Revisit the fundamental plane of black-hole activity from sub-Eddington to quiescent state

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ABSTRACT

It is very controversial whether radio–X-ray correlation as defined in low-hard state of X-ray binaries (XRBs) can extend to quiescent state (e.g., X-ray luminosity less than a critical value of \(L_{X,c} \sim 10^{-5.5} L_{\text{Edd}}\)) or not. In this work, we collect a sample of XRBs and low luminosity active galactic nuclei (LLAGNs) with wide distribution of Eddington ratios (\(L_X/L_{\text{Edd}} \sim 10^{-9} - 10^{-3}\)) to reexplore the fundamental plane between 5 GHz radio luminosity, \(L_R\), 2-10 keV X-ray luminosity, \(L_X\), and black hole (BH) mass, \(M_{BH}\), namely \(L_R = \xi_X \log L_X + \xi_M \log M_{BH} + \text{constant}\). For the whole sample, we confirm the fundamental plane of Merloni et al. and Falcke et al. that \(\xi_X \sim 0.6\) and \(\xi_M \sim 0.8\) even after including more quiescent BHs. The quiescent BHs follow the fundamental plane very well, and, however, FR I radio galaxies follow a steeper track comparing other BH sources. After excluding FR Is, we investigate the fundamental plane for BHs in quiescent state with \(L_X < L_{X,c}\) and sub-Eddington BHs with \(L_X > L_{X,c}\) respectively, and both subsamples have a similar slope, \(\xi_X \sim 0.6\), which support that quiescent BHs may behave similar to those in low-hard state. We further select two subsamples of AGNs with BH mass in a narrow range (FR Is with \(M_{BH} = 10^{8.8\pm0.4}\) and other LLAGNs with \(M_{BH} = 10^{8.9\pm0.4}\)) to simulate the behavior of a single supermassive BH evolving from sub-Eddington to quiescent state. We find that the highly sub-Eddington sources with \(L_X/L_{Edd} \sim 10^{-6} - 10^{-9}\) still roughly stay on the extension of radio–X-ray correlation as defined by other sub-Eddington BHs. Our results are consistent with several recent observations in XRBs that the radio–X-ray correlation as defined in low-hard state can extend to highly sub-Eddington quiescent state.

Key words: accretion, accretion discs — black hole physics — ISM:jets and outflows — X-rays: binaries — methods:statistical

1 INTRODUCTION

Accreting black holes (BHs) are widely accepted to be the central engines powering most of emission from X-ray binaries (XRBs) and active galactic nuclei (AGNs), where the BH masses are around 3-20 \(M_\odot\) in XRBs and \(10^2 - 10^9 M_\odot\) in the center of every large galaxy. The putative intermediate BHs (\(10^2 - 10^4 M_\odot\)) are still a matter of debate. XRBs are normally transient sources which display complex spectral and timing features during the outbursts, where three main states include high/soft (HS) state, low/hard (LH) state and intermediate state (or steep power-law state). The HS state is characterized by a strong thermal component and a weak power-law component, while the thermal component is weak and power-law component is dominant in LH state. The intermediate state is normally dominated by a steep power-law component (e.g., see McClintock & Remillard 2006 and Zhang 2013 for recent reviews and references therein). It is much complex in AGNs, where statistical investigations suggest that the different types of AGNs can be unified with several parameters (e.g., orientation and radio loudness, Urry & Padovani 1995). Several works have tried to establish connections between the different states of XRBs and different types of AGNs, where low luminosity AGNs (LLAGNs) are analogs of the XRBs in LH state, RQ quasars are analogs of the XRBs in HS state, while AGNs with relativistic jets may correspond to the XRBs in intermediate state (e.g., Falcke et al. 2004 and Kording et al. 2006a).

The HS state of XRBs and bright AGNs are believed to be powered by a cold, optically thick, geometrically thin standard accretion disc (SSD; Shakura & Sunyaev 1973), that accompanied with some fraction of hot optically thin corona above and below the disc. However, SSD component is normally weak or absent in LH state and most of the radiation comes from the non-thermal power-law component that may come from the hot, optically thin, geometrically thick advection-dominated accretion flows.
(ADAFs, also called radiatively inefficient accretion flows, RI- 
AFs; Ichimaru 1977; Narayan & Yi 1994; Abramowicz et al. 
1995; Wu & Cao 2006 and see Yuan & Narayan 2014 for a re-
cent review and references therein). The anti- and positive correla-
tions between hard X-ray index and Eddington ratio as found in both 
XRBs (e.g., Wu & Gu 2008) and AGNs (e.g., Wang et al. 2004; 
Shemmer et al. 2008; Gu & Cao 2009; Constantin et al. 2009) 
may support the transition of accretion modes (e.g., Cao 2006; 
Qiao & Liu 2013; Cao et al. 2014; Cao & Wang 2015).

The radio and X-ray correlation has long been studied in 
both XRBs and AGNs, which was used to explore the possible 
connection between jet and accretion disc (see also Yuan et al. 
2003; Liu & Wu 2013, for different opinion for the radio emission inqui-
sence with BH in XRBs). The quasi-simultaneous radio and X-
ray fluxes in state of XRBs roughly follow a universal non-
linear correlation ($L_{\text{R}} \propto F_{\text{X}}^\alpha$, $b \sim 0.5 - 0.7$. Hannikainen et al. 
1998; Corbel et al. 2003; Gallo et al. 2003; Corbel et al. 2013). 
Recently, more and more XRBs deviate from the universal correla-
tions (e.g., Xue & Cui 2007; Cadolle Bel et al. 2007; Soelberg et al. 
2010; Jonker et al. 2010; Coriat et al. 2011; Ratti et al. 2012) and 
form a different ‘outliers’ track with a much steeper radio–X-ray 
correlation ($\sim 1.4$ as initially found in H1743−322, Coriat et al. 
2011; Cao et al. 2014). Found that the X-ray spectral evolutions 
are different for the data points in the universal and ‘outliers’ 
tracks, which support that these two tracks may be regulated by radia-
tively inefficient and radiatively efficient accretion discs respec-
tively (see also Coriat et al. 2011; Huang et al. 2014; Qiao & Liu 
2015). It is the similar case in AGNs, where LLAGNs follow a shal-
lower radio-X-ray correlation (e.g., the index $b \sim 0.6$, Wu et al. 
2013) while bright AGNs normally follow a much steeper correla-
tion (e.g., $b \sim 1.6$, Dong et al. 2014; Panessa et al. 2015).

By taking into account the BH mass, the universal radio–X-ray 
correlation of $F_{\text{R}} \propto F_{\text{X}}^{0.6}$ was extended to AGNs, which is called 
“fundamental plane” of BH activity (e.g., Merloni et al. 2003).

$$\log L_{\text{R}} = 0.60^{+0.11}_{-0.11} \log L_{\text{X}} + 0.73^{+0.11}_{-0.05} \log M_{\text{BH}} + 7.33^{+0.07}_{-0.05},$$

(1)

where $L_{\text{R}}$ is 5 GHz nuclear radio luminosity in unit of erg s$^{-1}$, $L_{\text{X}}$ is 2-10 keV nuclear X-ray luminosity in unit of erg s$^{-1}$, and $M_{\text{BH}}$ is the BH mass in unit of M$_{\odot}$. (see also Falcke et al. 2004; Wang et al. 2006; Körding et al. 2006b; Li et al. 2008; Yuan et al. 2009; Gültekin et al. 2009a; Plotkin et al. 2012). This fundamental plane is tight for LH state of XRBs and sub-Eddington AGNs (Körding et al. 2006b). Both ‘outliers’ of XRBs and bright AGNs follow a steeper radio-X-ray correlation and a positive hard X-ray photon index–Eddington ratio correlation ($\Gamma - L_{\text{X}}/L_{\text{Edd}}$), which is most probably regulated by disc-corona model (Dong et al. 2014). Based on these similarities, Dong et al. (2014) proposed a new funda-
mental plane for radiatively efficient BHs, $L_{\text{R}} = 1.59^{+0.25}_{-0.20} \log L_{\text{X}} - 0.29^{+0.19}_{-0.22} \log M_{\text{BH}} - 28.97^{+0.45}_{-0.22},$

(2)

These two universal correlations of Merloni et al. (2003) and 
Dong et al. (2014) with much different slopes of $\alpha_{\text{X}}$ are most 
probably regulated by radiatively inefficient and radiatively efficient BH 
sources respectively.

The nature of BHs in quiescent state remains an open is-

sue. The anti-correlation between hard X-ray photon index and 
Eddington ratio ($\Gamma - L_{\text{X}}/L_{\text{Edd}}$) are found for LH-state of BHs 
with $L_{\text{X}}/L_{\text{Edd}} \lesssim 0.1\%$ (e.g., Wu & Gu 2008). However, this 
anti-correlation as found in LH state does not continue once the 
XRB enters quiescence, where $\Gamma$ keeps roughly a constant when 
$L_{\text{X}}/L_{\text{Edd}} \lesssim 10^{-7}$ (e.g., Plotkin et al. 2013, see also Yang et al. 
2015 for possible evidence in AGNs). The physical reason is still 
unclear, where Yang et al. (2015) proposed that the X-ray emission 
in quiescent state may be dominated by the jet and the value of $\Gamma$ 
should keep as a constant while the X-ray emission dominantly 
come from ADAF in LH state. The spectral energy distribution 
(SED) modeling also preferred the pure jet model for these quies-
cent BHs (e.g., Xie et al. 2014; Plotkin et al. 2015; Yuan & Cui 
2005) explored the universal correlation of $F_{\text{R}} \propto F_{\text{X}}^{\alpha}$ as found in 
LH state of XRBs based on ADAF-jet model and predicted that 
the radio–X-ray correlation will also deviate from that of LH state 
and will become steeper as $F_{\text{R}} \propto F_{\text{X}}^{-2}$ when the X-ray luminosity 
is lower than a critical luminosity ($L_{\text{X},c} \sim 10^{-6} - 10^{-7}L_{\text{Edd}}$), 
where both the radio and X-ray emission should dominantly 
come from the jet. Yuan et al. (2009)’s results seemed to support this pre-
diction based on a small sample of LLAGNs with X-ray luminosity 
roughly below the critical value. However, several quiescent BH 
XRBs seem to challenge this prediction that they still follow the 
radio–X-ray correlation as defined in LH state very well and do 
not evidently deviate even for $L_{\text{X}} < 10^{-9}L_{\text{Edd}}$ (Gallo et al. see 2006; 
2014, for A0620-00 and XTE J1118+480 and see also Calvelo et al. 
2010). Therefore, it is still unclear whether quiescent XRBs follow 
the radio–X-ray correlation as found in LH state of XRBs or not.

In recent years, more and more radio and X-ray observations 
were available for quiescent supermassive BHs in LLAGNs and 
the data also increased for XRBs in quiescent state. In this work, 
we aim to reexplore the radio–X-ray correlation and the funda-
mental plane for BH sources from sub-Eddington down to quies-
cent state by collecting more quiescent BHs. Throughout this 
work, we assume the following cosmology for AGNs: $H_0 = 
70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.27$ and $\Omega_{\Lambda} = 0.73$.

## 2 SAMPLE

For purpose of our work, we select the XRBs and LLAGNs from 
sub-Eddington to quiescent state, where we particularly include 
much more quiescent BHs compared former works. Yuan & Cui 
(2005) predicted that the X-ray emission should be dominated by 
jet and the radio–X-ray correlation will become steeper if the X-
ray luminosity of BH systems is lower than a critical value through 
modeling the radio–X-ray correlation of XRBs in LH state with the 
ADAF-jet model. This critical X-ray luminosity is

$$\log \frac{L_{\text{X},c}}{L_{\text{Edd}}} = -5.356 - 0.17 \log \frac{M_{\text{BH}}}{M_{\odot}},$$

(3)

where the critical Eddington ratio is also roughly consistent with 
the change of hard X-ray spectral evolution from LH to quies-
cent state in XRBs (e.g., $L_{\text{X}} \lesssim 10^{-5.5}L_{\text{Edd}}$, Plotkin et al. 2013). To 
separate the quiescent BHs from our samples, we simply use the 
criteria of equation (3).

For XRBs, we select three sources with fruitful simulta-
neous or quasi-simultaneous and X-ray observations with 
$L_{\text{X}} \lesssim 10^{-3}L_{\text{Edd}}$ in LH state (GX 339-4, Cao et al. 2014, 
XTE J1118+480 and V404 Cyg; Fender et al. 2010 and refer-
ces therein). Some LH-state XRBs that stay in ‘outliers’ track or 
have only few simultaneous observations are neglected. Five 
quiescent XRBs with simultaneous or quasi-simultaneous radio 
and X-ray observations were selected from literatures, which are 
XTE J11752-232 (Ratti et al. 2012, H1743-322 (Coriat et al. 2011), 
XTE J1118+480 (Gallo et al. 2014), A0620-00 and V404 Cyg 
(Fender et al. 2010). The radio luminosity at 5 GHz and X-ray 
luminosity in 2-10 keV band were adopted in our work, where the 
radio emission observed in different waveband is extrapolated to
Table 1. The data of XRBs in quiescent state.

| Name            | $d_L$ (kpc) | $L_X^{2-10keV}$ (log(ergs/s)) | $L_{5GHz}^{R}$ (log(ergs/s)) | $M_{BH}$ ($M_\odot$) | $L_X/L_{Edd}$ | $L_X/L_{R}$ | Ref. |
|-----------------|-------------|-------------------------------|------------------------------|----------------------|---------------|-------------|------|
| XTE J1752-223   | 3.5         | 32.80                         | 27.71                        | 0.99                 | -6.30 -5.52   | 1.2, 1      |
| H1743-322       | 7.5         | 33.00                         | 28.35                        | 1.12                 | -6.23 -5.55   | 3, 4, 4     |
| XTE J1118+480   | 1.7         | 30.52                         | 25.92                        | 0.88                 | -8.47 -5.51   | 6, 7, 7     |
| A0620-00        | 1.2         | 30.30                         | 26.85                        | 0.82                 | -8.63 -5.50   | 6, 8, 9     |
| V404 Cyg        | 7.5         | 31.98                         | 27.97                        | 1.08                 | -7.21 -5.54   | 10, 8, 9    |
| V404 Cyg        | 7.5         | 33.69                         | 28.75                        | 1.08                 | -5.50 -5.54   | 10, 8, 9    |

Note: a The reference for distance, X-ray luminosity, radio luminosity and BH mass respectively, which are shown as follows: 1) Shaposhnikov et al. (2010); 2) Ratti et al. (2012); 3) Jonker et al. (2010); 4) Coriat et al. (2011); 5) Russell et al. (2013); 6) Russell et al. (2006); 7) Fender et al. (2014); 8) Fender et al. (2010); 9) Zhang (2013); 10) Miller-Jones et al. (2009).

Table 2. The data of LLAGNs.

| Name            | $L_X^{2-10keV}$ (log(ergs/s)) | $L_{5GHz}^{R}$ (log(ergs/s)) | $M_{BH}$ ($M_\odot$) | $L_X/L_{Edd}$ | $L_X/L_{R}$ | Ref. |
|-----------------|-------------------------------|------------------------------|----------------------|---------------|-------------|------|
| NGC 266         | 40.88                         | 37.95                        | 8.37                 | 1.2, 2, 3     | -5.60 -6.78 | 1.2, 3, 6 |
| NGC 2768        | 39.46                         | 37.39                        | 7.94                 | 4, 2, 3       | -6.12 -6.71 | 1.2, 3, 6 |
| NGC 3031        | 39.38                         | 36.03                        | 7.73                 | 1.5, 3        | -6.46 -6.67 | 1.2, 3, 6 |
| NGC 3147        | 41.87                         | 37.91                        | 8.29                 | 1.2, 3        | -4.53 -6.77 | 1.2, 3, 6 |
| NGC 3169        | 40.17                         | 37.35                        | 8.10                 | 1.2, 3        | -5.07 -6.72 | 1.2, 3, 6 |
| NGC 3326        | 39.99                         | 37.20                        | 8.06                 | 1.2, 3        | -6.18 -6.73 | 1.2, 3, 6 |
| NGC 3227        | 41.70                         | 37.61                        | 8.13                 | 1.2, 3        | -5.58 -6.77 | 1.2, 3, 6 |
| NGC 3516        | 42.39                         | 37.28                        | 8.42                 | 1.2, 3        | -3.66 -6.71 | 1.2, 3, 6 |
| NGC 3718        | 40.44                         | 36.96                        | 7.69                 | 1.6, 3        | -5.36 -6.66 | 1.2, 3, 6 |
| NGC 3884        | 41.89                         | 37.94                        | 8.19                 | 1.7, 3        | -6.41 -6.75 | 1.2, 3, 6 |
| NGC 3941        | 39.27                         | 36.51                        | 7.37                 | 1.5, 3        | -6.21 -6.61 | 1.2, 3, 6 |
| NGC 3998        | 41.57                         | 38.36                        | 8.89                 | 8.2, 3        | -5.43 -6.87 | 1.2, 3, 6 |
| NGC 4138        | 40.11                         | 36.13                        | 7.19                 | 1.5, 3        | -5.19 -6.58 | 1.2, 3, 6 |
| NGC 4143        | 40.03                         | 37.18                        | 8.16                 | 1.2, 3        | -6.24 -6.74 | 1.2, 3, 6 |
| NGC 4168        | 39.87                         | 36.63                        | 7.97                 | 9.2, 3        | -6.21 -6.71 | 1.2, 3, 6 |

Note: a The reference for distance, X-ray luminosity, radio luminosity and BH mass respectively, which are shown as follows: 1) Shaposhnikov et al. (2010); 2) Nagar et al. (2005); 3) Ho et al. (2009); 4) Boroson et al. (2011); 5) Moore et al. (2011); 6) Miller-Jones et al. (2009).

References for radio luminosity, X-ray luminosity and BH mass: 1) Ho (2009); 2) Nagar et al. (2005); 3) Ho et al. (2009); 4) Boroson et al. (2011); 5) Ho & Ulvestad (2001); 6) Nagar et al. (2002); 7) Filho et al. (2006); 8) Younes et al. (2011); 9) Panessa et al. (2006); 10) Nagar et al. (2002); 11) Ho (2002); 12) Yuan et al. (2009); 13) Pellegrini et al. (2007); 14) Fabbiani et al. (1989); 15) Laurent-Muehleisen et al. (1997); 16) Miller-Jones et al. (2009).

Table 1, where radio and X-ray luminosities for LH state of XRBs can be found in above references.

For supermassive BH sources, we select a sample from a Palomar Survey of nearby galaxies, which is a magnitude-limited spectroscopic study of a nearly complete sample of 486 bright (B_r < 12.5 mag) northern (δ > 0°) galaxies (see Ho et al. (2009)).
Table 3. The data of FR Is.

| Name   | $L_X^{2-10\text{k}V}$ | $L_R^{5\text{GHz}}$ | $M_{\text{BH}}$ |Refs. | $L_X \geq L_{X,c}$ | $L_X \leq L_{X,c}$ | Name   | $L_X^{2-10\text{k}V}$ | $L_R^{5\text{GHz}}$ | $M_{\text{BH}}$ |Refs. |
|--------|-----------------------|--------------------|----------------|------|-------------------|-------------------|--------|-----------------------|--------------------|----------------|------|
| 3C 31  | 40.67                 | 39.45              | 8.70           | 1,1  | -6.14             | -6.84             | 3C 442A| 41.10                 | 38.21              | 8.40          | 1,1,6          |
| 3C 66B | 41.10                 | 39.97              | 8.84           | 1,1  | -5.85             | -6.86             | 3C 449 | 40.35                 | 39.08              | 8.54          | 1,1,2          |
| 3C 76.1| 41.28                 | 39.07              | 8.08           | 1,1  | -4.97             | -6.45             | 3C 465 | 41.04                 | 40.41              | 9.13          | 1,1,2          |
| 3C 83.1B| 41.13                | 39.46              | 9.01           | 1,1  | -5.99             | -6.89             | NGC 315| 41.63                 | 40.41              | 8.89          | 1,1           |
| 3C 84  | 42.91                 | 42.32              | 8.64           | 1,1  | -6.84             | -6.82             | NGC 507| 40.66                 | 37.67              | 8.91          | 1,1           |
| 3C 264 | 41.87                 | 39.98              | 8.61           | 1,5  | -5.04             | -6.85             | NGC 1052| 41.53                 | 39.85              | 8.25          | 1,1           |
| 3C 296 | 41.49                 | 39.68              | 8.80           | 1,1  | -5.34             | -6.85             | NGC 4261| 40.59                | 39.21              | 8.92          | 1,1           |
| 3C 305 | 41.42                 | 39.75              | 8.10           | 1,1  | -4.79             | -6.73             | NGC 6109| 40.35                 | 39.44              | 8.56          | 1,1,2          |
| 3C 338 | 40.31                 | 40.03              | 8.92           | 1,1  | -6.73             | -6.87             | NGC 6251| 41.60                 | 40.35              | 8.97          | 1,1,2          |
| 3C 346 | 43.40                 | 41.83              | 8.89           | 1,1  | -3.60             | -6.87             |         |                       |                    |               |                |

$L_X \geq L_{X,c}$

| Name   | $L_X^{2-10\text{k}V}$ | $L_R^{5\text{GHz}}$ | $M_{\text{BH}}$ |Refs. | $L_X \leq L_{X,c}$ | $L_X \leq L_{X,c}$ | Name   | $L_X^{2-10\text{k}V}$ | $L_R^{5\text{GHz}}$ | $M_{\text{BH}}$ |Refs. |
|--------|-----------------------|--------------------|----------------|------|-------------------|-------------------|--------|-----------------------|--------------------|----------------|------|
| 3C272.1| 39.35                 | 38.22              | 8.80           | 1,1,2| -7.56             | -6.85             | 3C274  | 40.59                 | 39.87              | 9.48          | 1,1,2          |
|        |                       |                    |                |      |                   |                   |         |                       |                    | -7.00         | -6.97          |

Note: $\alpha$ is the radio luminosity is derived from observation of VLBI.

References: 1) Hardcastle et al. (2009); 2) Wu et al. (2011); 3) Woo et al. (2002); 4) Laurent-Muehleisen et al. (1997); 5) Lara et al. (2004); 6) Wu et al. (2013); 7) Ho (2009); 8) Merloni et al. (2003); 9) Ho et al. (2003); 10) Murgia et al. (2011); 11) Fabiano et al. (2009).

1997a,b for more details, and references therein). The nuclear X-ray luminosities and central stellar velocity dispersions for the sources in this survey are further given in Ho (2009) and Ho et al. (2009) respectively, where the sources observed by Chandra and/or XMM – Newton are selected in this work. For our purpose, we exclude the sources with only upper limit of X-ray luminosity and the sources with $L_X > 10^{-3} L_{\text{Edd}}$ which may stay in radiatively efficient phase (e.g., Ho (2008)). The radio core emission of these sources is selected (e.g., Ho & Ulevad 2001). Nagar et al. 2001, 2005; Filho et al. 2006, where most of sources are observed by Very Large Array (VLA, at resolution of ~ 1") or even Very Long Baseline Array (VLBA) at higher resolution and NGC 3884 observed by MERLIN is also selected. The radio fluxes of 7 sources observed by VLA at 15 GHz are converted to 5 GHz by assuming $F_\nu \propto \nu^{-0.5}$ ($\alpha = 0.5$ is adopted, e.g., Ho & Peng 2001, Ho 2002). The fifteen putative Compton-thick sources are also neglected (NGC 1068, NGC 676, NGC 1167, NGC 1667, NGC 2273, NGC 3185, NGC 3489, NGC 3982, NGC 5194, NGC 7743, Panessa et al. 2006, Mrk 3, NGC 4945, NGC 7479, Georganopoulos et al. 2011) and NGC 2655, NGC 2639 (Terashima et al., 2005), since that the X-ray and other band emission may be seriously obscured. The BH mass of selected sources is calculated from the $M_{\text{BH}} - \sigma$ relation of Gilletkin et al. (2009). $\log \frac{M_{\text{BH}}}{M_\odot} = (8.12 \pm 0.08) + (4.24 \pm 0.41) \log \sigma_{200} \text{km/s}^{-1}$ (4)

In this work. The BH mass are also calculated from their central stellar velocity dispersions (Ho 2009, Wu et al. 2011). In total, we select 52 LLAGNs without evident relativistic large-scale jets (22 sources have $L_X < L_{X,c}$) and 21 FR Is with strong jets (2 sources have $L_X < L_{X,c}$), which are listed in Tables (2) and (3) respectively, where the X-ray luminosity, radio luminosity and BH mass for each selected source are reported.

3 METHOD AND RESULT

To explore the fundamental plane for the sub-Eddington and quiescent BHs, we take the form of $\log L_R = \xi X \log L_X + \xi M \log M_{\text{BH}} + c_0$ as in Merloni et al. (2003), where $L_R$ is 5 GHz radio luminosity, $L_X$ is 2-10 keV X-ray luminosity. To find the multi-parameter relation, we adopt a similar approach as that of Merloni et al. (2003) and minimize the following statistic, $X^2 = \sum_i \left( \frac{y_i - c_0 - \xi X_i - \xi M_i}{\sigma^{2}_{R}} + \xi^{2}_{X} + \xi^{2}_{M} \right)$, (5)

where $y_i = \log L_R$, $X_i = \log L_X$, $M_i = \log M_{\text{BH}}$ and $c_0$ is a constant. Instead of assuming the isotropic uncertainties with $\sigma_{L_R} = \sigma_{L_X} = \sigma_{M}$ as in Merloni et al. (2003), we adopt the typical observational uncertainties $\sigma_{L_R} = 0.2$ dex (e.g., Ho & Peng 2001), $\sigma_{L_X} = 0.3$ dex (e.g., Strateva et al. 2005), and $\sigma_{M} = 0.4$ dex (e.g., Vestergaard & Peterson 2006) for AGNs and the typical variations (within one day) $\sigma_{L_R}$, $\sigma_{L_X}$, $\sigma_{M}$ are 0.1 dex ($e.g.,$ Coriat et al. 2011, Corbel et al. 2013), and typical uncertainty of BH mass $\sigma_{M}$ is 0.15 dex (e.g., Zhan et al. 2013) for XRBs.

In top-left panel of Figure 1, we present the fundamental plane for all selected BH sources from sub-Eddington to quiescent state. The best fit for the whole sample is $\log L_R = 0.55^{+0.19}_{-0.17} \log L_X + 0.80^{+0.12}_{-0.13} \log M_{\text{BH}} + 9.17^{+0.34}_{-0.34}$ (6) with an intrinsic scatter of $\sigma_{M}$ = 0.36 dex. From this panel, we find (1) the quiescent BHs still roughly follow the correlation as defined by the whole sample and do not show evident deviation; (2) the FR Is seem to follow a steeper track comparing with other
Exclude FR Is

The fundamental plane for the BH activities, where the empty and solid points represent the sources with \( L_X < L_{X,c} \) and \( L_X > L_{X,c} \) respectively. Top-left panel represent the plane for all BH sources as selected in our sample; Top-right panel represent the plane for BH sources after excluding FR Is; Bottom panels represent the plane for BHs (exclude FR Is) with \( L_X > L_{X,c} \) (left) and \( L_X < L_{X,c} \) (right) respectively. The solid lines are the best fittings.

sources. After excluding the FR Is from the whole sample, we present the fundamental plane for other sources in top-right panel of Figure 1 and the best fit is

\[
\log L_R = 0.52^{+0.23}_{-0.19} \log L_X + 0.73^{+0.18}_{-0.13} \log M_{BH} + 9.97^{+0.31}_{-0.30},
\]

with an intrinsic \( \sigma_{\text{int}} = 0.20 \) dex. It can be found that the fundamental plane becomes a little bit tighter after removing FR I sources, even the slope of \( \xi_X \) is roughly unchanged.

We further divide the sample (excluding FR Is) into two sub-samples with \( L_X > L_{X,c} \) (sub-Eddington sources) and \( L_X < L_{X,c} \) (quiescent sources) respectively, where the fundamental planes are shown in bottom-left and bottom-right panels of Figure 1 respectively. The best fit for sources with \( L_X > L_{X,c} \) is

\[
\log L_R = 0.53^{+0.23}_{-0.19} \log L_X + 0.71^{+0.20}_{-0.16} \log M_{BH} + 10.36^{+0.29}_{-0.28},
\]

with an intrinsic \( \sigma_{\text{int}} = 0.16 \) dex. The best fit for sources with \( L_X < L_{X,c} \) is

\[
\log L_R = 0.55^{+0.17}_{-0.13} \log L_X + 0.77^{+0.14}_{-0.12} \log M_{BH} + 9.17^{+0.44}_{-0.42},
\]

with an intrinsic \( \sigma_{\text{int}} = 0.27 \) dex.

To investigate the radio–X-ray correlation and eliminate the mass effect in AGNs, we further select sources with BH mass in a narrow range but with a broad range of Eddington ratios, which can be used to simulate a single supermassive BH evolving from LH state to quiescent state in a statistical manner. Due to the evident differences in the slope of radio-X-ray correlation for FR Is and other LLAGNs, we explore this issue for these two populations separately (their BH mass distributions are also much different). We select 28 LLAGNs from Table (1), which have BH mass \( M_{BH} = 10^{8.4} M_\odot \) and Eddington ratios of \( L_{2-10keV}/L_{Edd} \sim 10^{-8.8} \) to \( 10^{-3} \). The result is shown in Figure 2, where the faintest sources with \( L_X \lesssim L_{X,c} \) (solid circles) roughly follow the trend of other sub-Eddington sources. The best-fit linear regression for all sources yields

\[
\log L_R = 0.49 \pm 0.04 \log L_X + 17.53 \pm 1.64, \tag{10}
\]

with a Spearman correlation coefficient of \( r = 0.75 \) and \( p = 2.41 \times 10^{-11} \), where the linear regressions were not given for sources with \( L_X > L_{X,c} \) and \( L_X \lesssim L_{X,c} \) respectively due to the narrow range and large scatter of the data in each population. A
The radio–X-ray correlation plays an important role in understanding the physics of BH central engines, which was widely explored in XRBs and AGNs. It is roughly consensus that faint BHs with \( L_{\text{bol}}/L_{\text{Edd}} \lesssim 1\% \) follow a shallower radio–X-ray correlation with \( \xi_X \gtrsim 0.5 - 0.7 \) (e.g., Corbel et al. 2003; Gallo et al. 2003; Corbel et al. 2013) while brighter BHs with \( L_{\text{bol}}/L_{\text{Edd}} \gtrsim 1\% \) follow a steeper track with \( \xi_X \sim 1.2 - 1.6 \) (e.g., Coriat et al. 2013). However, it is still debatable whether the quiescent BHs still follow the radio–X-ray correlation with \( \xi_X \sim 0.5 - 0.7 \) as defined in LH state of XRBs or not. Yuan et al. (2009) found the LLAGNs with \( L_X \lesssim L_{X,c} \) follow a steeper radio–X-ray correlation (e.g., \( L_R \propto L_X^{2.5} \)), which is roughly consistent with their model prediction in Yuan & Cui (2005) where the X-ray emission switches from being ADAF to jet dominated. However, several quiescent XRBs challenge this conclusion where the sources with \( L_X \lesssim 10^{-8.5} L_{\text{Edd}} \) still follow the radio–X-ray correlation as defined by LH state of XRBs very well (e.g., A0620-00, Gallo et al. 2006 and XTE J1118+480, Gallo et al. 2014). We further explore this issue using a large sample of BHs from highly sub-Eddington to sub-Eddington. We don’t find that the quiescent BHs with \( L_X < L_{X,c} \) are different from other sub-Eddington BHs based on the analysis of the radio–X-ray correlation and the fundamental plane. In particular, we also use two subsamples with similar BH mass (FR Is with \( M_{\text{BH}} = 10^{6.8\pm0.4} \) and other LLAGNs with \( M_{\text{BH}} = 10^{8.0\pm0.4} \)) to simulate the behavior of a single supermassive BH evolving across from sub-Eddington to quiescent state (e.g., LLAGNs with \( L_X \sim 10^{-9} \) to \( 10^{-3} L_{\text{Edd}} \) and FR Is have \( L_X \sim 10^{-7.6} \) to \( 10^{-3.6} L_{\text{Edd}} \)). The quiescent BHs still roughly follow that defined by the whole sample. Our results are consistent with that of XRBs (Gallo et al. 2006, 2014) but is different from that derived from AGNs (Yuan et al. 2009). The possible reason is that BH sources observed with large-scale relativistic jets (e.g., FR Is) are included in Yuan et al. (2009)’s sample, where RL AGNs normally follow a much steeper radio–X-ray correlation regardless of Eddington ratios (see also \( L_R \propto L_X^2 \), Li et al. 2008, de Gasperin et al. 2011 or FR Is sample in this work). The bimodal distribution of radio loudness in AGNs is still an open issue. From the slope of radio–X-ray correlation, we can find that the normal LLAGNs may be similar to LH state of XRBs while RL FR Is with relativistic jets may be intrinsically different. However, it should be noted that the intrinsic correlation may be different comparing with the observed radio–X-ray in RL AGNs, where the Doppler boosting effect is not considered in our work (also Li et al. 2008, Yuan et al. 2009).
Black-hole fundamental plane from sub-Eddington to quiescent state

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