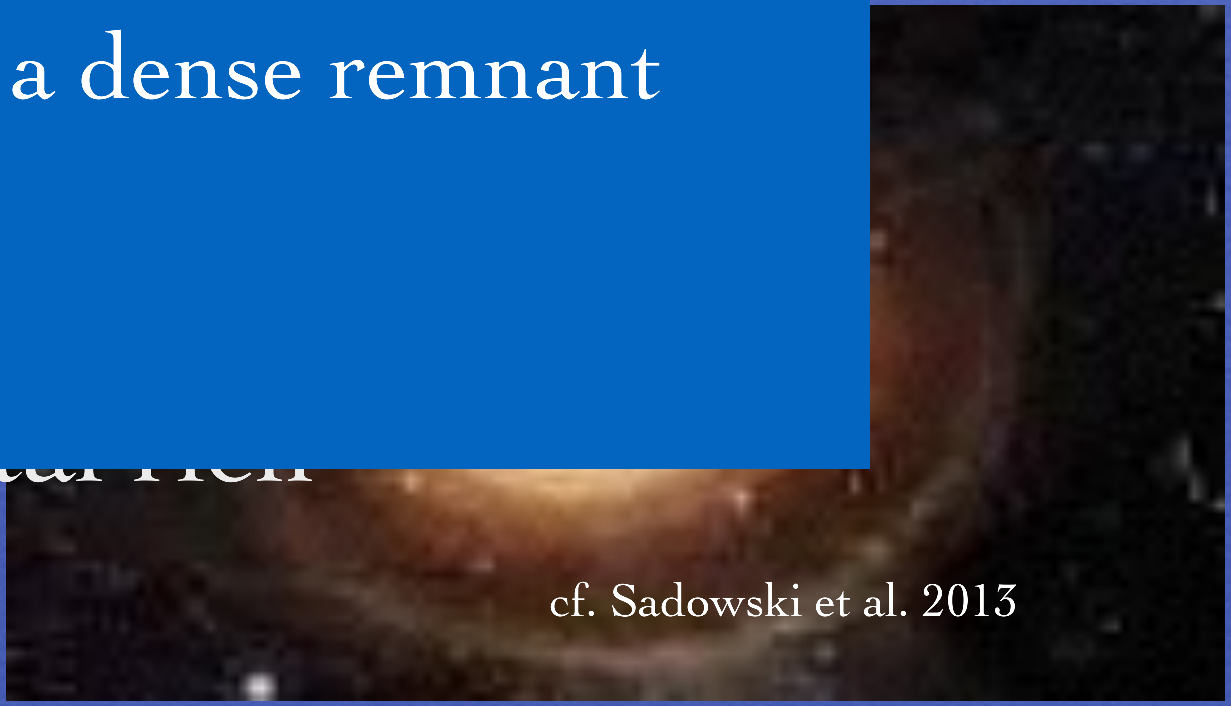


Enrich
Fuel

papers in
preparation

Highly
with po

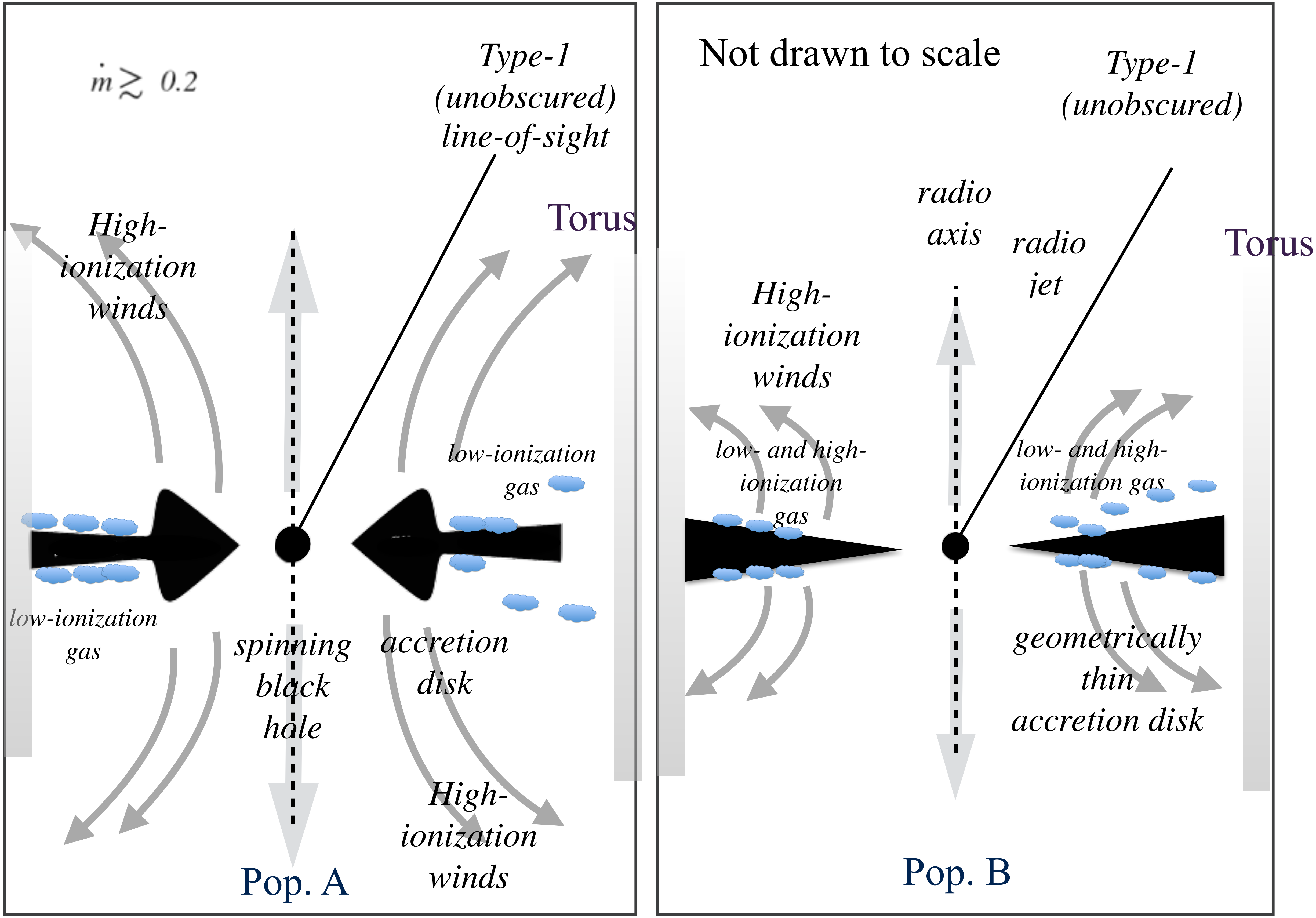
Extreme Population A



cf. Sadowski et al. 2013

Pop. A/B transition: geometrically thick/thin disk?

Abramowicz et al. 1988, Shakura & Sunyaev 1973



$\dot{m} \gtrsim 0.2$

Type-1 (unobscured) line-of-sight

Torus

High-ionization winds

low-ionization gas

low-ionization gas

spinning black hole

accretion disk

High-ionization winds

Pop. A

Not drawn to scale

Type-1 (unobscured)

radio axis

radio jet

Torus

High-ionization winds

low- and high-ionization gas

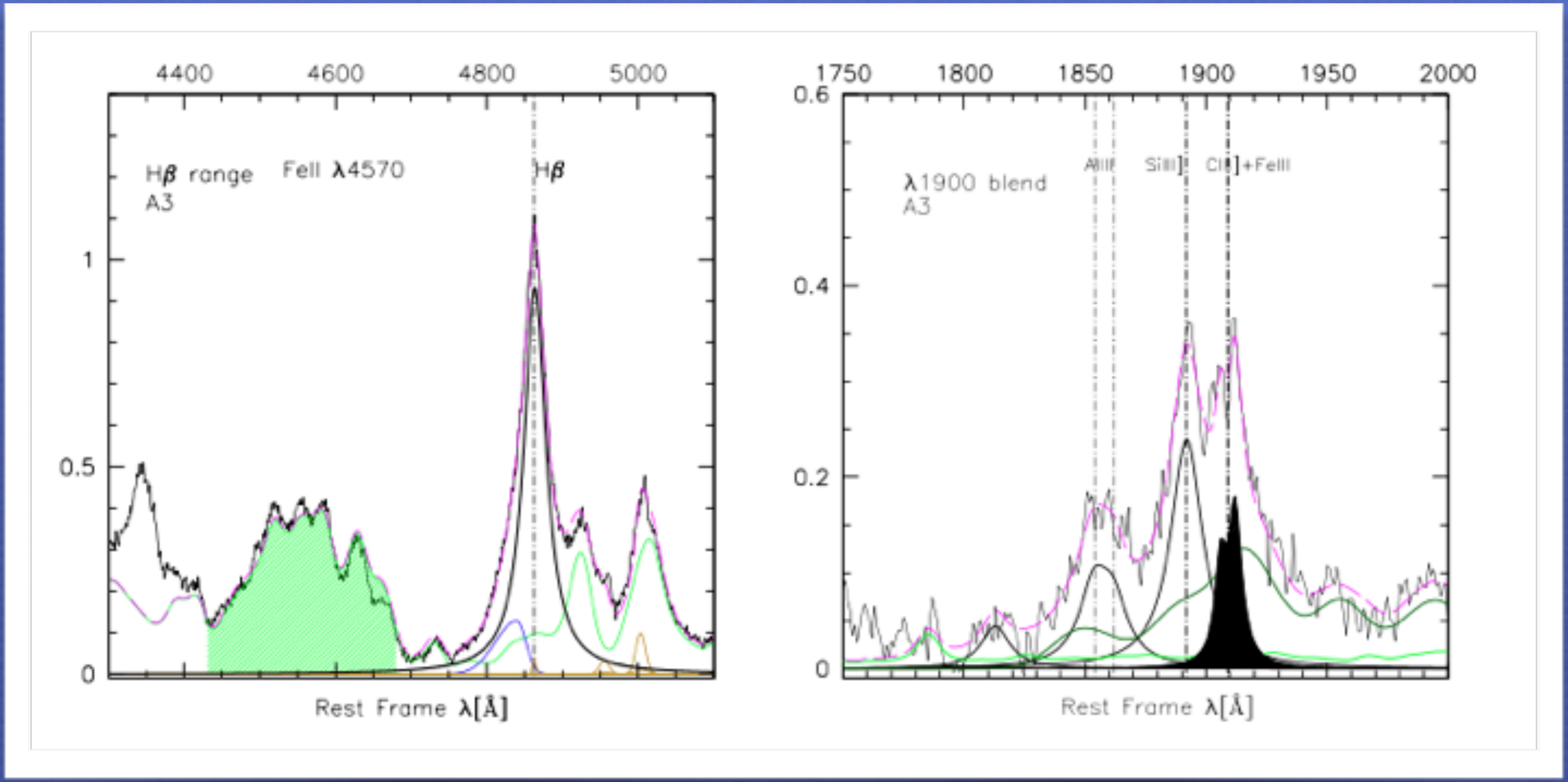
low- and high-ionization gas

geometrically thin accretion disk

Pop. B

Selection criterion based on UV intermediate ionization lines in extreme Pop. A (xA) sources

(Negrete et al. 2012; Marziani & Sulentic 2014)



Optical (z<1) R_{FeII} = I(FeIIλ4570)/I(Hβ)>1

UV (z>1.4) I(AlIIIλ1860)/I(SiIII]λ1892)>0.5

I(SiIII]λ1892)/I(SiIII]λ1909)>1

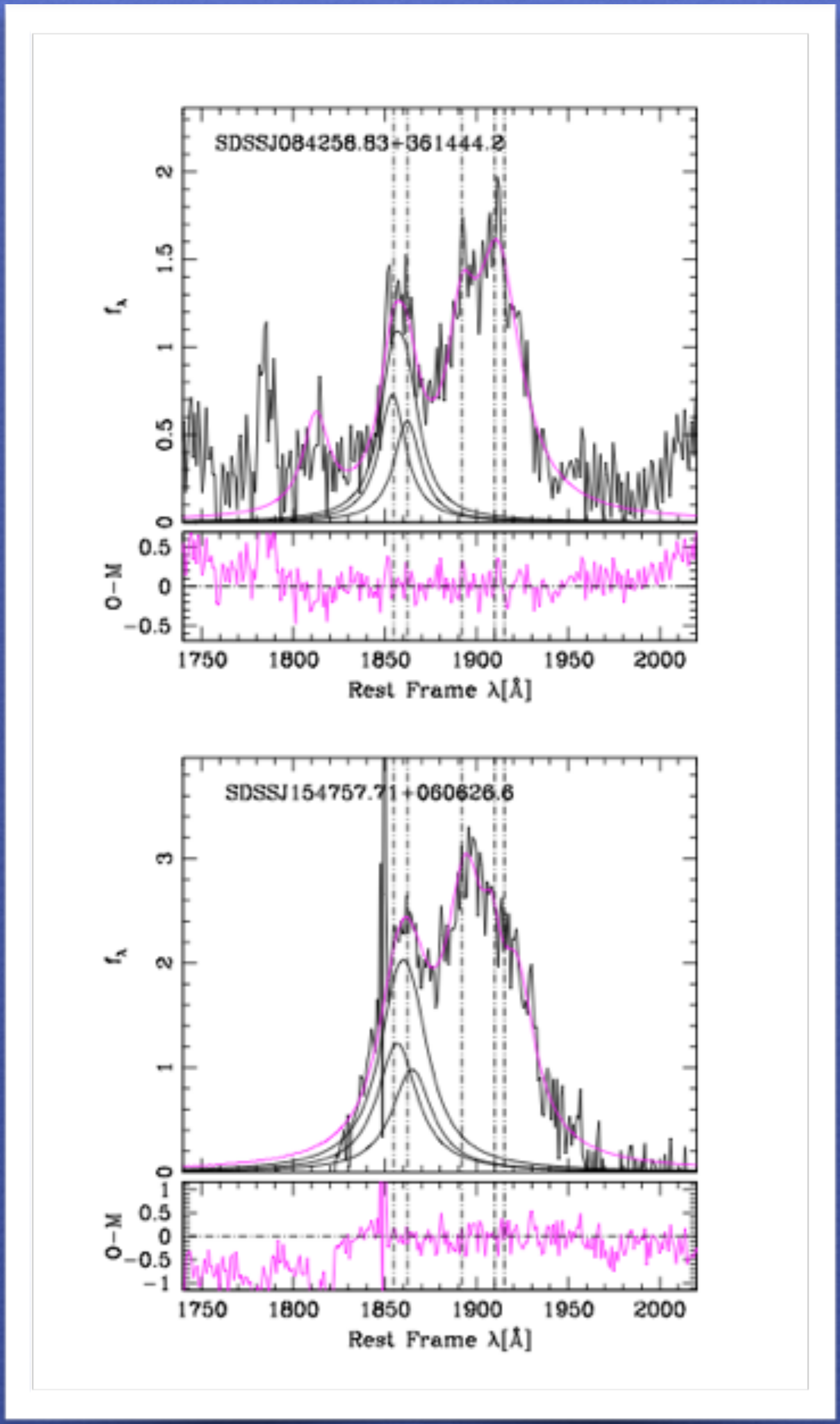
UV: ~200 sources ~3000 sources from DR4

3 preliminary quasar samples

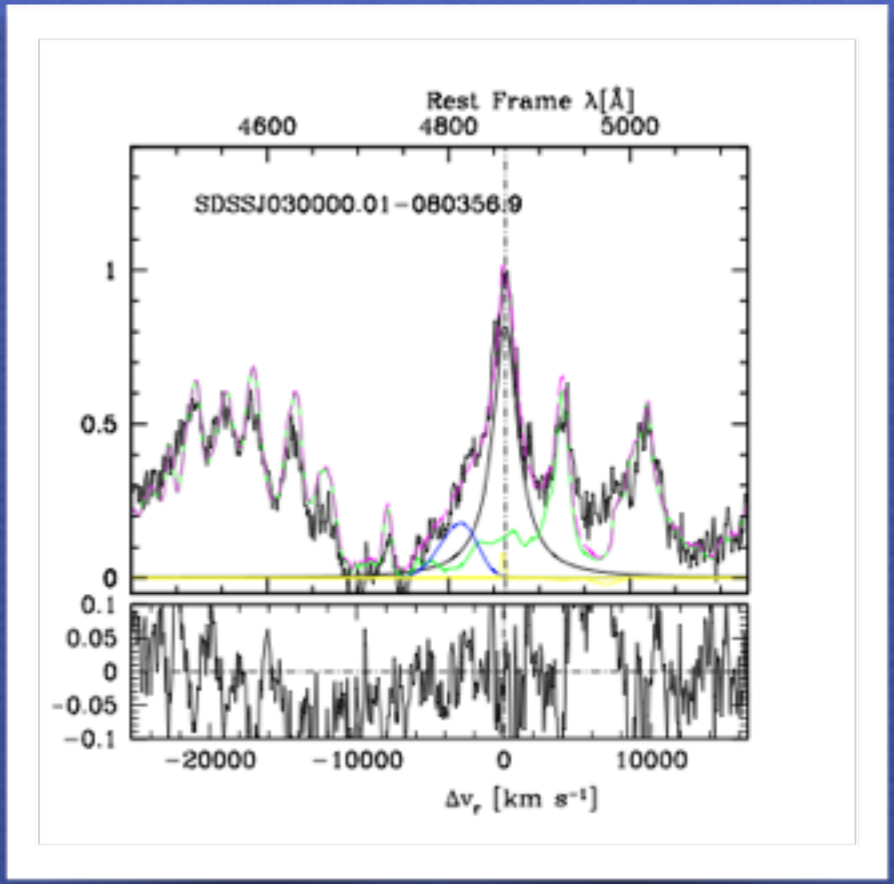
1. Hβ SDSS; $0.4 < z < 0.75$
2. Hβ VLT ISAAC Hamburg-ESO; $0.9 < z < 1.5$
3. SDSS UV AlIIIλ1860; $2 < z < 2.6$

92 sources in total

UV AlIIIλ1860



Hβ

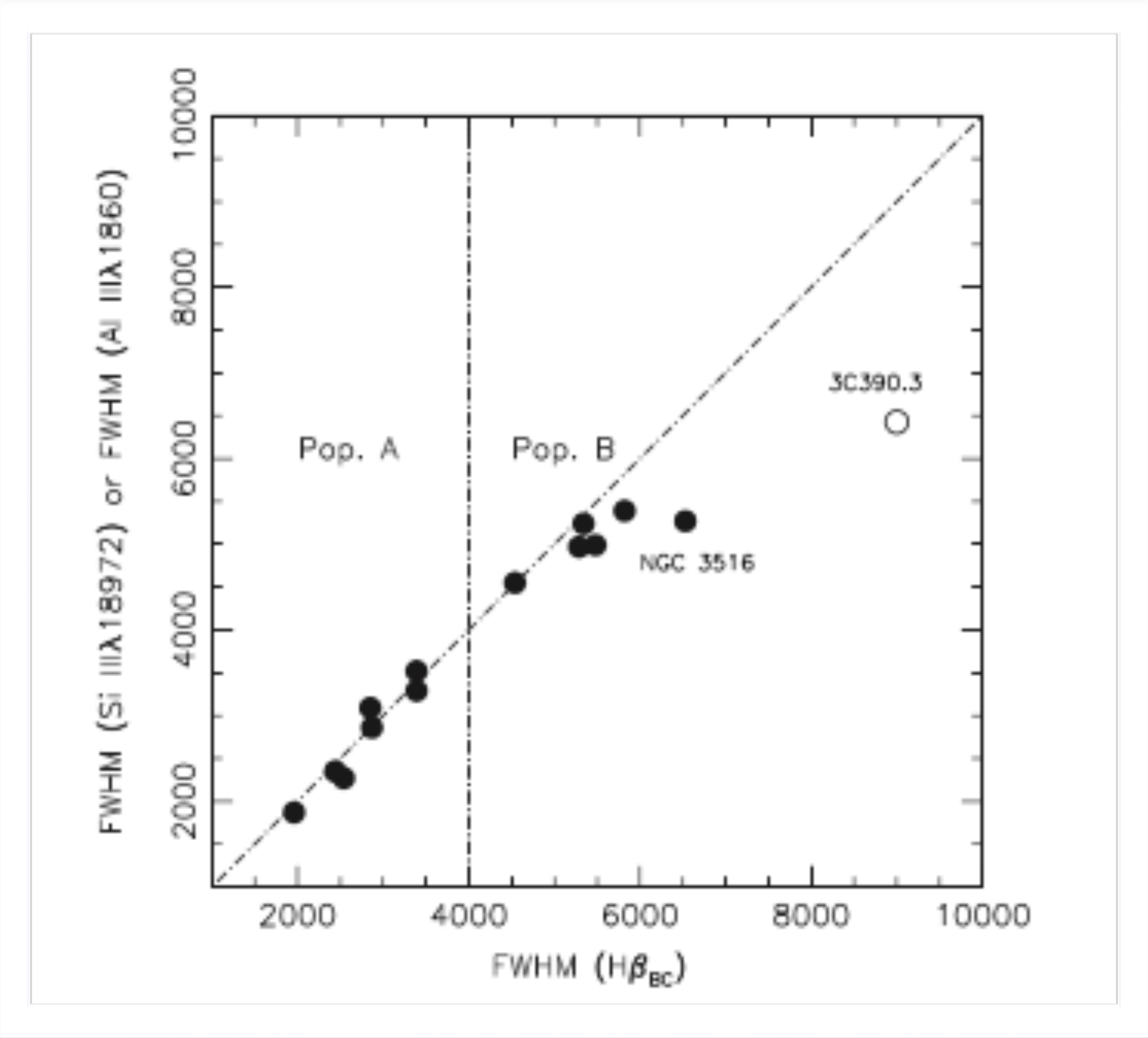


Measurements of line widths: Lorentzian FWHM

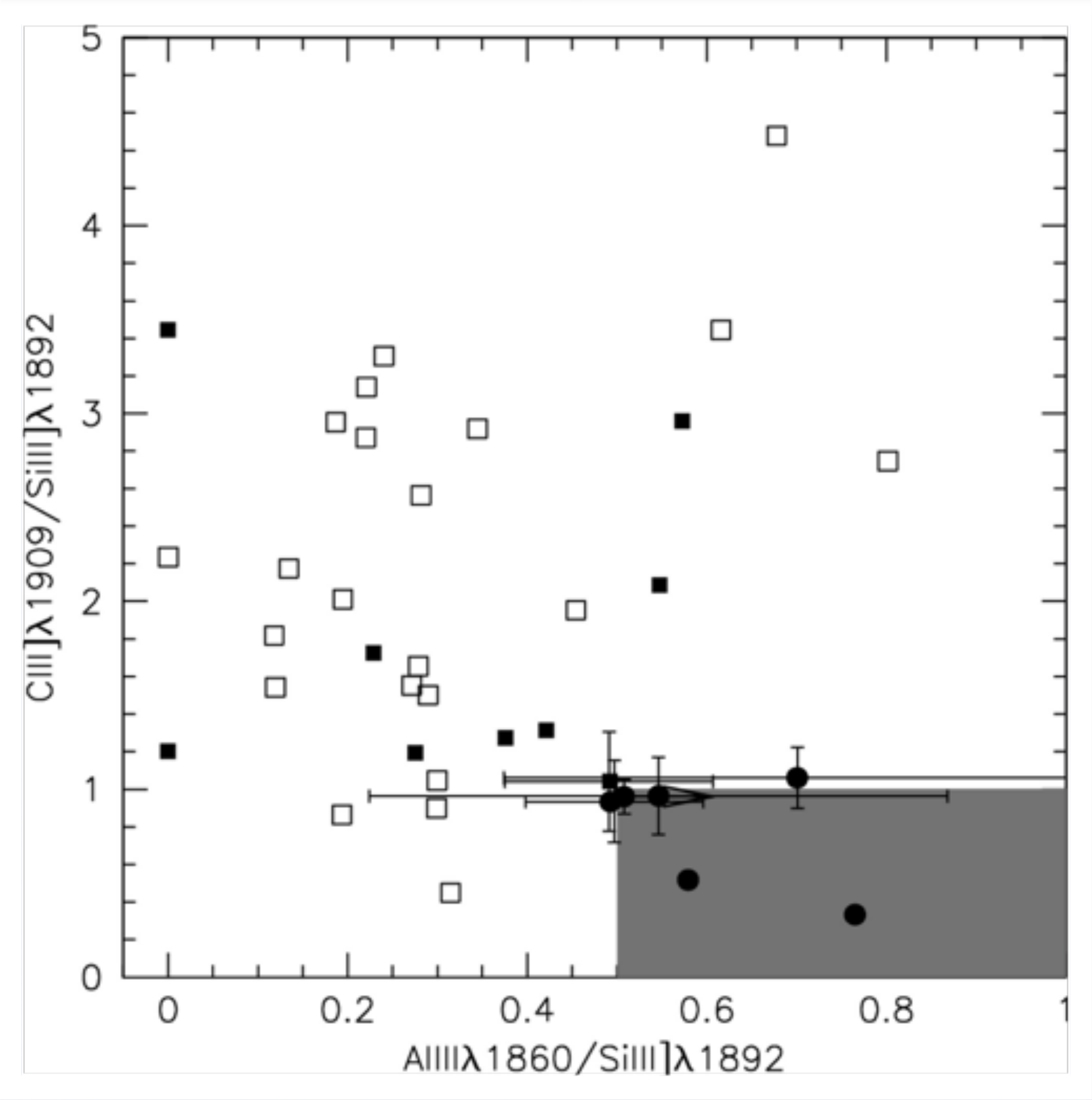
Consistency of optical and UV selection criteria and virial broadening estimators

Additional verification of selection criteria is needed; few objects have both the 1900 blend and the Hβ spectral range covered

FWHM(Hβ) consistent with the FWHM of SiIII]1892 and AlIII1860



Negrete et al. 2014



Marziani & Sulentic 2014

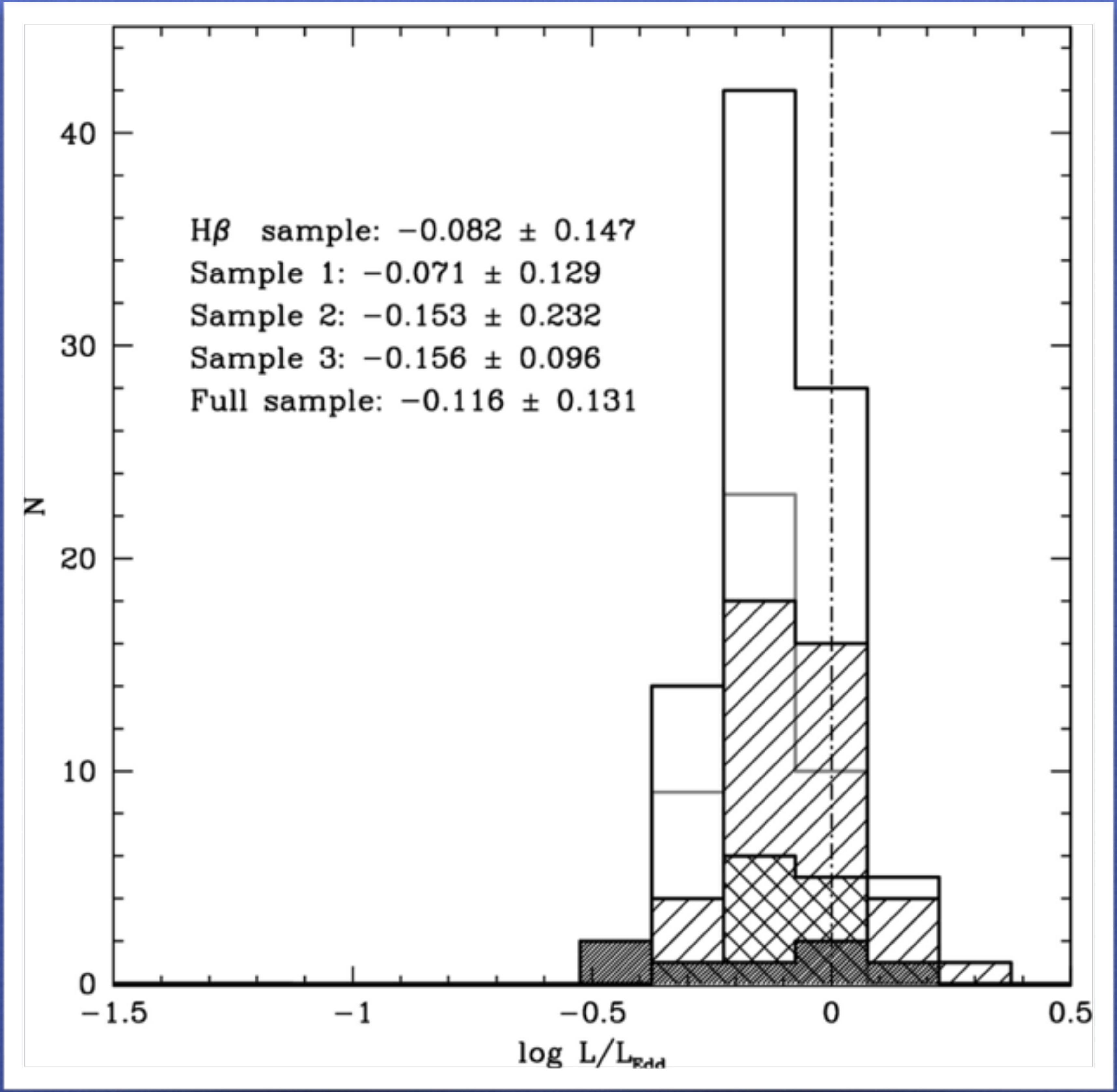
Dispersion in L/L_{Edd} and a posteriori verification:

Systematic differences are less than 0.08 dex; a concern for cosmological applications

$\delta \log L/L_{Edd} \approx -0.05$

$\rightarrow$

$\delta \log \Omega_M \approx 0.05$



Applying Eddington “standard candles” to estimate Ω_M (and Ω_Λ)

Virial Black Hole Mass

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

geometry
dynamics

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

$r_{\rm BLR}$

FHWM
s, FWZI

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

f = 2.0 more appropriate for Pop. A sources
Collin et al. (2006)

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_{BLR} a $L^{0.5}$

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

fraction of ionizing luminosity

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

average frequency of ionizing photons

Marziani & Sulentic 2014

Results: comparing "virial luminosity" *L*(*v*) and luminosity *L*(*z*) estimated from *z*

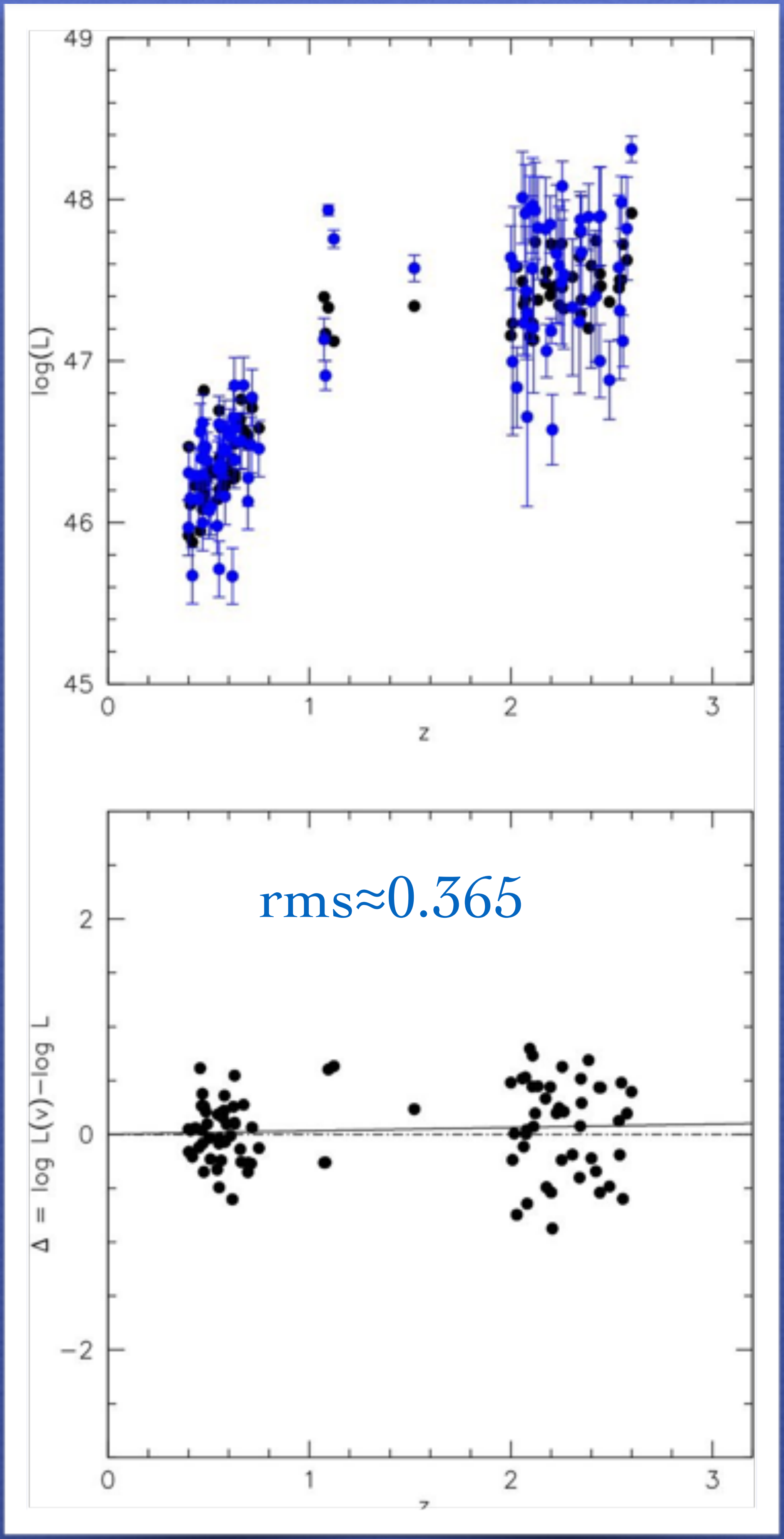
$$L \approx 7.8\ 10^{44}\,\frac{\eta_1^2\kappa_{0.5}f_2^2}{\bar{\nu}_{\mathrm{i}2.42\ 10^{16}}}\,\frac{1}{(nU)_{9.6}}\,v_{1000}^4 \quad \mathrm{erg\ s}^{-1}$$

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

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

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

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

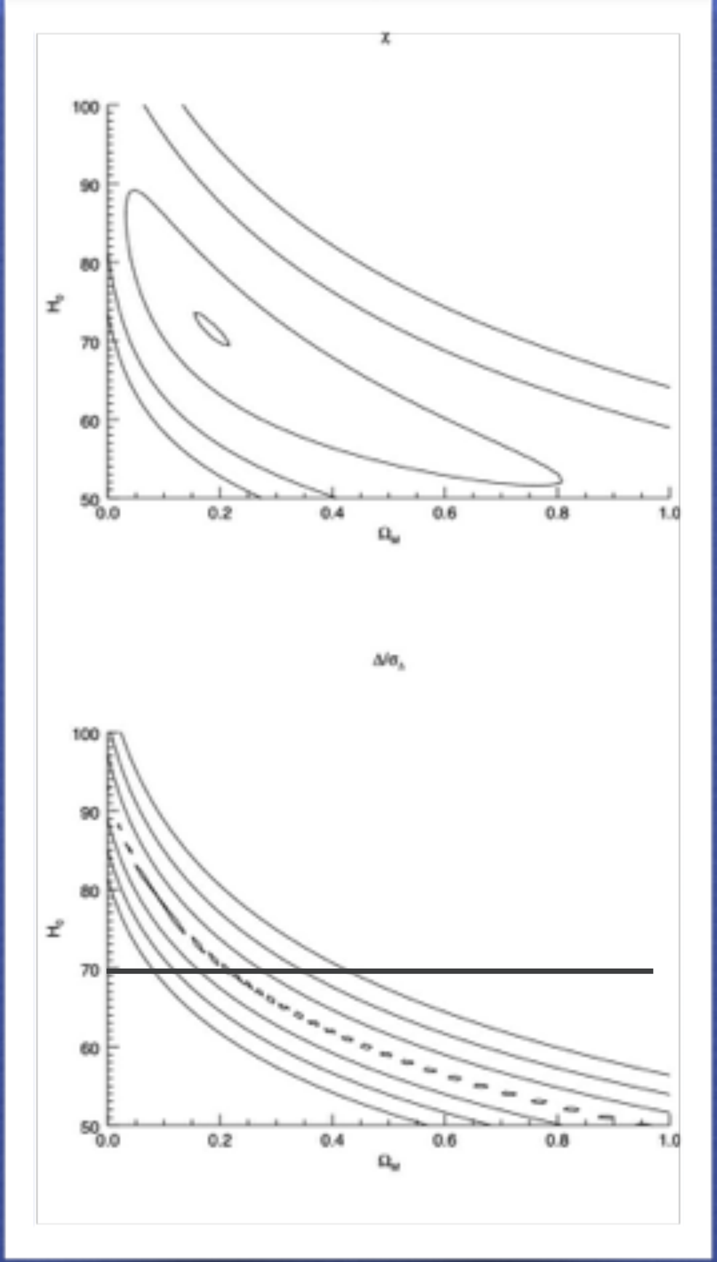


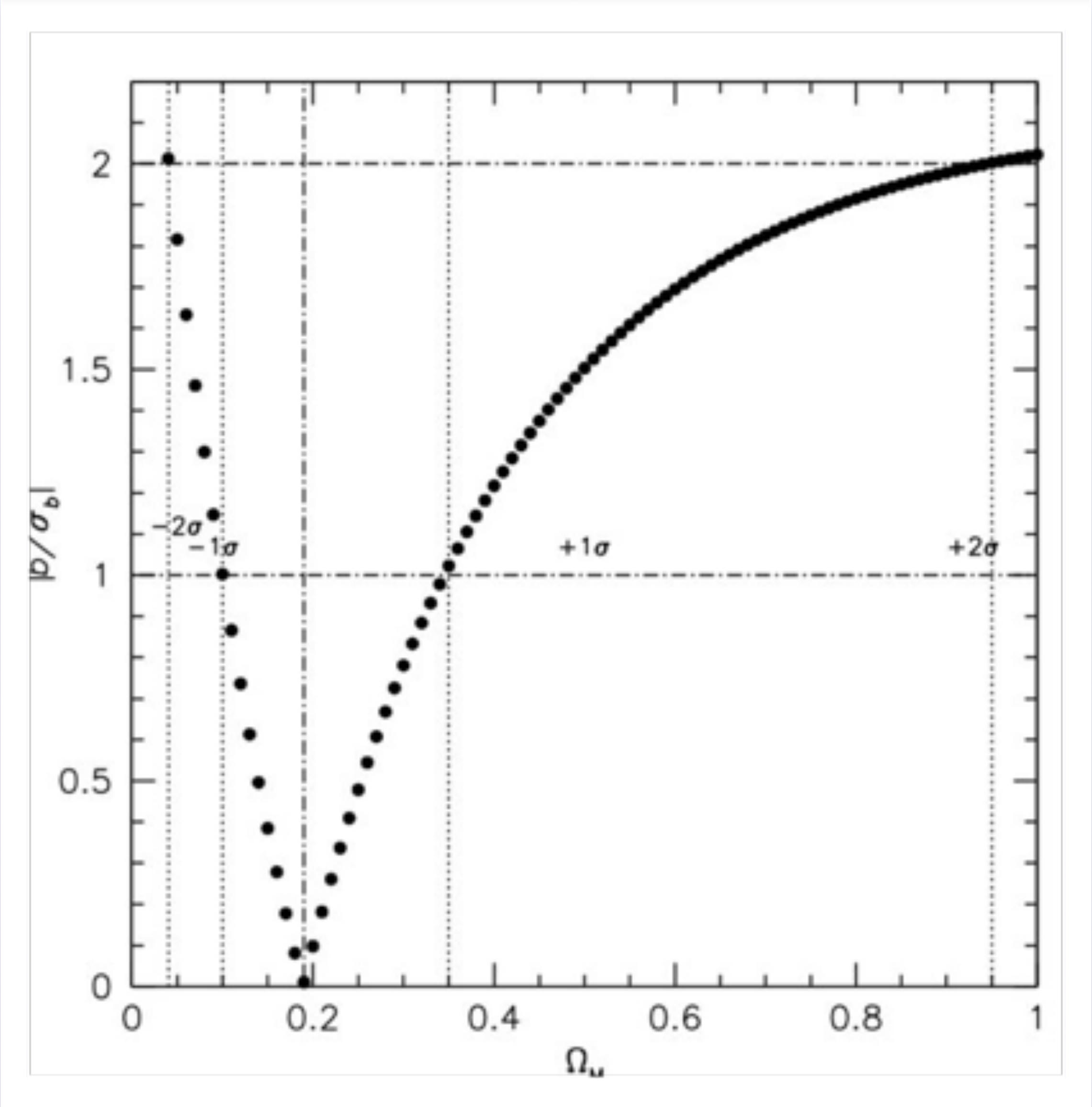
rms≈0.365

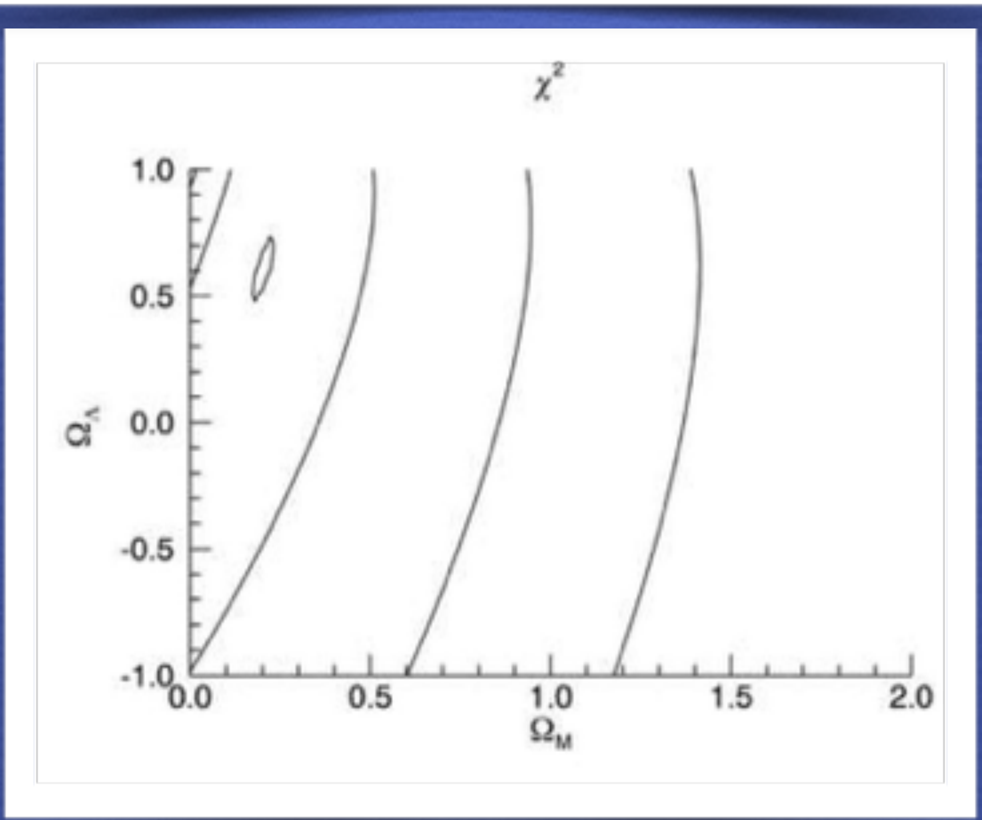
Results for samples 1,2,3:
n = 92, rms(log$L$)=0.365

$$\Omega_M \approx 0.19^{+0.16}_{-0.08} \quad (1\sigma)$$

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



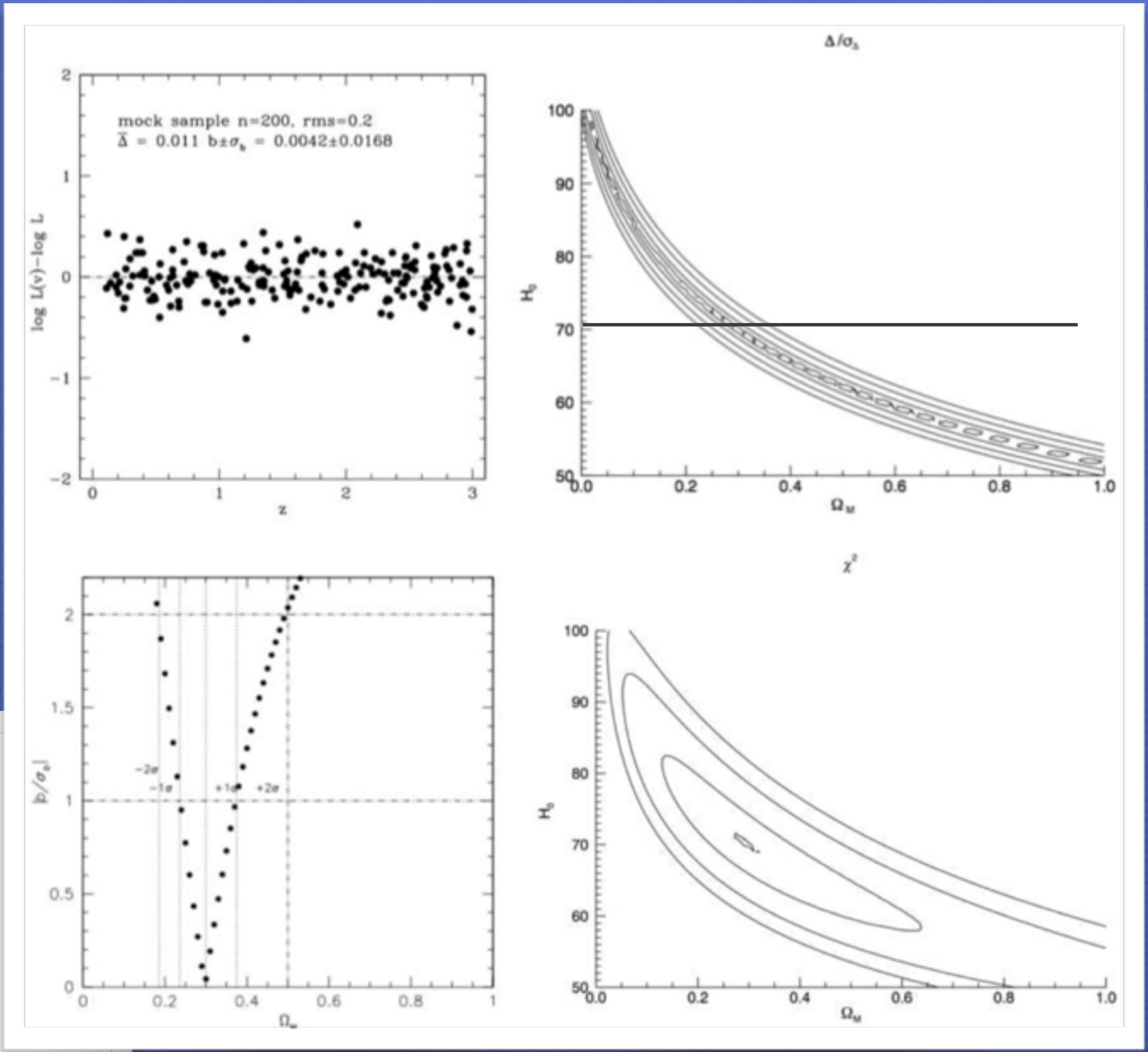


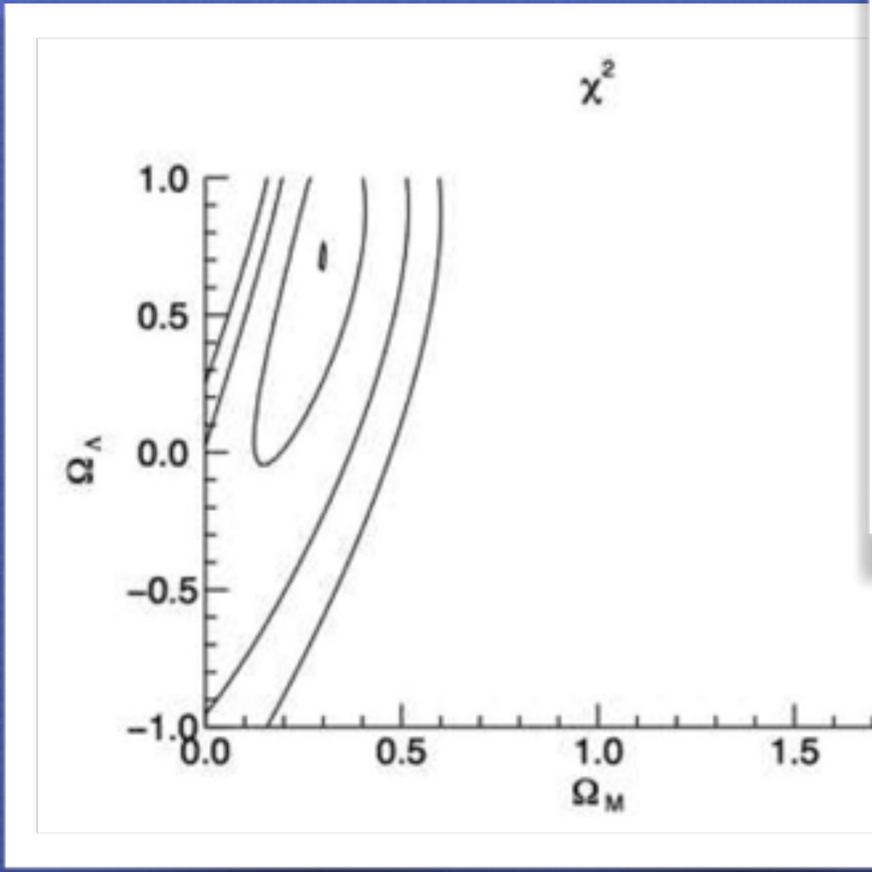


free
$\Omega_{\rm M}$
and
Ω_Λ

Marziani & Sulentic
2014

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





A simplified error budget for statistical errors

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

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

Main source of statistical error: FWHM measurement errors

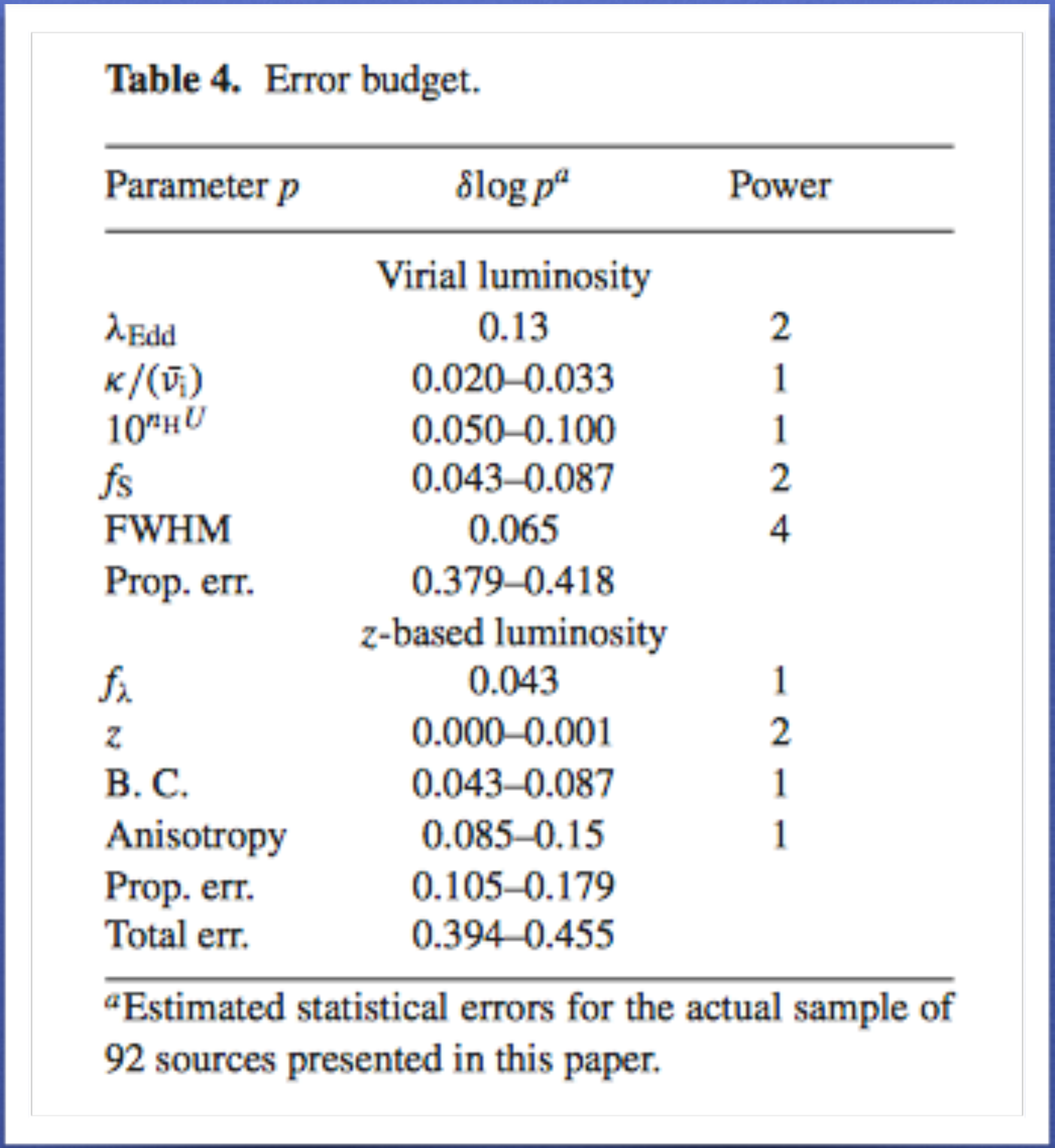


Table 4. Error budget.

Parameter p	$\delta \log p^a$	Power
	Virial luminosity	
λ_{Edd}	0.13	2
$\kappa/(\bar{\nu}_\mathrm{i})$	0.020–0.033	1
$10^{n_\mathrm{H}U}$	0.050–0.100	1
f_S	0.043–0.087	2
FWHM	0.065	4
Prop. err.	0.379–0.418	
	z-based luminosity	
f_λ	0.043	1
z	0.000–0.001	2
B. C.	0.043–0.087	1
Anisotropy	0.085–0.15	1
Prop. err.	0.105–0.179	
Total err.	0.394–0.455	

[a] Estimated statistical errors for the actual sample of 92 sources presented in this paper.

Effect of anisotropy for an accretion disk assimilated to a Lambertian radiator of + a limb darkening term *a*

$$\bar{L} = L_0 \frac{\int \frac{1}{1+a} \left[\cos(\theta + \theta_{\mathrm{d}})(1 + a\cos(\theta + \theta_{\mathrm{d}})\right] \sin\theta d\theta}{\int \sin\theta d\theta}$$

$\theta_d \ll 1$

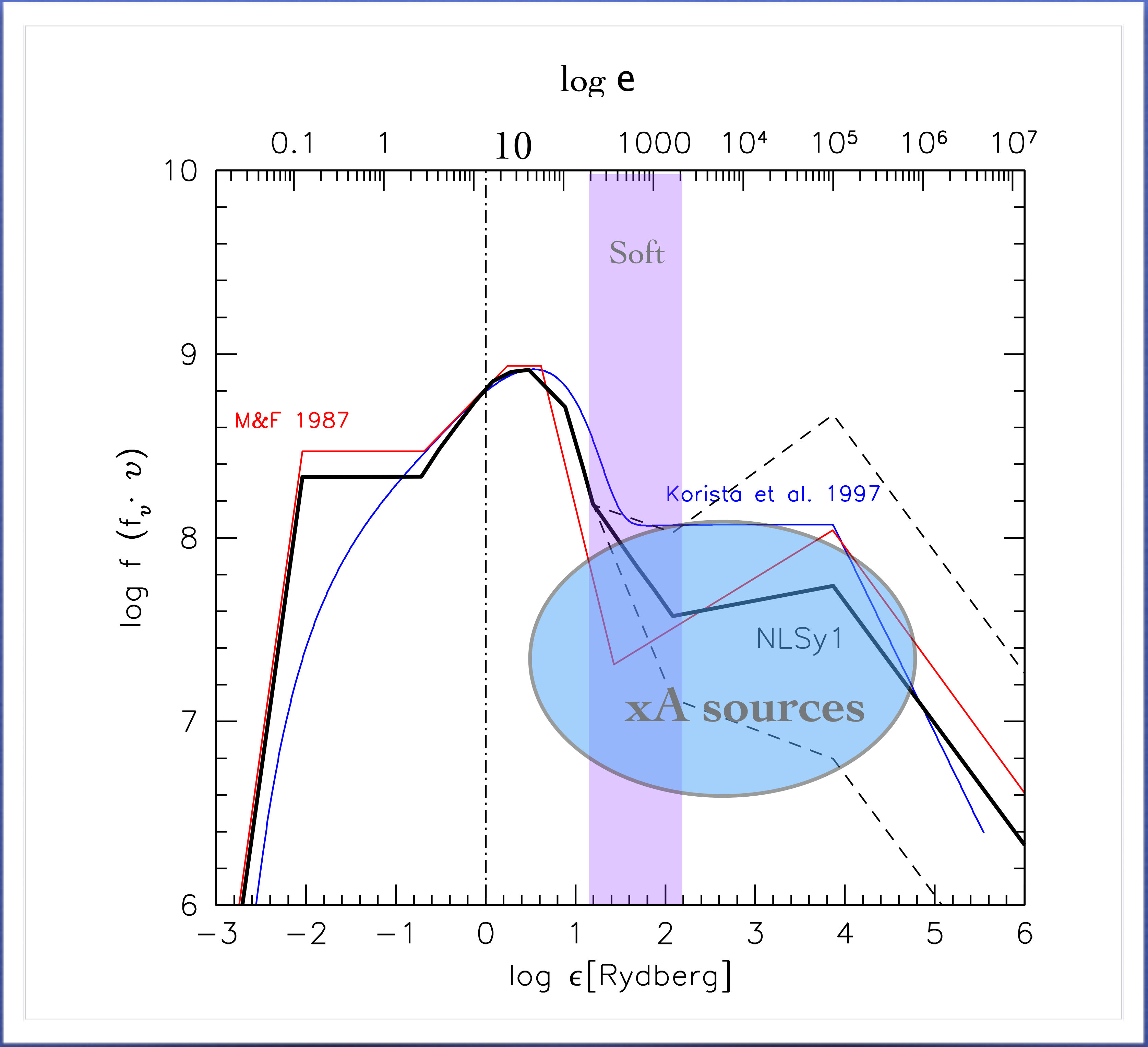
(9)

$$\sigma = \sqrt{\frac{\int \left\{ \frac{1}{1+a} \left[\cos(\theta + \theta_{\mathrm{d}})(1 + a\cos(\theta + \theta_{\mathrm{d}})\right] - \frac{1}{1+a} \left[\cos(\bar{\theta} + \theta_{\mathrm{d}})(1 + a\cos(\bar{\theta} + \theta_{\mathrm{d}})\right] \right\}^2 \sin\theta d\theta}{\int \sin\theta d\theta}}$$

Effect estimated around 10% - 20%

Ideally, luminosity equations should be written for a standardized value of θ

Constraining the continuum of xA sources



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

Statistical errors

are presently rms ≈ 0.37 dex

Efforts should be oriented toward obtaining a larger sample
(≳400 sources)
Find a reliable orientation estimator

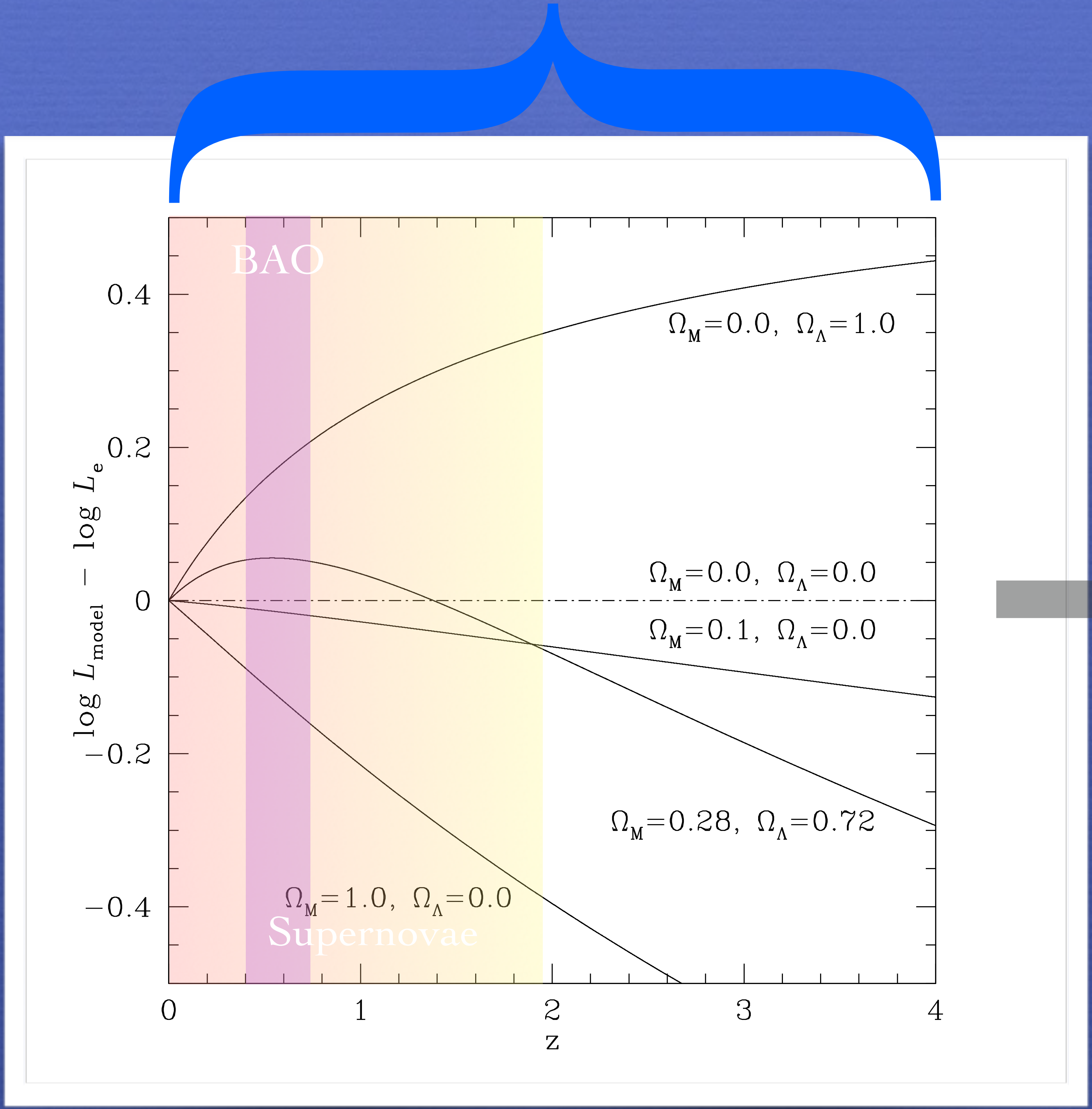
Systematic errors

1) trends involving R_{FeII} and AlIII λ1860/SIII]λ1892
2) SED and bolometric correction dependent on L

$\delta \log L/L_{\mathrm{Edd}} \approx -0.05 \rightarrow \delta \log \Omega_M \approx 0.05$

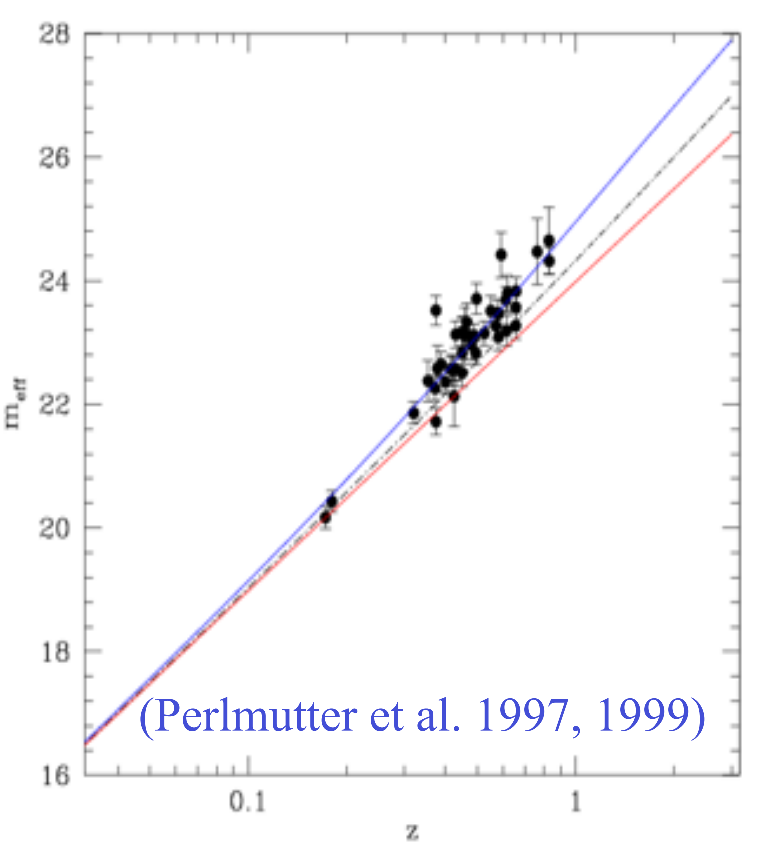
an analysis is possible only on a larger sample of real data

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



CMB
$z \sim 1000$

Cosmological parameters from Supernovae

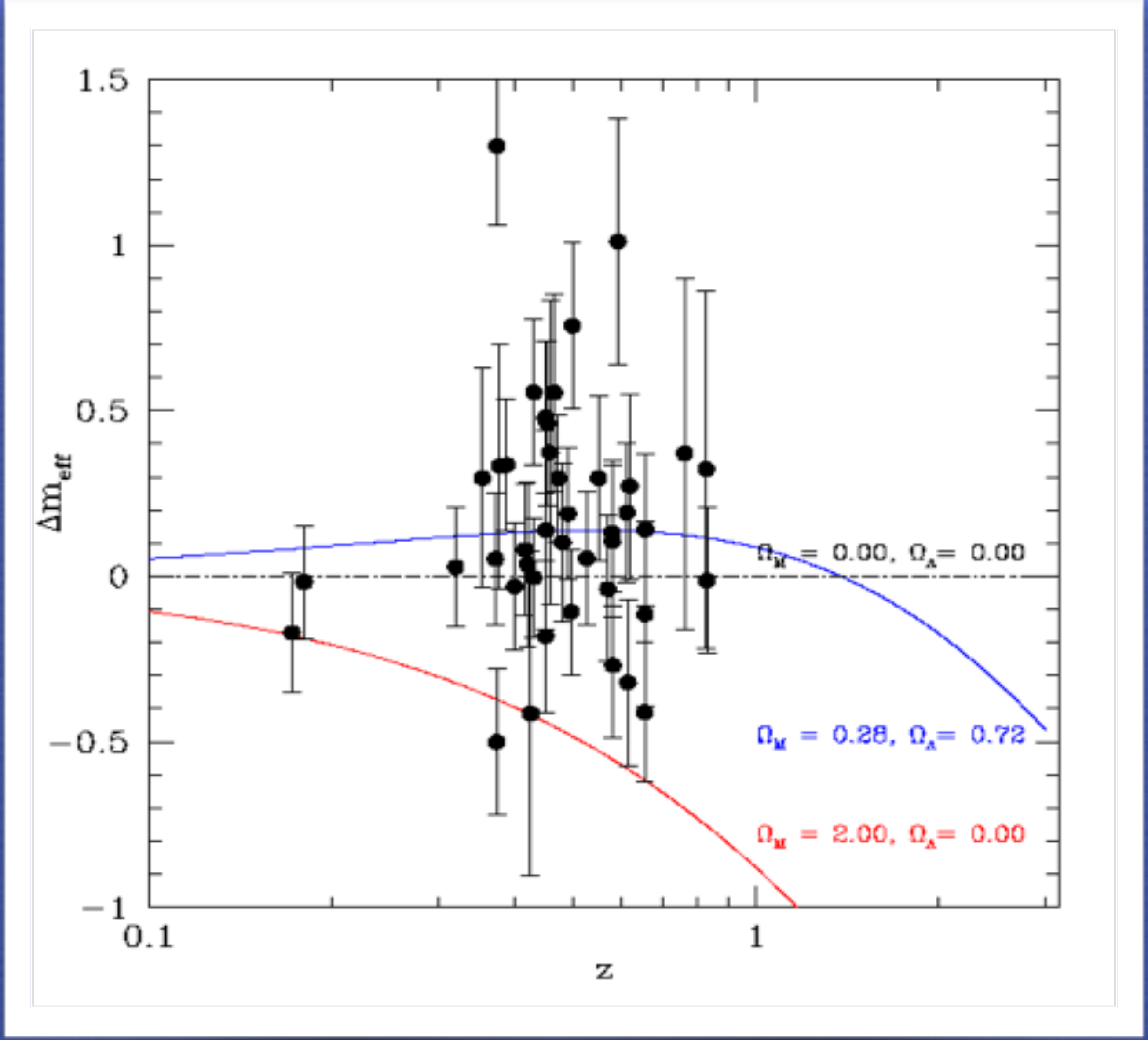


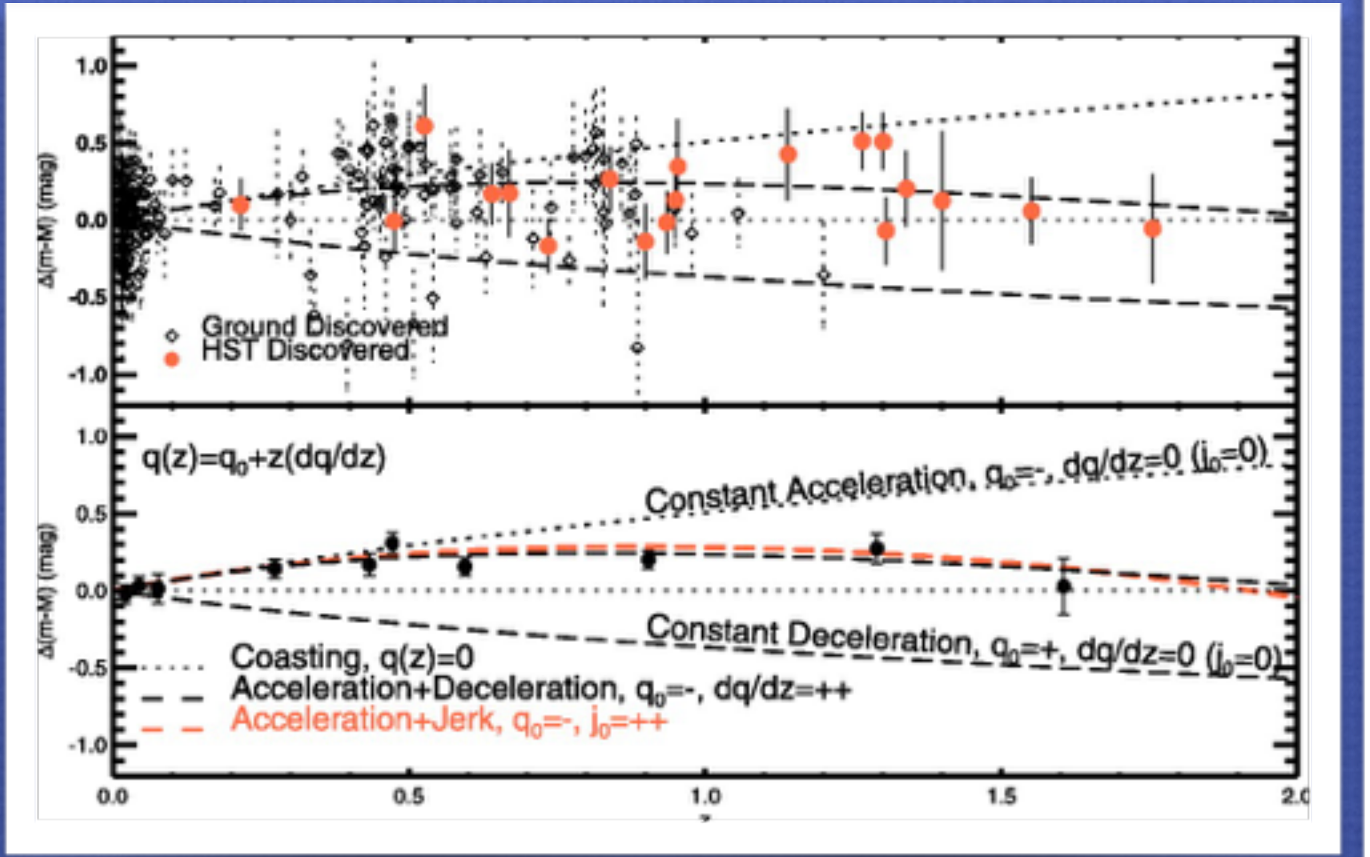
(Perlmutter et al. 1997, 1999)

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

Hubble diagram with type Ia Supernovae

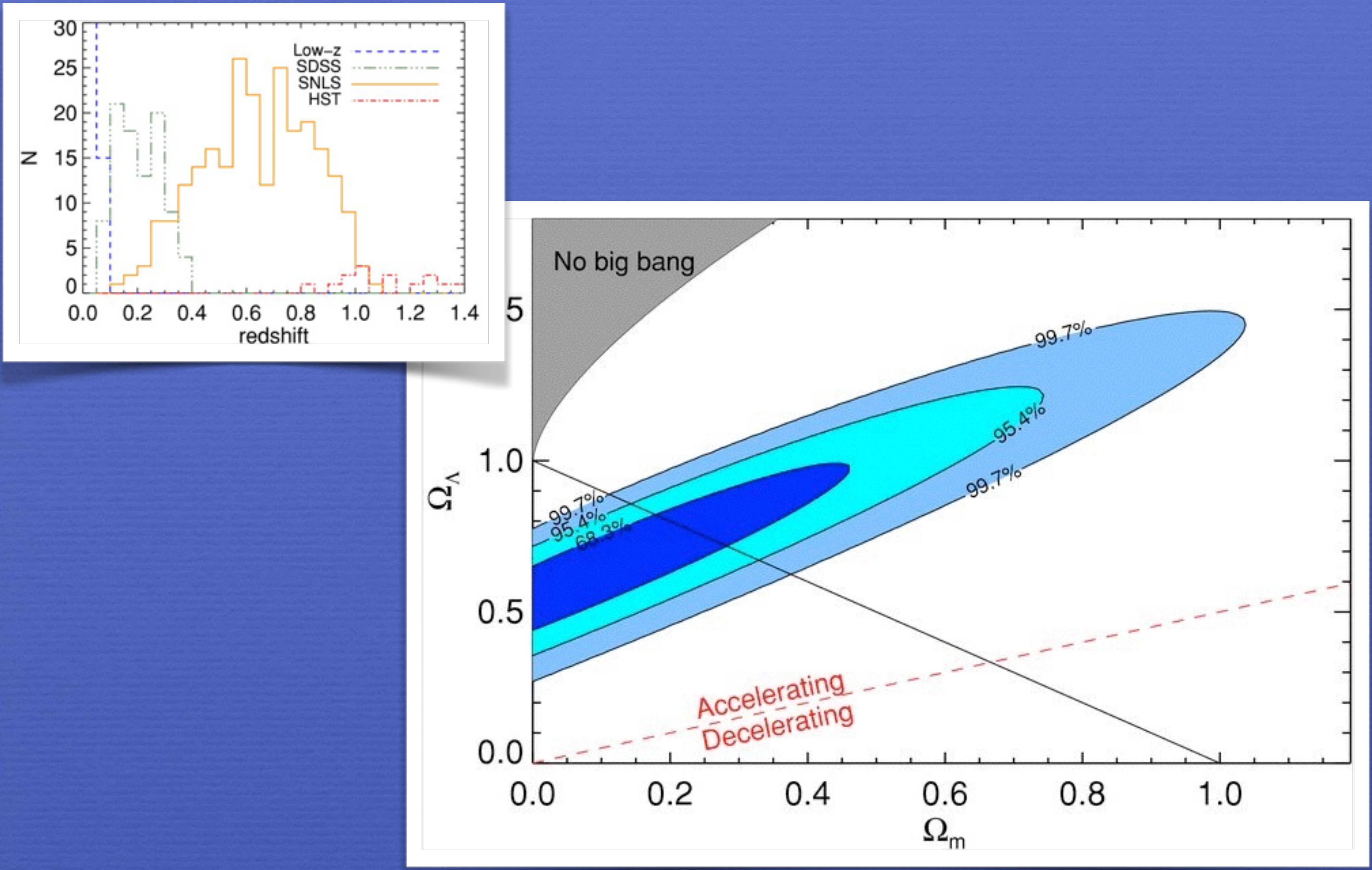
Supernova Cosmology Project





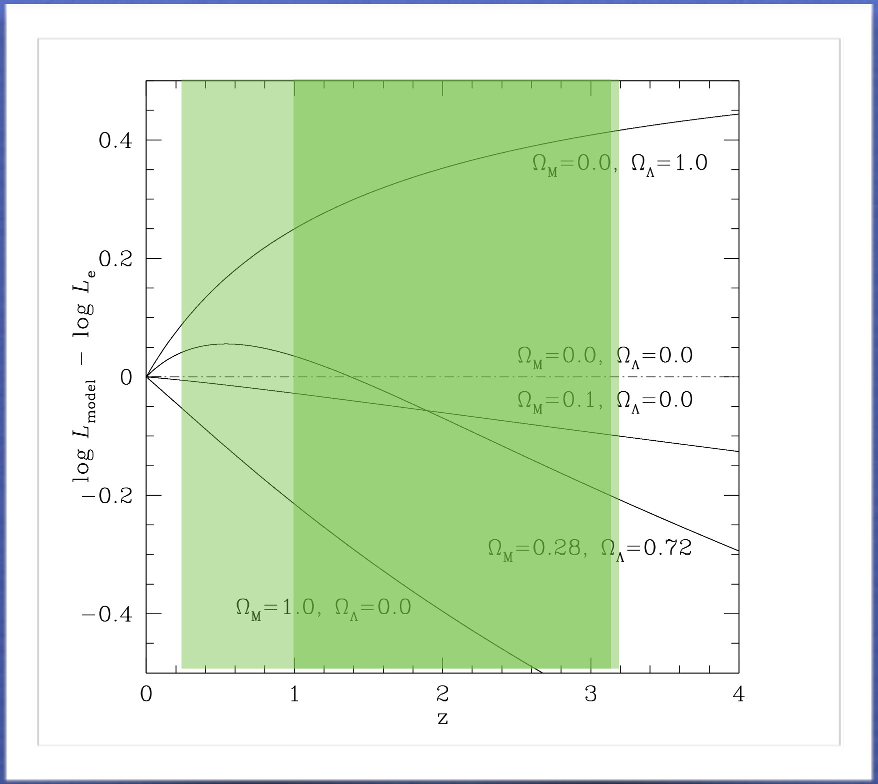
Riess et al. 2004

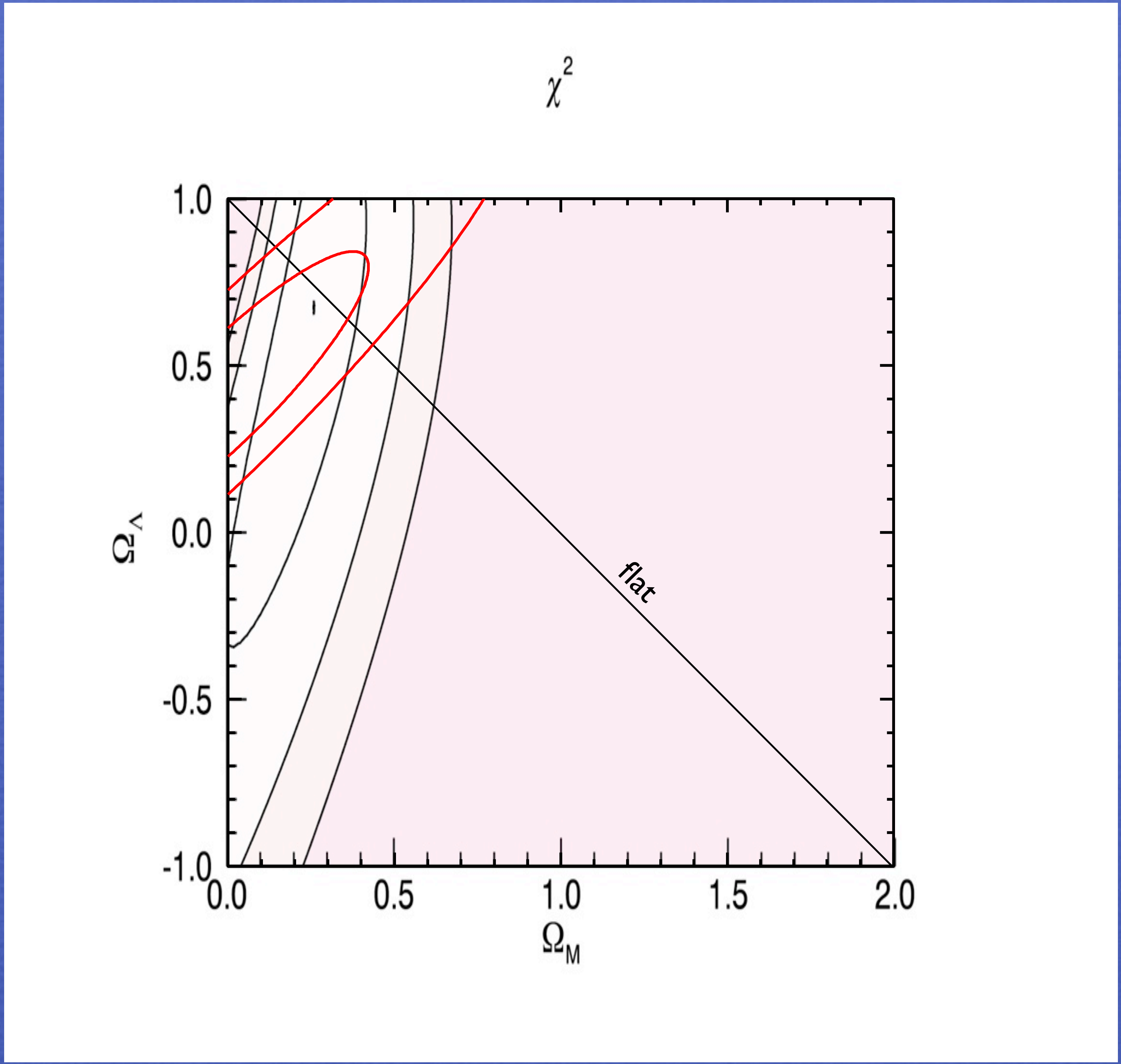
Supernova Legacy Survey



Conley et al. 2011

Mock sample of 400 quasars & supernova legacy survey comparison





Only statistical errors are included

Campbell et al. (2013)

Conclusions

Quasars' potential for cosmographic studies has not been yet exploited

A promising method involves the identification of quasars that may serve as "Eddington standard candles"

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

Work is in progress on a ~1000 candidates DR7 sample: highest S/N SDSS spectra

Realistic expectations are to obtain a reliable fully independent estimate of at least Ω_M once systematic effects are taken into account