Reverberation mapping of the quasar PG 1247+268

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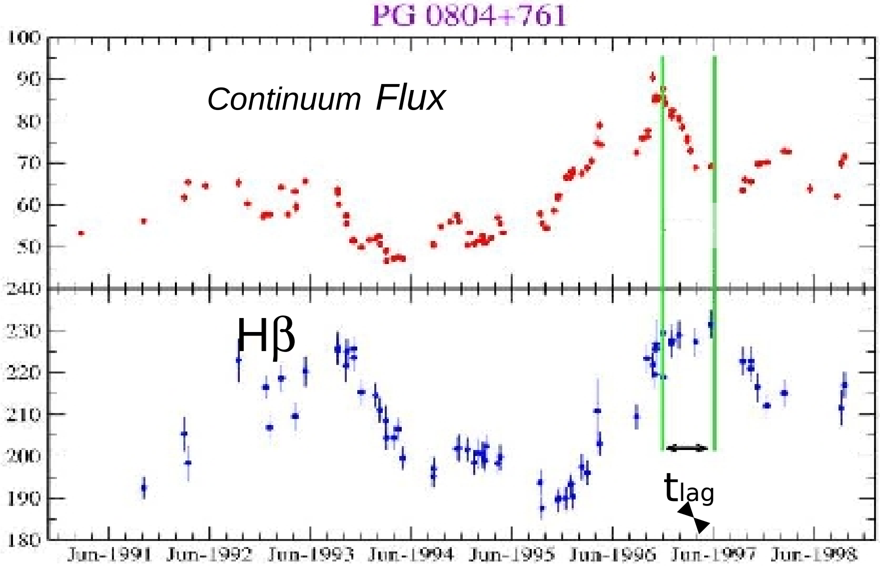
The masses of the AGN’s black holes

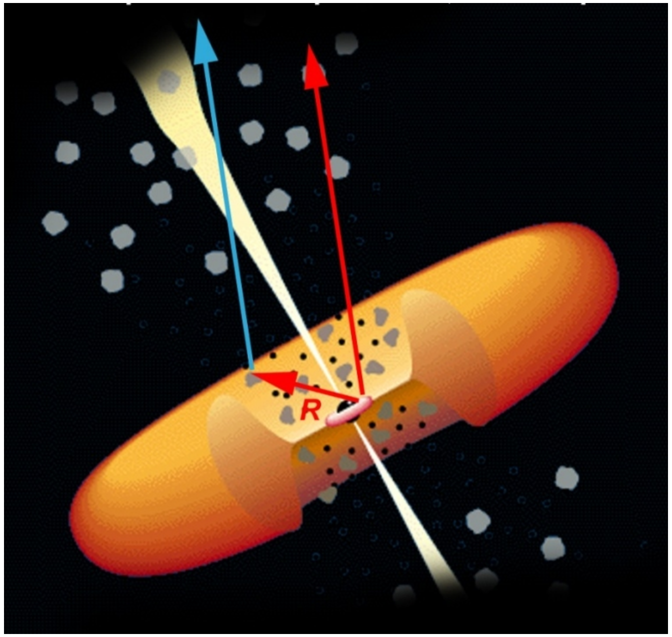
The emission-lines “*reverberate*” to the continuum changes.

$$t_{lag} = R_{BLR} / c$$

Reverberation Mapping:
BLR very close to BH.



Kaspi et al. 2000



High velocity, ionized clouds give rise broad emission lines.

Virial reverberation mass:

$$M_{\mathrm{BH}} = \frac{fR\Delta V^2}{G}$$

f, scale factor;
ΔV, line width ;
R, $R_{BLR} = c\ t_{lag}$.

Time Lag

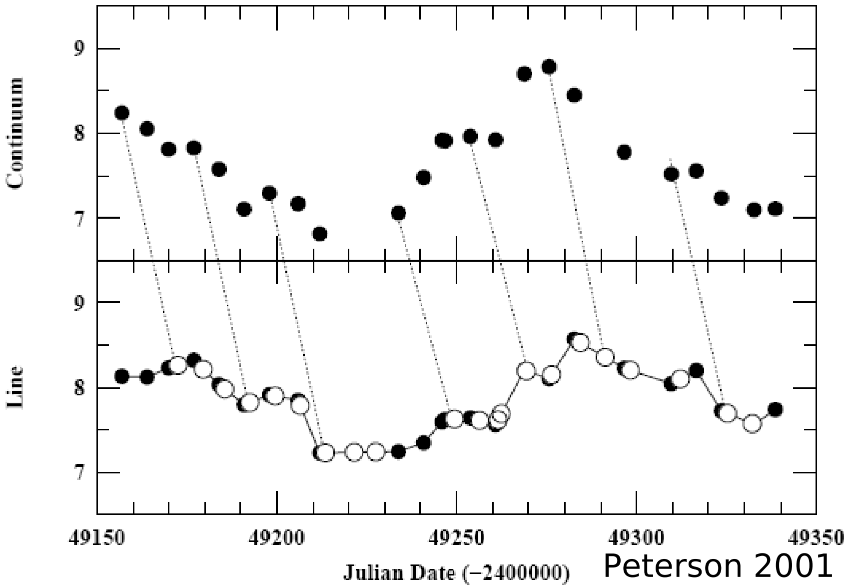
Cross-correlation function

$$CCF(\Delta t) = \frac{1}{N} \sum \frac{\left[L(t_i) - \bar{L}\right]\left[C(t_j - \Delta t) - \bar{C}\right]}{S_L S_C}$$

“Interpolation” method (ICCF)
(Gaskell & Peterson 1987),

“Discrete” CCF method (DCF)
(Edelson & Krolik 1988),

as implemented by White & Peterson94



Peterson 2001

Unbinned cross-correlation function

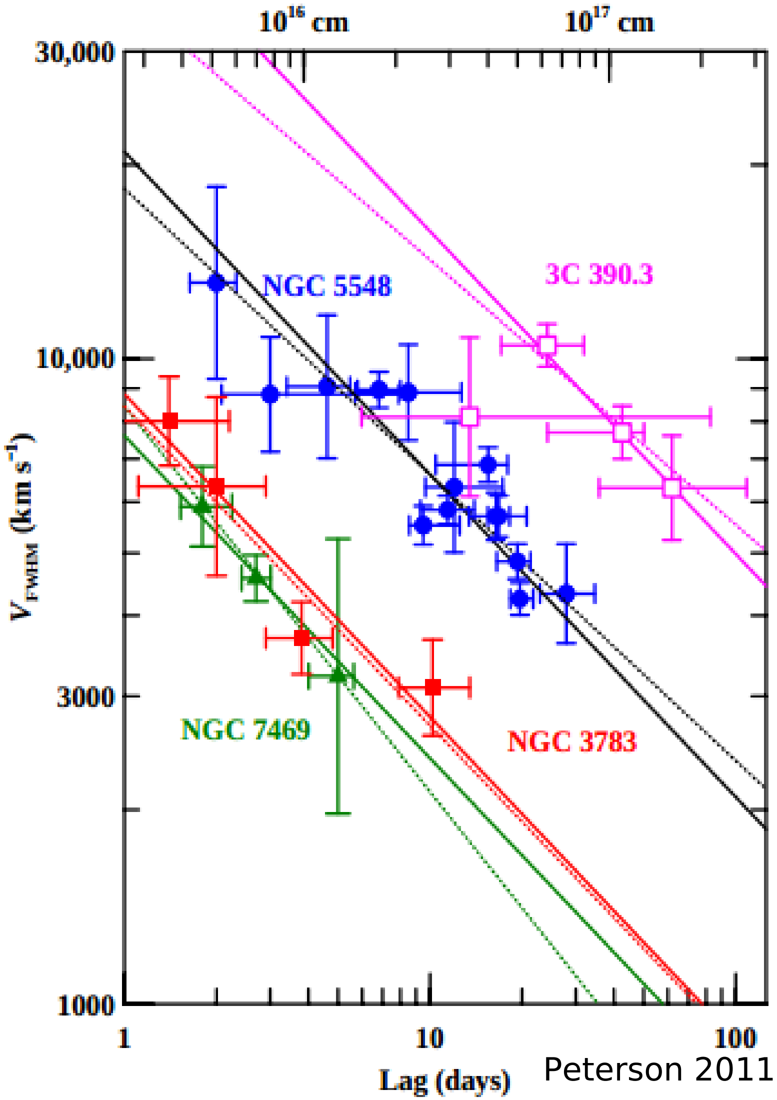
$$UDCF(\Delta t) = \frac{\left[L[t_i] - \bar{L}\right]\left[C(t_j) - \bar{C}\right]}{S_L S_C}$$

Averaging over M pairs for which
$\Delta t - \delta t/2 \leq t_i - t_j \leq \Delta t + \delta t/2$,
the discrete cross-correlation function is

$$DCF(\Delta t) = \frac{1}{M} \sum UDCF_{ij}$$

Uncertainties?

BLRs virialized?

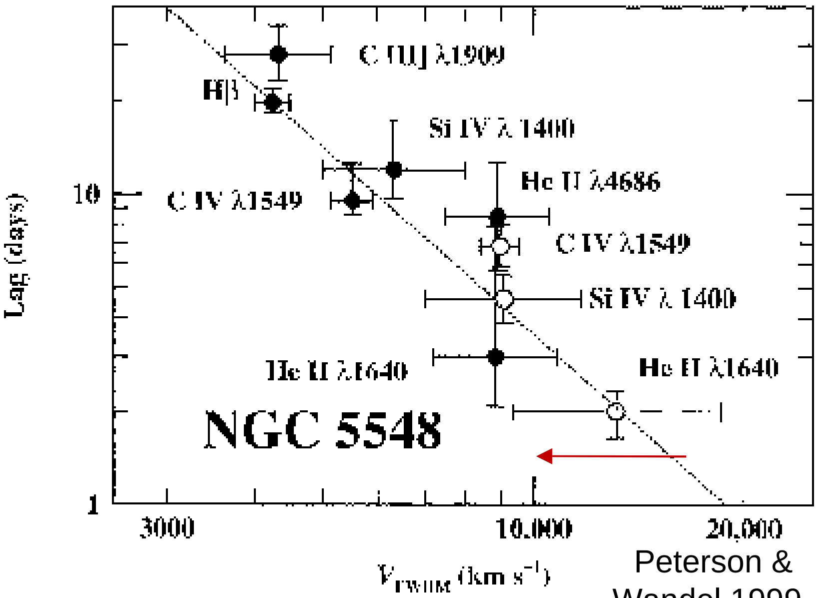


Peterson 2011

Dotted lines: best fit slopes
Solid lines: best fit virial relationship

$R \propto \Delta V^{-2}$

$log(c\tau) = a - 2log(\Delta V)$



Peterson & Wandel 1999

• : 1989 data from *IUE* and ground-based telescopes.

o : 1993 data from *HST* and *IUE.*

✎ virial relationship with *M* = 6 × 107 *M*□.

Highest ionization emission-lines respond most rapidly to continuum changes.
There is ionization stratification of the BLR.

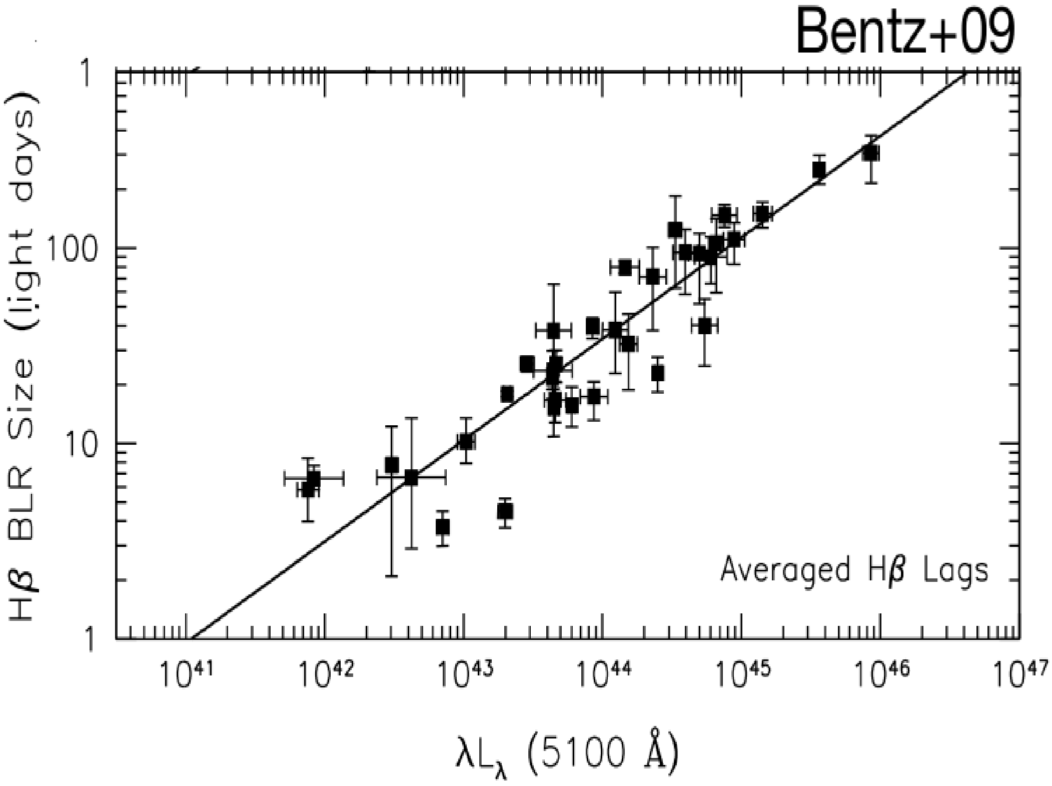
L-R relation

For qso with $L \leq 10^{46} ergs^{-1}$:

Hβ BLR size scales with the 5100 Å luminosity as

$$\boxed{R \propto L^{0.5}}$$

(Kaspi et al. 2005; Bentz et al. 2006, 2009a)



Expand the range to high L will require some 5-10 yr of observation

Single-epoch determination

$$R_{BLR} = c_1 L_\lambda^\gamma \qquad M_{BH} = c_2 L_\lambda^\gamma (\Delta V)^2$$

single-epoch (S.E.) determination of the M_{BH} from their luminosity and with FWHM of emission-line.

$$M_{BH} = 8.3 \cdot 10^6 \left(\frac{\mathrm{FWHM}(\mathrm{H}\beta)}{10^3\ \mathrm{km/s}} \right)^2 \left(\frac{\lambda L_\lambda(5100A)}{10^{44}\ \mathrm{ergs/s}} \right)^{0.50} M_\odot$$

Vestergaard & Peterson 2006

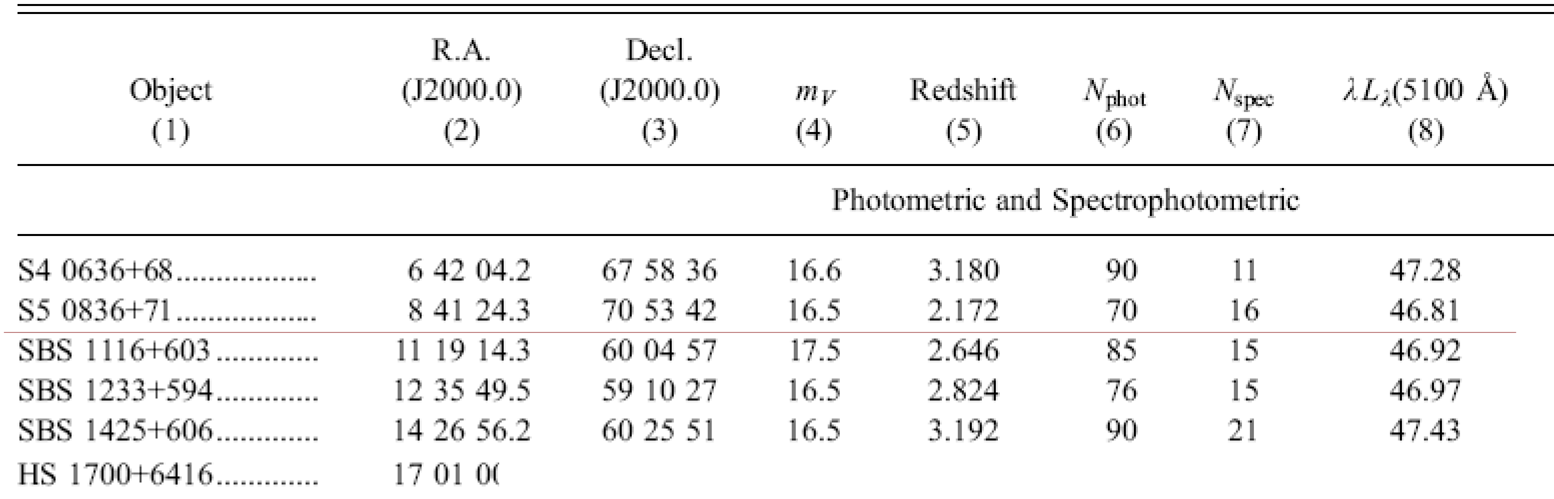
Empirical method for large statistical sample: cosmological evolution of the mass function.

S.E. relation requires the extrapolation to high luminosity and redshift of a relation whose calibration performed for $L \lesssim 10^{46}\ \mathrm{erg\ s^{-1}}$ and $z \leq 0.4$

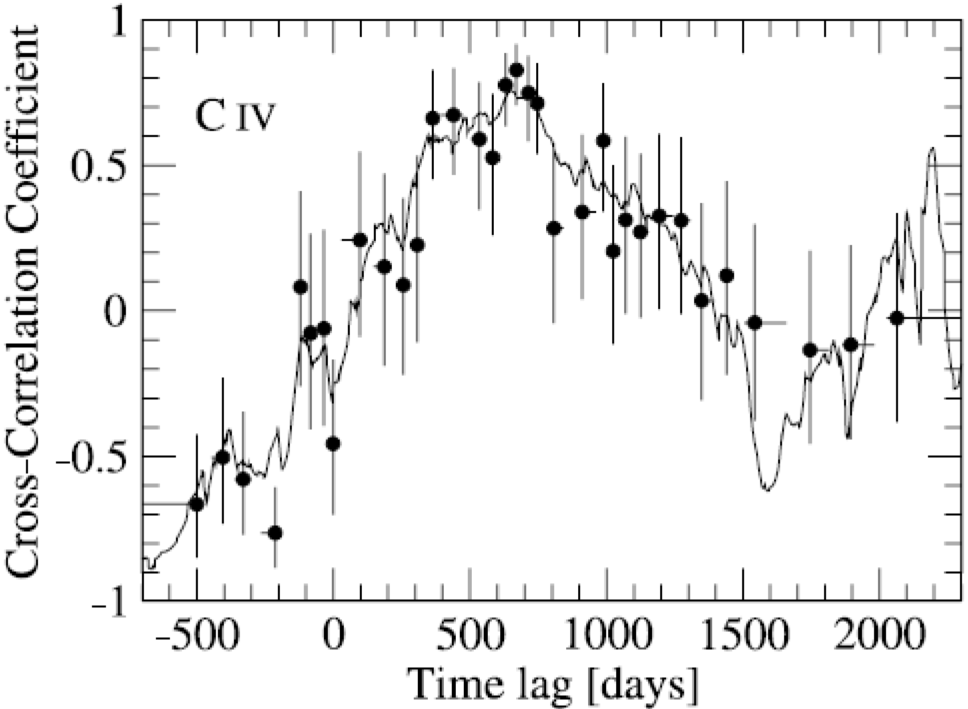
New campaign for spectrophotometric monitoring of luminous, intermediate redshift QSOs

Single-epoch determination

From Kaspi et al. 2007



Object (1)	R.A. (J2000.0) (2)	Decl. (J2000.0) (3)	m_V (4)	Redshift (5)	$N_{\rm phot}$ (6)	$N_{\rm spec}$ (7)	λL_λ(5100 Å) (8)
				Photometric and Spectrophotometric			
S4 0636+68...................	6 42 04.2	67 58 36	16.6	3.180	90	11	47.28
S5 0836+71...................	8 41 24.3	70 53 42	16.5	2.172	70	16	46.81
SBS 1116+603.............	11 19 14.3	60 04 57	17.5	2.646	85	15	46.92
SBS 1233+594.............	12 35 49.5	59 10 27	16.5	2.824	76	15	46.97
SBS 1425+606.............	14 26 56.2	60 25 51	16.5	3.192	90	21	47.43
HS 1700+6416.............	17 01 0						

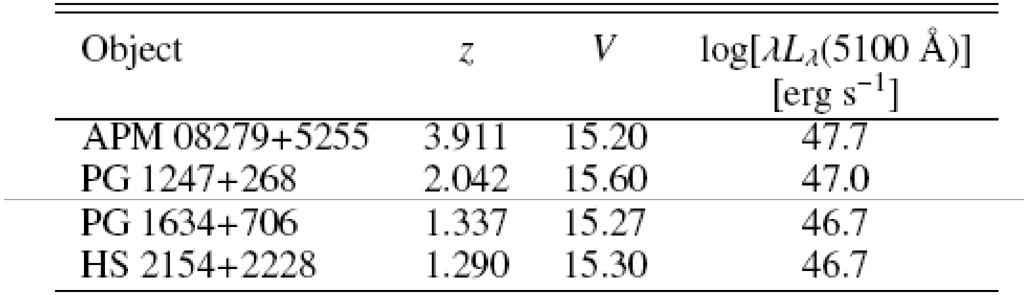


rest-frame delay of 188 days

$$2.6 \times 10^{9}\ M_{\odot}$$

The campaign, PG 1248+268

Copernico telescope classic Cassegrain, 1820 mm (Osservatorio Astronomico di Asiago)



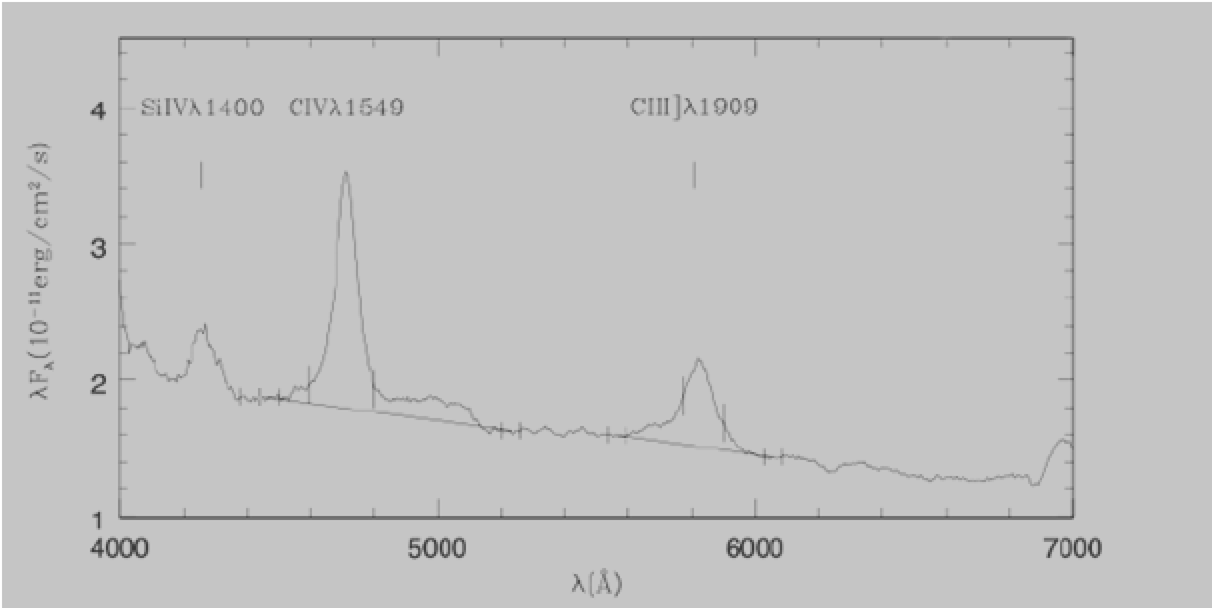
Object	z	V	$\log[\lambda L_\lambda(5100\ \text{Å})]$ [erg s^{-1}]
APM 08279+5255	3.911	15.20	47.7
PG 1247+268	2.042	15.60	47.0
PG 1634+706	1.337	15.27	46.7
HS 2154+2228	1.290	15.30	46.7

$$\lambda_{continuum} \in [4408, 4450]$$

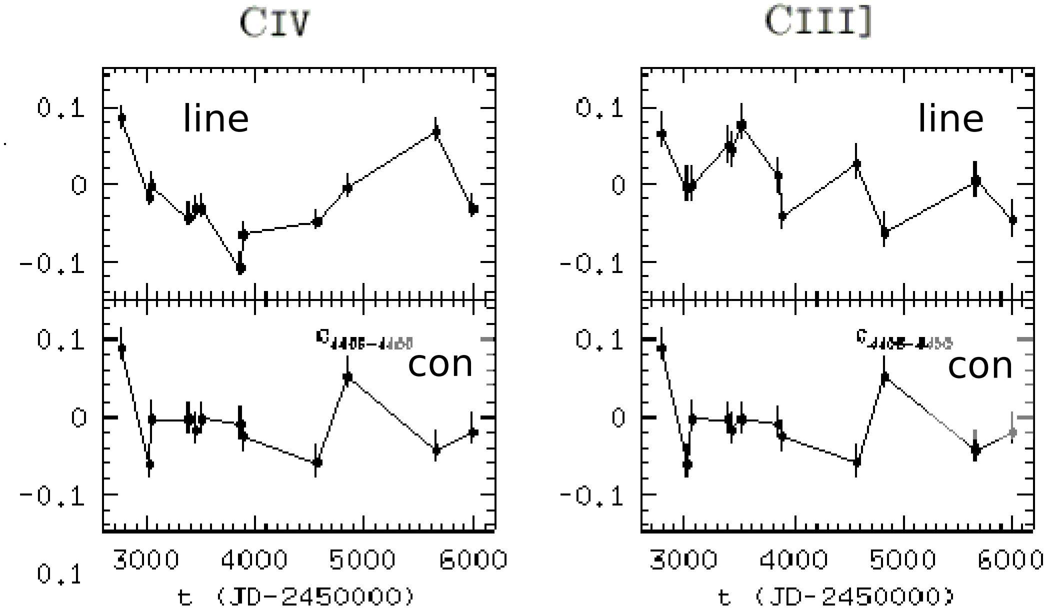
$$\lambda_{short} \in [4450, 4502]\ and\ \lambda_{long} \in [5202,5262]\ (CIV)$$

$$\lambda_{short} \in [5535, 5695]\ and\ \lambda_{long} \in [6025,6085]\ (CIII])$$

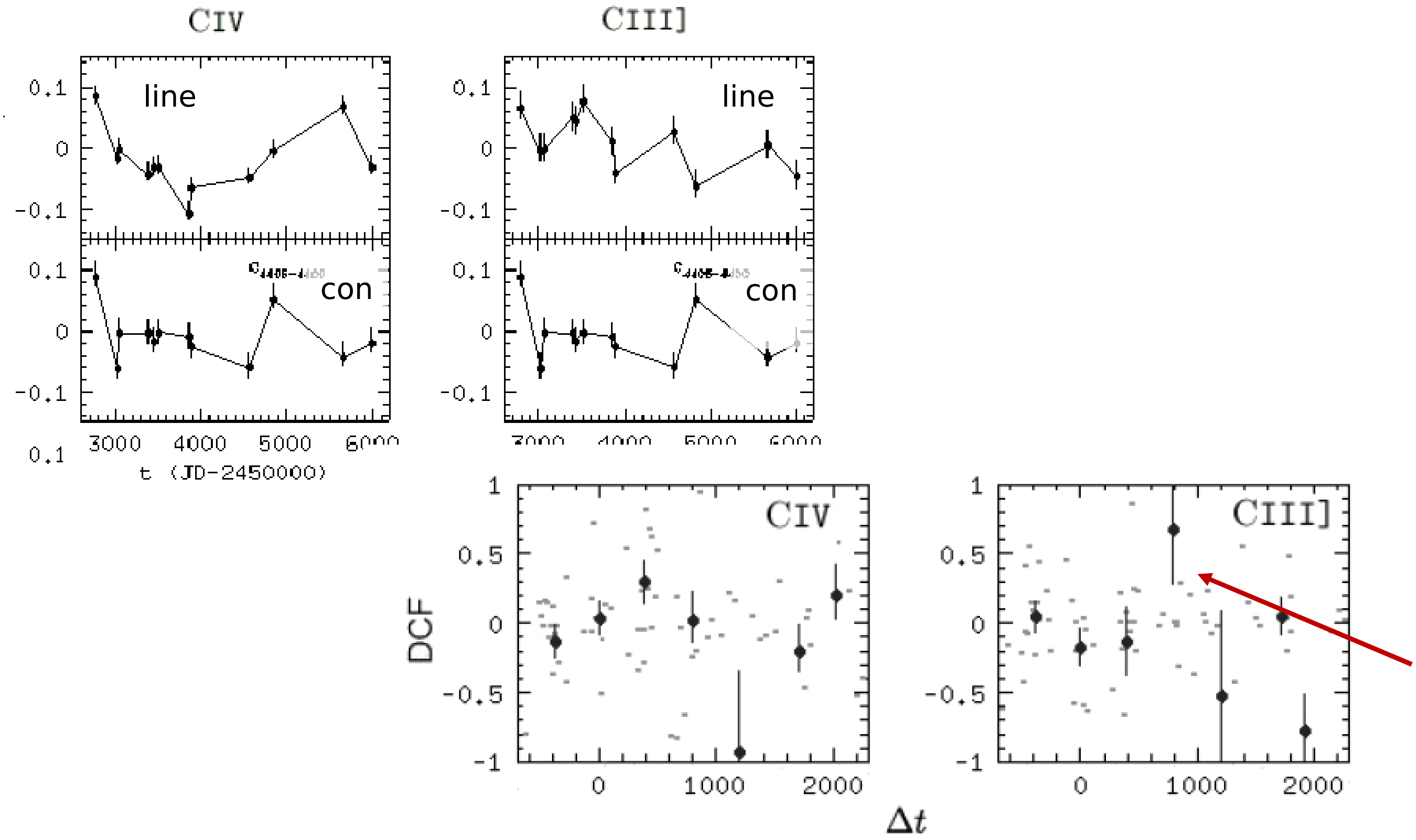
Absence of Hα, Hβ, Hγ observed in the low redshift study



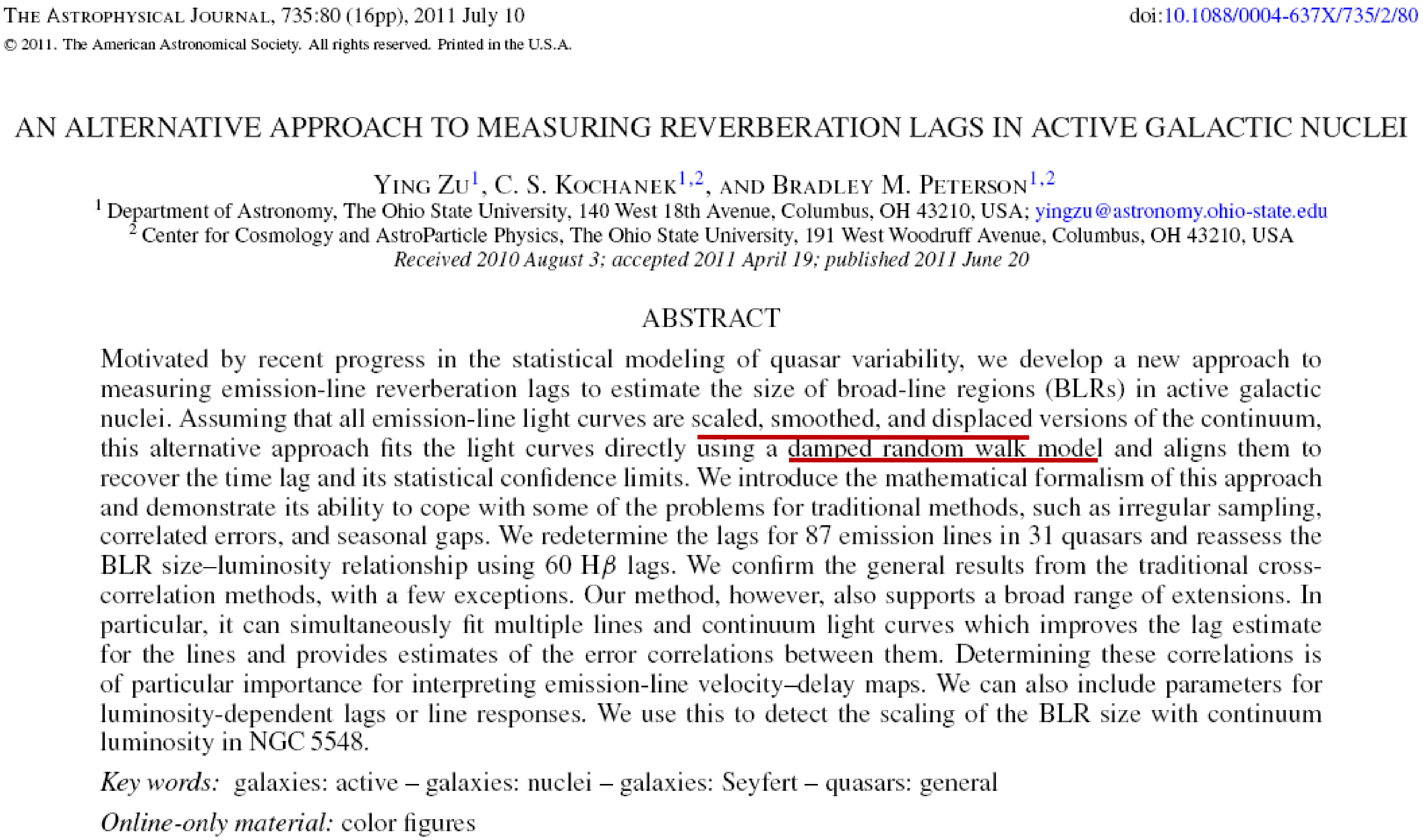
PG 1247+268: discrete cross-correlation



PG 1247+268: discrete cross-correlation



SPEAR (Stochastic Process Estimation for AGN Reverberation)



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AN ALTERNATIVE APPROACH TO MEASURING REVERBERATION LAGS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

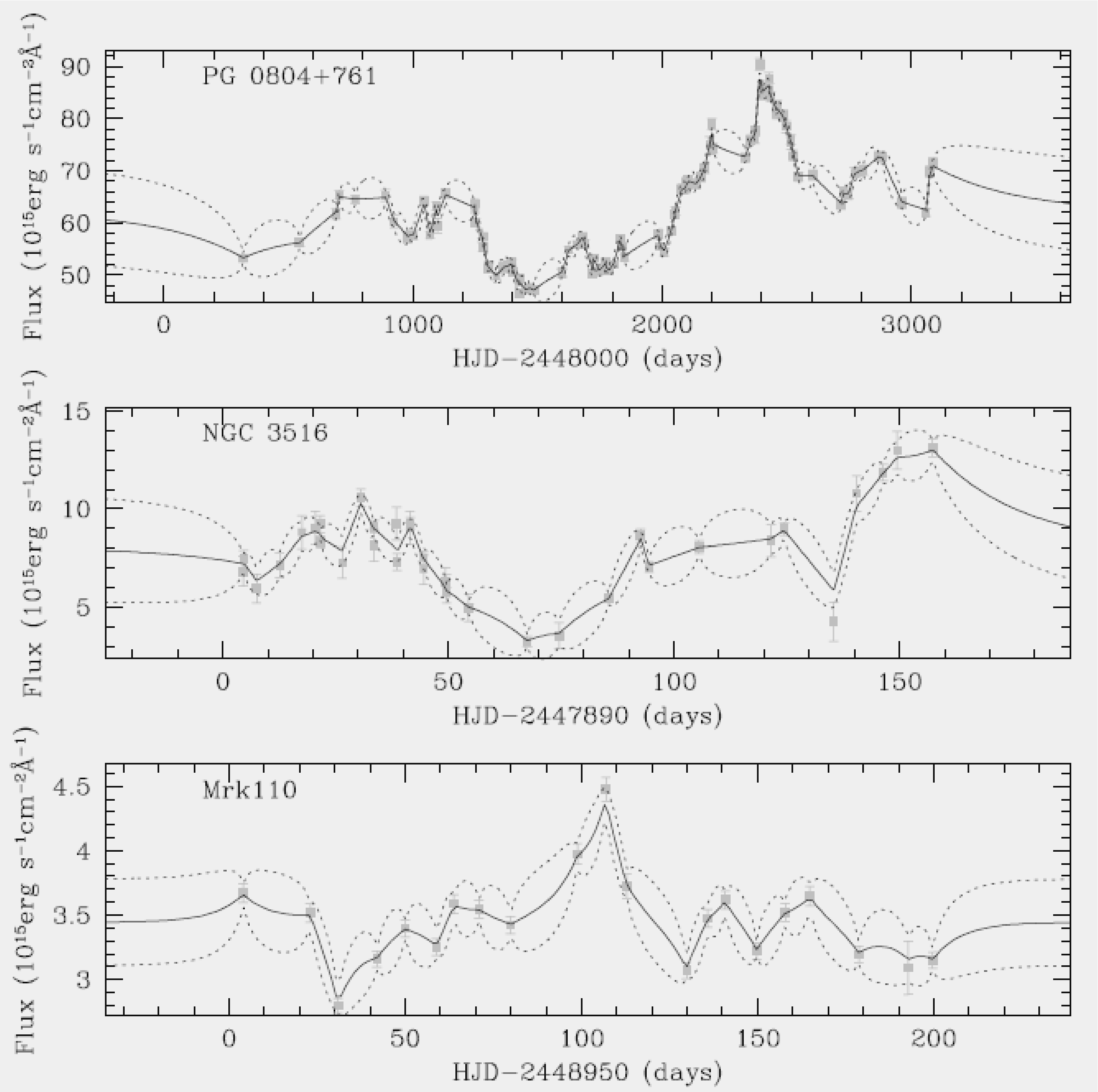
Motivated by recent progress in the statistical modeling of quasar variability, we develop a new approach to measuring emission-line reverberation lags to estimate the size of broad-line regions (BLRs) in active galactic nuclei. Assuming that all emission-line light curves are scaled, smoothed, and displaced versions of the continuum, this alternative approach fits the light curves directly using a damped random walk model and aligns them to recover the time lag and its statistical confidence limits. We introduce the mathematical formalism of this approach and demonstrate its ability to cope with some of the problems for traditional methods, such as irregular sampling, correlated errors, and seasonal gaps. We redetermine the lags for 87 emission lines in 31 quasars and reassess the BLR size–luminosity relationship using 60 Hβ lags. We confirm the general results from the traditional cross-correlation methods, with a few exceptions. Our method, however, also supports a broad range of extensions. In particular, it can simultaneously fit multiple lines and continuum light curves which improves the lag estimate for the lines and provides estimates of the error correlations between them. Determining these correlations is of particular importance for interpreting emission-line velocity–delay maps. We can also include parameters for luminosity-dependent lags or line responses. We use this to detect the scaling of the BLR size with continuum luminosity in NGC 5548.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – quasars: general

Online-only material: color figures

SPEAR (Stochastic Process Estimation for AGN Reverberation)

Each interpolated point is a linear combination of all measured points, based on the available information on the autocorrelation function



Zu et al. 2011

SPEAR (Stochastic Process Estimation for AGN Reverberation)

Quasar variability well described by a *damped random walk*

$$\langle s_c(t_i) s_c(t_j)\rangle = \sigma^2 exp\left(-\left|t_i - t_j\right|/\tau\right)$$

Continuum-continuum Covariance

Amplitude $\sigma^2 = \hat{\sigma}^2\tau/2$

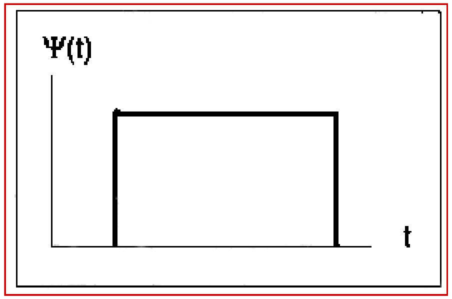
Damping time scale **τ**

Line-continuum Covariance $\langle s_l(t_i) s_c(t_j)\rangle = \int dt' g(t_i - t')\left\langle(s_c(t') s_c(t_j)\right\rangle$

Transfer function $g(t - t') = A(t_2 - t_1)^{-1} \quad per \quad t_1 \leq t - t' \leq t_2$

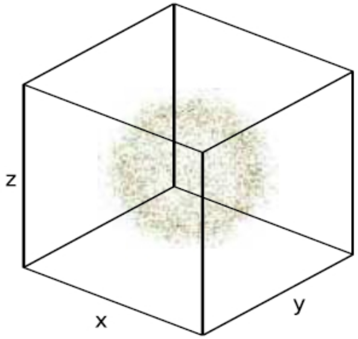
Mean lag $t_{lag} = (t_1 + t_2)/2$

Temporal width $\Delta t = t_2 - t_1$

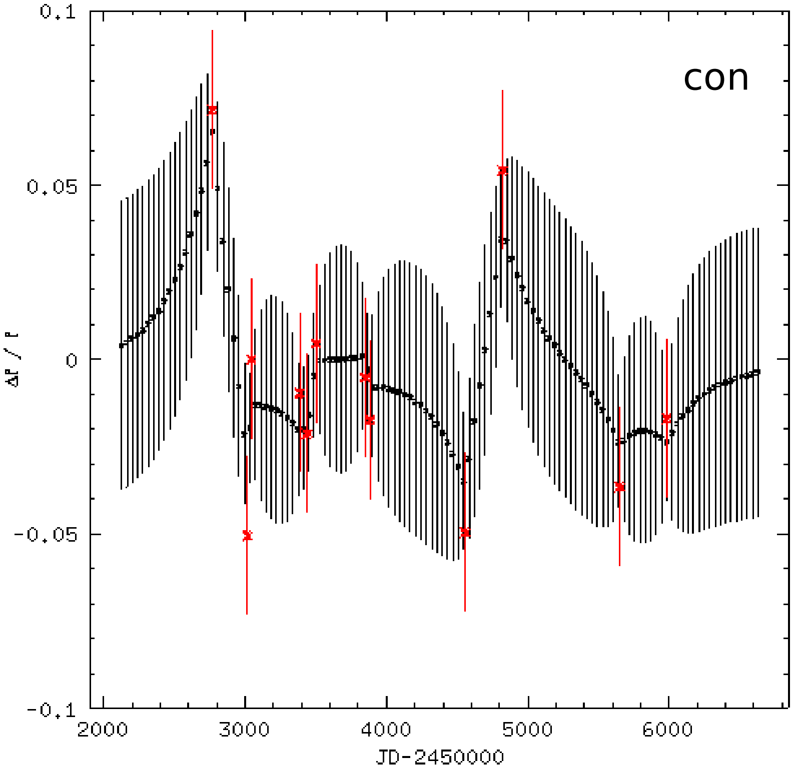


-BLR uniform thin shell
(t_1 ->0)

-delta function
(Δt ->0)

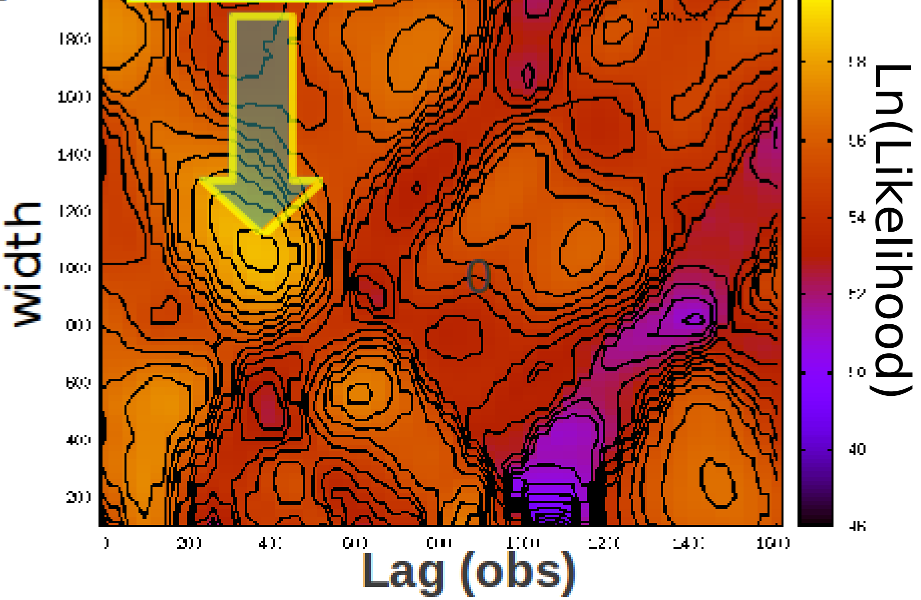


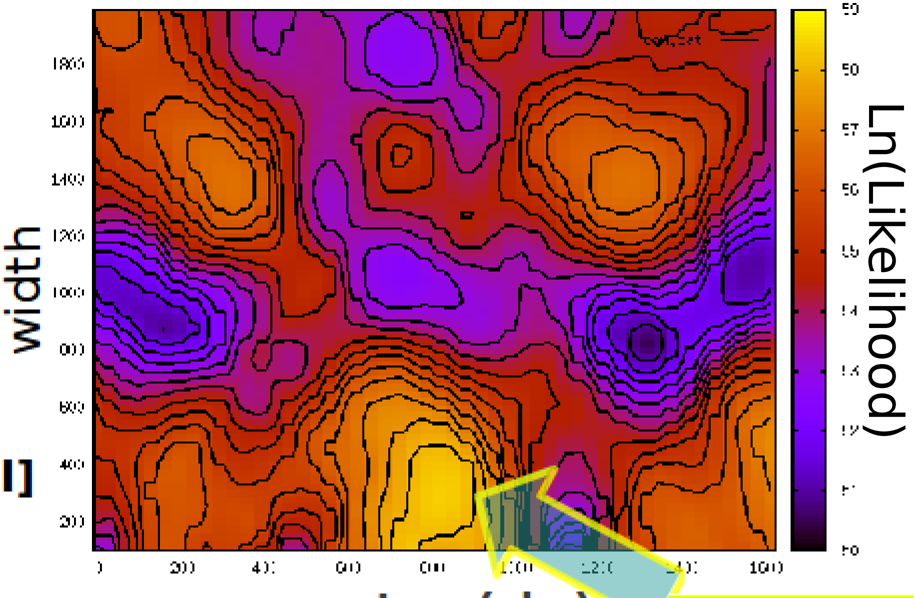
PG 1247+268: SPEAR



CIV

$\chi^2/ndof=1.16$





CIII]

$\chi^2/ndof=1.07$

PG 1247+268: SPEAR

$$t_{lag\ CIII]} = 252^{+39}_{-25}\ days$$

$$t_{lag\ CIV} = 107^{+32}_{-54}\ days$$

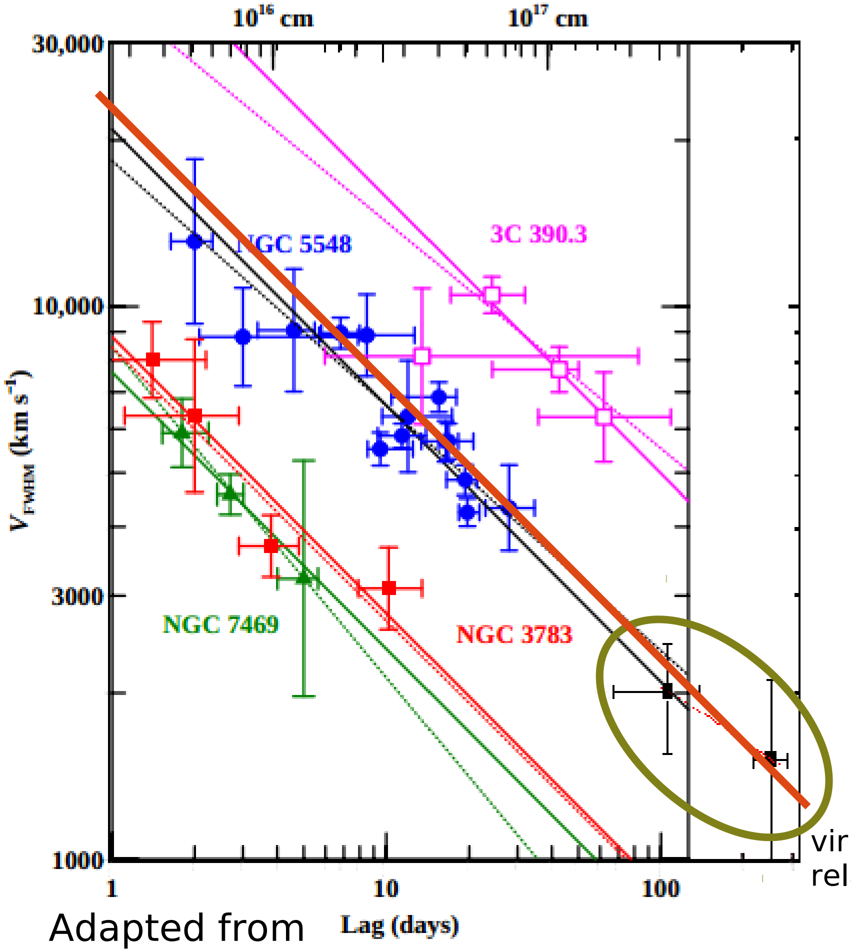
$$t_{lag\ C\mathrm{III]}} \approx 2-3\ t_{lag\ C\mathrm{IV}}$$

(Onken & Peterson 2002; Wandel & Peterson 1999)

$$t_{lag\ CIII]} \approx 2.4\ t_{lag\ CIV}$$

PG1247+268: measures of Line Width

To determine FWHM and velocity dispersion σ_{line} (second moment of the profile) and their associated uncertainties, we employ a bootstrap method (Peterson+2004).



virial relationship

Adapted from Peterson 2011

Rms spectrum

$$S(\lambda) = \left\{ \frac{1}{N-1} \sum_{i=1}^{N} \left[F_i(\lambda) - \overline{F(\lambda)} \right]^2 \right\}^{1/2}$$

$$\Delta V_{\sigma_{line}}(CIV - rms\ spectrum) = 2012 \pm 453\ km/s$$

$$\Delta V_{\sigma_{line}}(CIII] - rms\ spectrum) = 1533 \pm 583\ km/s$$

PG 1247+268: M_{BH}

$$\boxed{M_{\rm BH} = \frac{fR\Delta V^2}{G}}$$

f = 3 (Netzer 1990):

$$\Delta V_{\sigma_{line}}(CIII] - rms\ spectrum) = 1533 \pm 583\ km/s$$

$$t_{lag\ CIII]} = 252^{+39}_{-25}\ days \Rightarrow M_{Rev}(CIII] - \sigma_{line}) = 3.5^{+4.2}_{-2.3} \cdot 10^8 M_\odot$$

$$\Delta V_{\sigma_{line}}(CIV - rms\ spectrum) = 2012 \pm 453\ km/s \Rightarrow M_{Rev}(CIV - \sigma_{line}) = 2.5^{+2.4}_{-1.8} \cdot 10^8 M_\odot$$

$$t_{lag\ CIV} = 107^{+32}_{-54}\ days$$

S5 0836+71 (LUV = 1.12 •10^{47} erg/s , z = 2.172):

factor of 8 higher mass than PG 1247+268 (LUV = 1.94 •10^{47} erg/s, z=2.042); FWHM and t_{lag} : factor ½ higher than PG1247+268.

PG 1247+268: S.E. M_{BH}

Single-Epoch determination:

$$M_{BH} = 4.5 \cdot 10^{6} \left(\frac{\mathrm{FWHM(CIV)}}{10^{3}\,\mathrm{km/s}} \right)^{2} \left(\frac{\lambda L_{\lambda}(1350A)}{10^{44}\,\mathrm{ergs/s}} \right)^{0.53} M_{\odot}$$

Vestergaard & Peterson 2006

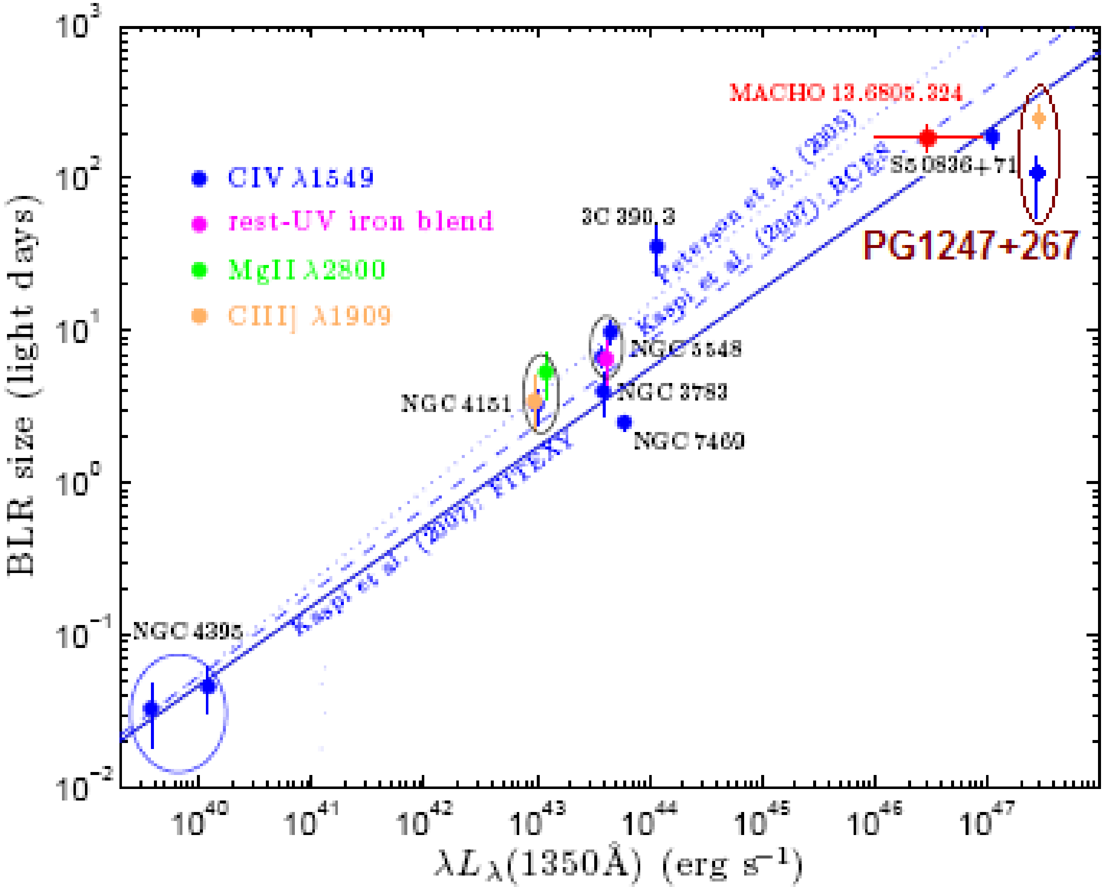
	$M_{PG1247+267}(10^{8} M_{\odot})$	$M_{S50836+71}(10^{8} M_{\odot})$
$M_{Rev}(CIV - FWHM)$	$3.0^{+3.0}_{-2.1}$	26^{*}
$M_{S.E.}(CIV - FWHM)$	$33.5^{+1.9}_{-1.9}$	100^{*}

	PG 1247+267	S5 0836+71
$\left(\frac{M_{S.E.}}{M_{Rev.}}\right)_{FWHM(media)}$	11	4

S.E. relation from R(Hβ)-LUV, not from R(CIV)-LUV.

R(Hβ)-LUV vs R(CIV)-LUV

R(Hβ)-LUV, Vestergaard & Peterson 2006;
slope α=0.53.



Adapted from Chelouche, Daniel, Kaspi 2012

Points confirm and accentuate the decrease in slope suggested by Kaspi et al. 2007

Conclusions

- t_{CIV} has the same order of magnitude of the CIV delay of S5 0836+71
- t_{CIV} is factor of 2.4 larger than $t_{CIII]}$
- There appears to be a virial relationship between CIII] and CIV
- We estimated the mass of PG 1247+268, the most luminous QSO ever analyzed with RM
- If the estimate is maintained, the CIV lag will confirm and accentuate the decrease in slope of L_{UV}-R_{CIV} relation.

PG 1247+268: M_{BH}

$$\boxed{M_{\rm BH} = \frac{fR\Delta V^2}{G}}$$

f = 3 (Netzer 1990):

$$\Delta V_{\sigma_{line}}(CIII] - rms\ spectrum) = 1533 \pm 583\ km/s$$

$$t_{lag\ CIII]} = 252^{+39}_{-25}\ days$$

$$\Delta V_{FWHM}(CIII] - mean\ rms\ spectrum) = 3344 \pm 1976\ km/s$$

$$M_{Rev}(CIII] - \sigma_{line}) = 3.5^{+4.2}_{-2.3} \cdot 10^8 M_{\odot}$$

$$M_{Rev}(CIII] - FWHM) = 4.1^{+7.9}_{-3.5} \cdot 10^8 M_{\odot}$$

$$\Delta V_{\sigma_{line}}(CIV - rms\ spectrum) = 2012 \pm 453\ km/s$$

$$t_{lag\ CIV} = 107^{+32}_{-54}\ days$$

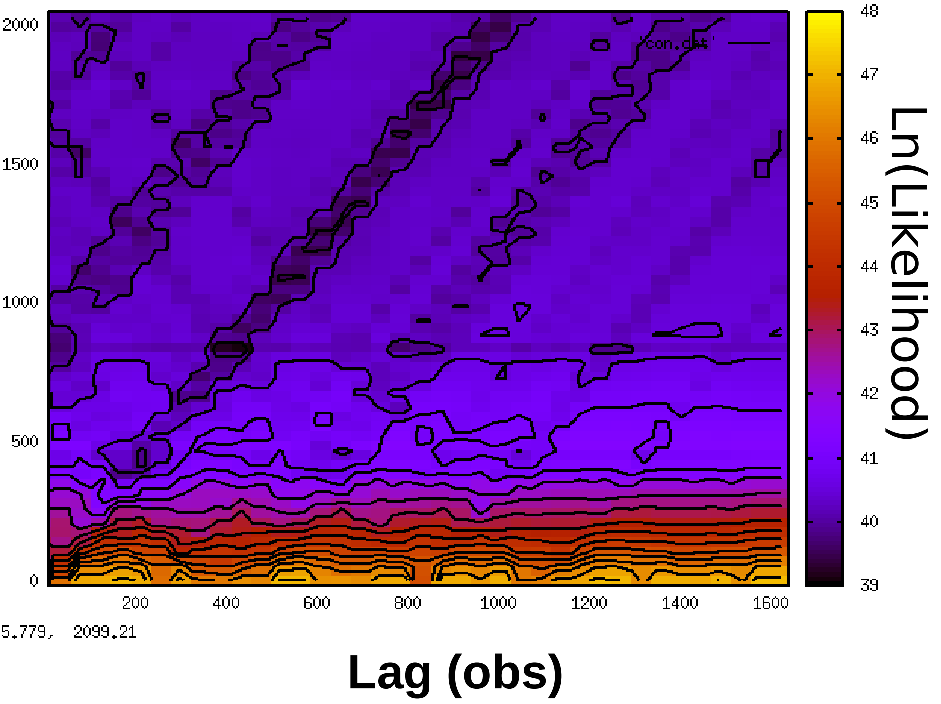
$$\Delta V_{FWHM}(CIV - rms\ spectrum) = 4346 \pm 1013\ km/s$$

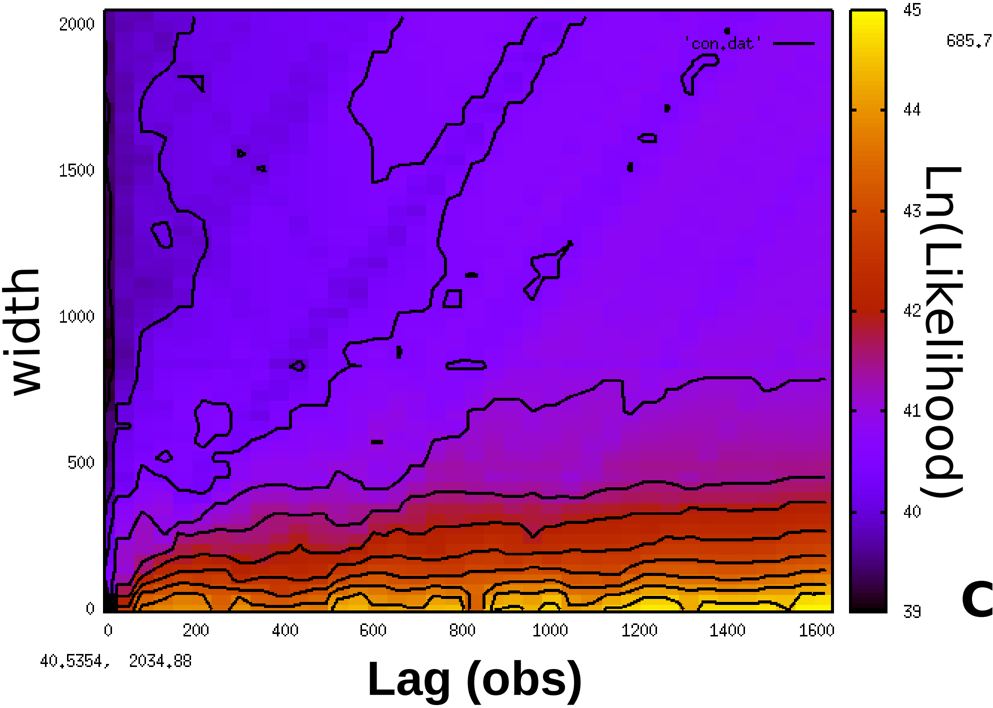
$$M_{Rev}(CIV - \sigma_{line}) = 2.5^{+2.4}_{-1.8} \cdot 10^8 M_{\odot}$$

$$M_{Rev}(CIV - FWHM) = 3.0^{+3.0}_{-2.1} \cdot 10^8 M_{\odot}$$

SPEAR simulations

CIV





CIII]