Reverberation mapping of high luminosity quasars

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Summary

- *Reverberation Mapping*

- *SPEAR* (*Stochastic Process Estimation for AGN Reverberation*, Zu et al. 2011) to estimate the lags between the AGN continuum and emission line light curves and their statistical confidence limits.

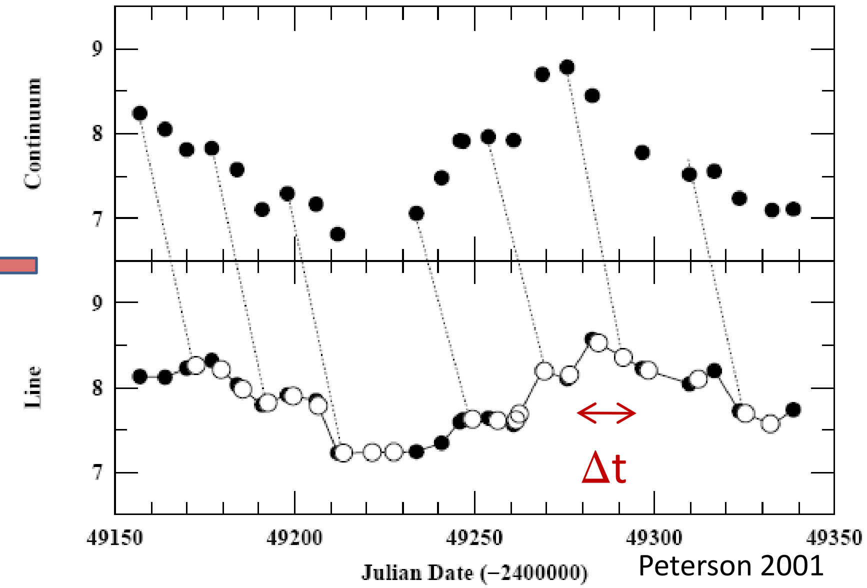
- Spectrophotometric monitoring campaign at Asiago 1.82 m telescope, for intermediate z, high luminosisty QSOs.

- The mass of PG 1247+267, the most luminous QSO ever analyzed with RM

The masses of the AGN's black holes

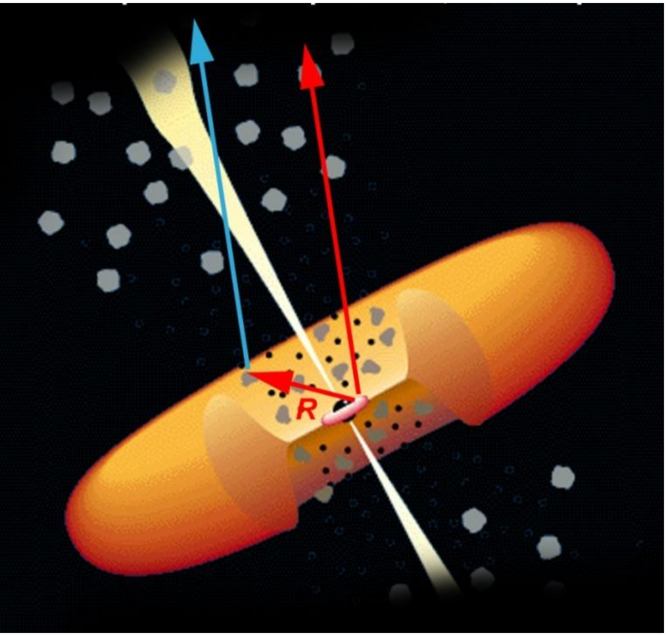
The emission-lines "*reverberate*" to the continuum changes.

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



Peterson 2001

Reverberation Mapping:
BLR very close to BH.



High velocity, ionized clouds give rise broad emission lines.

Virial reverberation mass:

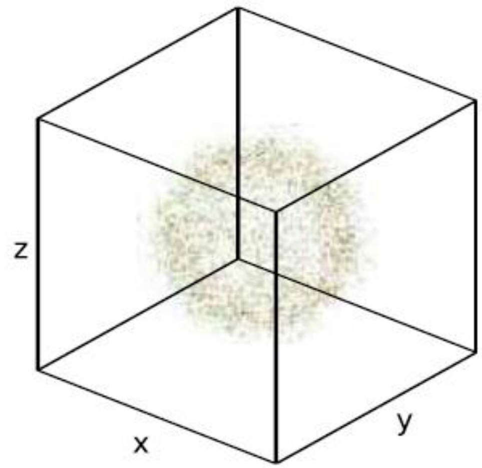
$$M_{\rm BH} = \frac{fR\Delta V^2}{G}$$

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

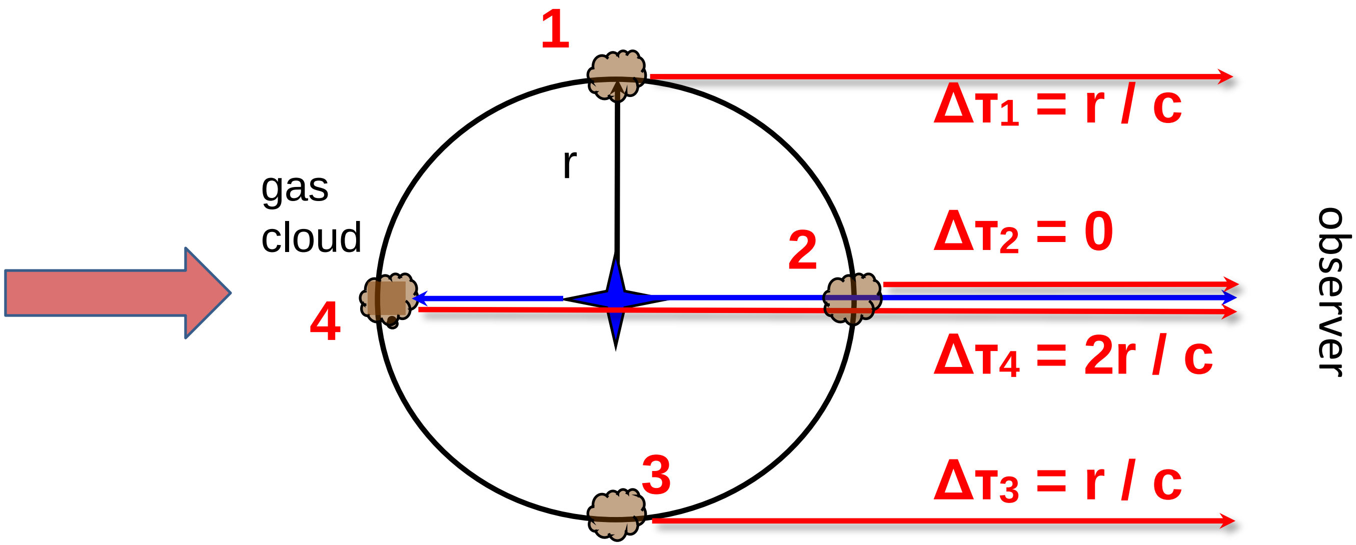
Time Lag

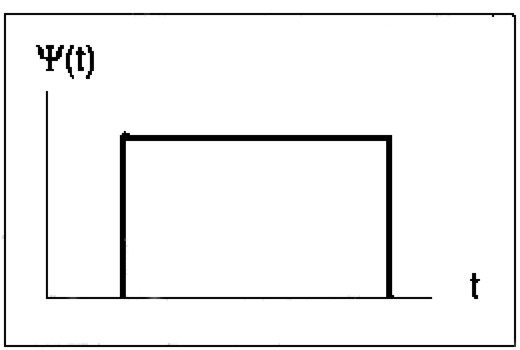
Transfer function

$$L(t) = \int_{-\infty}^{\infty} \Psi(t')C(t-t')\,dt'.$$



BLR uniform thin shell





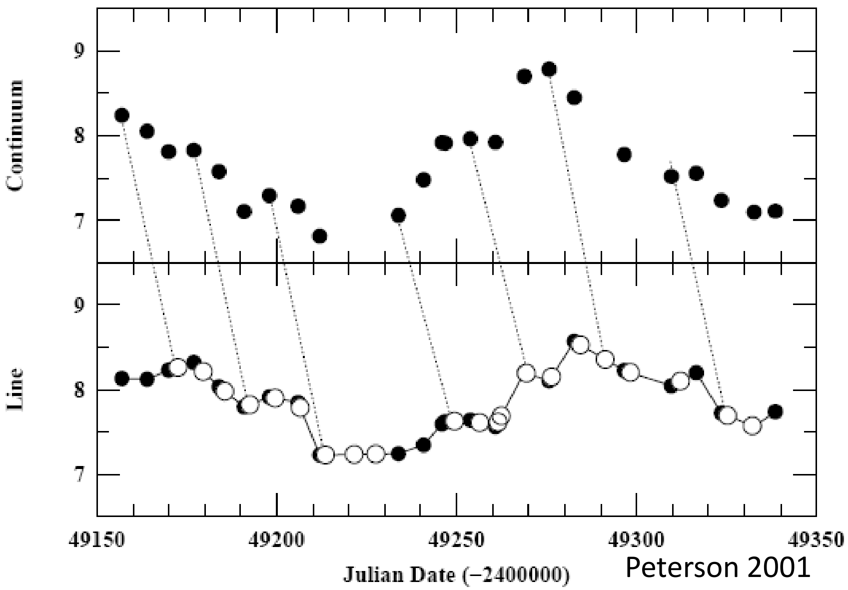
Ψ Transfer function

Transfer function Ψ for a thin spherical shell
within the range $0 \leq t' \leq 2\, r/c$

Time Lag

Cross-correlation function $$CCF_{x,y}(\Delta t) = \frac{\langle (x(t_i - \Delta t) - \bar{x})(y(t_i) - \bar{y}) \rangle}{\sigma_x \sigma_y}$$

“Interpolation” metod (ICCF)
(Gaskell & Peterson 1987)



Peterson 2001

“discrete” CCF method (DCF)
(Edelson & Krolik 1988)

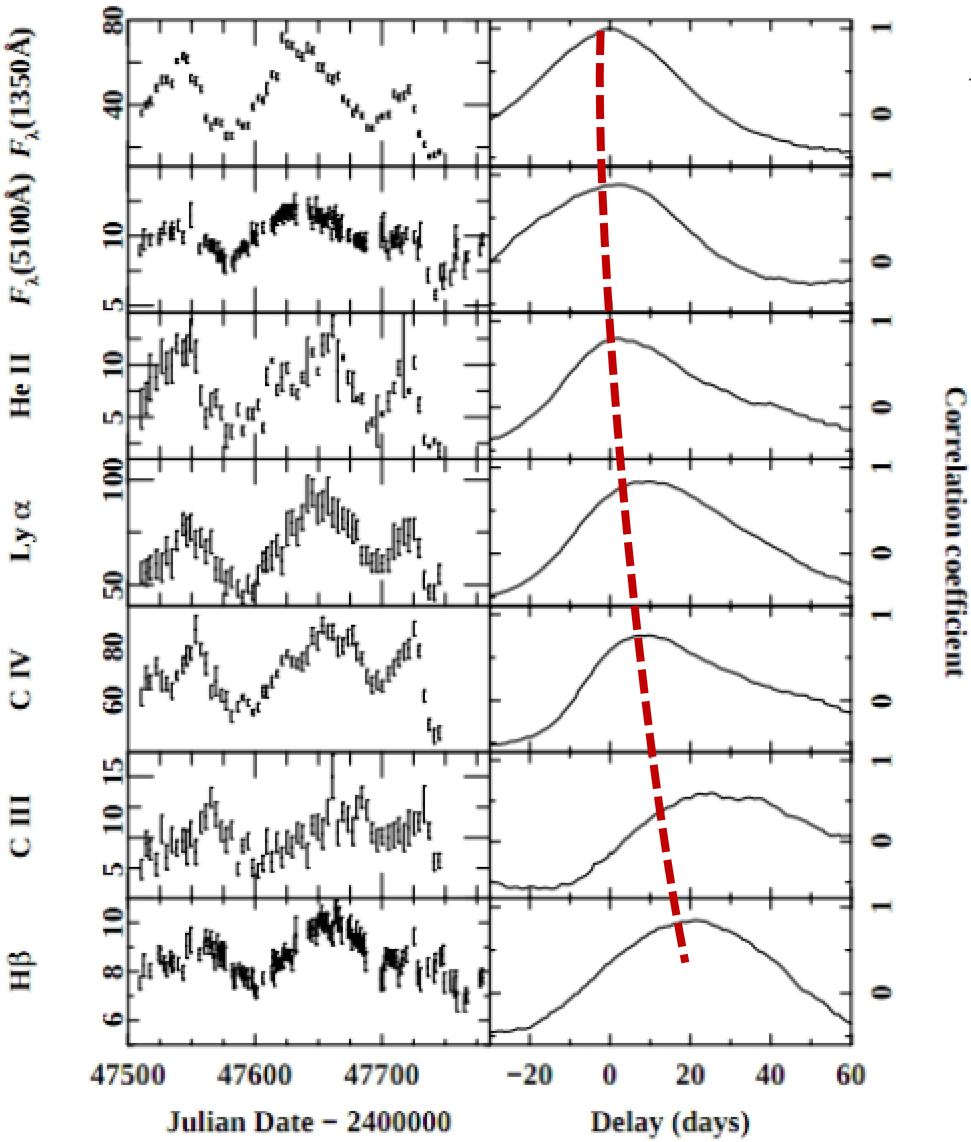
Unbinned cross-correlation function

$$\mathrm{UDCF}_{ij} = \frac{(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sigma_x^2 - e_x^2)(\sigma_y^2 - e_y^2)}}$$

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

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

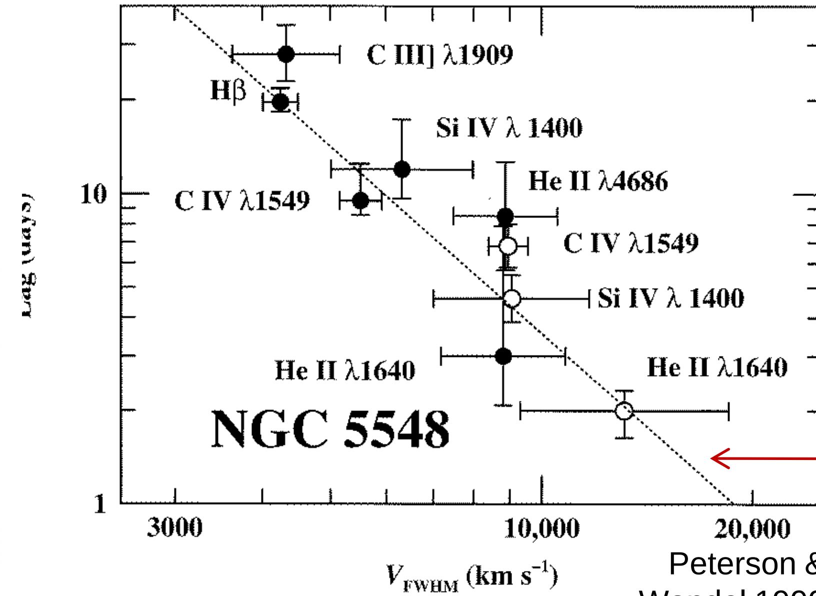
Time Lag



Light curves **CCF**

Peterson 2001

$R \propto \Delta V^{-2}$ ⇨ $log(c\tau) = a - 2log(\Delta V)$



Peterson & Wandel 1999

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

○ : 1993 data from *HST* and *IUE*.

… virial relationship with $M = 6 \times 10^7 M_\odot$.

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

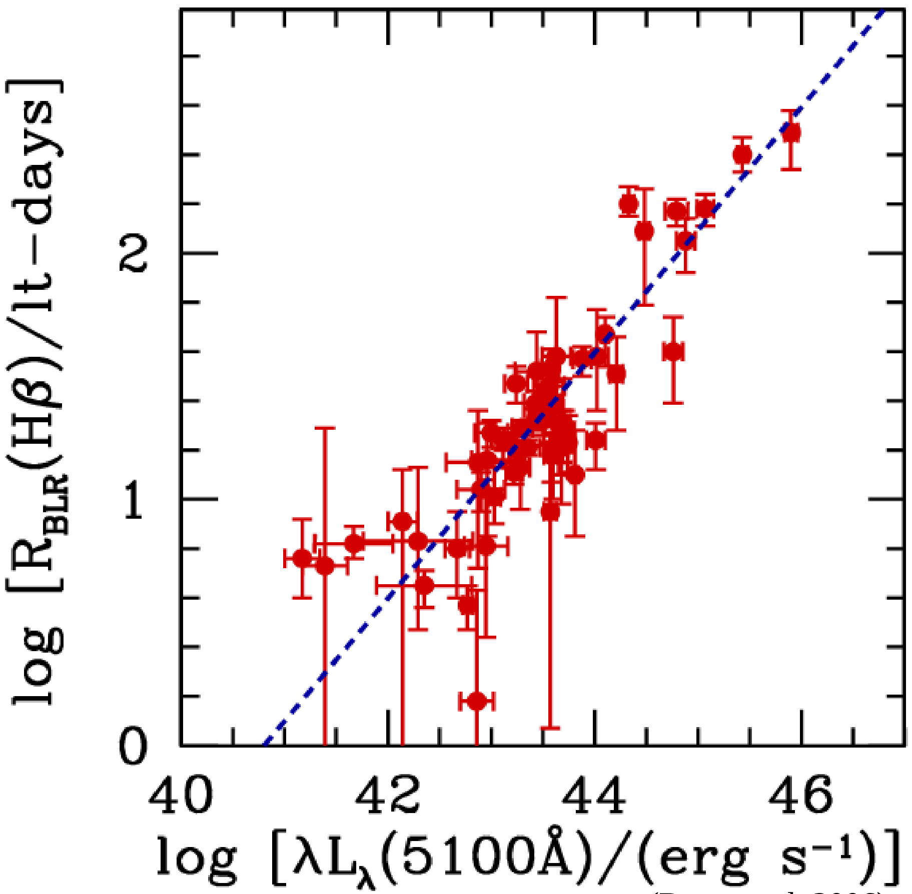
L-R relation

Kaspi et al. 2000, for qso with $L \lesssim 10^{46}\,\mathrm{erg\,s^{-1}}$, obtain:

BLR size scales with
the 5100 Å luminosity as

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

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



(Bentz et al. 2006)

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

Single-epoch determination

From R-L relation: $R_{BLR} = c_1 L_\lambda^\gamma$ ⇒ $M_{BH} = c_2 L_\lambda^\gamma (\Delta V)^2$

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

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

Vestergaard & Peterson 2006

⇓

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

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

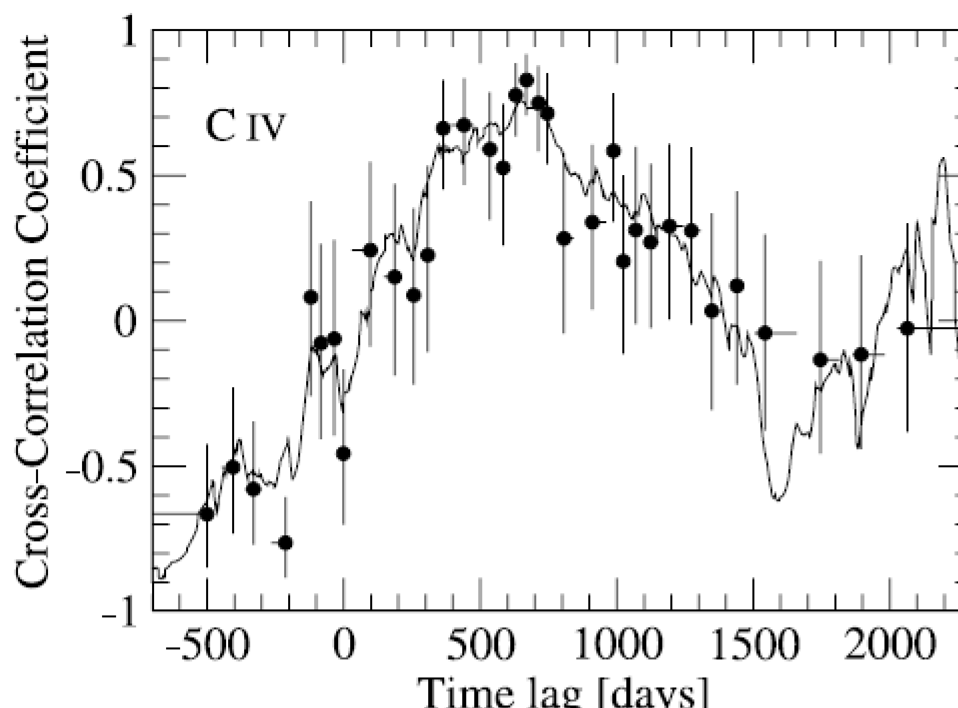
⇓

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_{phot} (6)	N_{spec} (7)	$\lambda L_\lambda(5100\ \text{Å})$ (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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HS 1700+6416	[illegible]						



rest-frame delay of 188 days

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

The campaign, PG 1247+267

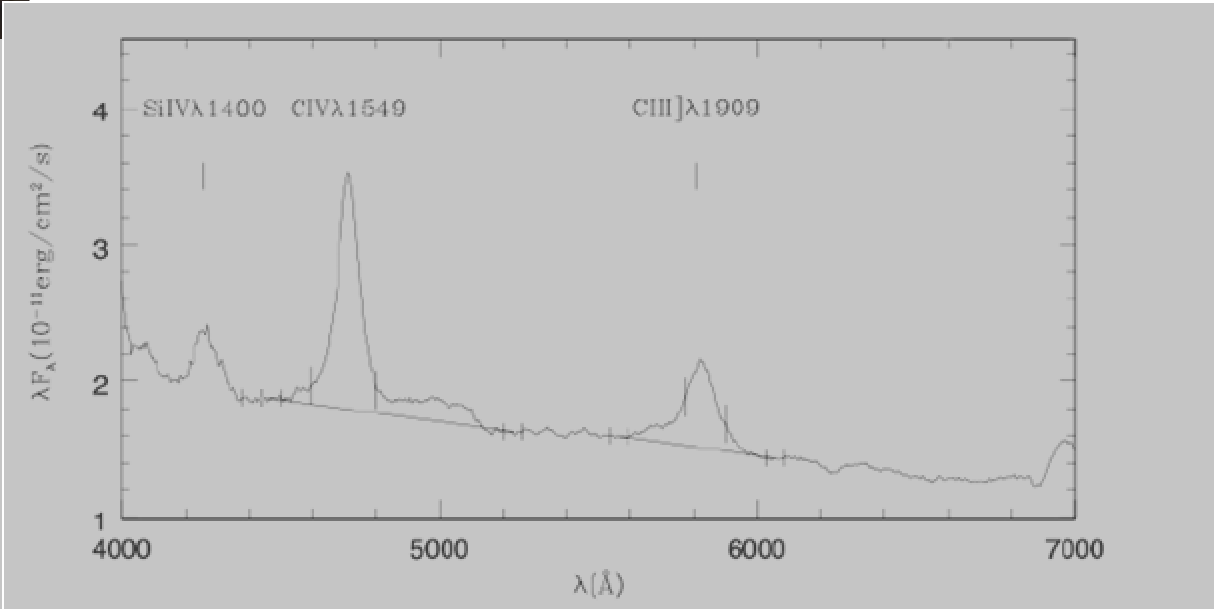
Object	z	V	$\log[\lambda L_\lambda(5100\ \text{Å})]$ [erg s^{-1}]
APM 08279+5255	3.911	15.20	47.7
PG 1247+268	2.042	15.60	47.0
PG 1634+706	1.337	15.27	46.7
HS 2154+2228	1.290	15.30	46.7

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

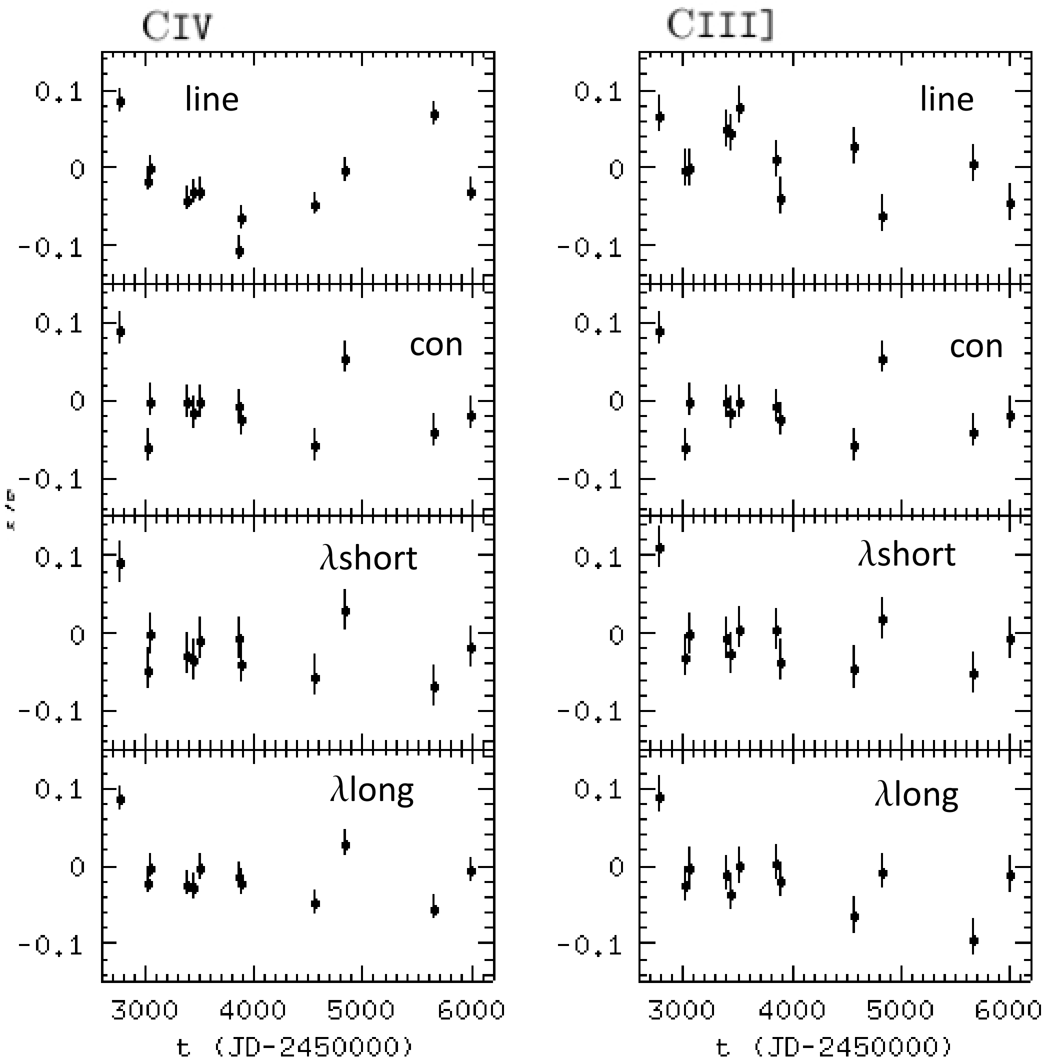
$$\lambda_{short} \in [4450, 4502]\ and\ \lambda_{long} \in [5202,5262]\quad (CIV)$$

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

Absence of Hα, Hβ, Hγ observed in the low redshift study of Kaspy et al. (2000)



PG 1247+267: discrete cross-correlation



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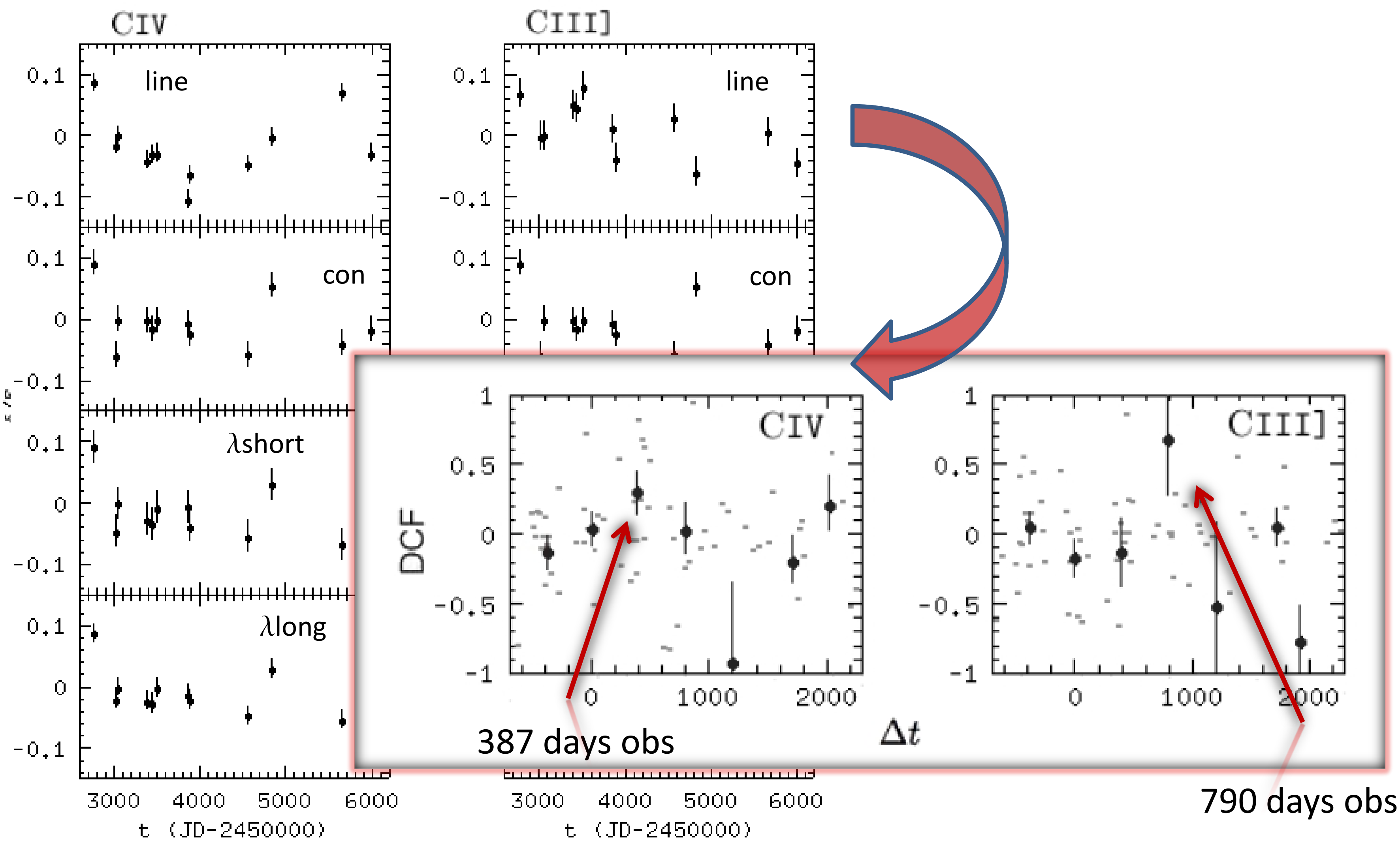

SPEAR (Stochastic Process Estimation for AGN Reverberation)

The Astrophysical Journal, 735:80 (16pp), 2011 July 10 doi:10.1088/0004-637X/735/2/80

AN ALTERNATIVE APPROACH TO MEASURING REVERBERATION LAGS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

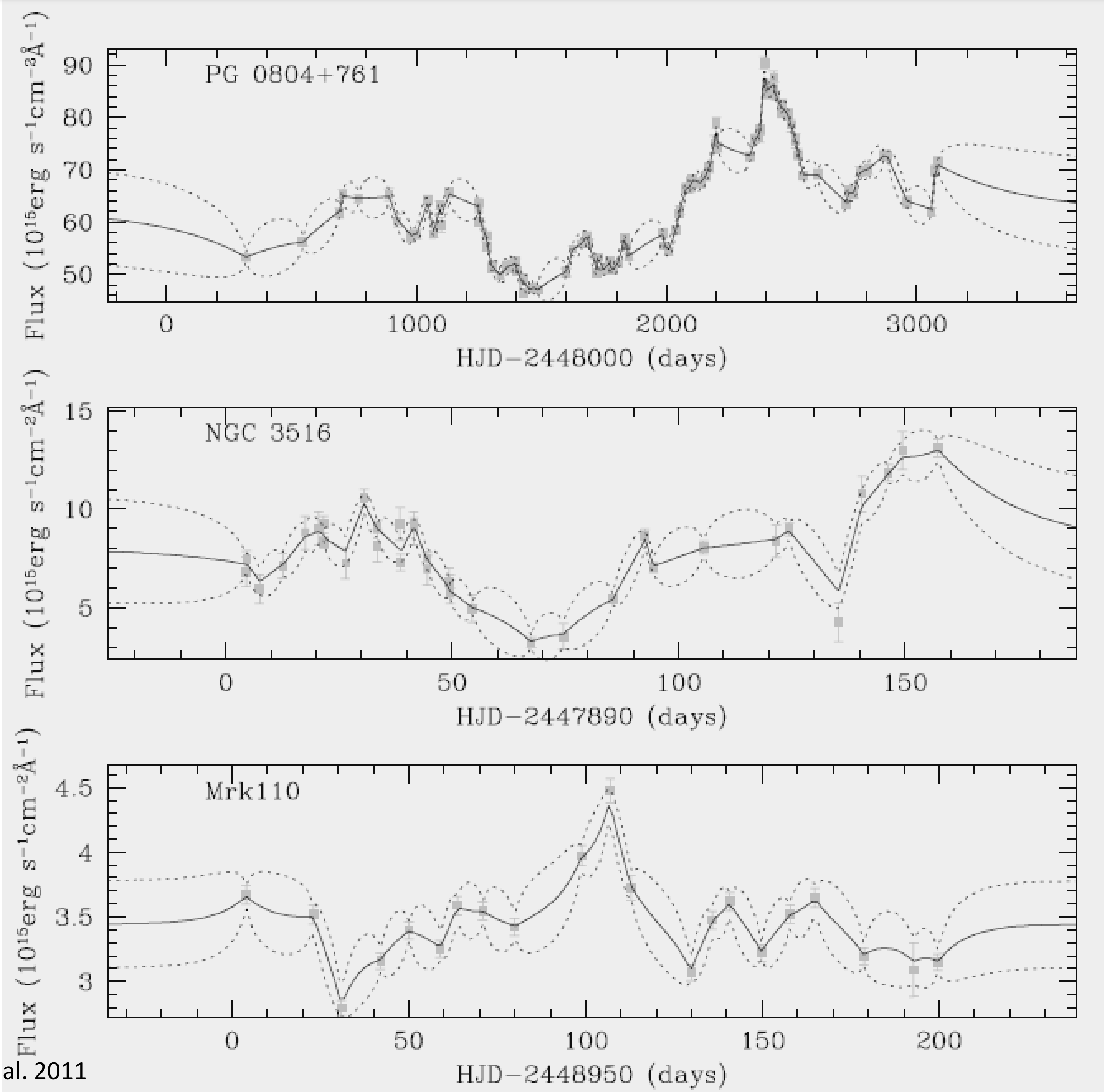
Motivated by recent progress in the statistical modeling of quasar variability, we develop a new approach to measuring emission-line reverberation lags to estimate the size of broad-line regions (BLRs) in active galactic nuclei. Assuming that all emission-line light curves are scaled, smoothed, and displaced 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 describet by a *damped random walk;*
Power spectrum of the process is

$$P_Y(f) = \frac{2\hat{\sigma}^2\tau^2}{1+(2\pi\tau f)^2}$$

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

Damping time scale τ

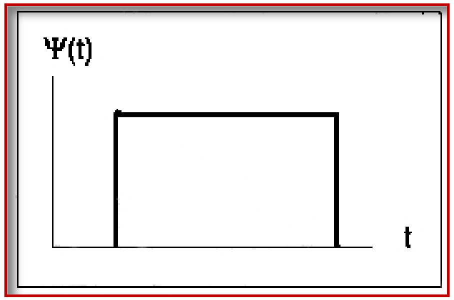
$$\langle s_c(t_i)s_c(t_j)\rangle = \sigma^2 exp\left(-\left|t_i - t_j\right|/\tau\right)$$ Covariance continuum-continuum

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

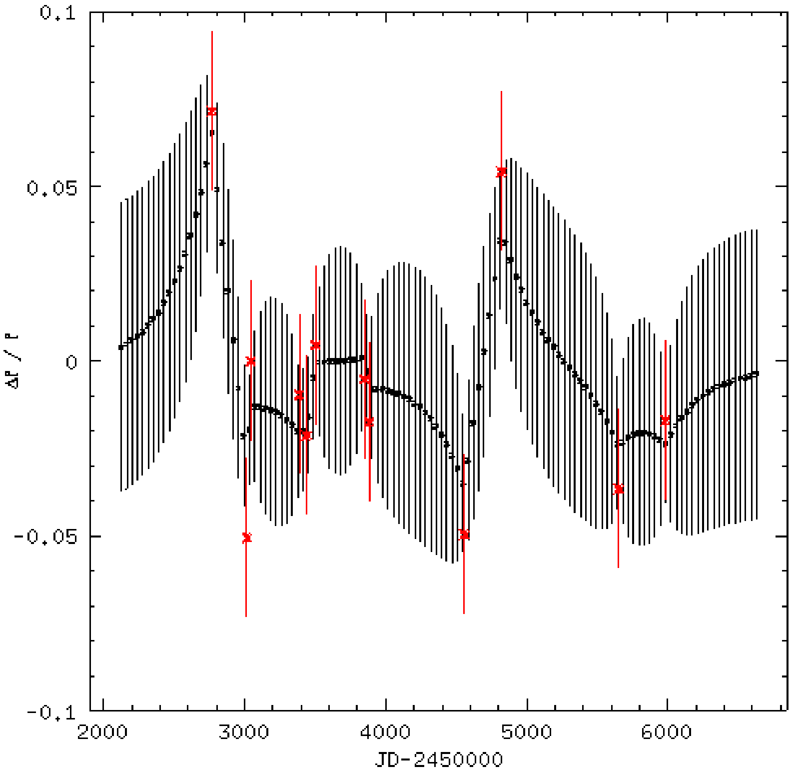
Transfer function $$g(t-t') = A(t_2 - t_1)^{-1} \qquad per \quad t_1 \leq t - t' \leq t_2$$

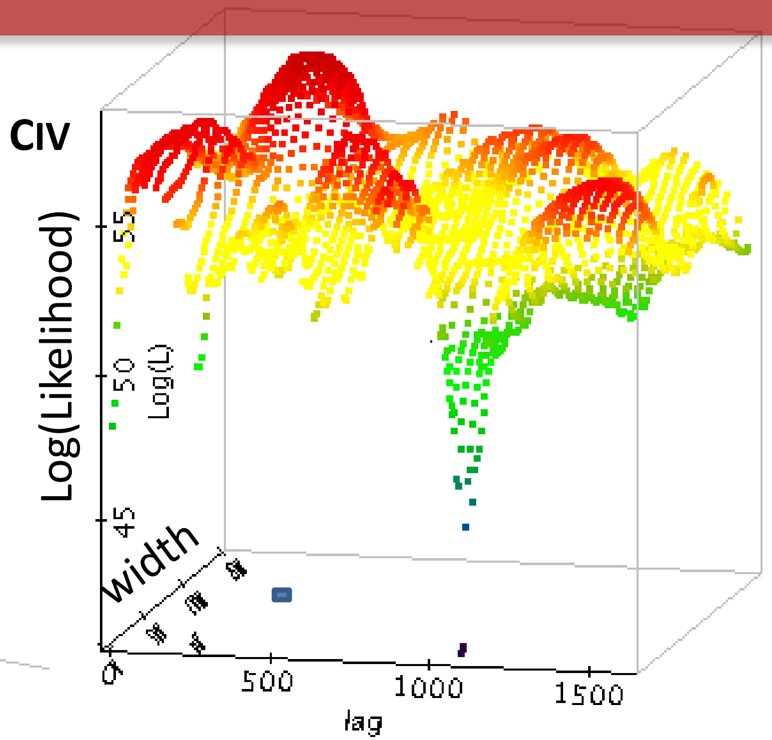
Mean lag $t_{lag} = (t_1 + t_2)/2$

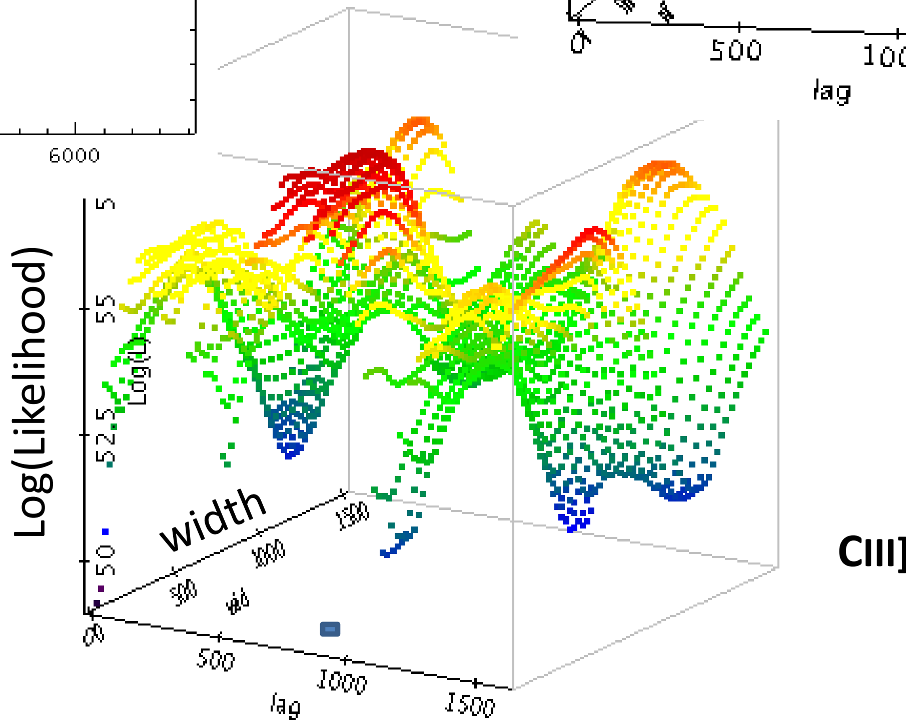
Temporal width $\Delta t = t_2 - t_1$



PG 1247+267: SPEAR







PG 1247+267: 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+267: measures of Line Width

To determine FWHM and σ_{line}

$$\sigma^2_{\mathrm{line}}(\lambda) = \langle \lambda^2 \rangle - \lambda_0^2 = \left[\int \lambda^2 P(\lambda) d\lambda \Big/ \int P(\lambda) d\lambda \right] - \lambda_0^2$$, with $$\lambda_0 = \int \lambda P(\lambda) d\lambda \Big/ \int P(\lambda) d\lambda$$

and their associated uncertainties, we employ a bootstrap method.

Mean spectrum $\overline{F(\lambda)} = \frac{1}{N} \sum_{i=1}^{N} F_i(\lambda)$

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+267: M_{BH}

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

f = 3 (Netzer 1990):

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

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

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

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

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

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

S5 0836+71 (LUV = 1.12 $\cdot 10^{47}$ erg/s , z = 2.172): factor of 8 highter mass than PG 1247+267 (LUV = 1.94 $\cdot 10^{47}$ erg/s, z=2.042).
FWHM and t_{lag} : factor ½ higther than PG1247+267.

$$R \propto \Delta V^{-2} \Rightarrow 1.3 \pm 0.8 = \frac{\Delta V_{CIV}}{\Delta V_{CIII]}} \approx \sqrt{\frac{t_{lag\ CIII]}}{t_{lag\ CIV}}} = 1.5 \pm 0.3$$

PG 1247+267: M_{BH}

Single-Epoch determination:

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

Vestergaard & Peterson 2006

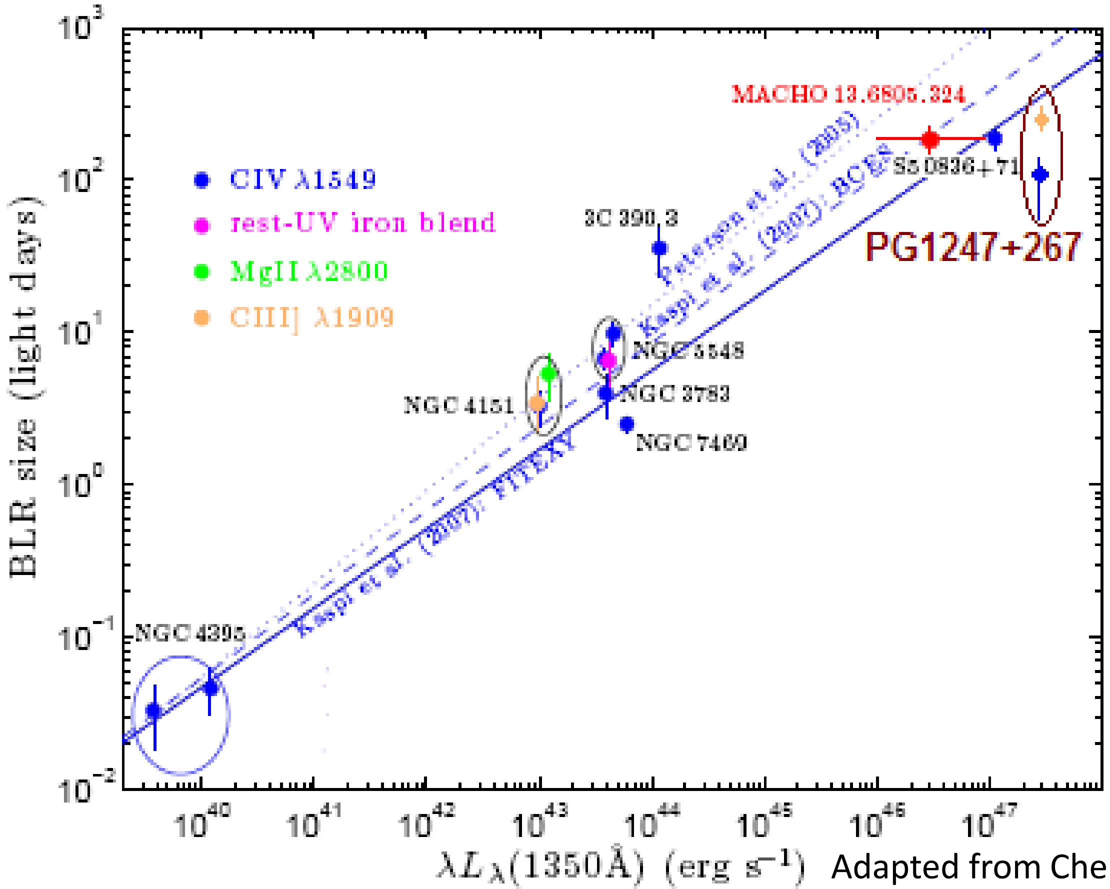
	$M_{PG1247+267}(10^8 M_\odot)$	$M_{S50836+71}(10^8 M_\odot)$
$M_{Rev}(CIV - FWHM)$	$3.0^{+3.0}_{-2.1}$	26^{*}
$M_{S.E.}(CIV - FWHM)$	$33.5^{+1.9}_{-1.9}$	100^{*}

	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 confirms and accentuates the decrease in slope suggested by Kaspi et al. 2007

Conclusions

- We used the SPEAR method to estimate continuum-line lags t_{CIV} and $t_{CIII]}$

- We estimated the mass of PG 1247+267, the most luminous QSO ever analyzed with RM

- The CIV lag confirms and accentuates the decrease in slope of L_{UV}-R_{CIV} relation.

SPEAR (Stochastic Process Estimation for AGN Reverberation)

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

Light curve of a line $$s_l(t) \equiv \int dt' g(t-t')s_c(t)$$

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

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

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

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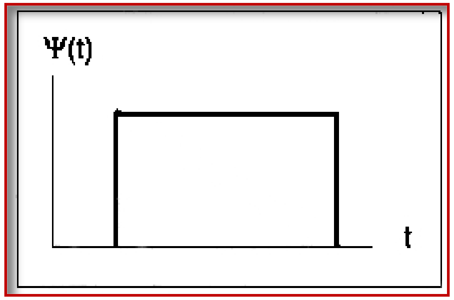

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$$M_{\rm BH} = \frac{fR\Delta V^2}{G}$$

f = 3 (Netzer 1990):

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

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

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

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

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

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

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

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

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

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

PG 1247+267: DCF with continuum snake