Relation between X-ray Black Hole Mass and X-ray Variability

– Expectation for MAXI –

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Abstract

X-ray variability of AGNs has been employed to constrain the size of the emission region as well as the mechanism of the emission. We propose an empirical method to estimate the black hole (BH) masses in AGNs from their X-ray variability and apply the method to various classes of AGNs, broad line Seyfert 1 galaxies (BLS1s), narrow line Seyfert 1 galaxies (NLS1s), and low luminosity AGNs (LLAGN). Stability of the power spectrum density is examined, and alternative definitions of the variability time scales are compared. Comparison with independent BH mass estimation indicates X-ray variability provides order of magnitude estimation for the BH mass scale, though deviation is evident in some cases. Further studies with various AGNs at various flux states reveal how the X-ray variability is affected by other parameters than BH mass, e.g., accretion rate or class of AGNs. We expect for long term observations with MAXI to provide clue to such an issue.

Key words: active—galaxies: nuclei—X-rays: galaxies: variability: black hole

1. Black Hole Mass Estimation from X-ray Variability

Variability of radiation from AGNs has been used to estimate the size of their emission region. The size estimated in such a way, together with a huge amount of the radiation, is considered to be one of the observational proof of the existence of super-massive black holes (SMBHs) in AGNs. X-ray variability is especially important and efficient to estimate the size of the BHs, because it usually has a shorter time scale than that in the longer wavelength. In fact, Barr and Mushotzky (1986) indicated that the time scale of the X-ray variability of AGNs, for which they employed the shortest doubling time, has a positive correlation with their X-ray luminosities. The upper limits of BH masses were provided by Wandel and Mushotzky (1986) from the same data.

We have proposed a new and empirical method to estimate the black hole masses in AGNs from their X-ray variability (Hayashida et al. 1998). Key assumptions of the method are 1) X-ray variability of BHs, from stellar BHs to AGN, are similar each other, 2) the variability time scales are linearly proportional to the central BH masses, and 3) Cyg X-1 BH mass is 10 $M_\odot$. We employ the normalized power spectrum density (NPSD) of X-ray light curve to define a variability time scale, where the NPSD is the power spectrum density normalized by the average intensity squared. If the X-ray variability is similar for different size of BHs, their NPSDs should align along the 1/frequency line, as we shown in Hayashida et al. (1998) by a simple arithmetic. In other word, if we make NPSD × frequency of those sources, they should stand side by side in the diagram. Their positions in the NPSD × f diagram reflect the relative system size of those BHs. These procedures are illustrated in Fig. 1.

We first applied the method to several Seyferts observed with the Ginga satellite (Hayashida et al. 1998). We have expanded the work to various classes of AGNs observed with the ASCA satellite, and we compared the estimated BH masses with those by other methods. We introduce those works in this paper. In addition, we also propose possible targets of future all sky X-ray monitor experiments, such as MAXI. Note that some of the plots are cited from Hayashida et al. (2003).

2. Black Hole Mass and X-ray Variability for Various Classes of AGNs

2.1. Narrow Line Seyfert 1 and Broad Line Seyfert 1

Narrow Line Seyfert 1 (NLS1) galaxies are known to show a rapid and large amplitude X-ray variability. We quantified the X-ray variabilities of NLS1s by their NPSDs and estimated their BH masses. Fig. 2 cited from Hayashida (2000) illustrate systematic trends that the NLS1s have lower mass black hole than BLS1s; the BH masses in NLS1s range from $10^5 - 10^7$ $M_\odot$, while those in BLS1s $10^7 - 10^8$ $M_\odot$ according to our estimations. We think this is the most important factor which distinguish these two classes of Seyfert.

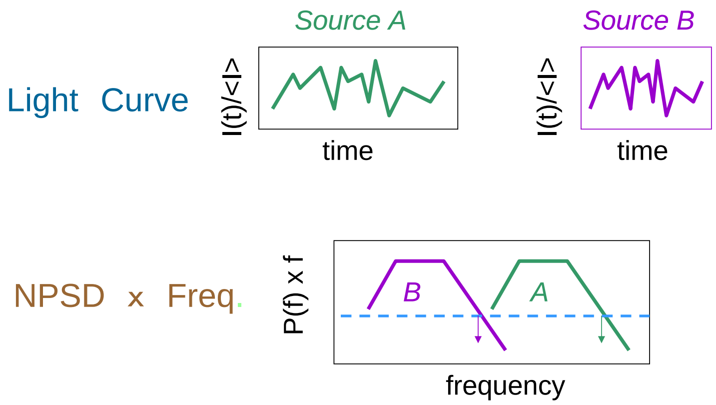

Fig. 1. Schematic Diagram of Scaling Relation of Variability. We consider there are two sources of which sizes are different by some factor. The assumption we made is that their X-ray light curves normalized by their average intensity is self similar expect for the scale of the time axis (top panels), and the time scale is linearly proportional to the BH size or mass. The corresponding NPSDs align in the NPSD×Frequency diagram side by side. The position of the two NPSD are differ by the ratio of their system size (BH mass). We measure the position from the corssing point of the NPSD and the horizontal bar (in our case we set fP(f)=1/1000). See Hayashida et al. (1998, 2003)on detailed description.

Another remarkable point of the NLS1s is their enhanced soft X-ray component, usually approximated with a blackbody of temperature of 0.1-0.2keV. If we regards the component as a thermal emission from an accretion disk, it constrains the BH mass and accretion rate of the source. Such discussions are found in, e.g., Hayashida (2000) and Mineshige et al (1999).

2.2. Low Luminosity AGNs and Seyfert 2

It is known that there is a class of AGNs of which luminosities are significantly lower than typical Seyferts or quasars. We investigated the X-ray variabilities of such low luminosity AGNs (LLAGN), including LINERs, observed with ASCA (Awaki et al., 2001). Although they usually show a small amplitude X-ray variability, we obtained at least the lower limit of the BH mass from them. The results indicate those LLAGNs contain BHs 10^6 or larger, and they emit at extremely low efficiency, less than 1% of the Eddington luminosity (see Fig.3, which is cited from Awaki et al. (2001)). Long term X-ray variability of the LLAGN, M81, were investigated by Ishisaki et al. (1996) and Iyomoto et al. (2001) . Iyomoto et al. (2001) employed a structure function in order to quantify the X-ray variability from highly gaped data.

On the other hands, we found a contrasting case in NGC4395, which is known as the least luminous Seyfert. Regardless of its low luminosity (Lx$\sim$ 10^{39} erg/s) the optical-UV spectrum of NGC4395 is similar to that in a Seyfert type. We found rapid X-ray variability in the source, leading to the mass estimation of the BH of $10^4 - 10^5$ $M_\odot$ (Iwasawa et al., 2000).

Examination of the unification model of the type 1 and 2 AGNs is one of the most important issues in AGN study. If the unification scheme holds, the distributions of the BH masses should be identical for the two types of AGNs. Awaki et al. (2006) examined that issue in terms of RMS fractional variability.

2.3. Blazars

X-ray variabilities of blazars were systematically studied by Kataoka et al. (2001). It is found that the shape of the power spectrum densities of blazars is systematically different from that of Seyferts. Power law index of the PSD for blazars ranges from 2 to 3, while that for Seyferts 1 to 2. It may reflect their difference in the emission mechanism from radio quiet AGNs. Application of the scaling relation between stellar black hole candidates and Seyferts, which we assumed, may not be appropriate for the blazars. Instead, physical interpretation of the knee frequency of the power spectrum and size estimation from it are presented in Kataoka et al. (2001).

3. Calibration of BH mass estimation from X-ray Variability

3.1. Stability and canonicality of the normalized power spectrum density

Stability of the NPSD (at high frequency part) of stellar mass BHs was one of the motivation of our using it as a BH scale measure. We now have some data to check the stability of the NPSD of AGNs. We confirm that the NPSD was stable within factor of two for MCG-6-30-15 observed several times with Ginga and ASCA. In the case of 1H0707-495, the NPSD was unchanged regardless of a flux drop of factor of 6 from 1995 to 1998 (see Fig.4). On the contrary, we found inconsistency of nearly one order of magnitude in the NPSD of NGC5548, which might be due to a short data length compared with the variability time scale.

3.2. Various Definitions of the Variability Time Scales

X-ray variability of the AGN can be characterized by various measures. Break frequency of the X-ray power spectrum density (PSD) is one of them, which has been

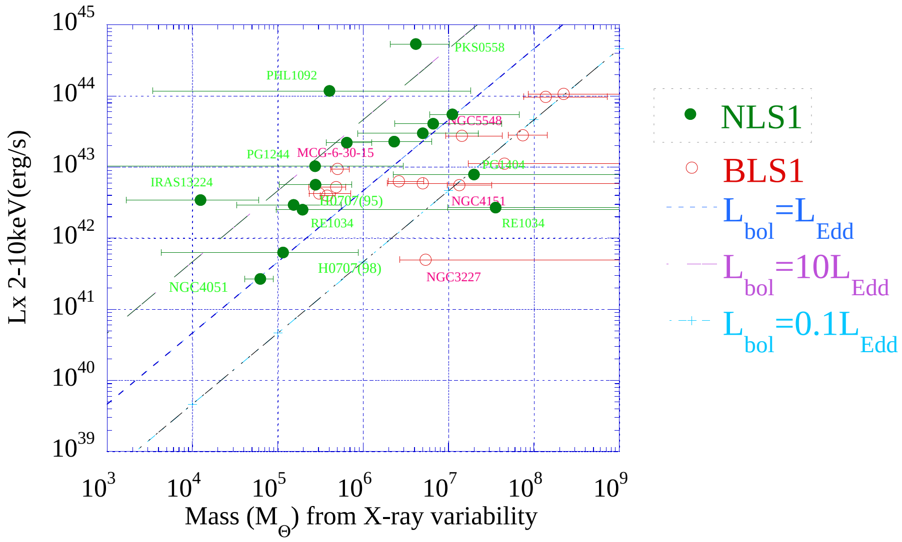

Fig. 2. BH masses Estimated from X-ray Variability. The figure is cited from Hayashida (2000). Closed circles indicate NLS1s, while open circles do BLS1s. Dotted, dashed, dotted-dashed lines indicate 1,10, 0.1 times of the Eddington luminosity, respectively, where bolometric correction of 27.2 is assumed. Cited from Hayashida et al. (2003).

employed by authors. One of the reason why we used the time scale $fP(f) = 1e-3$ (Fig.1) not the break frequency was that the break frequency had been obtained only for a few AGNs. Nevertheless, extensive long term observations of AGNs with RXTE have been providing the PSD break frequencies for more than 10 sources (e.g., Markowitz et al. 2003, Uttley & McHardy 2005). Note that there are two breaks in the PSD of stellar BHs in their hard state, one from f^0 to f^{-1} and the other from f^{-1} to f^{-2}. The break frequency employed in the X-ray variability studies of AGNs corresponds to the latter one.

If the X-ray variability scales to the BH mass, as we assumed, the time scale corresponding to the break frequency should be proportional to that of $fP(f) = 1e-3$. We compare the two scales in Fig.5, showing rough proportionality among them McHardy et al. (2006) indicated that the break frequency gives physical scale (or BH masses) more accurately by considering the accretion rate (or luminosity) as the second parameter. Deviation from the proportionality shown in Fig.5 might be resolved by considering such dependence. Examination of the accretion rate dependence may be one of the important task for the MAXI mission.

On the other hand, fractional rms variability is simply an integration of the NPSD, and can be used as a conventional measure of the X-ray variability. When we establish the NPSD scaling relation, we can reduce it to the scaling relation in the rms variability. In this case, one have to be care about the time bin size to calculate the rms variability.

3.3. Various ways to estimate BH Masses

BH masses in AGNs has been dynamically evaluated from the line width from the broad line region (BLR) either by applying the photo-ionization model or by performing the reverberation mapping. The latter is considered to be more reliable. In Fig. 6, we compare the BH masses from the BLR reverberation mapping summarized in Wandel, Peterson, and Malkan (1999) with those from the X-ray variability for the AGNs both estimates are presented. It is found that the both methods agree within about one order of magnitude. Since Wandel et al. (1999) estimated the systematic error of their BH mass estimation is a factor of a few, the systematic error of our method is at most one order of magnitude.

Recent studies emplying the PSD break frequency with accretion rate (luminosity) dependence taken into account (McHardy et al. 2006) gives tighter relation. This assures that the X-ray variability gives BH mass scales, and implies that the BH accretion physics is very similar for various scales of BHs.

Dynamical masses of BHs in galactic, not only active but also normal, nuclei are estimated by observing the stellar kinematics or gas motion. One of the most accurate estimation was given for NGC4258 as 3.6×10^7 $M_\odot$

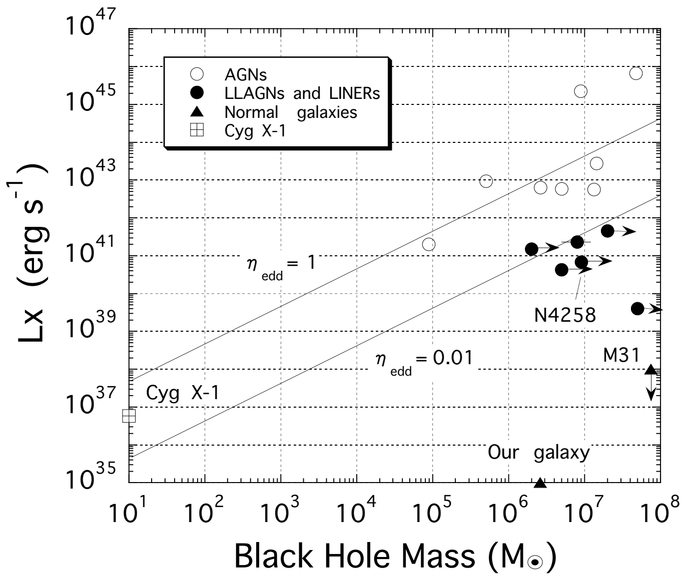

Fig. 3. The Lower limit of the BH Masses in LLAGNs Estimated from X-ray Variability. The lower limit of the BH masses are larger than 10^6 $M_\odot$, indicating those LLAGNs have super massive black hole as large as Seyferts and quasars but emit much lower power than those typical AGNs. The figure is cited from Awaki et al. (2001).

through maser line mapping (Miyoshi et al., 1995), which is now considered to be the most striking evidence for the existence of a SMBH. Observations of stellar kinematics through optical imaging spectroscopy also provide the BH masses in nearby galaxies. The number of such observations have rapidly increased these years, revealing most of them have SMBH at their nuclei. Large number of BH masses also lead to the finding of a interesting correlation between the BH mass and the velocity dispersion of galactic bulge (e.g., Gebhardt et al., 2000, Ferrarese et al., 2000). The correlation is so tight that it will be used to estimate the BH masses from the velocity dispersion of bulge.

There are many ways to estimate the masses of SMBHs in galactic nuclei. Each method has merits and demerits, and its application range is different. It is now important to compare the results each other in order to check their validity. In the future, when the number of SMBHs of which dynamical mass are accurately measured is large enough, empirical methods (BH mass estimation from the X-ray variability or that from bulge velocity dispersion) will be less important. Nevertheless, the study on the X-ray variability or those on BH mass bulge velocity dispersion will still be important to examine the BH accretion physics or the formation of SMBHs in galaxies in turn.

4. Targets of MAXI mission

One of the distinctive features of the MAXI mission is its high sensitivity or low detection limit. It will enable us to obtain daily X-ray fluxes for tens of AGNs. If we adopt the scaling hypothesis on the X-ray variability of AGNs such as we made, the longer time scale variability will extend out work to larger mass AGNs, namely, quasars. X-ray variability data for quasars with time scales longer than days is also important in the sense that there is a possibility to observe a possible break in their power spectrum. For a 10^6 $M_\odot$ BH, the light crossing time for 10 Schwarzshild radius (Rs) is 100s, while that for 10^9 $M_\odot$ BH is 10^5 s, longer than 1 day. The X-ray light curves of quasars obtained with the MAXI mission will first enable us to examine significant reduction of the power corresponding to such a scale.

We also need to check the deviation from simple scaling relation on the BH mass and X-ray variability. As shown by McHardy et al. (2006), the deviation might be explained by accretion rate as the second parameter. If that is the case, examination of the X-ray variability of a single object at different flux state will be a clue to that issue.

We assumed the X-ray variability of AGNs is aperiodic. In fact, there have been only a few reports on the possible detection of the periodicity in AGNs; IRAS18325-5926 (Iwasawa et al., 1998), and Mrk766 (Boller et al., 2001). Nevertheless, the observation span might have been too short for the periodicity to be detected. Whatever the origin of the periodicity is, the time scale must directly tell us the size of some physical processes in the AGNs. We will expect systematic search for the periodicity in X-rays from AGNs with the MAXI

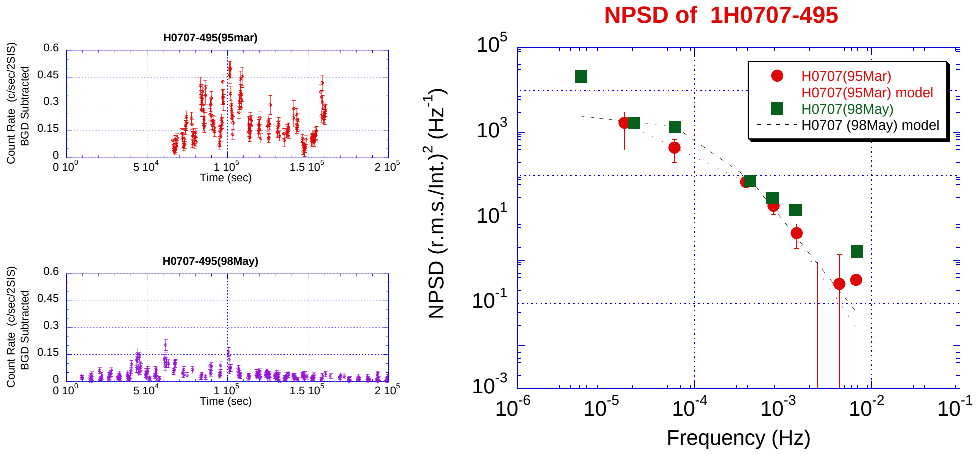

Fig. 4. X-ray Light Curves and NPSDs of 1H0707-495 Observed with ASCA both in 1995 and 1998. The X-ray flux decreased by factor of 6, while the NPSD was almost unchanged. Cited from Hayashida et al. (2003).

mission.

Finally, we would point out another point of long term unbiased X-ray monitoring of AGNs. Most of the AGNs currently observed with X-ray missions are selected from the sample observed in the previous missions or all sky surveys. As mentioned in Horikawa et al. (2003), some of the AGNs, in particular NLS1s, show X-ray variability over one order of magnitude. The number of AGNs of which X-ray flux was observed to decrease by more than one order of magnitude is larger than that of the increasing case. We might have missed to catch AGNs of which X-ray flux increased suddenly, namely bursting phase of the AGN phenomena.

References

Awaki, H., Sakano, M., Terashima, Y. and Hayashida, K. 2001, PASJ, 53, 647

Awaki, H., Murakami, H., Ogawa, Y., Leighly, K., 2006, ApJ, 645, 928

Barr, P., Mushotzky, R.F., 1986, Nature, 320, 421

Boller, Th., Keil, R., Trumper, J., O'Brien, P. T., Reeves, J., Page, M., 2001, A&A, 365, L146

Ferrarese, L., Merritt, D., 2000, ApJ, 539, L9

Gebhardt, K., Bender, R. Bower, G., Dressler, A., Faber, S., Filippenko, A., Green, R., Grillmar, C., Ho, L., Kormendy, J., Iauer, R., Magorrian, J., Pinkney, J., Richston, D., Tremain, S., ApJ, 2000, 539, L13

Hayashida, K., Miyamoto, S., Kitamoto, S., Negoro, H., Inoue, H. 1998, ApJ, 500, 642

Hayashida, K. 2000, New Astron. Reviews, 44, 419

Hayashida, K., Horikawa, T., R. Fujita, H. Awaki, 2003, MAXI Workshop on AGN Variability, 153

Horikawa, T., Hayashida, K., Katayama, H., 2003, MAXI Workshop on AGN Variability, 143

Ishisaki, Y., Makishima, K., Iyomoto, K., Hayashida, K., Inoue, H., Mitsuda, K., Tanaka, Y., Uno, S., Kohmura, Y., Mushotzky, R.F., Petre, R., Selemitsos, P.J., Terashima, Y., 1996, MNRAS, 48, 237

McHardy, I.M., Koerding, E., Knigge, C., Uttley, P., Fender, R.P., Nature, 2006, 444, 730

Mineshige, S., Kawaguchi, T., Takeuchi, M., Hayashida, K., 2000, PASJ, 52, 499

Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., Inoue, M., 1995, Nature, 373, 127

Iwasawa, K., Fabian, A. C., Brandt, W. N., Kunieda, H., Misaki, K., Terashima, Y., Reynolds, C. S., 1998, MNRAS, 295, L20

Iwasawa, K., Fabian, A. C., Almaini, O., Lira, P., Lawrence, A., Hayashida, K., Inoue, H., 2000, MNRAS, 318, 879

Iyomoto, N., Makishima, K., 2001, MNRAS, 321, 767

Kataoka, J., Takahashi, T., Wagner, S.J., Iyomoto, N., Edwards, P.G., Hayashida, K., Inoue, S., Madejski, G.M., Takahara, F., Tanihata, C., Kawai, N., 2001, ApJ, 560, 659

Sunyaev, R. and Revnivtsev, M. 2000, A&A, 358, 617

Uttley, P. and McHardy, I.M., 2005, MNRAS, 363, 586

Vaughan, S., Iwasawa, K., Fabian, A. C., Hayashida, K., 2005, MNRAS, 356, 524

Wandel, A., Mushotzky, R.F., 1986, ApJ, 306, L61

Wandel, A., Peterson, B., and Malkan, M.A., 1999, ApJ, 526, 57

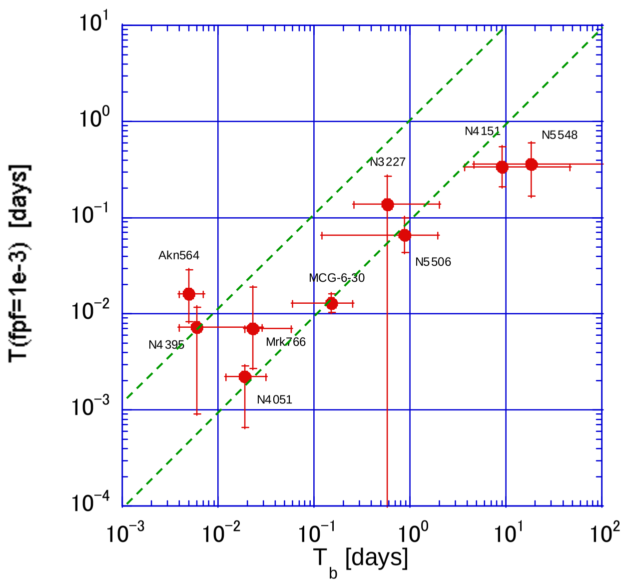

Fig. 5. Comparison of two variability time scales for 9 AGNs. The horizontala axis show the PSD break time scale taken from the compilation by Uttley & McHardy 2005, whereas the vertical axis show our variability time scale based on the $fP(f) = 1e-3$ condition (Hayashida et al. 1998, 2000). The two time scale show rough proportionality, though deviation within one order of magnitude is visible.

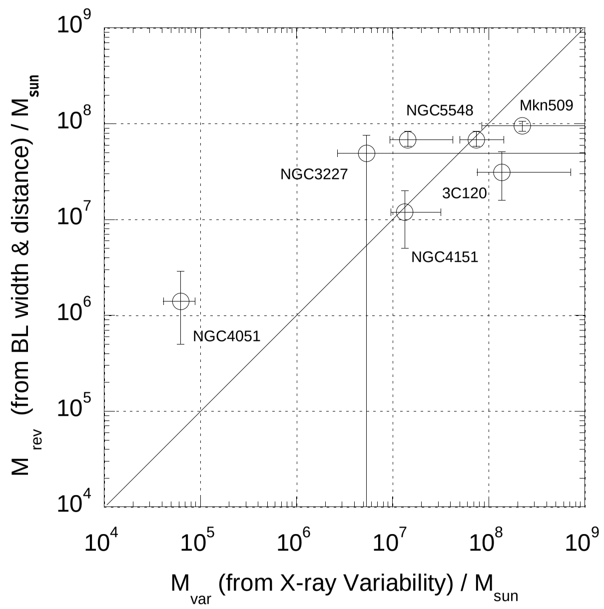

Fig. 6. BH Masses from Reverberation Mapping vs those from X-ray Variability. The masses are in the solar mass unit. The data of reverberation mapping are from Wandel et al. (1999). Agreement within about one order of magnitude indicates the systematic error of BH mass estimation from X-ray variability. Cited from Hayashida et al. (2003)