The Broad-line Region of Mrk 79 as a Disk Wind

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Background

- The blueshift of the C IV is found to be nearly ubiquitous in radio-quiet (RQ) AGNs (Richards+11)

- Ultra-Fast Outflows (i.e., highly ionised absorbers) have been detected in ~20 AGNs (based on X-ray spectrum between 7 and 10 keV) (e.g, Tombesi+11, 12)
  ---Mrk 79 is one of the AGN with UFOs, UFOs velocity of 0.092*c* (*c* is light speed) (Tombesi+11)

- ~20 AGNs have constructed the kinematic information of the BLR, but the outflowing BLR just exists in ~3/20 AGNs before this work (based on reverberation mapping)
  Mrk 142 (Du+16), NGC 3227 (Denny+2009), NGC 4151 (Brotherton's talk)

- Mrk 79 has been monitored by 3-season reverberation mapping (RM) campaigns (Peterson+98, 04)
  ---No Kinematic information of the BLR

Q1: What is the kinematics of the BLR in Mrk 79?
Q2: What is the origin of the outflowing BLR?
Q3: What is the connection between the BLR and disk wind?

To investigate these questions, we developed a reverberation campaign to **monitor the AGNs with UFOs**.

Observation and data reduction(1)

1. Lijiang 2.4 m telescope (LTJ) of Lijiang observatory

---Administered by YNAO

---Coordinates: N: 26:41:42 E: 100:01:48

---Altitude: 3200 m

---Averaged seeing: ~ 1.2 arcsec (observation station)

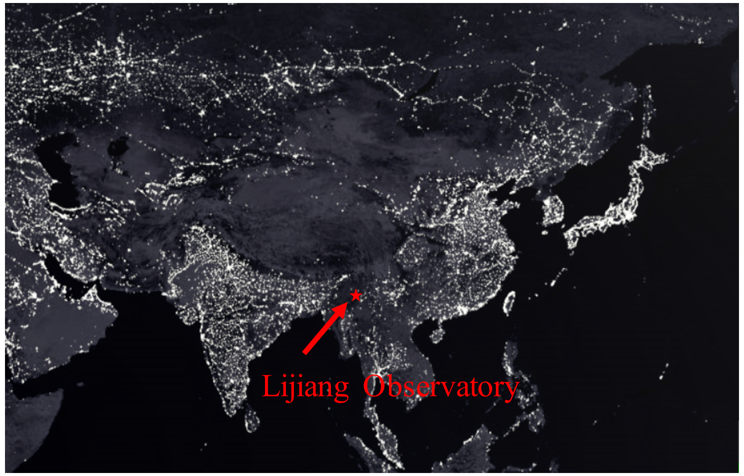
---The best seeing: ~ 0.6 arcsec

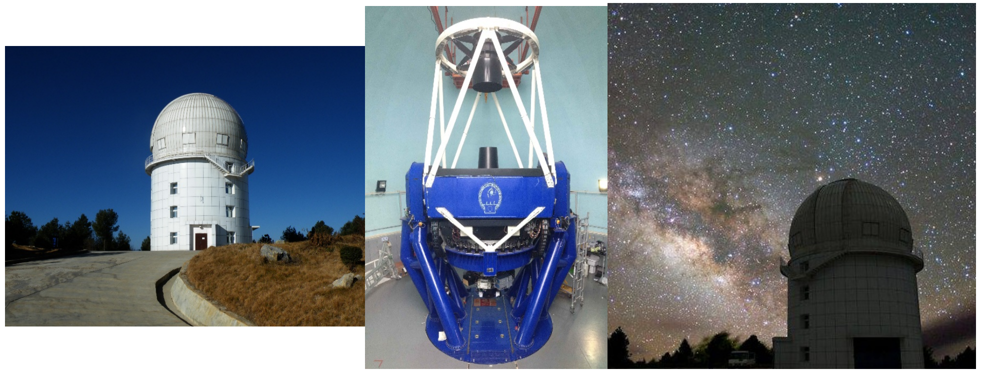
---Observational season: ~Oct. to ~Jul.

---Available nights : ~230 days / 2000 hrs

---Sky background: V = 21.54 mag

B = 22.34 mag





clear sky, no pollution of light

Observation and data reduction(2)

2. Spectroscopy:

Mrk 79: 2017.11.01 to 2018.03.13, period=132 days

---Mrk 79 and comparison star are observed in long-slit simultaneously (Maoz+90; Kaspi+00; Du+14)

slit=2.5", resolution=1.8 angstrom/pixel

---72 samples: median and mean cadence are **1.0 and 1.8 days**

---S/N: >35

---Median air mass: 1.15

3. Photometry

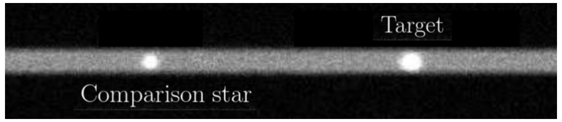
---Johnson *V* band (FOV=10"x10")

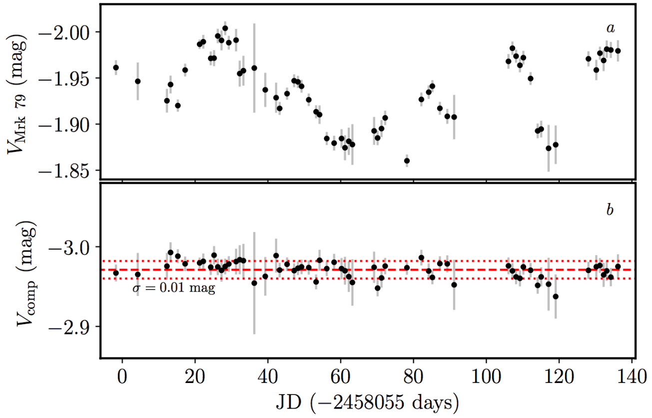
---62 samples

---90s for each individual observation

4. Data reduction

---Data are reduced using the standard IRAF(v2.16) package:





The comparison star is stable enough to be used for the flux calibration of the spectra.

Spectral calibration and measurements(1)

1. Flux calibration: See Maoz+90; Kaspi+00; Du+14; Du+18
The observed spectra are corrected by comparison star
(Kaspi and Hu's talk) More details later

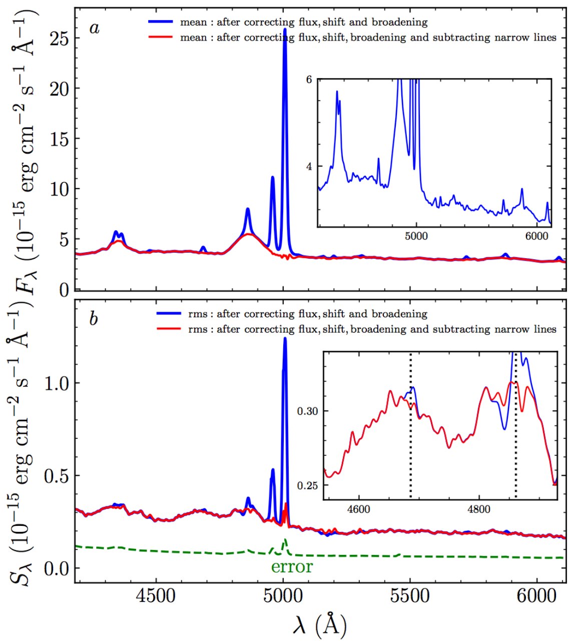
2. Mean and RMS spectrum:

- Flux-calibration spectra are processed by correcting Galactic extinction, wavelength shift, broadening → processed spectrum

- Calculated mean and rms spectrum from processed spectra (see blue traces)

---[O III] should not vary on BLR reverberation timescales

W1: Why does [O III] remain in the rms spectrum?



Spectral calibration and measurements(2)

3. Spectral fitting scheme (SFS):

- blended emission lines
- contamination of strong host galaxy

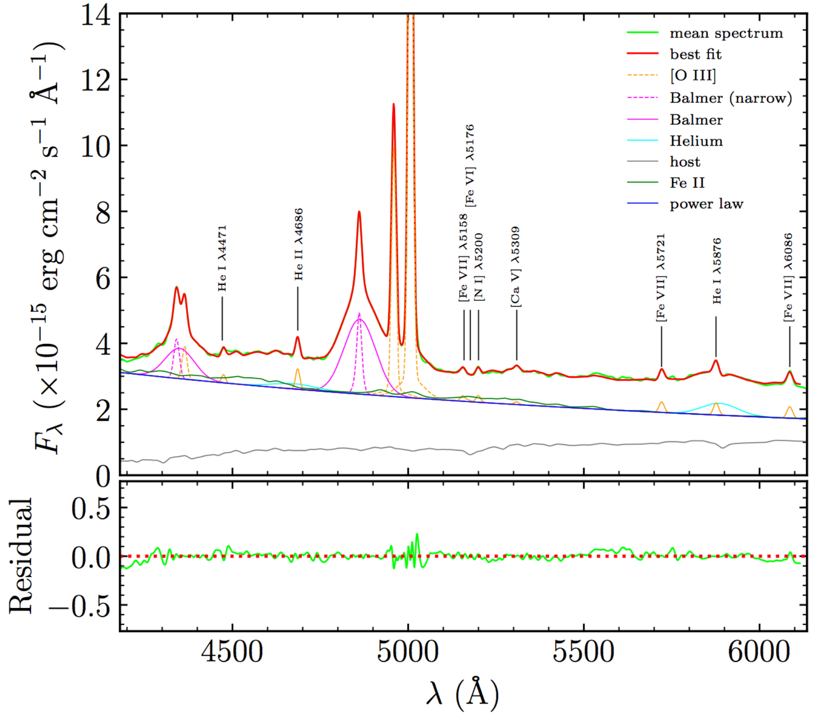
Templates: Bruzual & Charlor (2003); Boroson & Green (1992)

4. Generating light curves:

- We generated next light curve from the best-fit components:

continuum at 5100 angstrom (F_{AGN});
broad emission lines (Balmer & He);
[O III] λ5007;
host galaxy.

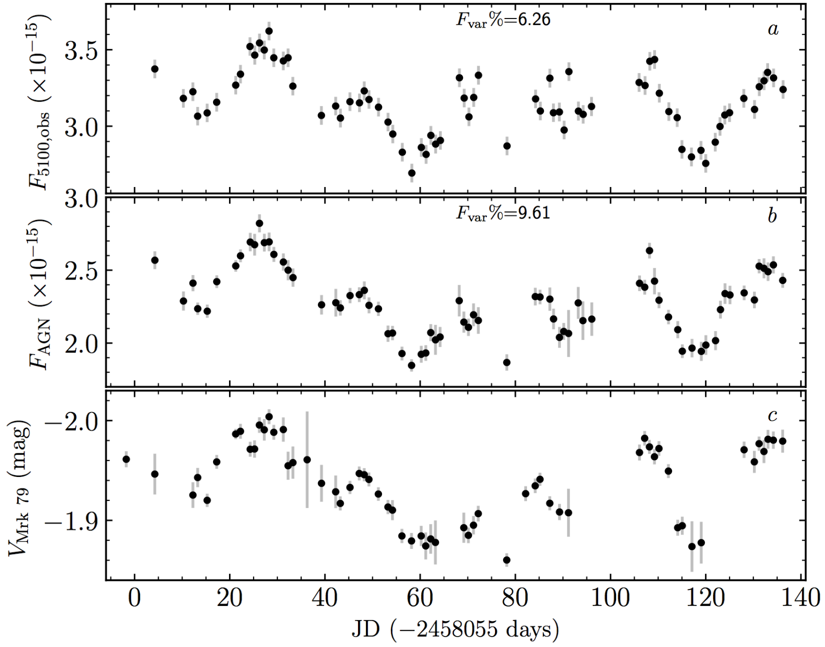
We also generated the light curve of continuum from the processed spectra ($F_{5100,obs}$)



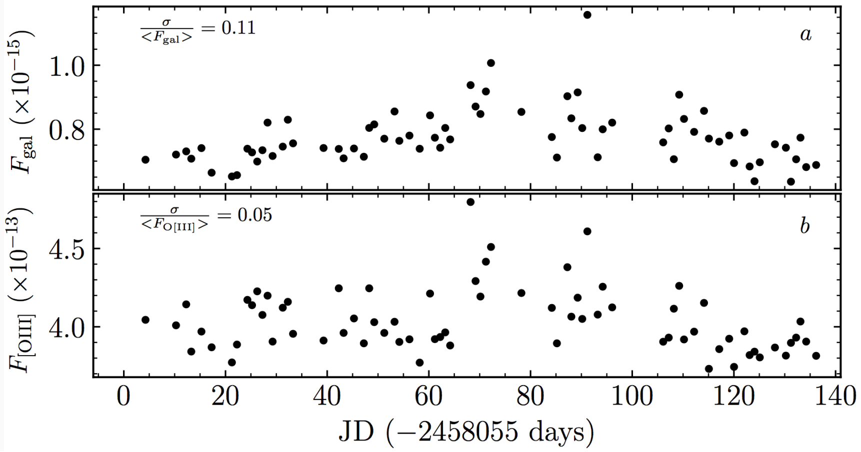
Fitting procedure is similar to Hu et al. 2015

Light curves(1)

Light curves measured from the spectra are consistent with photometry



F_{AGN} : the featureless power law
$F_{5100,\mathrm{obs}}$: contaminated by host galaxy

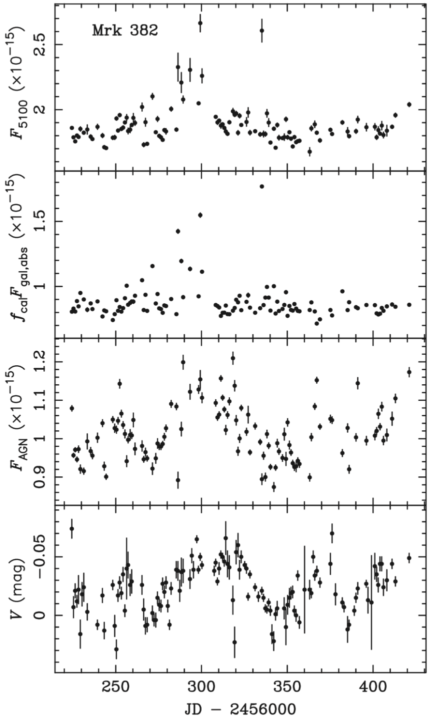


➢ F_{AGN} and $F_{5100,\mathrm{obs}}$ are consistent with the differential magnitudes
→**Stable star can provide precision flux calibration**

Light curves(1)

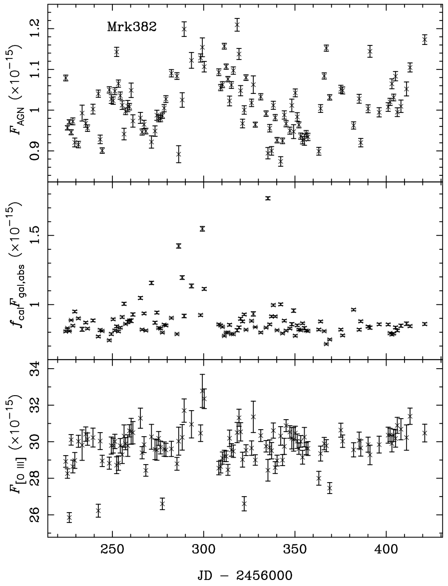
SUPERMASSIVE BLACK HOLES WITH HIGH ACCRETION RATES IN ACTIVE GALACTIC NUCLEI. III. DETECTION OF Fe II REVERBERATION IN NINE NARROW-LINE SEYFERT 1 GALAXIES

CHEN HU[1], PU DU[1], KAI-XING LU[1,2], YAN-RONG LI[1], FANG WANG[6], JIE QIU[1], JIN-MING BAI[6], SHAI KASPI[7], LUIS C. HO[4,5], HAGAI NETZER[7], AND JIAN-MIN WANG[1,3,8]
(SEAMBH COLLABORATION)



In fact, similar phenomena are found in Mrk 382

Details referee to Hu et al. (2015)

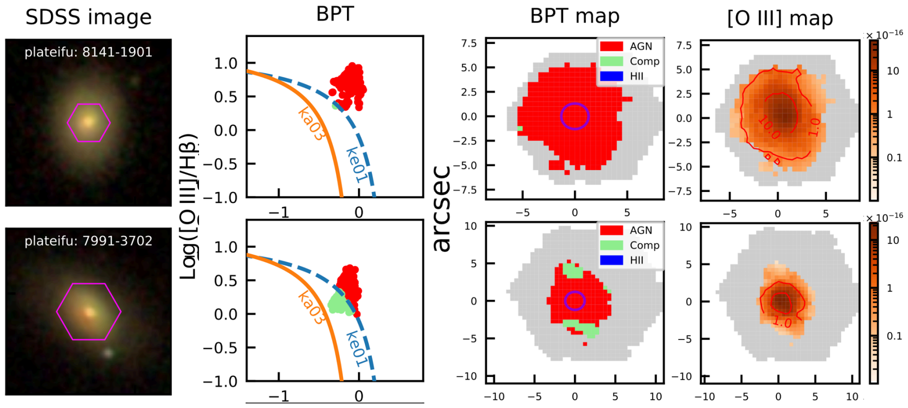


W2: Why is the [O III]'s light curve similar to the host-galaxy light curve?

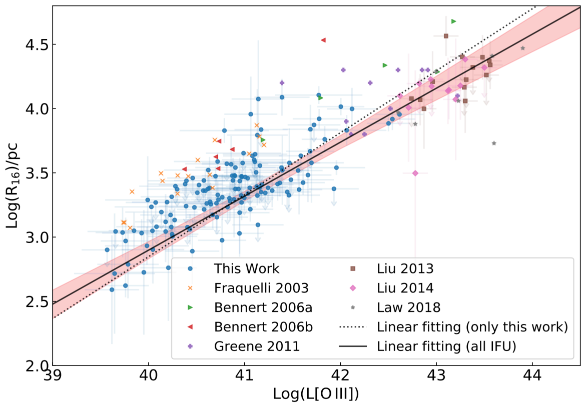
W3: Why is the scatter of the [O III]'s light curve 5%?

Light curves(2)

The nature of [O III]-emission region: Extended Narrow-line region (ENLR)



Chen Jian-hang , et al. MNRAS, 2019



Chen et al. 2019, MNRAS

$$R_{\rm NLR} - L_{\rm [O\ III]} : \log(\frac{R_{\rm NLR}}{\rm pc}) = (0.42 \pm 0.02)\log(\frac{L_{\rm [O\ III]}}{\rm erg\ s^{-1}}) - (14.10 \pm 0.92).$$

$$\textbf{For Mrk 79}: \quad \log(\frac{L_{\rm [O\ III]}}{\rm erg\ s^{-1}}) = 41.65, \quad ==> \ R_{\rm NLR} = 2.35\ {\rm Kpc},$$

$$\textbf{So}: \ R''_{\rm NLR} = \frac{R_{\rm NLR}\ ({\rm Kpc})}{{\rm Distance}\ ({\rm Kpc})} \times \frac{1}{3.14} \times (180 \times 60 \times 60)'' = 5.20'' > 2.5''.$$

Also see:

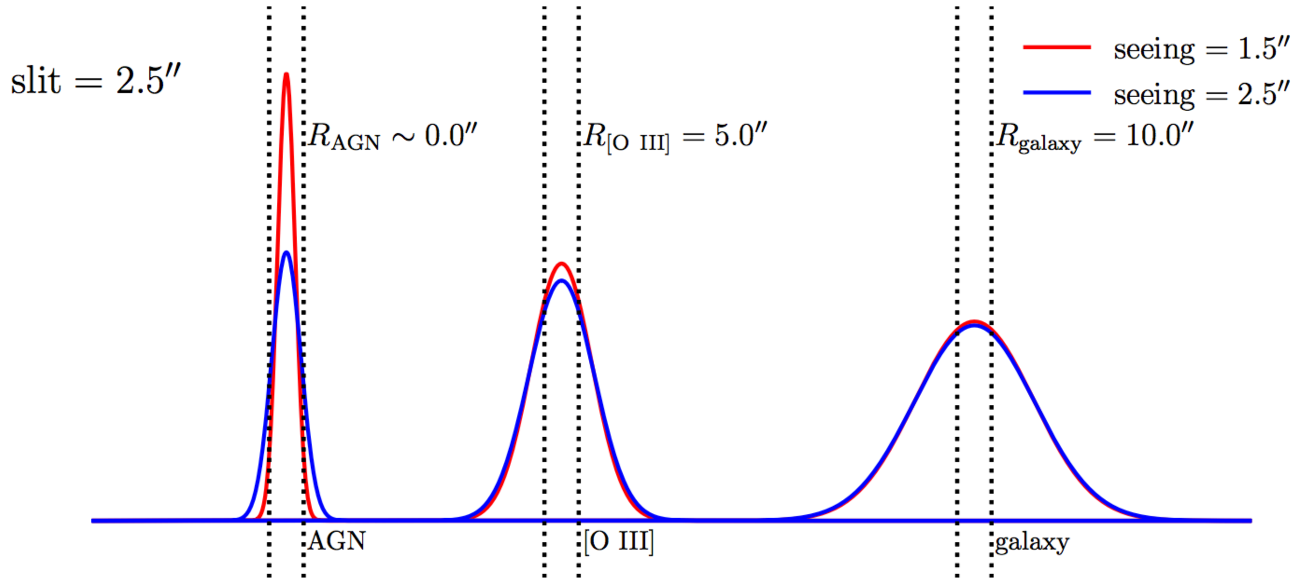
Husemann et al. 2019, ApJ, 879:75

Hainline et al. 2014, ApJ, 787:65

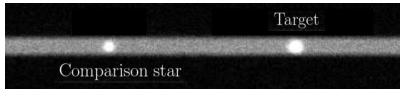
Schmitt et al. 2003, ApJ, 597:768

Bennert et al. 2002, ApJ, 574:L105

Light curves(3) Insight into the details of the spectroscopic observation and flux calibration



Schematic diagram

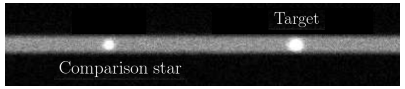


➢ The fractions of light loss are dependent on the **size of the object** in the slit and **seeing**

---Seeing could change from one exposure to the next, and can be measured from the photometric image (i.e., FWHM)

Light curves(3)

Insight into the details of flux calibration



ψ^* represent the percentage of flux remaining in the aperture

$F^*_{\rm abs}$ represent the absolute flux

The observed flux of the comparison star

$$F^{\rm star}_{\rm obs} = \psi^{\rm star} \times F^{\rm star}_{\rm abs}, \qquad (1)$$

the AGN

$$F^{\rm AGN}_{\rm obs} = \psi^{\rm AGN} \times F^{\rm AGN}_{\rm abs}, \qquad (2)$$

the extended NLR

$$F^{\rm [O\ III]}_{\rm obs} = \psi^{\rm [O\ III]} \times F^{\rm [O\ III]}_{\rm abs}, \qquad (3)$$

and the host galaxy

$$F^{\rm gal}_{\rm obs} = \psi^{\rm gal} \times F^{\rm gal}_{\rm abs}. \qquad (4)$$

The calibrated flux

$$F^*_{\rm cal} = F^*_{\rm obs} \times \frac{F^{\rm star}_{\rm abs}}{F^{\rm star}_{\rm obs}} = \frac{1}{\psi^{\rm star}} \times F^*_{\rm obs}, \qquad (5)$$

The calibrated flux of the AGN

$$F^{\rm AGN}_{\rm cal} = \frac{1}{\psi^{\rm star}} \times F^{\rm AGN}_{\rm obs} = \frac{\psi^{\rm AGN}}{\psi^{\rm star}} \times F^{\rm AGN}_{\rm abs} = f^{\rm AGN}_{\rm cal} \times F^{\rm AGN}_{\rm abs}, \qquad (6)$$

the extended NLR

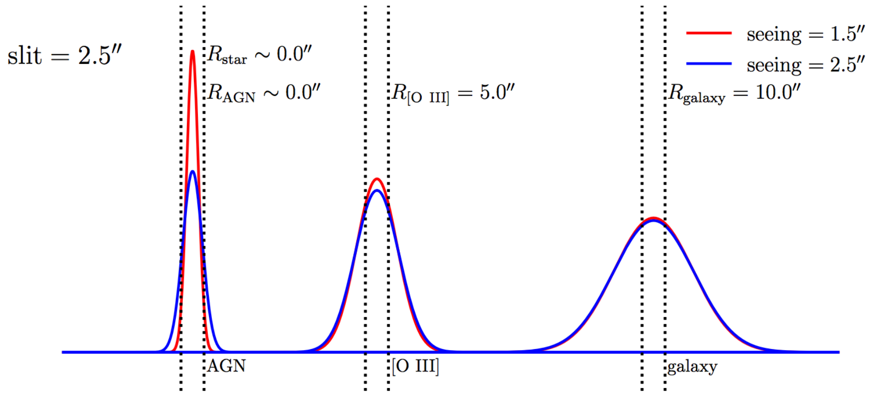
$$F^{\rm [O\ III]}_{\rm cal} = \frac{1}{\psi^{\rm star}} \times F^{\rm [O\ III]}_{\rm obs} = \frac{\psi^{\rm [O\ III]}}{\psi^{\rm star}} \times F^{\rm [O\ III]}_{\rm abs} = f^{\rm [O\ III]}_{\rm cal} \times F^{\rm [O\ III]}_{\rm abs}, \qquad (7)$$

and the host galaxy

$$F^{\rm gal}_{\rm cal} = \frac{1}{\psi^{\rm star}} \times F^{\rm gal}_{\rm obs} = \frac{\psi^{\rm gal}}{\psi^{\rm star}} \times F^{\rm gal}_{\rm abs} = f^{\rm gal}_{\rm cal} \times F^{\rm gal}_{\rm abs}. \qquad (8)$$

Light curves(3)

Insight into the details of flux calibration



For Mrk 79, the radii of different components including the AGN, the extended NLR, and the host galaxy meet

$$R_{AGN} < R_{ENLR}(\sim 5'') < R_{gal}(> 10'') \qquad (9)$$

relation. When FWHM increases, the percentages of flux remaining in the aperture meet

$$\psi^{AGN} = \psi^{star} < \psi^{[OIII]} < \psi^{gal} \qquad (10)$$

relation, The result is that the flux-calibration factors meet

$$1 = f_{cal}^{AGN} < f_{cal}^{[O\ III]} < f_{cal}^{gal} \qquad (11)$$

relation.

- Two point sources kept in a line parallel to the slit, the fractions of light loss due to varying FWHM are identical
- The extended component in the same slit, the fractions of light loss due to varying FWHM are much less than point source

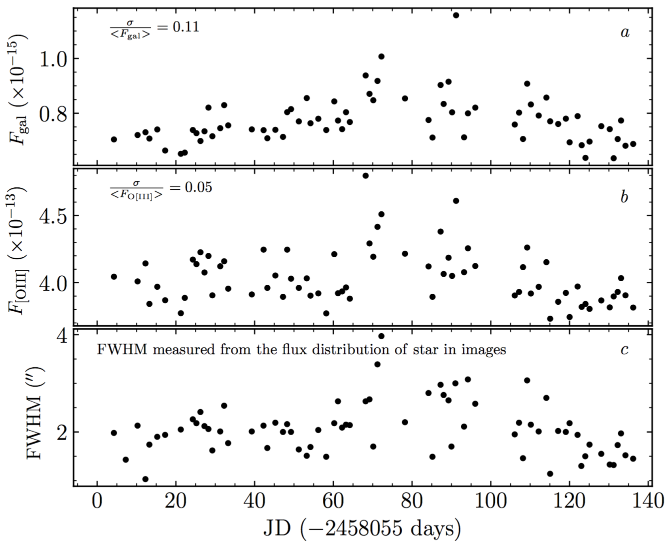
→The calibrated flux of the extended component should correlate with the FWHM

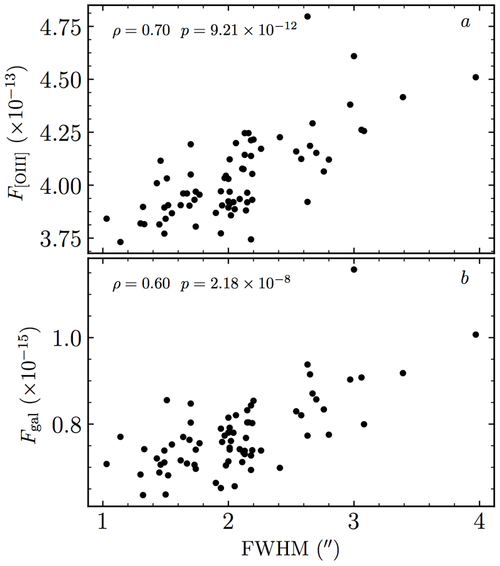
→The host-galaxy light curve should be more scatter than [O III]'s light curve

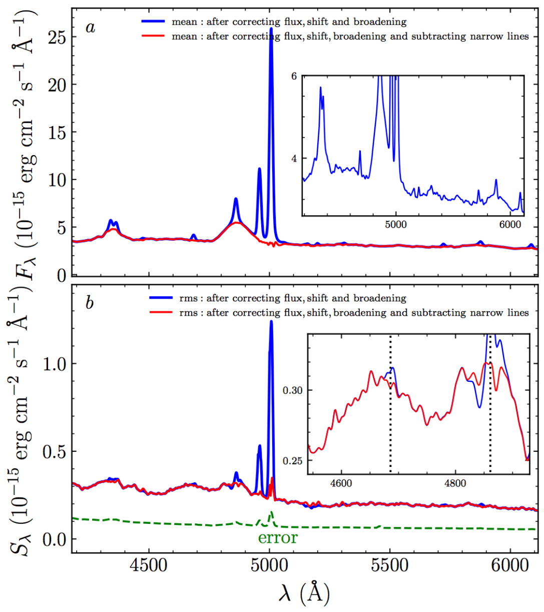
Light curves(4)

Relation between the flux of extended component and the FWHM

The FWHM is the width of flux distribution of star in the image







→For a narrow slit, varying observing condition will give rise to the scatter of [O III]'s flux and [O III] remains in the rms spectrum.

W1 W2 W3

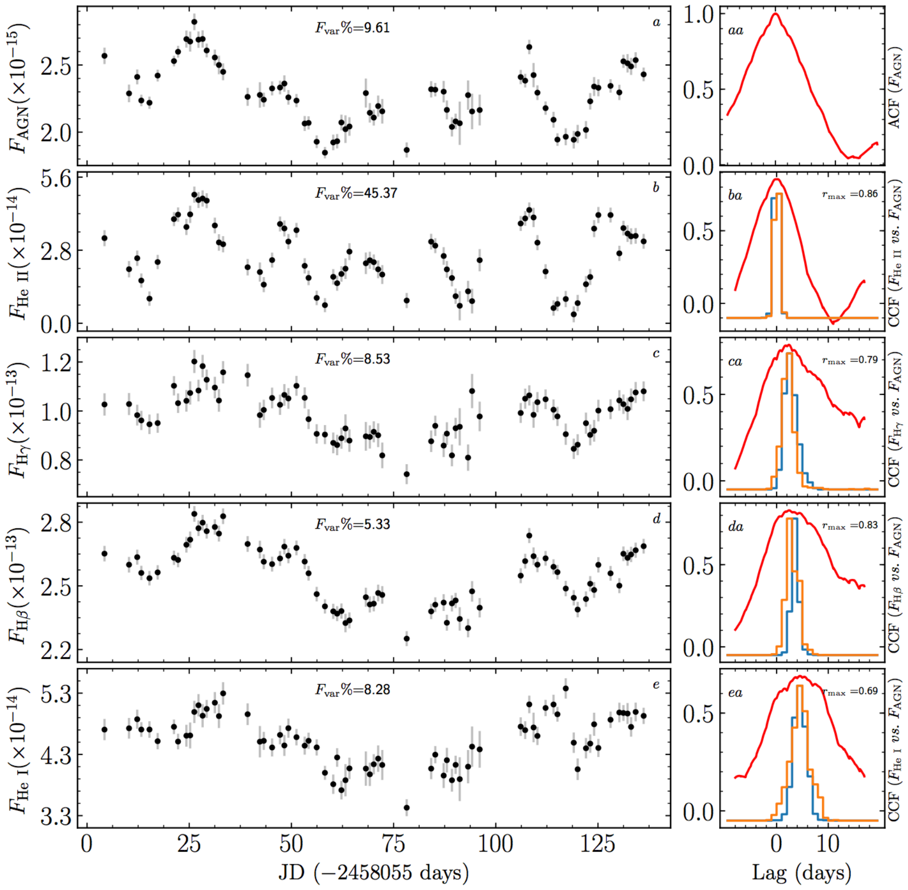
Time series analysis(1)

1. **BLR size**

---the light curves are measured from the best-fit model

---Standard interpolation cross-correlation function (ICCF) are employed to measure reverberation lags

	Line vs. $F_{\rm AGN}$		
Lines	$\tau_{\rm cent}$	$\tau_{\rm peak}$	$r_{\rm max}$
(1)	(2)	(3)	(4)
Hγ	$2.43^{+1.55}_{0.88}$	$2.32^{+1.00}_{-1.17}$	0.79
He II	$-0.05^{+0.50}_{-0.40}$	$0.21^{+0.28}_{-0.77}$	0.86
Hβ	$3.49^{+0.62}_{-0.60}$	$2.36^{+2.03}_{-0.49}$	0.83
He I	$4.39^{+1.26}_{-1.12}$	$4.43^{+1.73}_{-1.80}$	0.69



Time series analysis(2)

2. Velocity-resolved lag profile (VRLP)

- Calculated rms spectrum of these broad lines
- Selected a wavelength range, divided the rms profiles into nine uniformly spaced bins
- Obtained velocity-dependent light curves by integrating the fluxes in the bin
- Calculated velocity-dependent time lags

→ BLR kinematics of Mrk 79

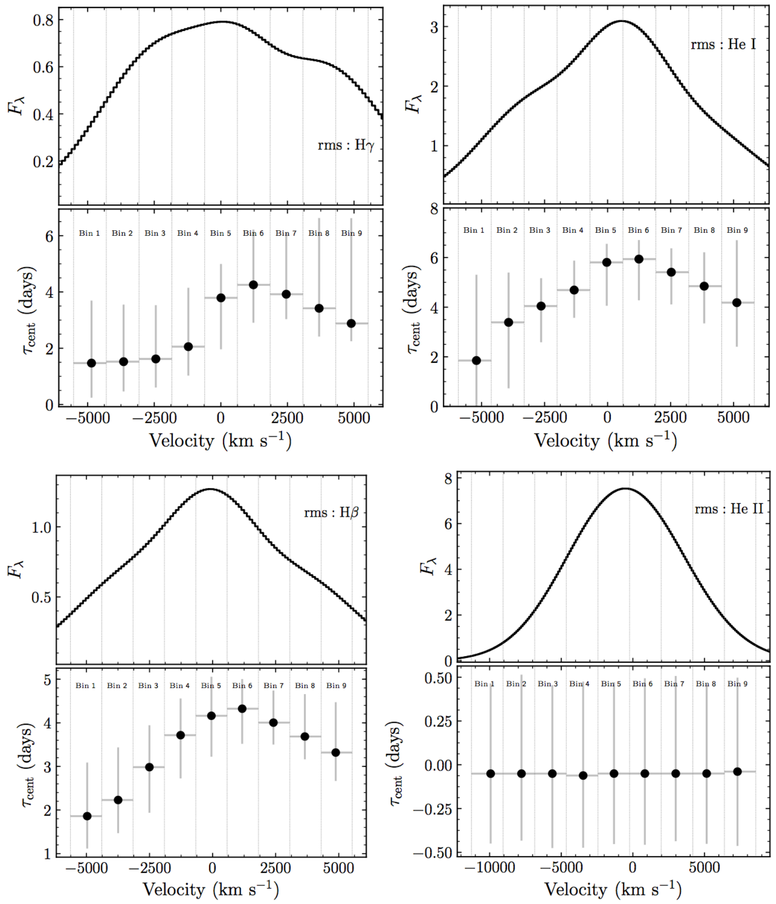
- higher sampling is necessary to construct lag profile of He II
- VRLPs of Hγ, Hβ, and He I show same structures

---The lags in the blue side are shorter the lags in the red side

---VRLPs do not strictly demonstrate a one-fold gradient,
the largest lag in the red side,
and the lags of the last three bin shorten

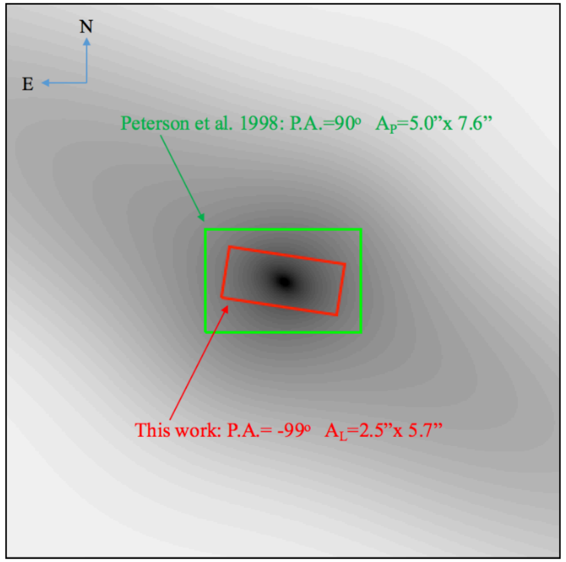
→ Mrk 79 has a virialized BLR with outflowing component

Q1



AGN properties (1): **Host galaxy, Optical luminosity**

HST image of Mrk 79 has been decomposed by Bentz et al. (2009) and Kim et al. (2017)



The host galaxy of Mrk 79

The ratio of total photons of host galaxy: $\mathrm{A_L}/\mathrm{A_P} = 0.60$.

Bentz et al. (2013) measured the flux of $\mathrm{A_P}$:

$F_{\mathrm{host,A_P}}[1+z] = 1.42 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}.

–> $F_{\mathrm{host,A_L}}[1+z] = 0.85 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}.

Fitting mean spectrum yields an average host-galaxy flux:

$F_{\mathrm{host}}[1+z] = (0.80 \pm 0.09) \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}.

So, $F_{\mathrm{host,A_L}}[1+z] \sim F_{\mathrm{host}}[1+z]$ within the uncertainties.

Flux density:

$F_{\mathrm{AGN}}[1+z] = (2.33 \pm 0.23) \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}

Monochrome luminosity:

($H_0 = 67$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.68$, and $\Omega_\mathrm{M} = 0.32$)

–> $L_{5100} = (1.45 \pm 0.14) \times 10^{43}$ erg s^{-1}

AGN properties (2): Black hole mass, Accretion rates

1. Line profile measurements

---The width of emission lines are measured from the best-fit model

	Mean spectra		rms spectra	
Line	FWHM (km s^{-1})	σ_{line} (km s^{-1})	FWHM (km s^{-1})	σ_{line} (km s^{-1})
(1)	(5)	(6)	(7)	(8)
Hγ	6730±312	2739±216	10757±377	3679±137
He II	—	—	9585±815	4003±121
Hβ	6539±154	2660±136	8431±621	3458±132
He I	6124±223	2470±156	8182±598	3345±134

2. Black hole mass

$$M_\bullet = f_{\rm BLR}\frac{c\tau_{\rm BLR}V_{\rm BLR}^2}{G} \equiv f_{\rm BLR}{\rm VP}$$

3. Accretion rates (Du+14)

$$\dot{\mathscr{M}} = \frac{\dot{M}_\bullet}{L_{\rm Edd}c^{-2}} = 20.1\left(\frac{\ell_{44}}{\cos i}\right)^{3/2} M_7^{-2}$$

For $\sigma_{\rm line}$ measured from rms spectrum,

$f_{\rm BLR} = 6.3 \pm 1.5$ for classical bulges (Ho & Kim 2014).

BLR size $\tau_{\rm BLR} = 3.49^{+0.62}_{-0.60}$.

${\rm VP}|_{\sigma_{\rm H\beta}} = 0.82^{+0.16}_{-0.15} \times 10^7 M_\odot$.

–> black hole mass: $M_\bullet = 5.13^{+1.57}_{-1.55} \times 10^7 M_\odot$.

Using the latest $M_\bullet - \sigma_*$ relation (Kormendy et al. 2013),

$\sigma_*|_{\rm Mrk79} = (130 \pm 12)$ km s^{-1} (Nelson et al. 2004).

–> $M_\bullet|\sigma_* = 4.68 \times 10^7 M_\odot$ with the scatter of 0.34 dex.

Mrk 79: $i = 24^o$ (Gallo et al. 2011), L_{5100}, $M_\bullet$

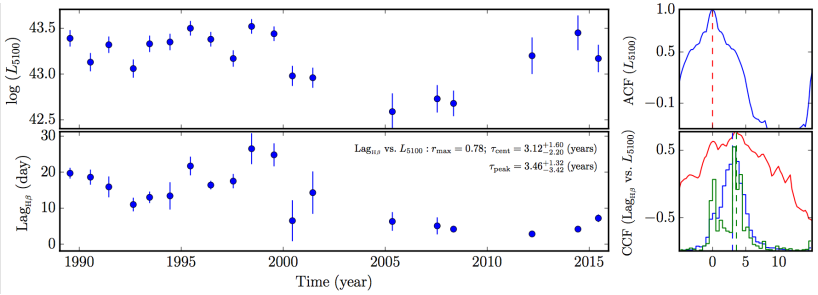
–> mass accretion rates: $\dot{M}_\bullet = (0.05 \pm 0.02)\, L_{\rm Edd}\, c^{-2}$.

Discussion(1) 1. R_{BLR}-L_{5100} relationship

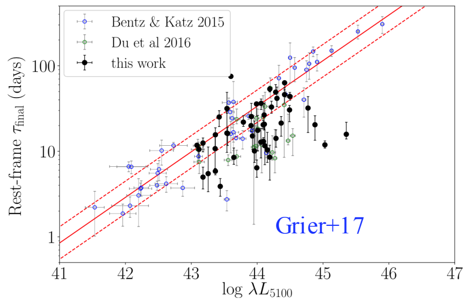
- Great changes of the luminosity and the BLR size in Mrk 79 are similar to NGC 5548 (e.g., Lu+16).

Epoch (JD: days)	$F_{obs}[1+z]$	$F_{host}[1+z]$	$F_{AGN}[1+z]$	L_{5100} (erg s^{-1})	Hβ Lags (days)	Ref.
2447838−2448044	6.96±0.15	1.42 ± 0.07	5.54±0.18	$(3.45 \pm 0.12) \times 10^{43}$	$9.0^{+8.3}_{-7.8}$	(1,2)
2448193−2448393	8.49±0.16	1.42 ± 0.07	7.07±0.19	$(4.41 \pm 0.11) \times 10^{43}$	$16.1^{+6.6}_{-6.6}$	(1,2)
2448905−2449135	7.40±0.16	1.42 ± 0.07	5.98±0.19	$(3.73 \pm 0.12) \times 10^{43}$	$16.0^{+6.4}_{-5.8}$	(1,2)
2458059−2458192	3.22±0.22	0.80 ± 0.09	2.33±0.23	$(1.45 \pm 0.14) \times 10^{43}$	$3.49^{+0.62}_{-0.60}$	(3)

In Mrk 79: $\Delta L_{5100} \sim 1$ mag, $\Delta R_{BLR} \sim 12$ days



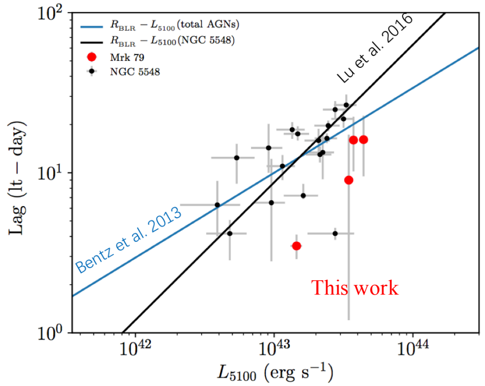
NGC 5548: Lu+16



- Many measurements deviate from the global *R*-*L* relation, AGNs get bluer when they get brighter?

---(1) R_{BLR} variations follows L_{5100} variation with a lag in NGC 5548, this lag coincides with the BLR's dynamical timescale (Lu+16; Kriss+19, ApJ)

---(2) The shortened lags are correlated with accretion rates (Du+16 & 18)



Constructing many AGN-dependent R_{BLR}-L_{5100} and investigating their similarities and differences may provide another clue to understand the scatter (~0.3 dex) of the global R_{BLR}-L_{5100}

Discussion(2)

2. The BLR of Mrk 79 as a disk wind: Indirect evidence

➢ **He II has a marginal blue-shift velocity of -448km/s**

---Created 200 rms spectra from 200 randomly Chosen subsets of spectra (the method is similar to Grier et al. 2012)

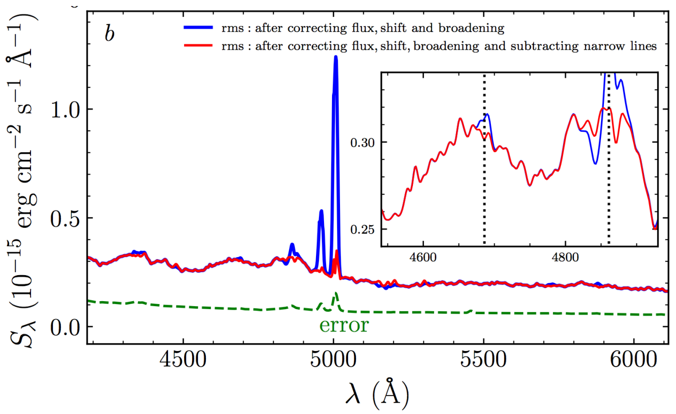
---Obtained distributions of line widths (FWHM) and positions of line core (C)

$$C_{\mathrm{He\ II}\ \lambda4686} = 4678.6 \pm 3.9\ \text{Å},$$

$$\text{He II}\ \lambda4686\ \text{blueshift:}\ -448\ \text{km s}^{-1}$$

---In Hu et al. (2015)'s work, blue-shift He II is considered to reasonably decompose the spectrum of 7 AGNs

Based on line-driven wind from the accretion disk, Murray et al. (1995) predicted that the high-ionization emission lines should be blueshifted relative to the low-ionization emission lines.



Object	He II blueshift (km s^{-1})	UFOs	Ref.
Mrk 335	-620	-	Hu et al. 2015
Mrk 1044	-942	$0.100 \pm 0.010c$	Hu et al. 2015
Mrk 382	-1322	-	Hu et al. 2015
Mrk 142	-757	-	Hu et al. 2015
MCG +0626012	-927	-	Hu et al. 2015
IRAS F12397+3333	- 334	-	Hu et al. 2015
Mrk 486	-724	-	Hu et al. 2015
Mrk 493	-1580	-	Hu et al. 2015
Mrk 79	-448	$0.092 \pm 0.004c$	This work

(Hu et al. 2015's sample + Mrk 79)

Discussion(2)

➤ **The BLR of Mrk 79 presents outflowing component**

--- ~4/20 AGNs show the signature of BLR outflow.

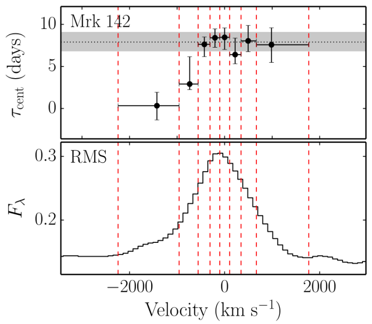
Mrk 142: Hβ presents the outflowing BLR (Du+16)
(super-Eddington accretion AGN)

NGC 3227: Hβ presents the outflowing BLR in 2007 (Denny+09)
while turns to virialized BLR in 2012 (De Rosa+18)

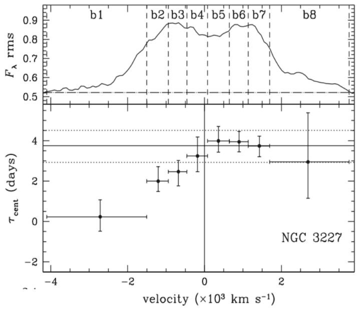
NGC 4151: Hβ presents the outflowing BLR (Brotherton's talk)

Mrk 79: Hγ, Hβ, and He I present the outflowing BLR simultaneously

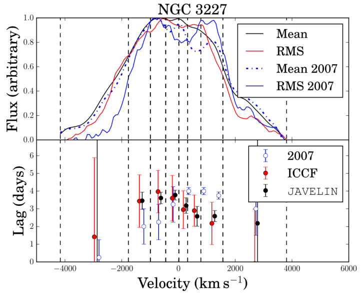
Although Mrk 79, NGC 3227 NGC 4151 are sub-Eddington accretion AGNs, they have been detected UFOs and warm absorbers (WAs)



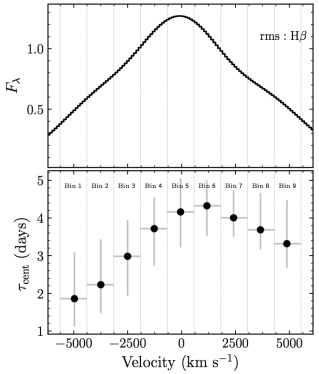
Mrk 142: Du et al. (2016)



NGC 3227 in 2007: Denny et al. (2009)



NGC 3227 in 2012: De Rosa et al. (2018)



Mrk 79: this work

Discussion(2)

➢ Multiphase disk wind: (Murray+95; Leighly+14; O'Brien+05; Kazanas+12; Tombesi+13; Czerny+17; Baskin & Laor 2018)

---The model of (large-scale) multiphase disk wind was developed to explain the observed phenomenon

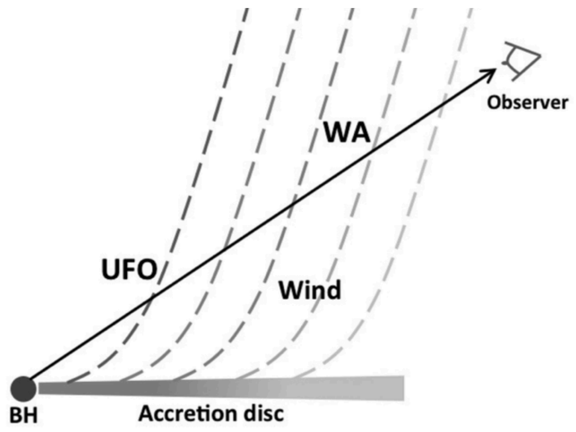
---Based on the X-ray and UV monitoring of NGC 5548, Kriss 2019 suggested that the "BLR holiday" of NGC 5548 could relate to the disk wind launched in the brightening state. (Kriss et al. A&A, 2019a; Kriss et al. ApJ, 2019b)

In the context of multiphase disk wind,
All findings of Mrk 79 including:

---**UFOs**;
---**warm absorbers**;
---**the kinematics of the high- and low-ionization gas**,

may suggest that the BLR of Mrk 79 probably originates from multiphase disk wind.

Q2 Q3 ?



Multiphase disk winds (Tombesi et al. 2013)

Nevertheless, simultaneous observations of multi-band spectra (X-ray, UV, optical) are necessary to confirm this speculation.

Discussion(3)

3. Relation between blue-shift velocity and AGN properties

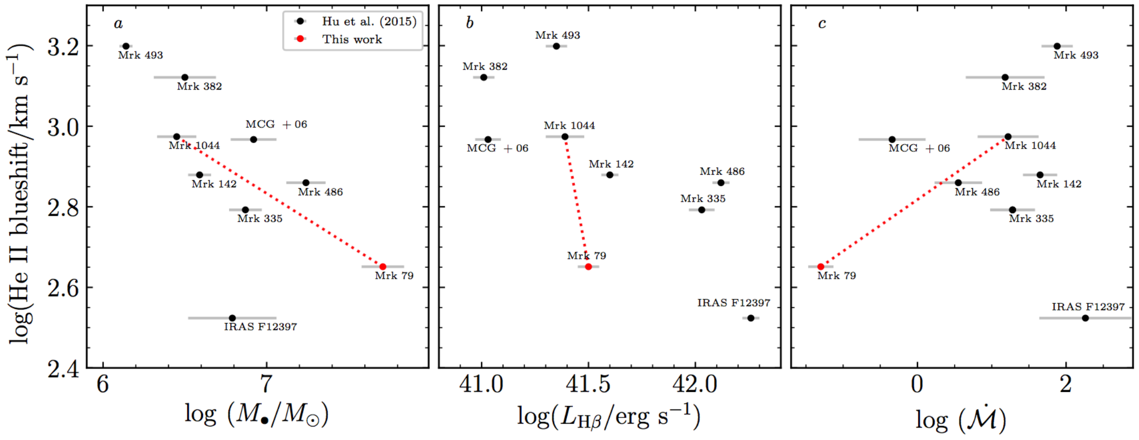
Object	He II blueshift (km s^{-1})	UFOs
Mrk 335	-620	-
Mrk 1044	-942	$0.100 \pm 0.010c$
Mrk 382	-1322	-
Mrk 142	-757	-
MCG +0626012	-927	-
IRAS F12397+3333	- 334	-
Mrk 486	-724	-
Mrk 493	-1580	-
Mrk 79	-448	$0.092 \pm 0.004c$

➢ AGNs' outflow (disk wind or BLR outflow) should be jointly triggered and controlled by central gravity and magnetic or (and) radiation pressure

We roughly found that the He II of 8 AGNs have blue-shifted velocity (Hu+15's sample + Mrk79)

---UFOs were just detected in Mrk 79 and Mrk 1044

Panel A seemingly shows that the blue-shift velocity could correlate with the BH mass, which may indicate that the central gravity of the BH may play a potential role on the terminal velocity of outflowing emitter?



To responsibly investigate the relation between blue-shift velocity of He II and AGN properties, we need a larger samples

Conclusion

1. Mrk 79 is seeming to come out the faint luminosity state, the average flux density at 5100 A˚ approximates a magnitude fainter
than previous RM record.

2. We successfully measured the time delays of the broad Hβ λ4861, Hγ λ4340, He II λ4686, and He I λ5876 emission lines with respect to the continuum variation

3. We simultaneously obtained the velocity-resolved lag profiles of broad Hγ λ4340, Hβ λ4861, and He I λ5876 emission lines for the first time. Mrk 79 has a virialized BLR with outflowing component during the monitoring period

4. Measured BH mass of Mrk 79 in this campaign is consistent with the estimated BH mass from $M_{\bullet}-\sigma_{*}$ relation.

5. Mrk 79's $R_{\rm BLR}-L_{5100}$ relation slightly deviates from the global $R_{\rm BLR}-L_{5100}$ (slope=0.53) and NGC 5548's $R_{\rm BLR}-L_{5100}$ (slope=0.86) relationships

6. In the context of multiphase disk wind, many findings of Mrk 79 including UFOs, warm absorbers , and the kinematics of the high and low ionization BLR, suggest that the BLR of Mrk 79 probably originates from (or connects with) multiphase disk wind launched from the inner accretion disk. Nevertheless, simultaneous observations of multi-band spectra are necessary to confirm this speculation.

Thank you!