Reverberation Mapping of Super-Eddington Accreting Massive Black Holes (SEAMBHs)

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(on behalf of SEAMBH collaboration)

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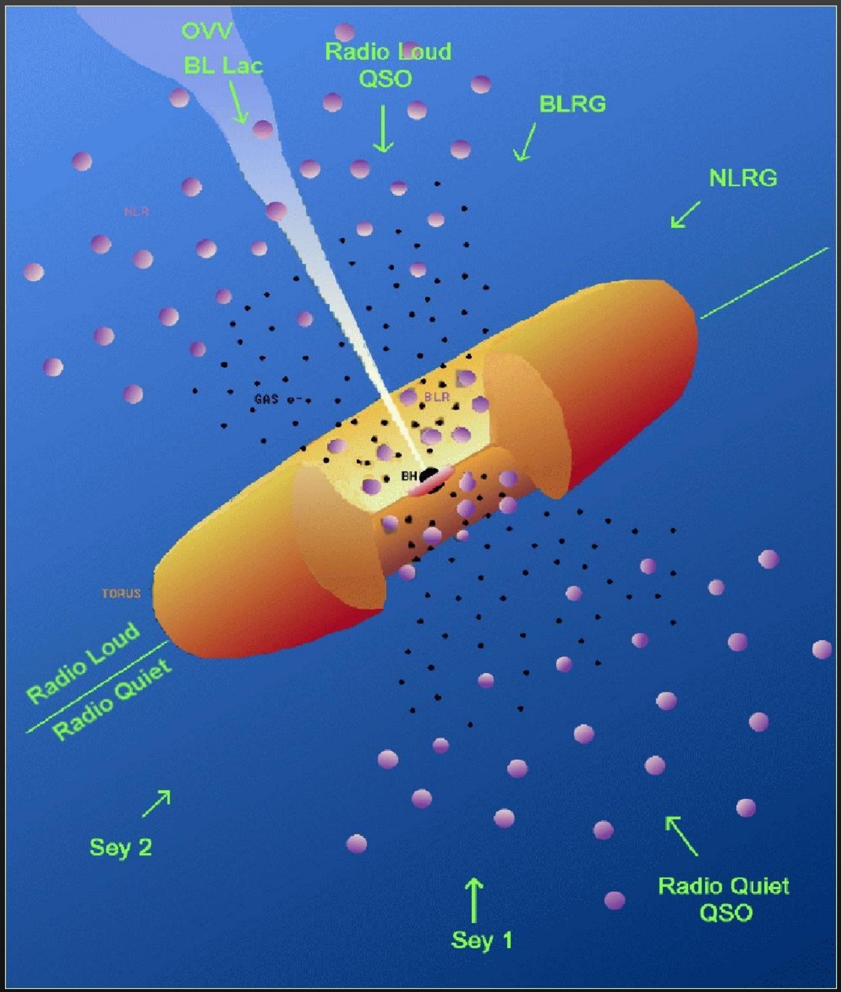
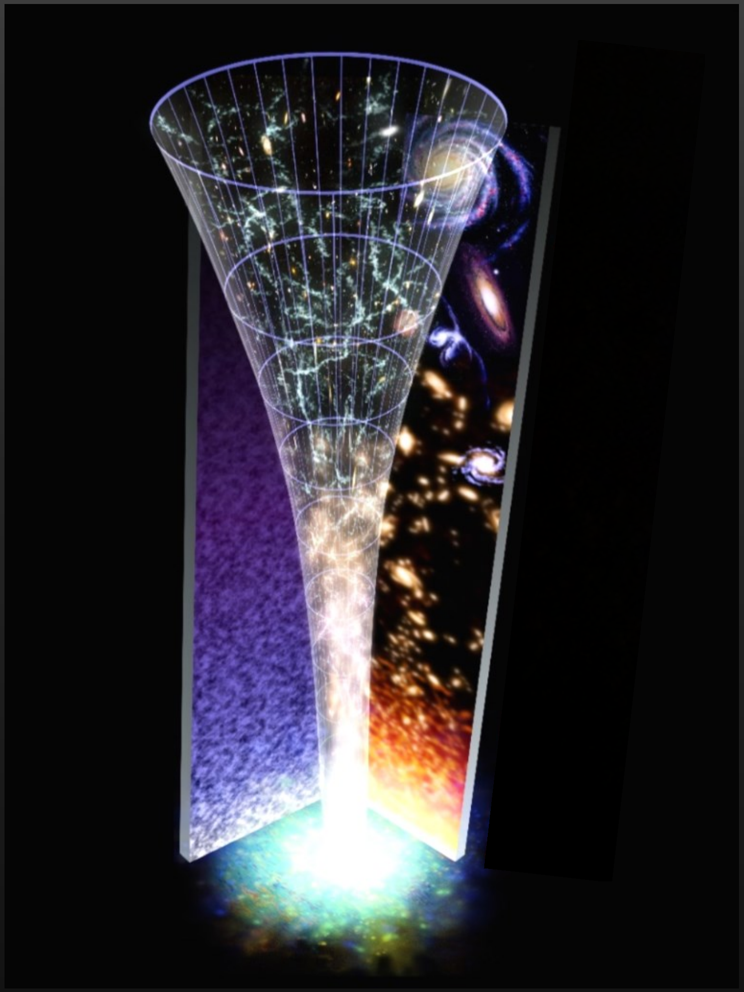
2016.10.24 China - Lijiang

Why SEAMBHs?



AGN Physics



Cosmology

Outline

- Observation
- Shortened time lags of Hbeta
- New scaling relationship of BLR
- Fundamental plane
- R-L deconvolution and velocity-resolved time lags
- NGC 5548 and radiation pressure
- SEAMBH candles and their presicion

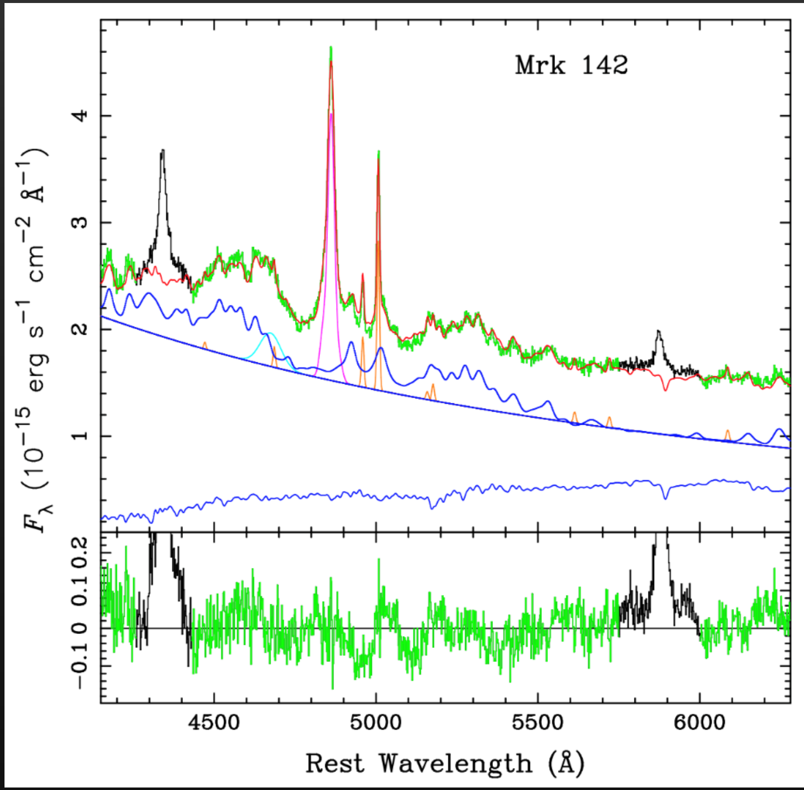
Sample selection

Select high accretion rate AGN from single-epoch spectroscopy based on

$$\dot{\mathscr{M}} = 20.1\left(\frac{l_{44}}{\cos i}\right)^{3/2} m_7^{-2},$$

(standard thin disk equation)

1. Strong Fe II emission;
2. Narrow (<~2000km/s) Hbeta line;
3. Weak [O III] lines.



- SEAMBH2012: 10 objects with z<0.1 (9 detected)
- SEAMBH2013: 8 objects with 0.1<z<0.3 (5 detected)
- SEAMBH2014: 10 objects with 0.1<z<0.4 (5 detected)
- SEAMBH2015-2016: 10 objects are being observed

CHINA
0 km 200 400 600 km
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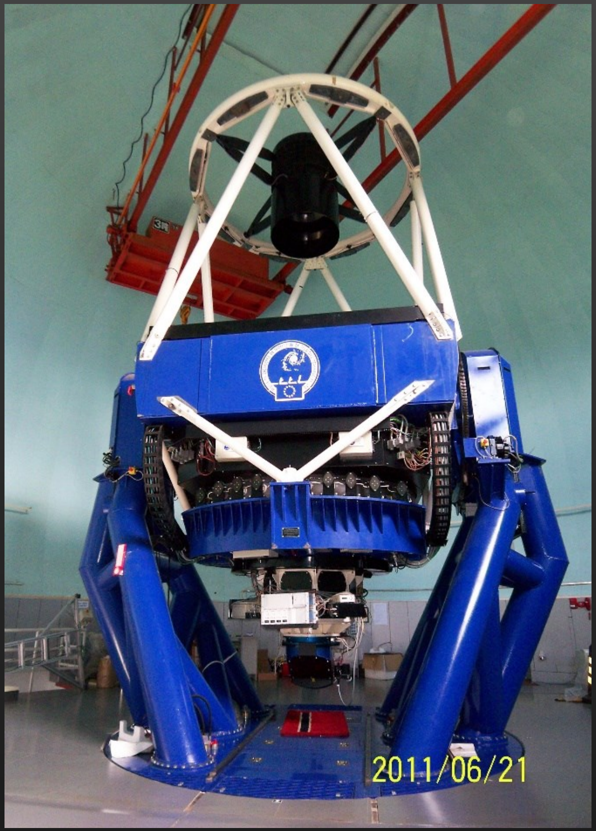
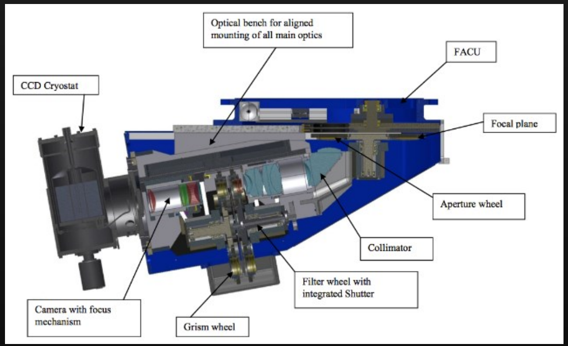
National Capital (11,510,000 in 2000)
over 10,000,000
over 6,000,000
over 2,500,000
over 1,000,000
other main city
other city
Capital of autonomous region
Capital of province
Shanghai Government-controlled municipality
Hong Kong* Special administrative region
RUSSIAN FEDERATION
RUSSIAN FEDERATION
MONGOLIA
Ulan Bator
Gobi Desert
XINJIANG UYGUR (SINKIANG)
Taklimakan Shamo
Tarim Pendi
Kunlun Shan
Altun Shan
Tien Shan
Qilian Shan
Qaidam Pendi
QINGHAI
Qing Zang Gaoyuan (Plateau of Tibet)
XIZANG (TIBET)
Himalaya
NEI MONGOL (INNER MONGOLIA)
NINGXIA HUI
GANSU
SICHUAN
YUNNAN
GUIZHOU
GUANGXI ZHUANG
GUANGDONG
HUNAN
HUBEI
HENAN
SHAANXI
SHANXI
HEBEI
SHANDONG
JIANGSU
ANHUI
ZHEJIANG
JIANGXI
FUJIAN
LIAONING
JILIN
HEILONGJIANG
Manchuria
HAINAN
TAIWAN
BEIJING (PEKING)
Tianjin (Tientsin)
Shanghai
Chongqing
Hong Kong*
Macau
Harbin
Changchun
Shenyang
Dalian
Qingdao
Jinan
Zhengzhou
Xi'an
Lanzhou
Xining
Chengdu
Kunming
Guiyang
Nanning
Guangzhou (Canton)
Shenzhen
Wuhan
Changsha
Nanchang
Hangzhou
Nanjing
Hefei
Fuzhou
T'aipei
Taiyuan
Shijiazhuang
Hohhot
Baotou
Yinchuan
Ürümqi
Lhasa
Haikou
Irkutsk
Chita
Ulan-Ude
Blagoveshchensk
Vladivostok
Lake Baikal
Barnaul
Abakan
NORTH KOREA
SOUTH KOREA
Pyongyang
Seoul
JAPAN
YELLOW SEA
EAST CHINA SEA
SOUTH CHINA SEA
Gulf of Tonkin
Hainan
TAJIKISTAN
Kashmir
DISPUTED TERRITORIES
NEPAL
Kathmandu
Mt Everest
BHUTAN
INDIA
New Delhi
Jaipur
VIETNAM
Hanoi
LAOS
Vientiane
THAILAND
PHILIPPINES
Aksai Chin
K2
ezilon.com

2.4-m telescope



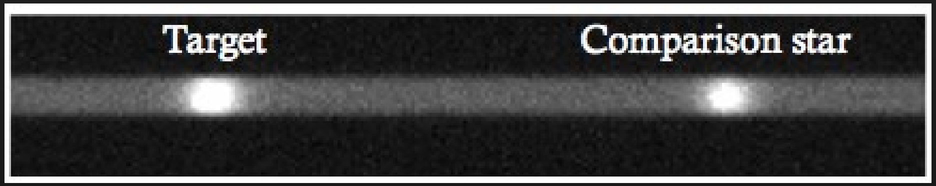
longitude:100°01’51”E
latitude: 26°42’32”N
altitude: 3193 m

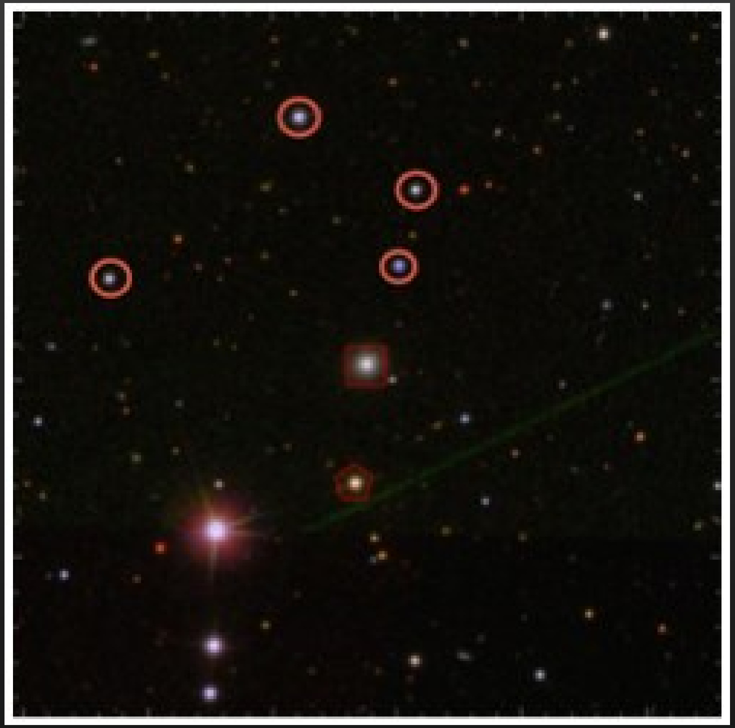
Average seeing： ~1.5”
Rainy season: Jun. – Sep.
tracking accuracy: < 0.5”/h



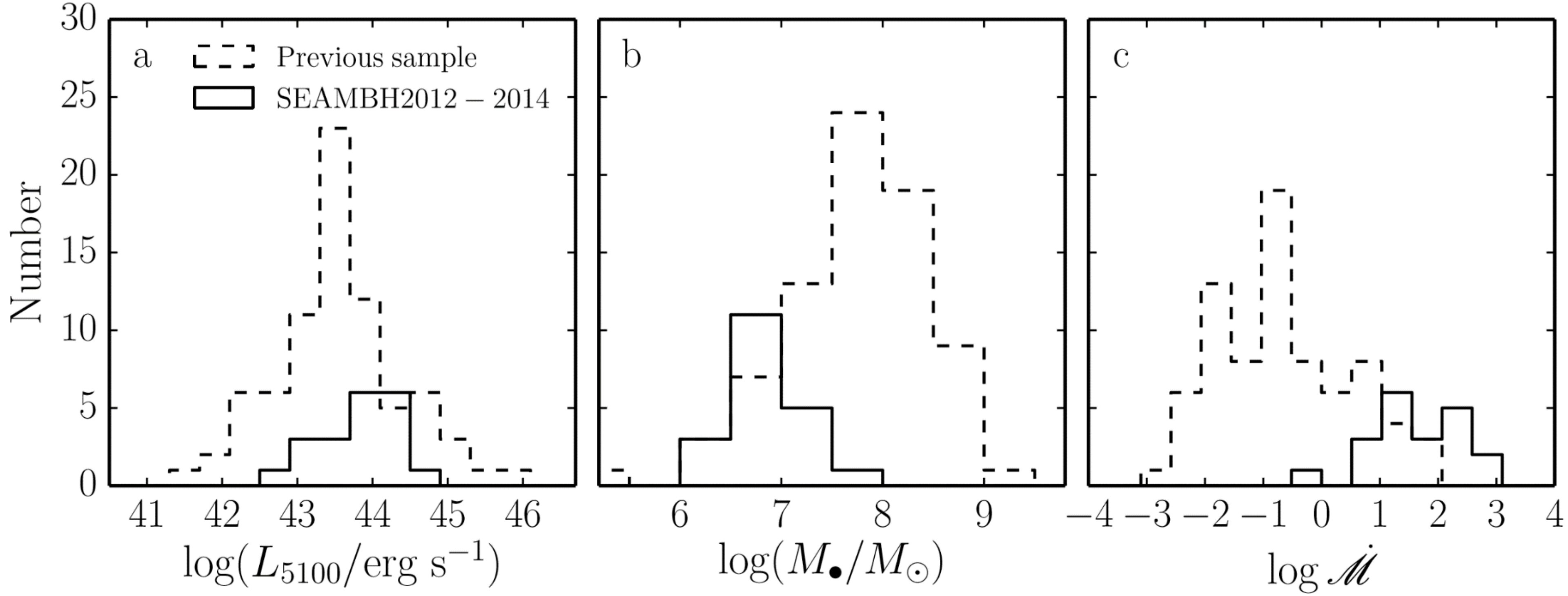
Observing strategy

- observe a nearby comparison star along the slit simultaneously
- photometry to test calibration



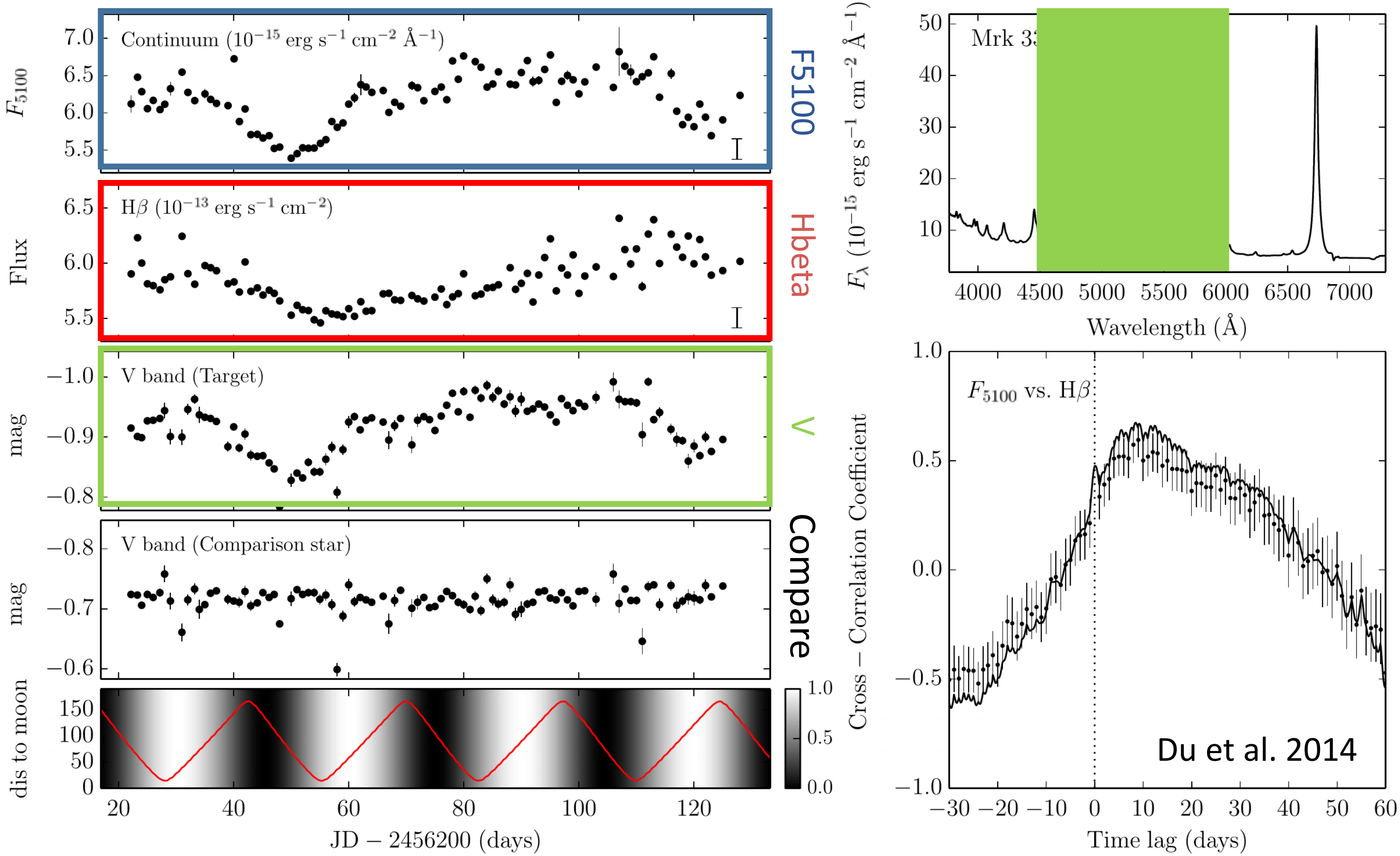


Properties



$$\dot{\mathscr{M}} = 20.1 \left(\frac{l_{44}}{\cos i} \right)^{3/2} m_7^{-2},$$

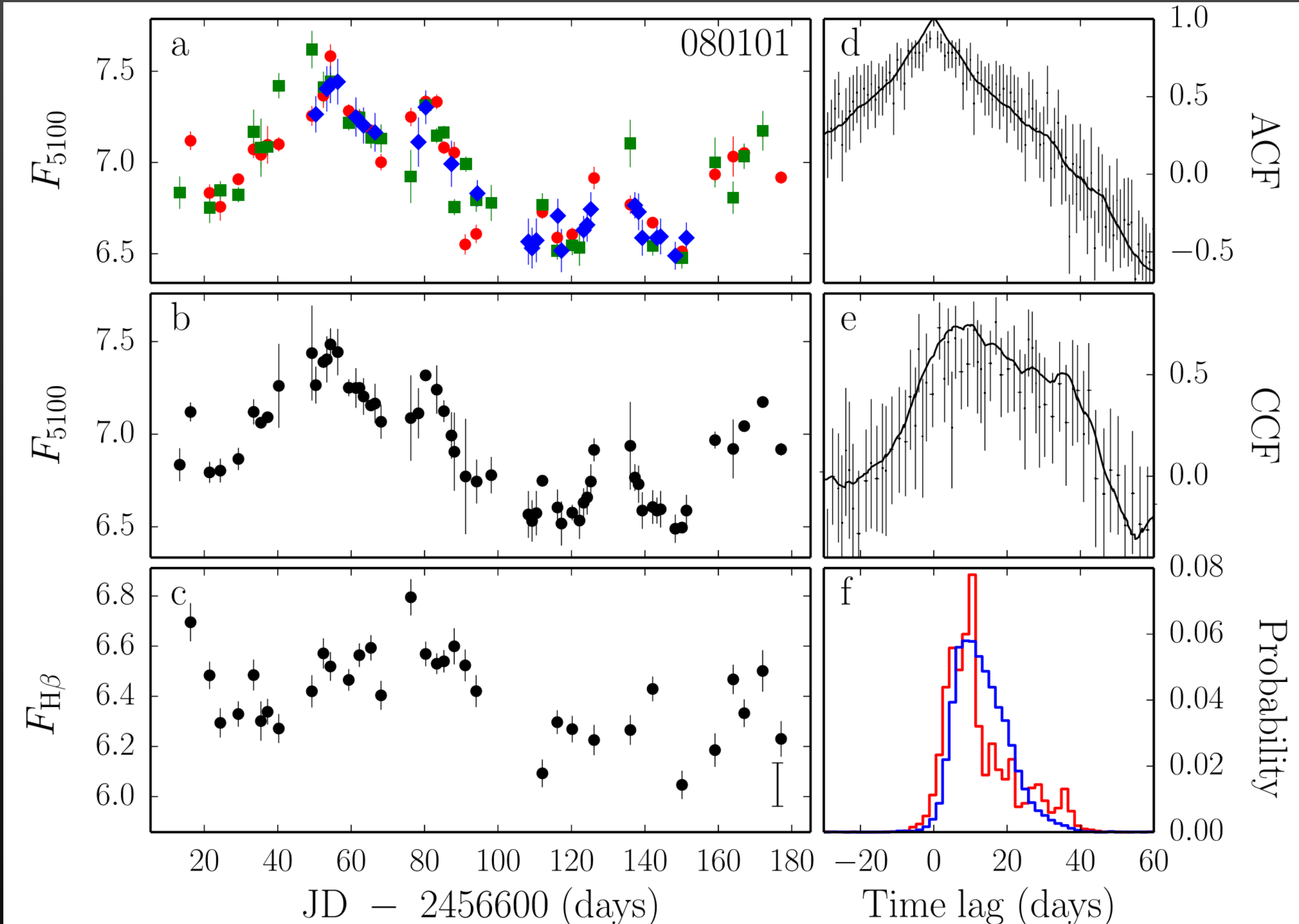
Mrk 335



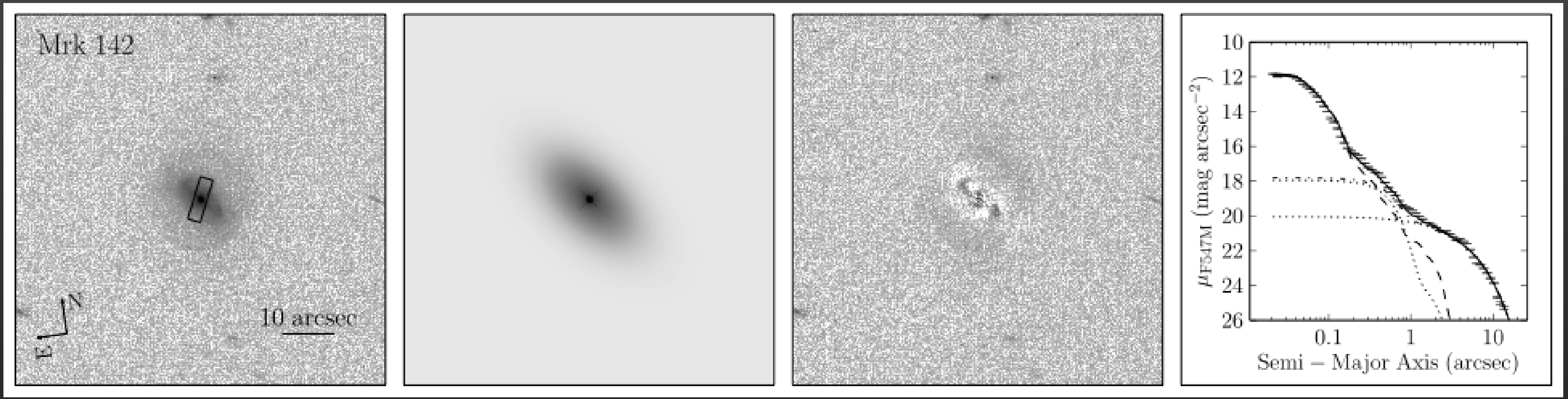
Continuum (10^−15 erg s^−1 cm^−2 Å^−1)
F5100
Hβ (10^−13 erg s^−1 cm^−2)
Hbeta
V band (Target)
V
V band (Comparison star)
Compare
dis to moon
JD − 2456200 (days)
Flux
mag
Mrk 33
Wavelength (Å)
Fλ (10^−15 erg s^−1 cm^−2 Å^−1)
F5100 vs. Hβ
Cross − Correlation Coefficient
Time lag (days)
Du et al. 2014

Light curves in 2013

(Du et al. 2015)



Host subtraction

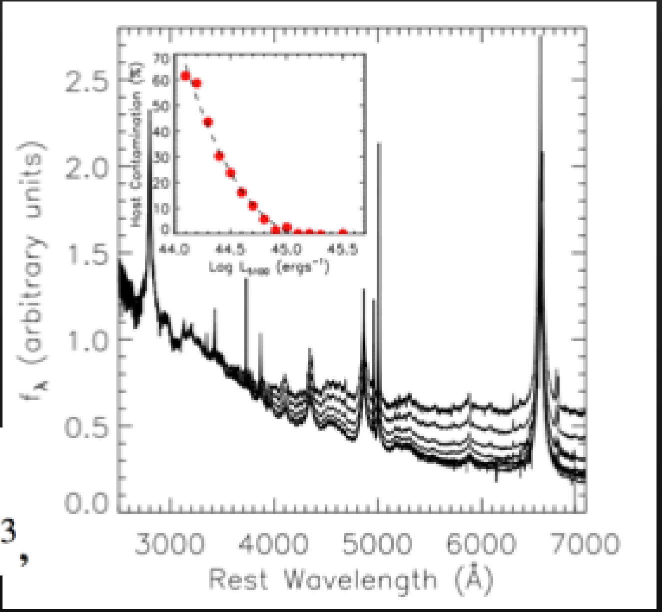


SEAMBH2012: HST images

From SEAMBH2013: empirical relationship in large sample

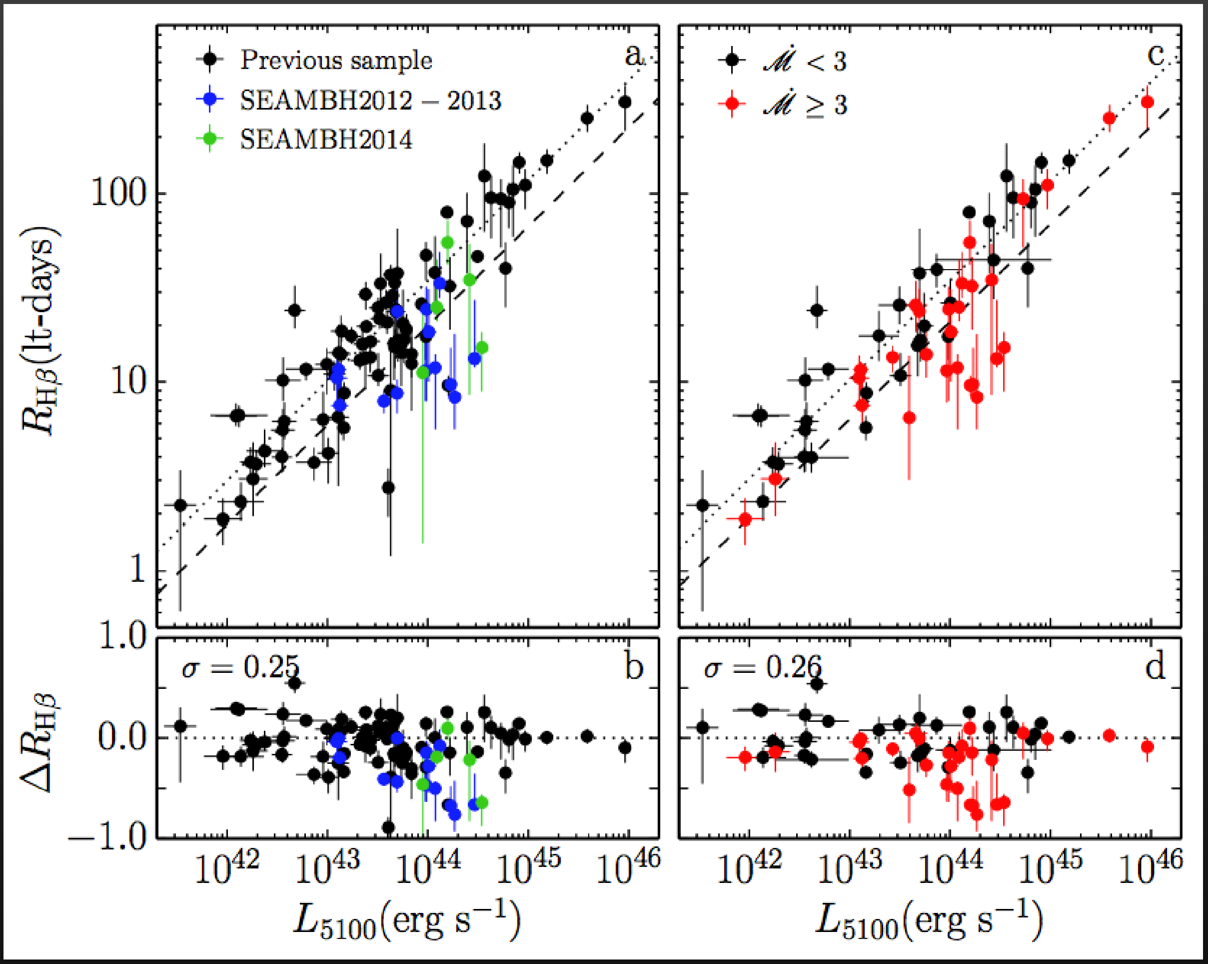
$$x = \log\left(L_{5100}^{\rm tot}/10^{44}\ {\rm erg\ s^{-1}}\right)$$

$$L_{5100}^{\rm host}/L_{5100}^{\rm AGN} = 0.8052 - 1.5502x + 0.912x^2 - 0.1577x^3,$$



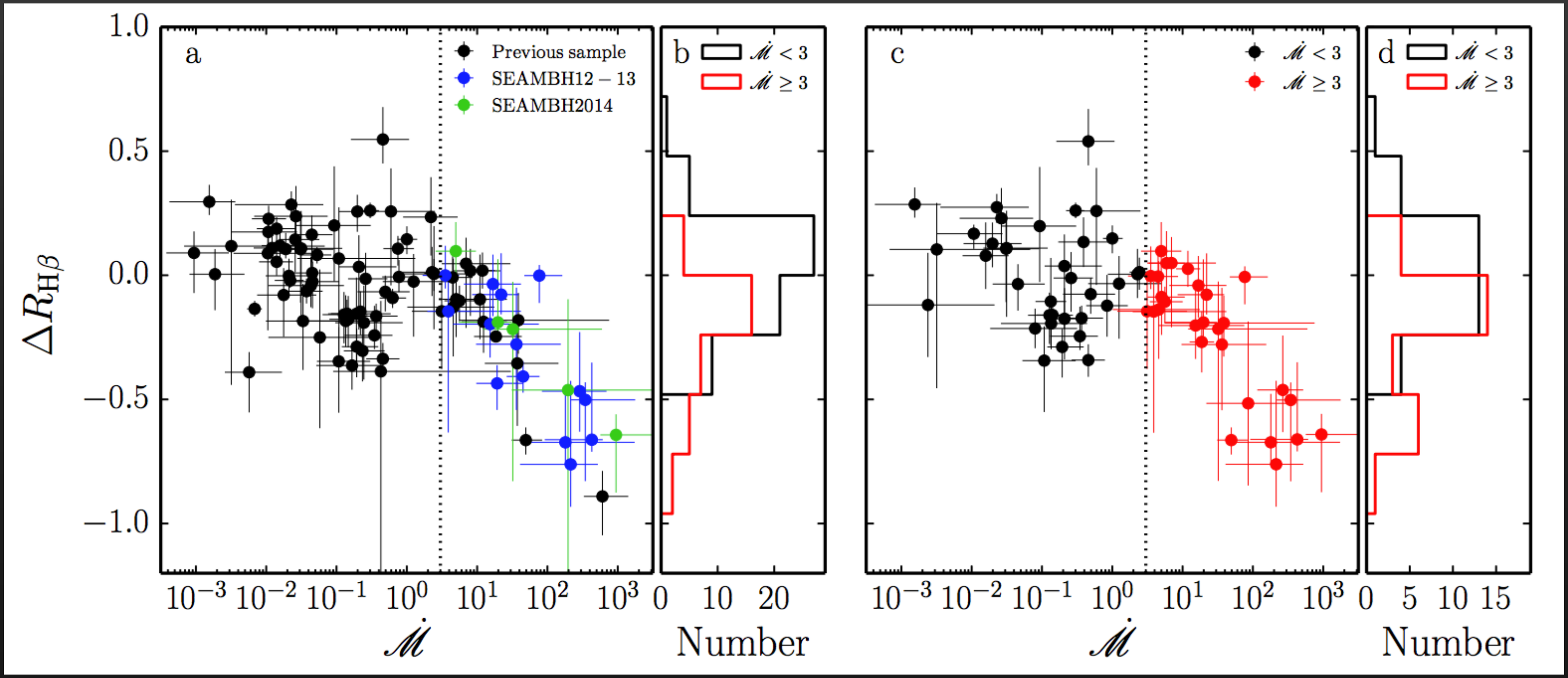
Where are SEAMBHs in the R-L relationship?

R-L relationship



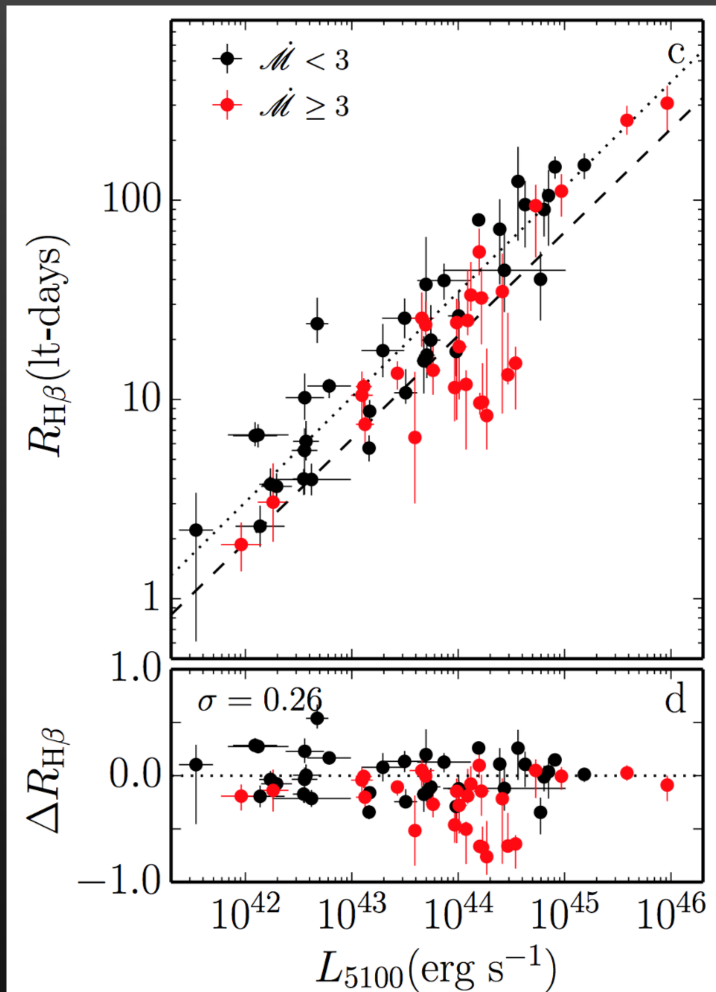
Du et al. (2016a)

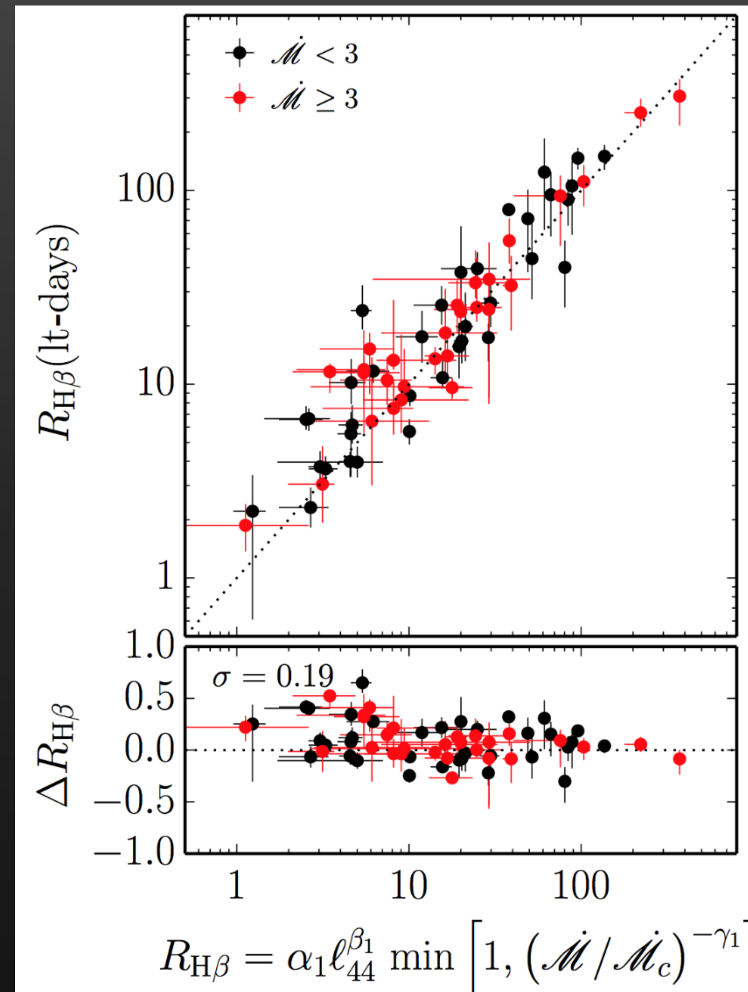
R-L relationship



Du et al. (2016a)

A New Size-Luminosity Scaling Relation



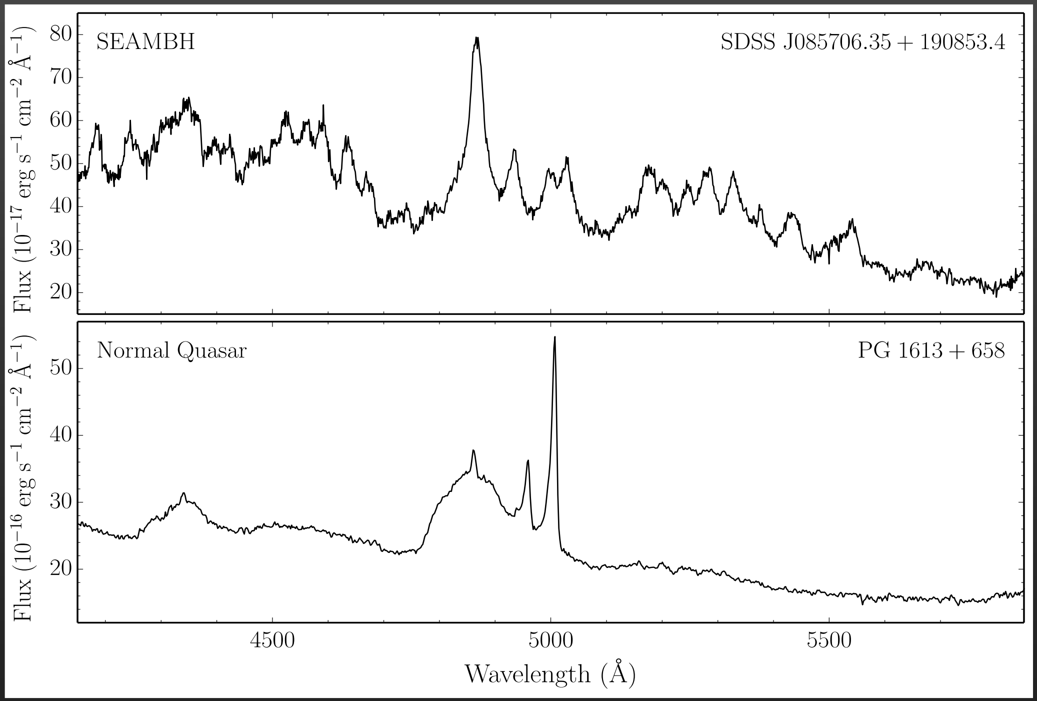


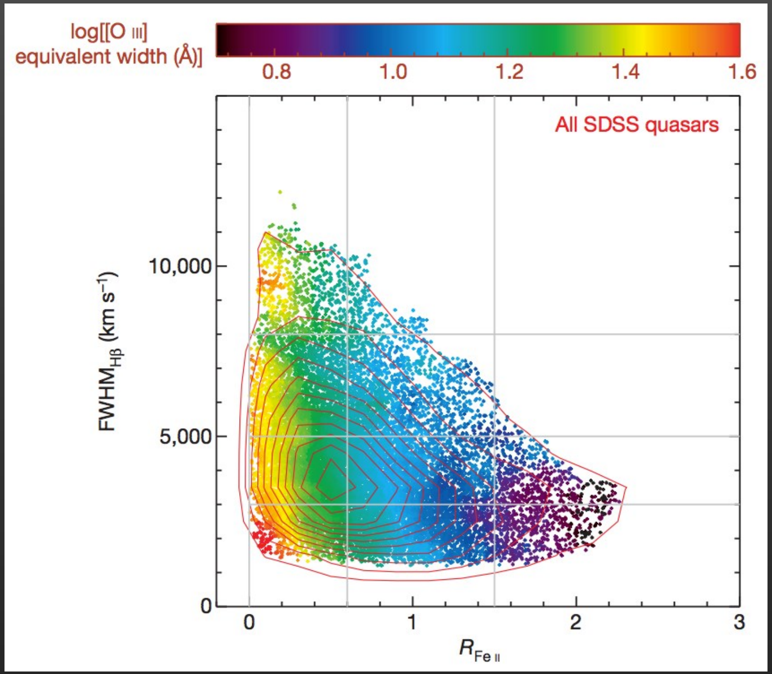
Du et al. (2016a)

$$R_{\mathrm{H}\beta} = \alpha_1 \ell_{44}^{\beta_1} \min\left[1, \left(\frac{\dot{\mathscr{M}}}{\dot{\mathscr{M}}_c}\right)^{-\gamma_1}\right], \quad \alpha_1 = 29.6^{+2.7}_{-2.8}; \quad \beta_1 = 0.56^{+0.03}_{-0.03}; \quad \gamma_1 = 0.52^{+0.33}_{-0.16}; \quad \dot{\mathscr{M}}_c = 11.19^{+2.29}_{-6.22}.$$

If possible to estimate Mdot directly from the spectra?

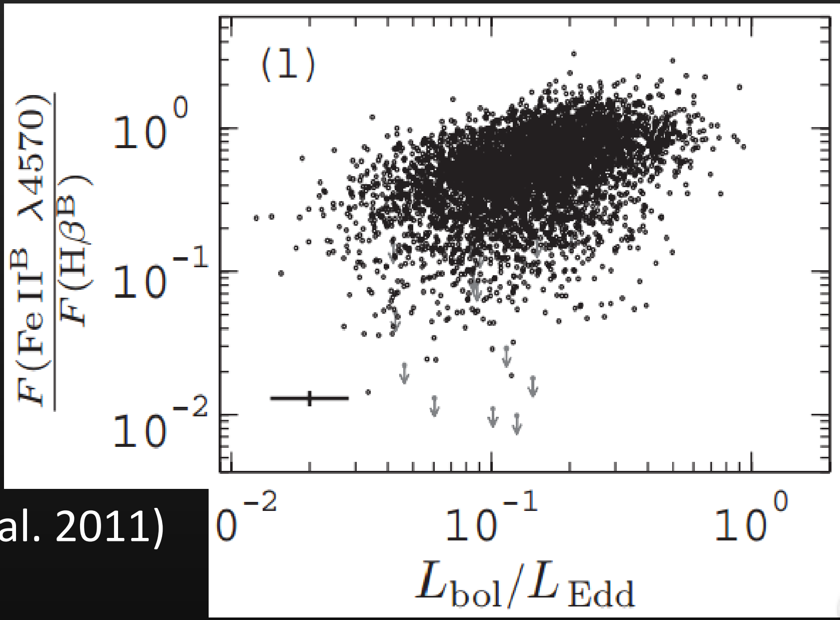
Strength of Fe II





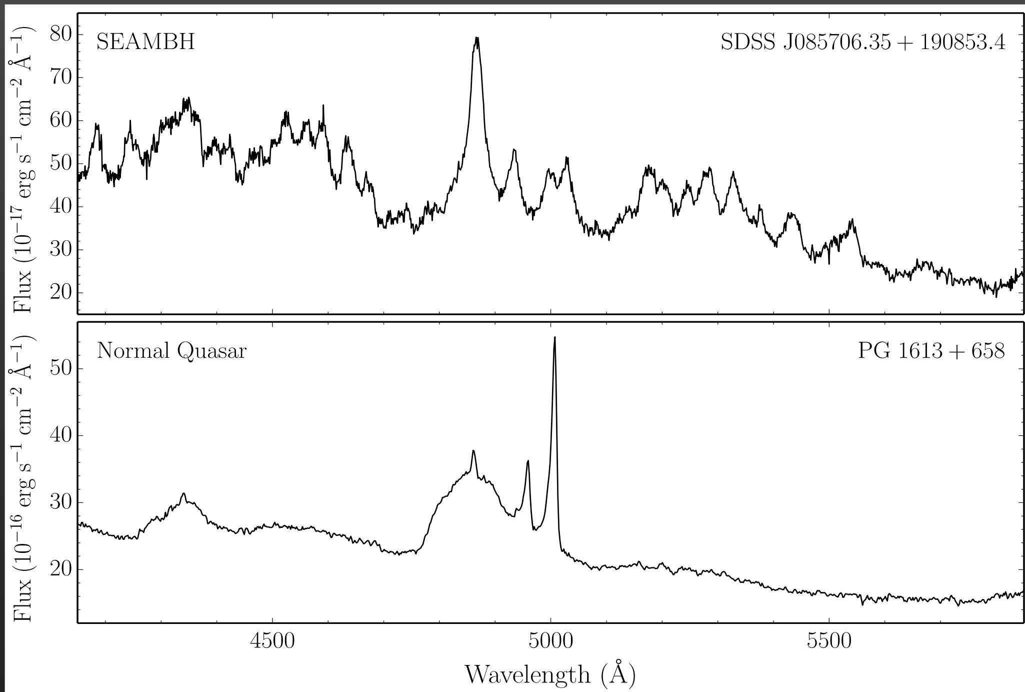
$$\mathcal{R}_{\rm Fe} = \frac{F_{\rm FeII}}{F_{\rm H\beta}},$$

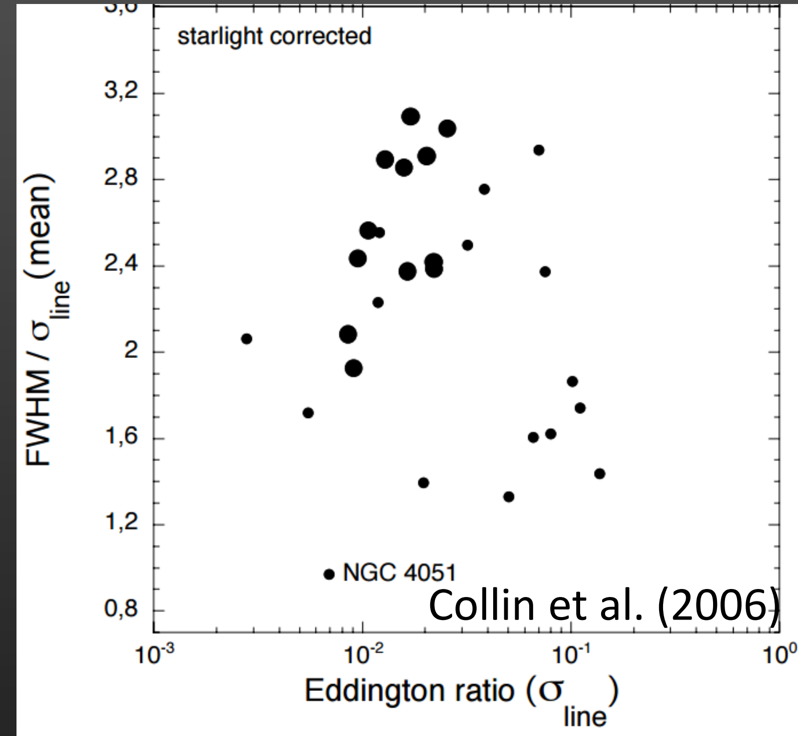
Correlates with Eddington ratio



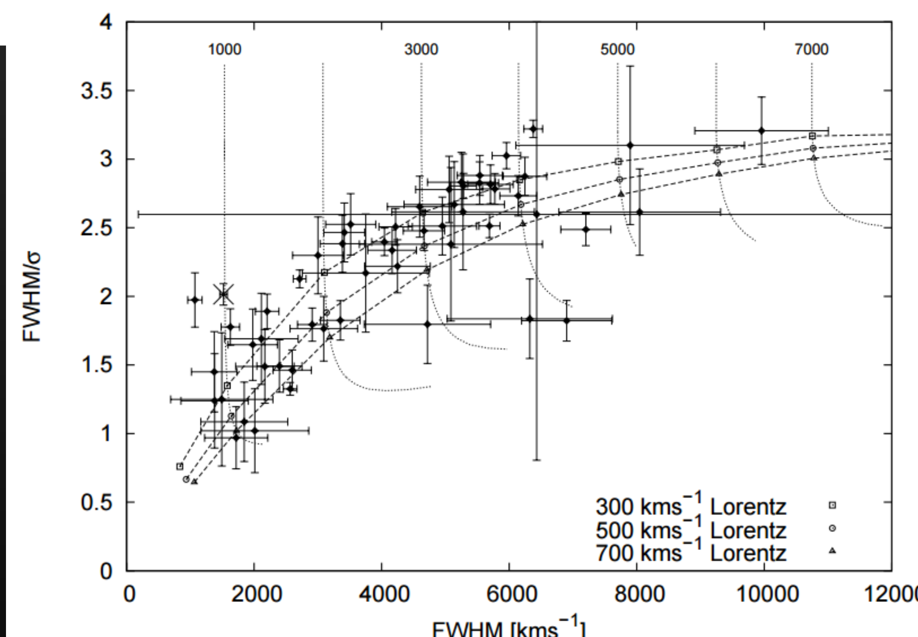
(e.g., Boroson & Green 1992; Hu et al. 2008; Dong et al. 2011)

Hbeta profile



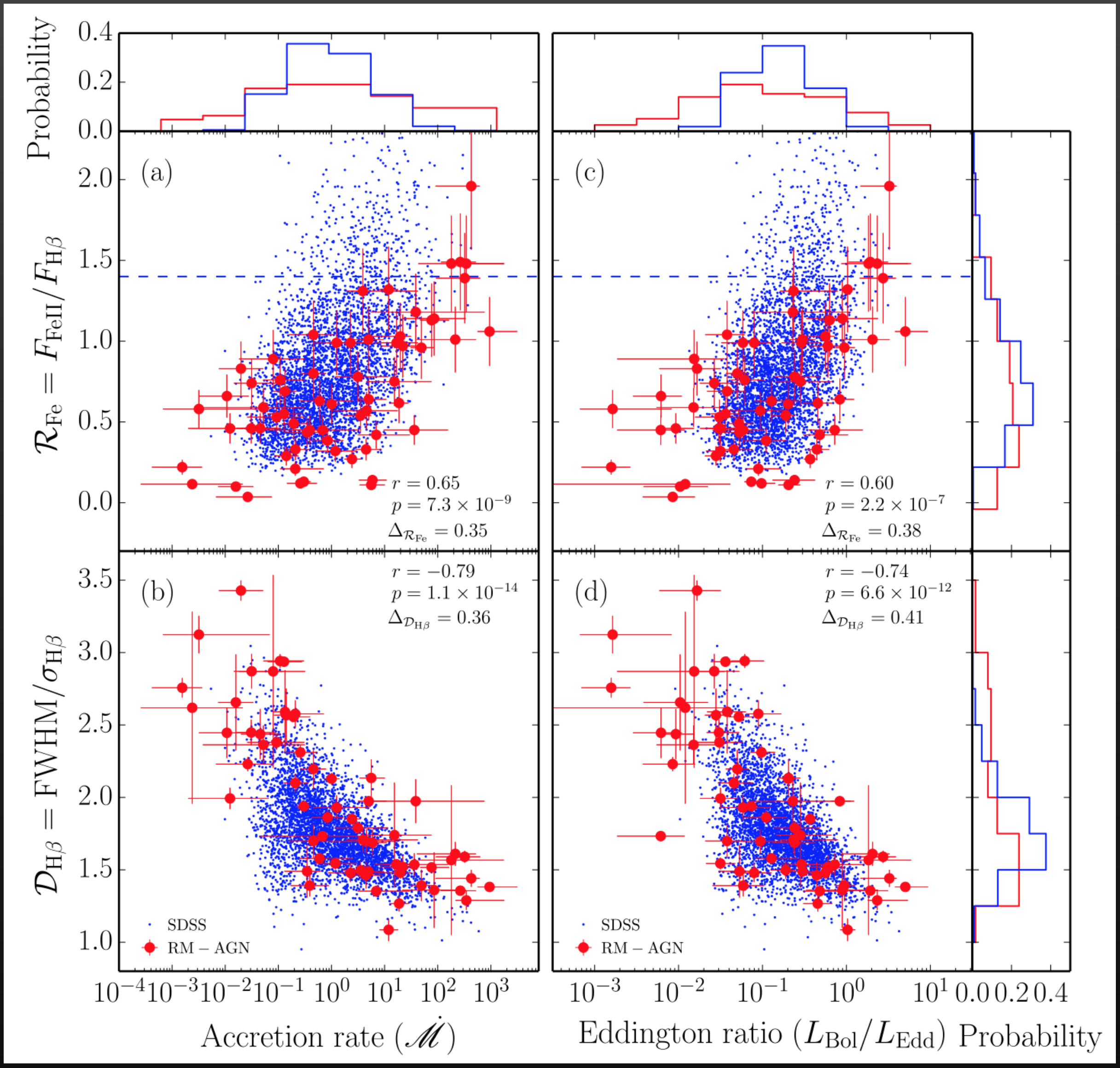


$$\mathcal{D}_{\mathrm{H}\beta} = \frac{\mathrm{FWHM}}{\sigma_{\mathrm{H}\beta}},$$



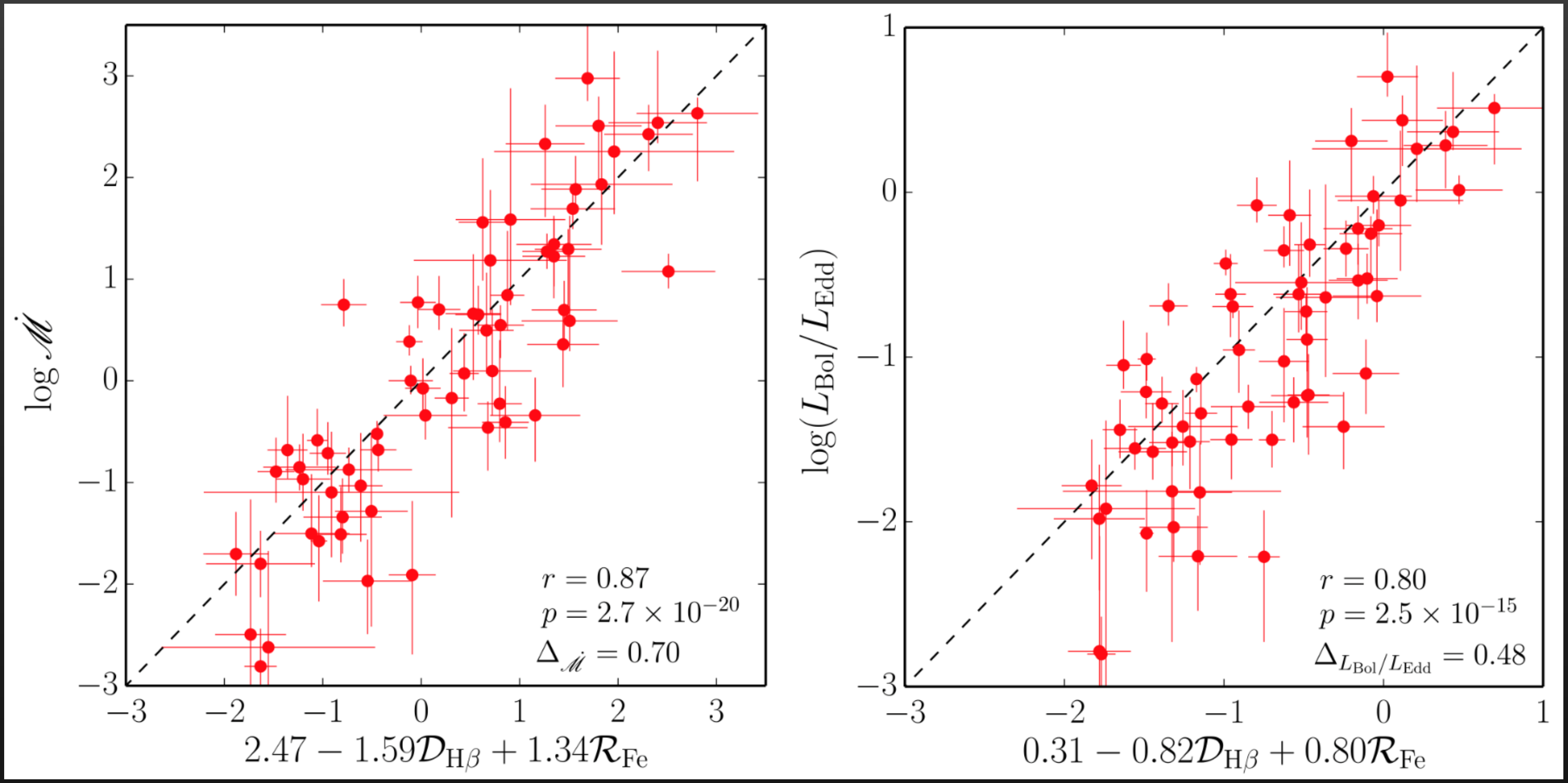
(e.g., Kollatschny & Zetzl 2011)

Accretion rate estimator? -- fundamental plane



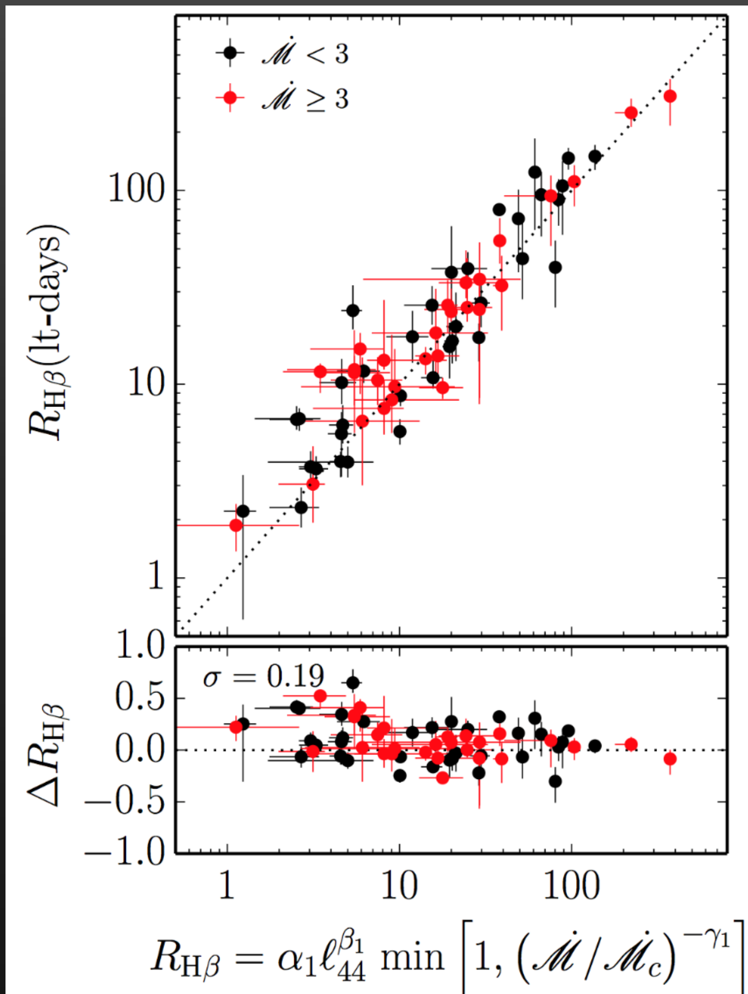
Du et al. (2016b)

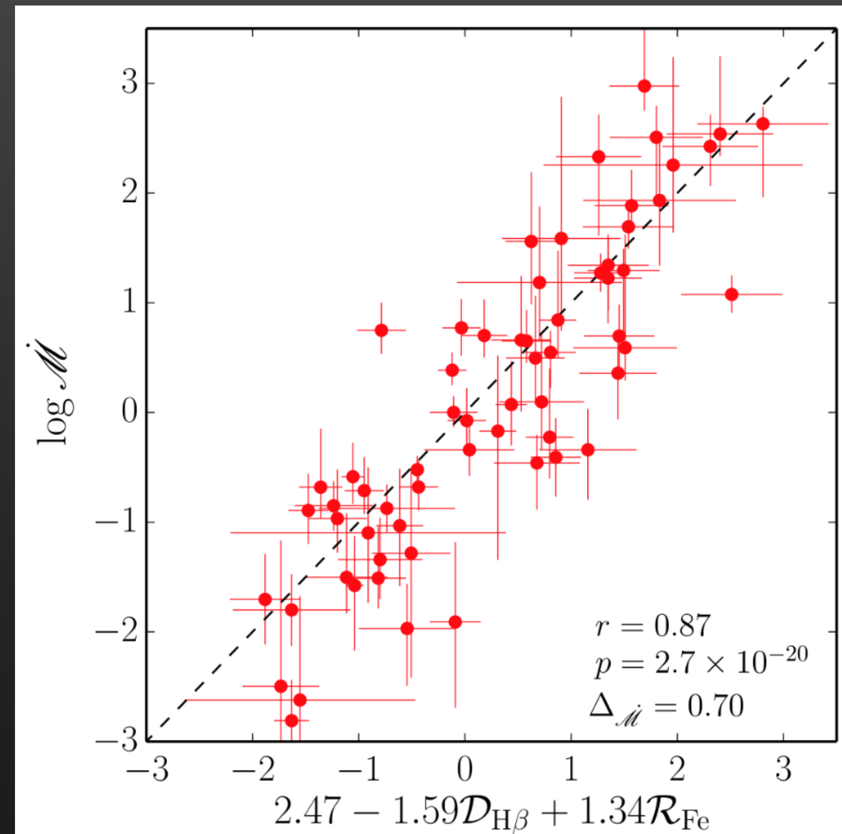
Accretion rate estimator? -- fundamental plane



Du et al. (2016b)

New scaling relation + Fundamental plane

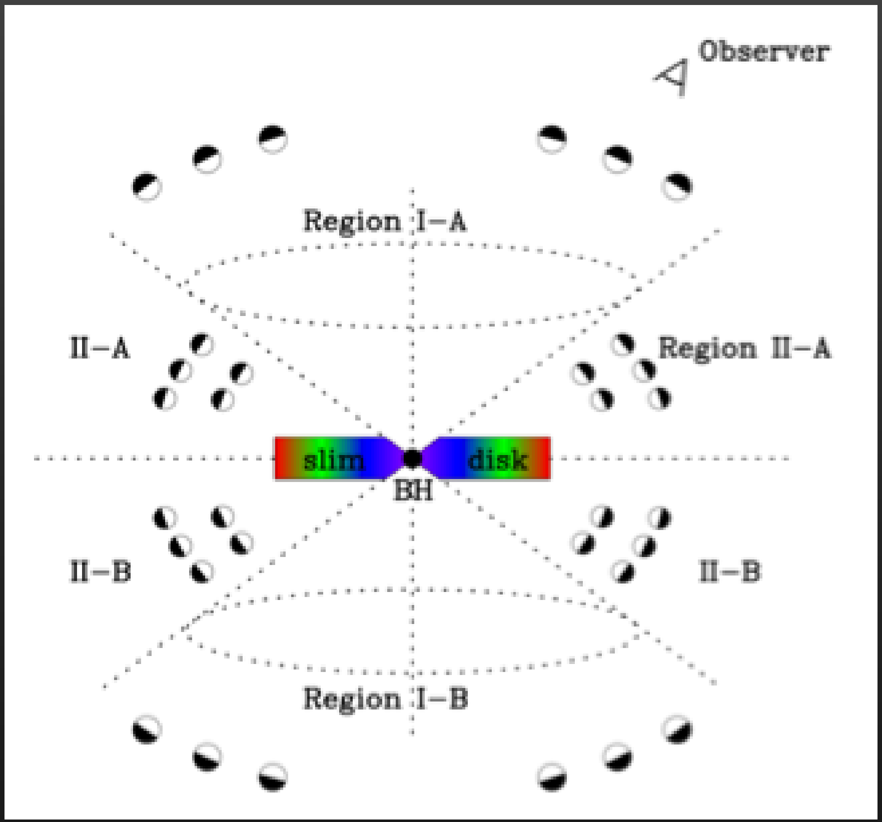




$$R_{\mathrm{H}\beta} = \alpha_1 \ell_{44}^{\beta_1} \min\left[1, \left(\frac{\dot{\mathscr{M}}}{\dot{\mathscr{M}}_{\mathrm{c}}}\right)^{-\gamma_1}\right],$$

$$\log \dot{\mathscr{M}} = 2.47 - 1.59\mathcal{D}_{\mathrm{H}\beta} + 1.34\mathcal{R}_{\mathrm{Fe}}$$

one of predictions in slim disk

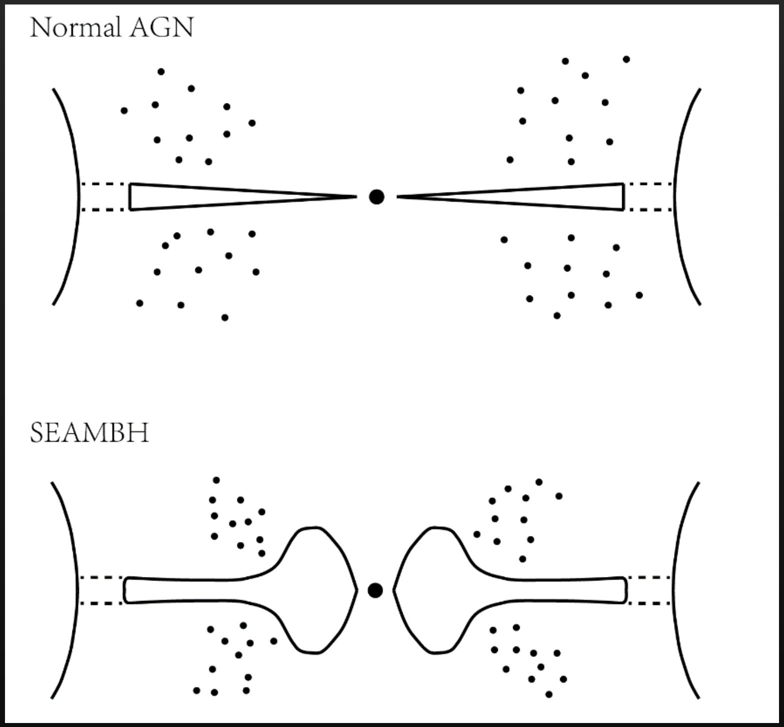


(Wang et al. 2014)

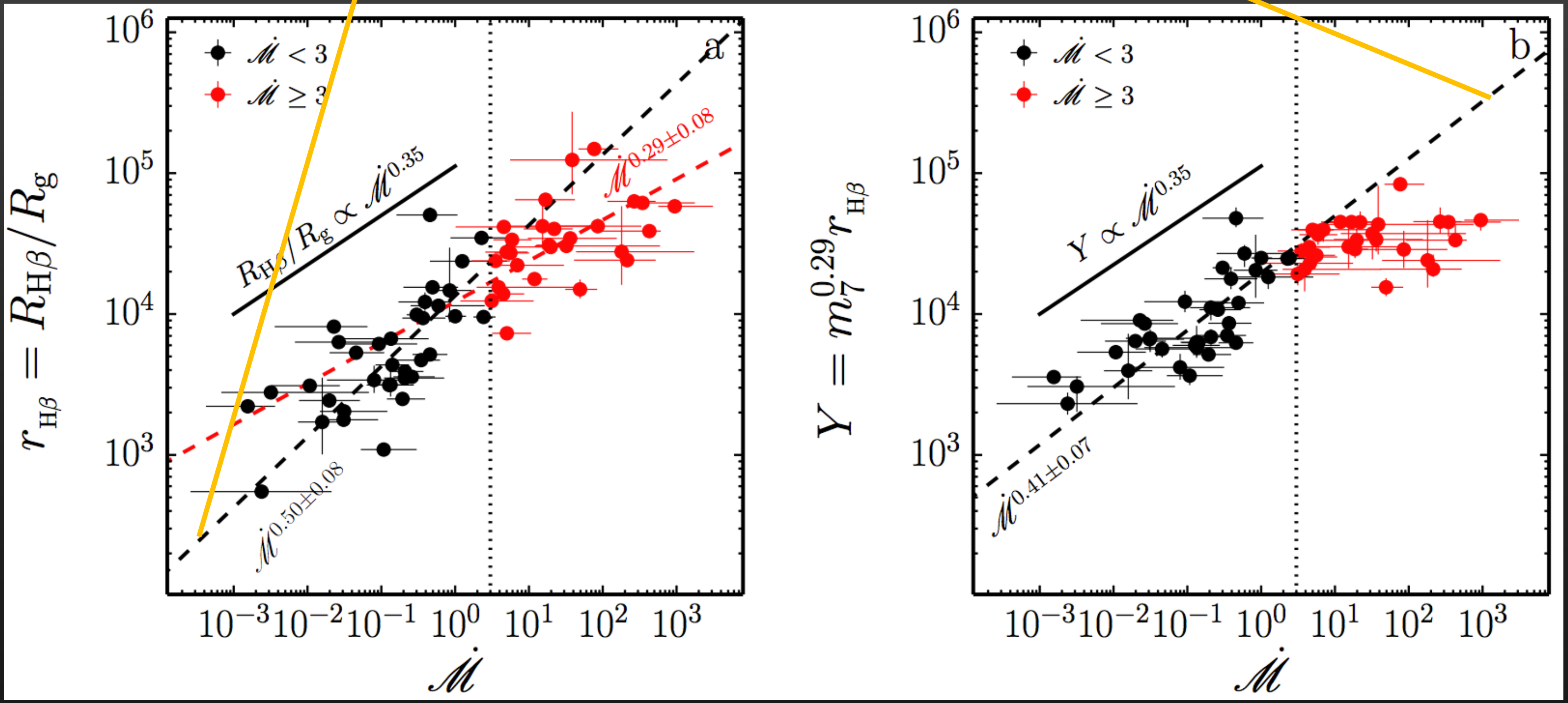
$$\frac{R_{\rm BLR,I}}{R_{\rm BLR,II}} \approx 2.0 \dot{\mathscr{M}}_{50}^{0.3},$$

Self-shadowing effect of slim accretion disk

$$\frac{R_{\rm BLR,I}}{R_{\rm BLR,II}} = \left(\frac{L_{\rm ion,I}}{L_{\rm ion,II}}\right)^{1/2} = \left(\frac{F_{\rm ion,I}}{F_{\rm ion,II}}\right)^{1/2},$$



Prediction of geometrically thin disk



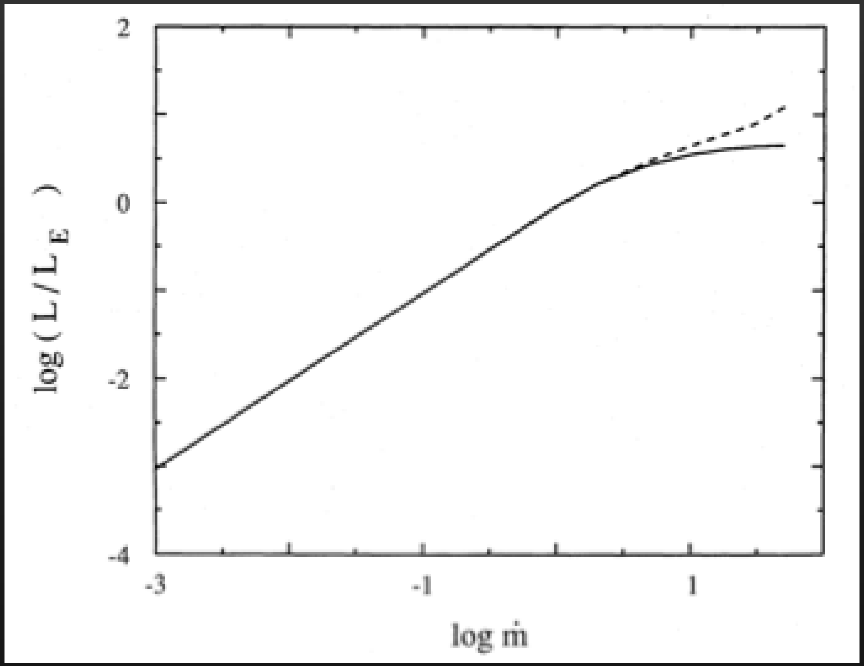
Du et al. (2016a)

$$r_{H\beta} = \frac{R_{H\beta}}{R_g} = 1.9 \times 10^4 \dot{\mathscr{M}}^{0.35} m_7^{-0.29},$$

$$Y = m_7^{0.29} r_{H\beta} = 1.9 \times 10^4 \dot{\mathscr{M}}^{0.35}$$

Slim accretion disk --- photon trapping effect

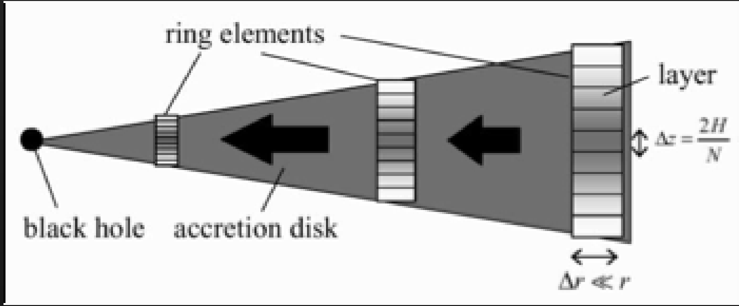
- Slim accretion disks (e.g., Abramowicz et al. 1988, Wang & Zhou 1999, Mineshige et al. 2000, Watarai et al. 2001, …)



$$Y = m_7^{0.29} r_{\mathrm{H}\beta}$$

$$L_{\bullet} = l_0(1 + a \ln \dot{M}_{\bullet}) M_{\bullet}$$

Photon trapping



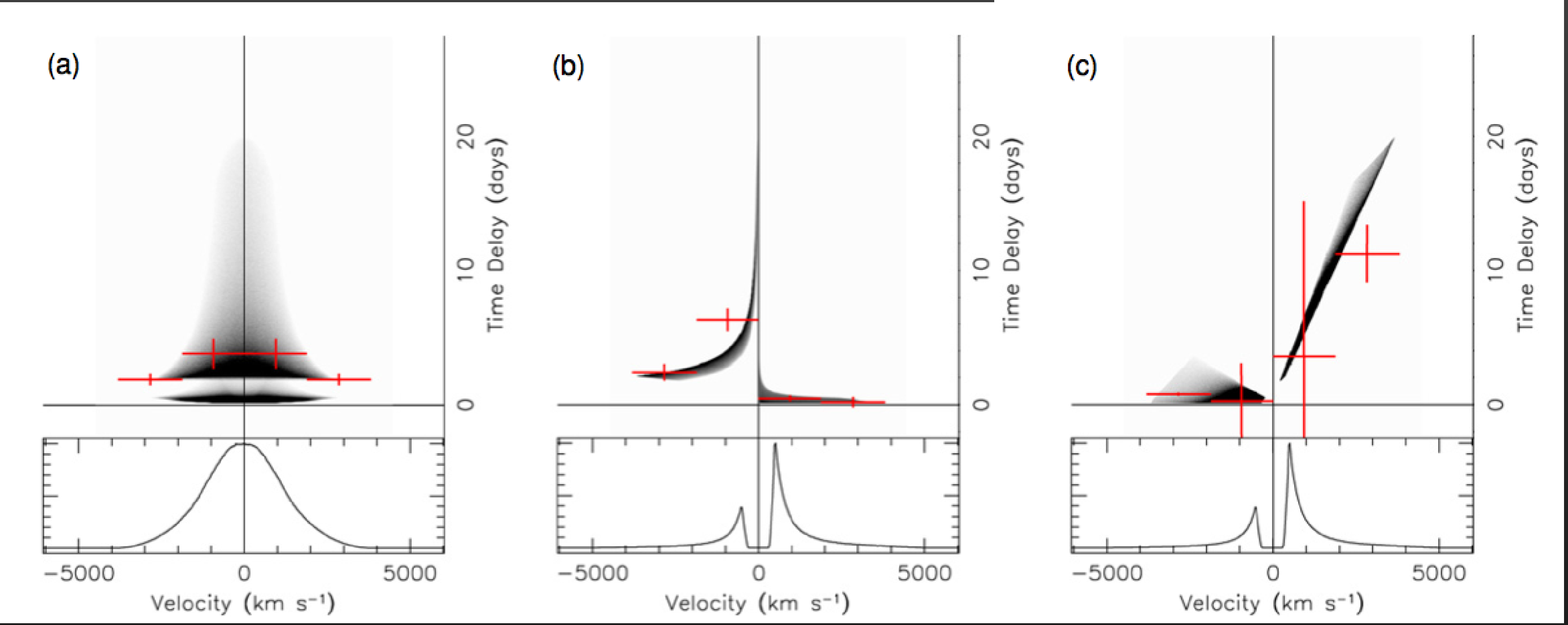
The dependence of L_{ion} on Mdot is weak.

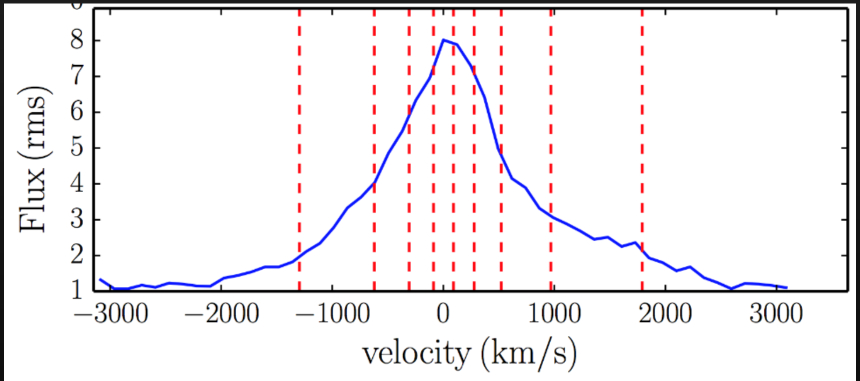
The dependence of R_{BLR} on Mdot is weak.

geometry and kinematics of BLR

Velocity-resolved time lags

$$\Delta L(V,t) = \int_0^\infty \Psi(V,\tau)\Delta C(t-\tau)d\tau$$



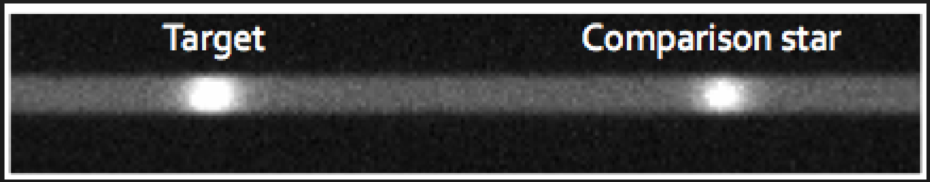


Broadening caused by the instruments

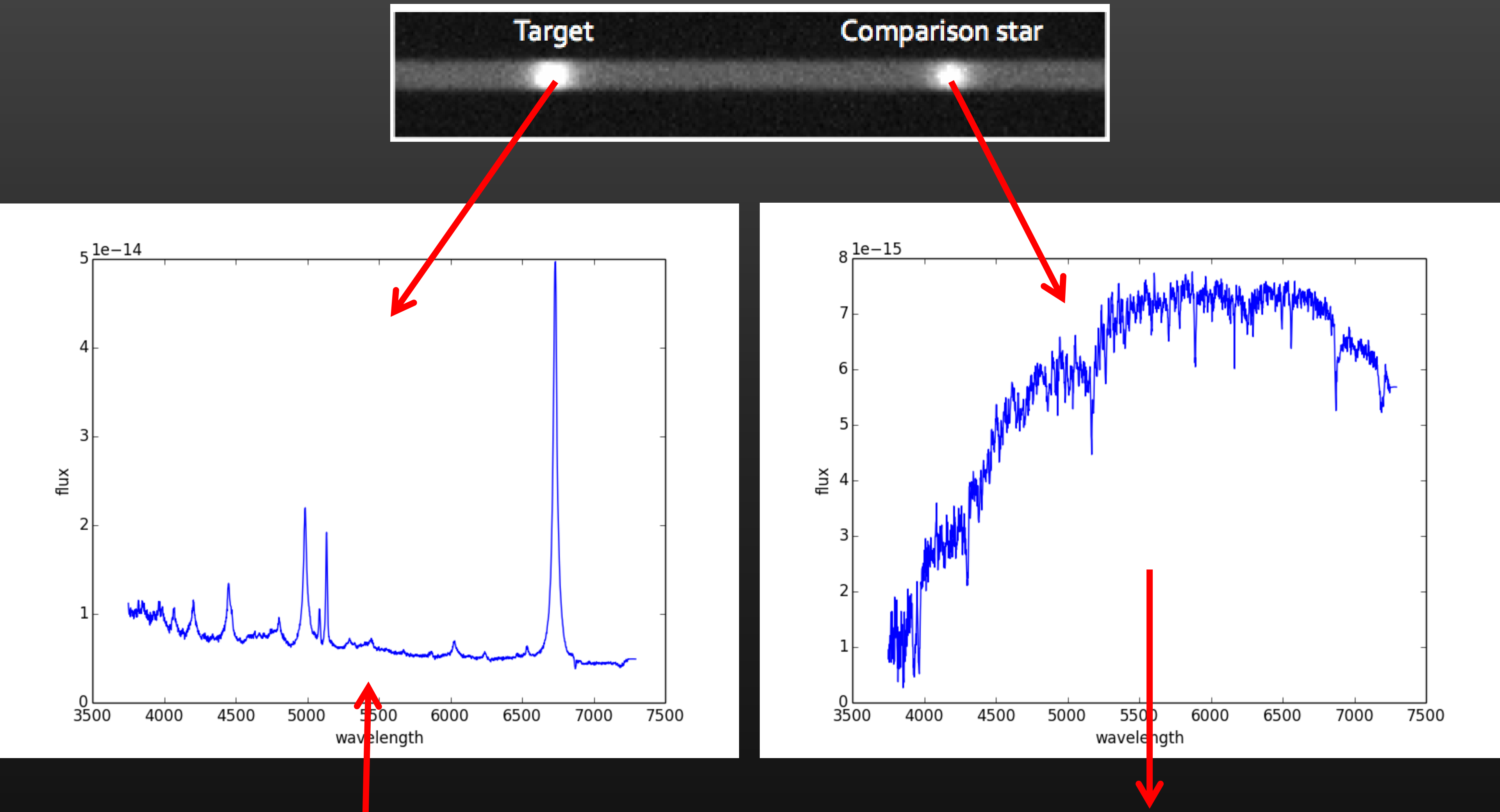
- Broadening ~ 500km/s, FWHM ~ 1000-1500km/s
- Wider slit --- more serious broadening
- The information in the dispersion direction --- lost

$$I_{\rm obs}(\lambda) = I_{\rm int}(\lambda) \otimes \xi(\lambda) = \int I_{\rm int}(\lambda')\xi(\lambda - \lambda')d\lambda'.$$

Fortunately



Richardson-Lucy deconvolution



Deconvolve ← Broadening Kernel

Du et al. 2016c

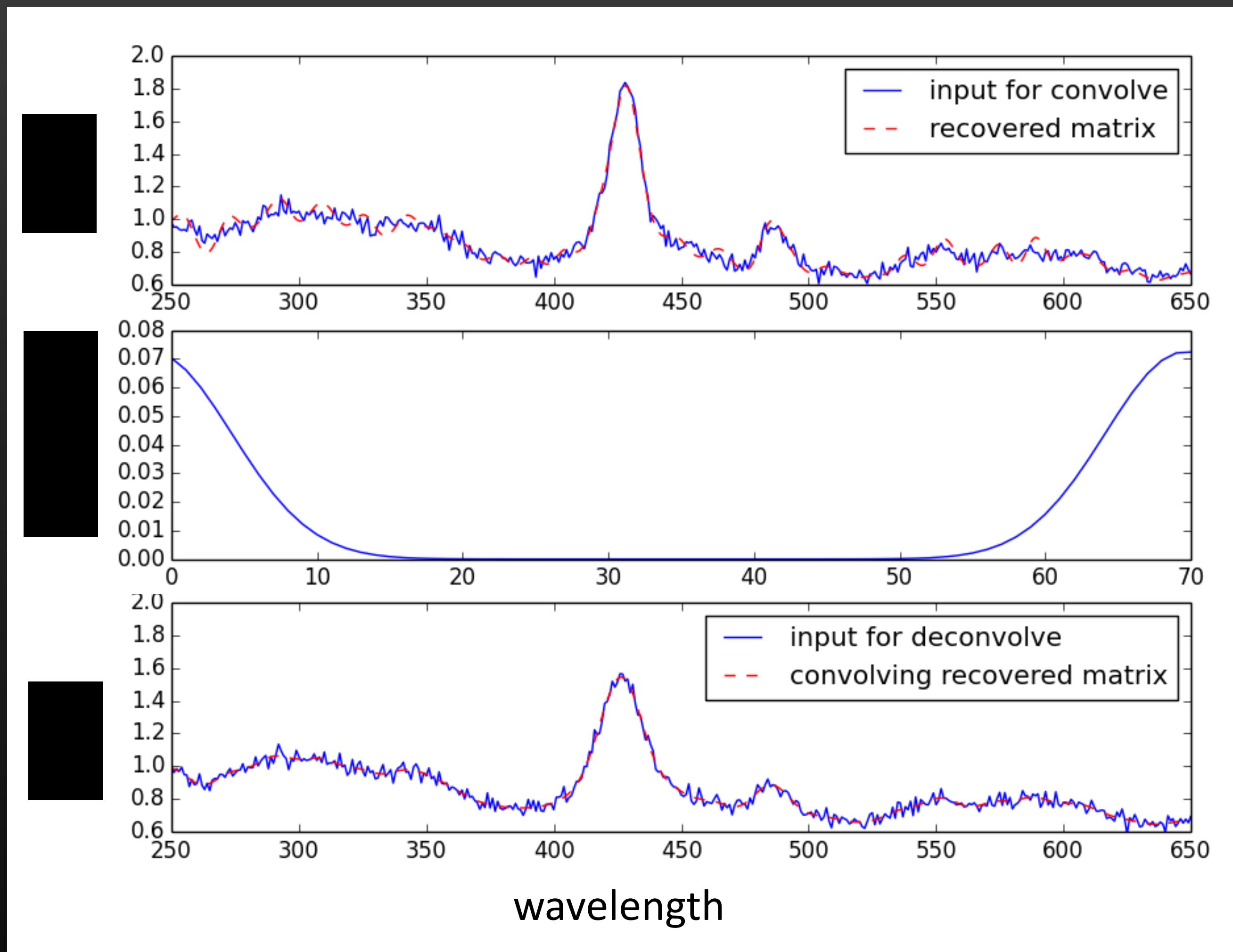
Richardson-Lucy deconvolution

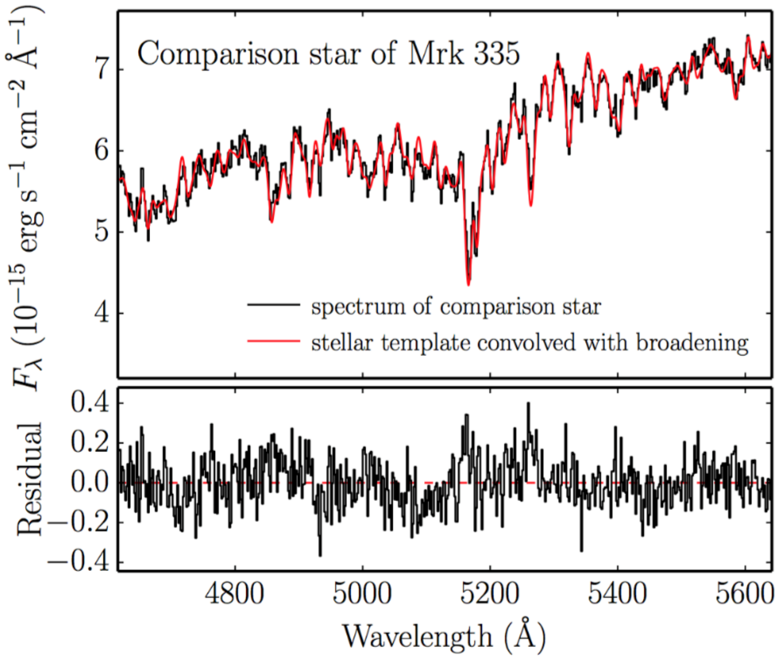
$$I_{\rm int}^{n+1}(\lambda') = I_{\rm int}^{n}(\lambda') \int \frac{I_{\rm obs}(\lambda)}{I_{\rm obs}^{n}(\lambda)} \xi(\lambda - \lambda') d\lambda,$$

where

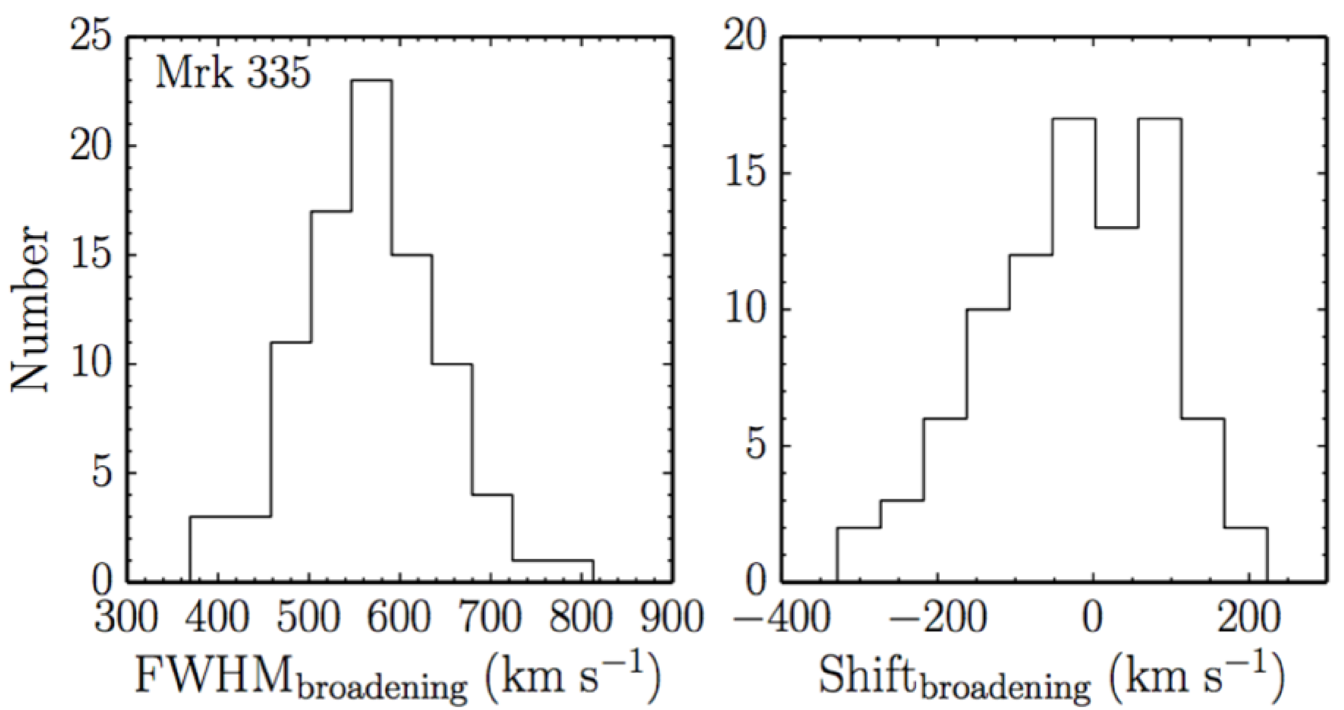
$$I_{\rm obs}^{n}(\lambda) = \int I_{\rm int}^{n}(\lambda') \xi(\lambda - \lambda') d\lambda'.$$

Richardson (1972) and Lucy (1974)



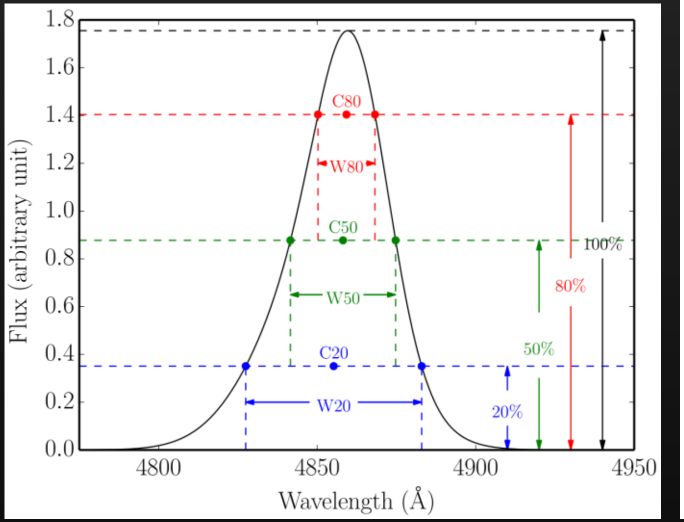


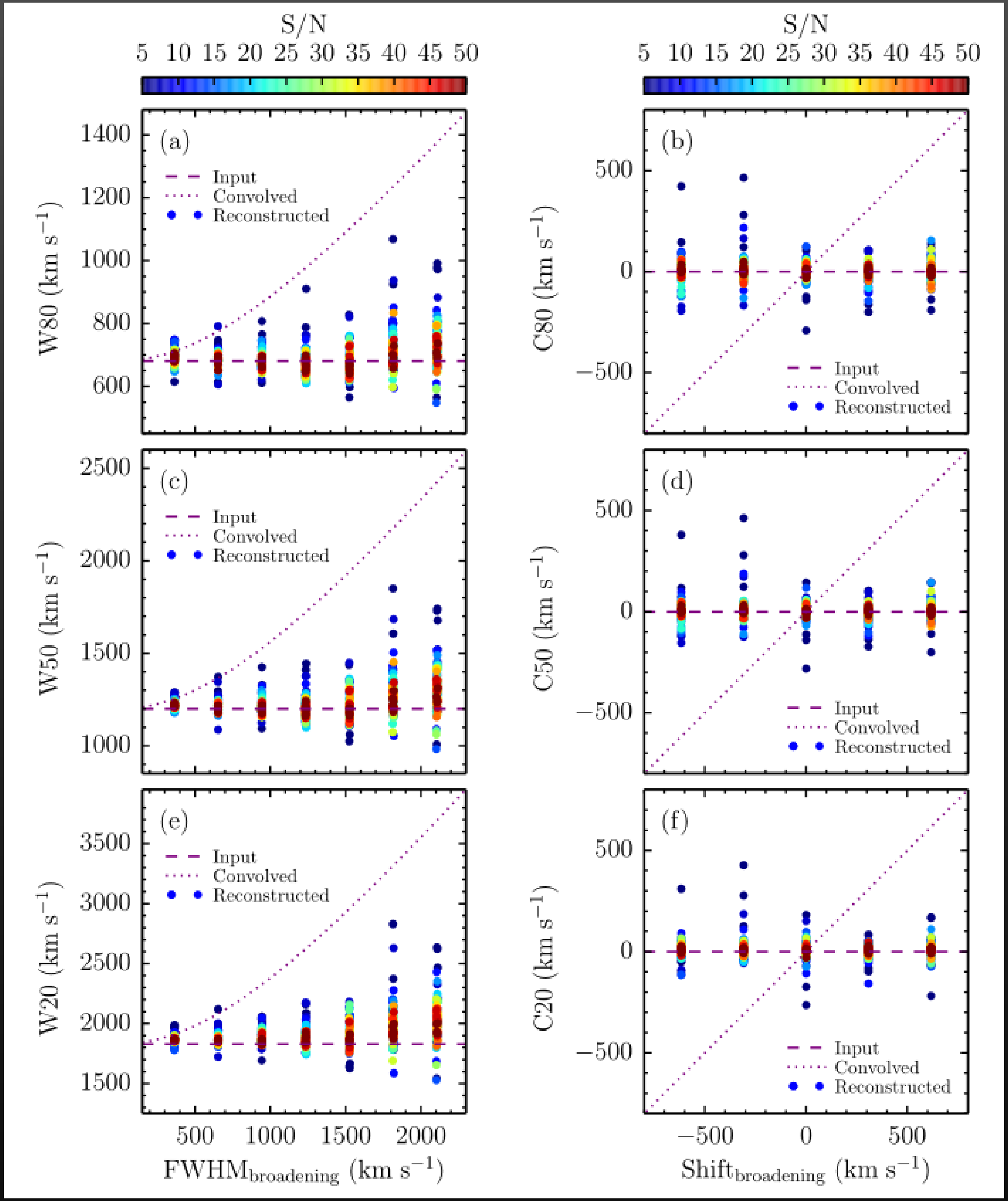
broadening

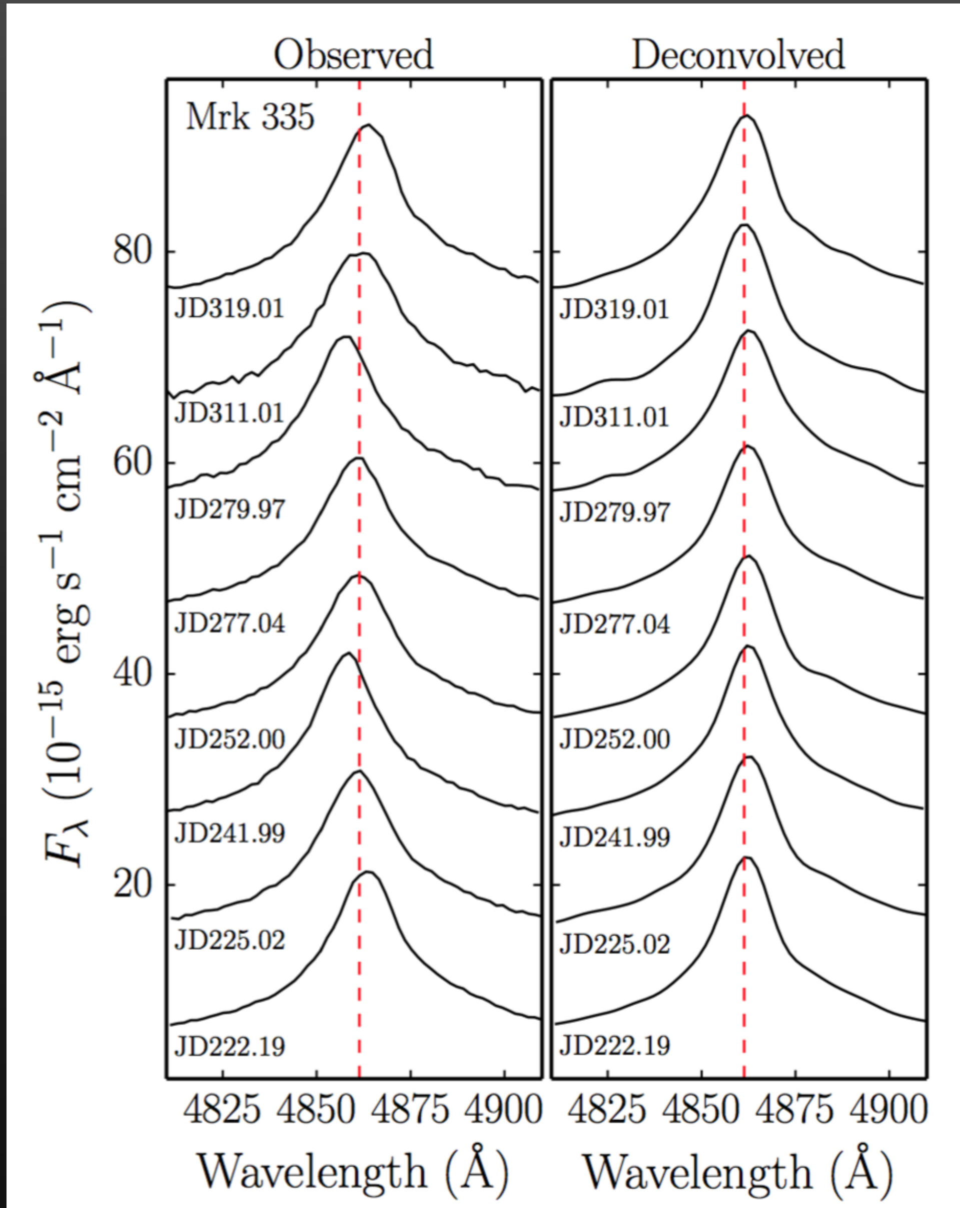


Du et al. 2016c

Simulations







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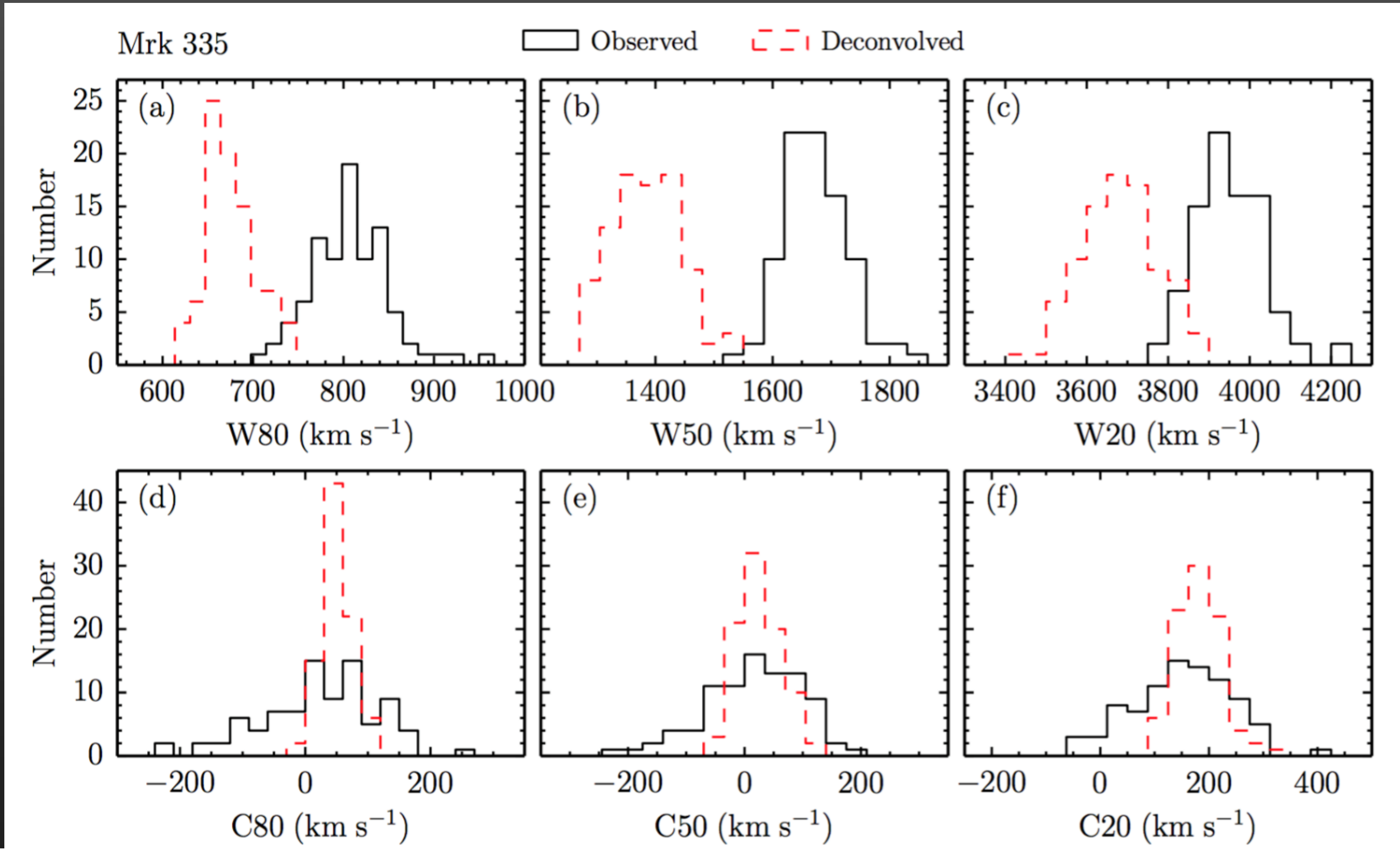
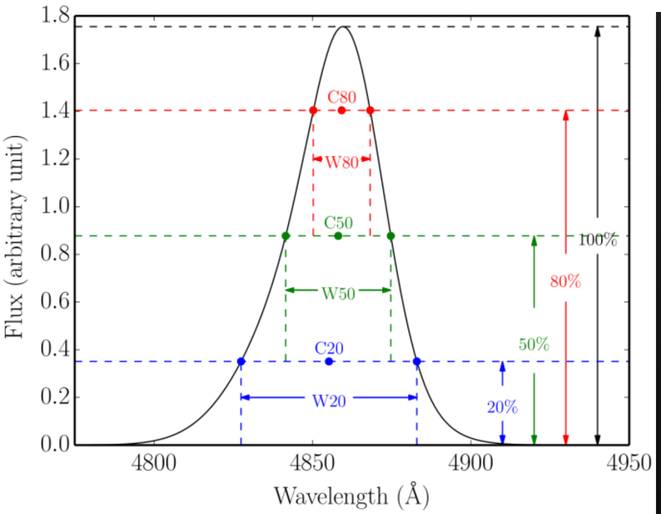
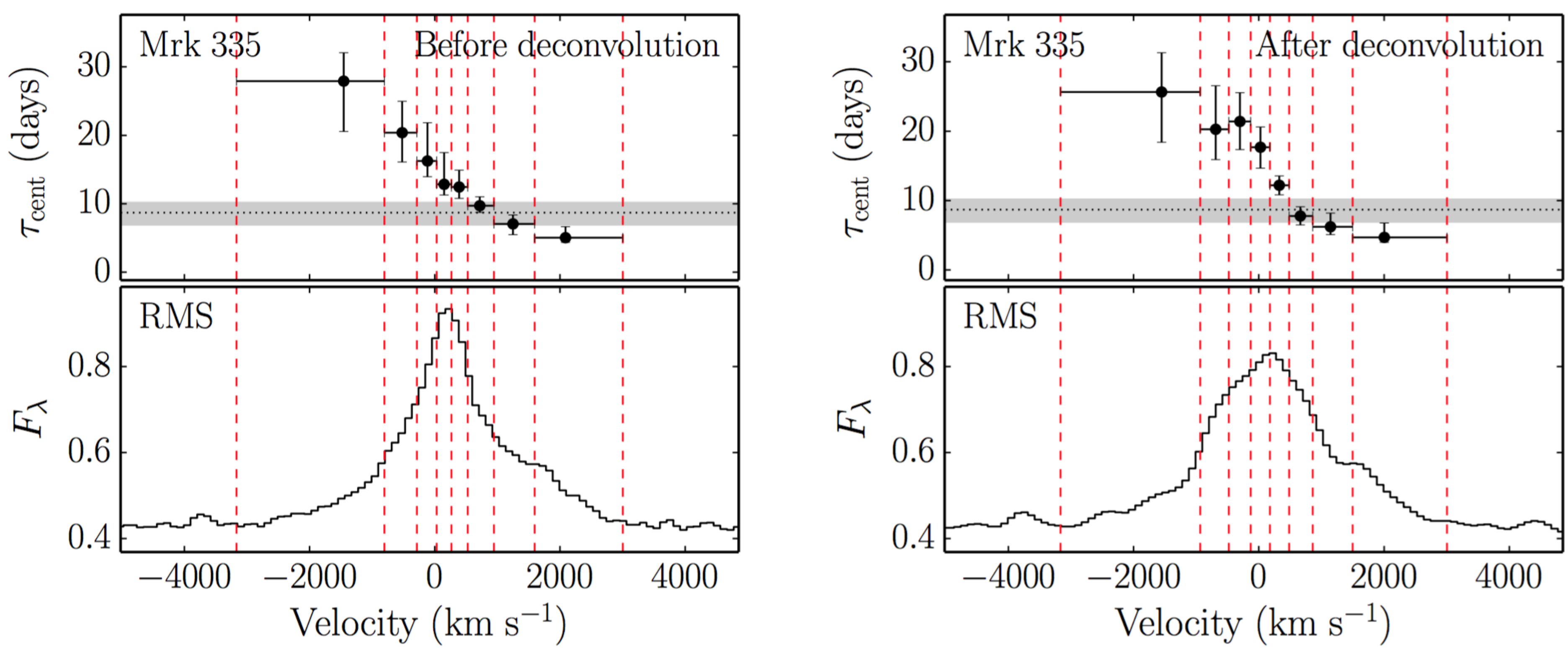


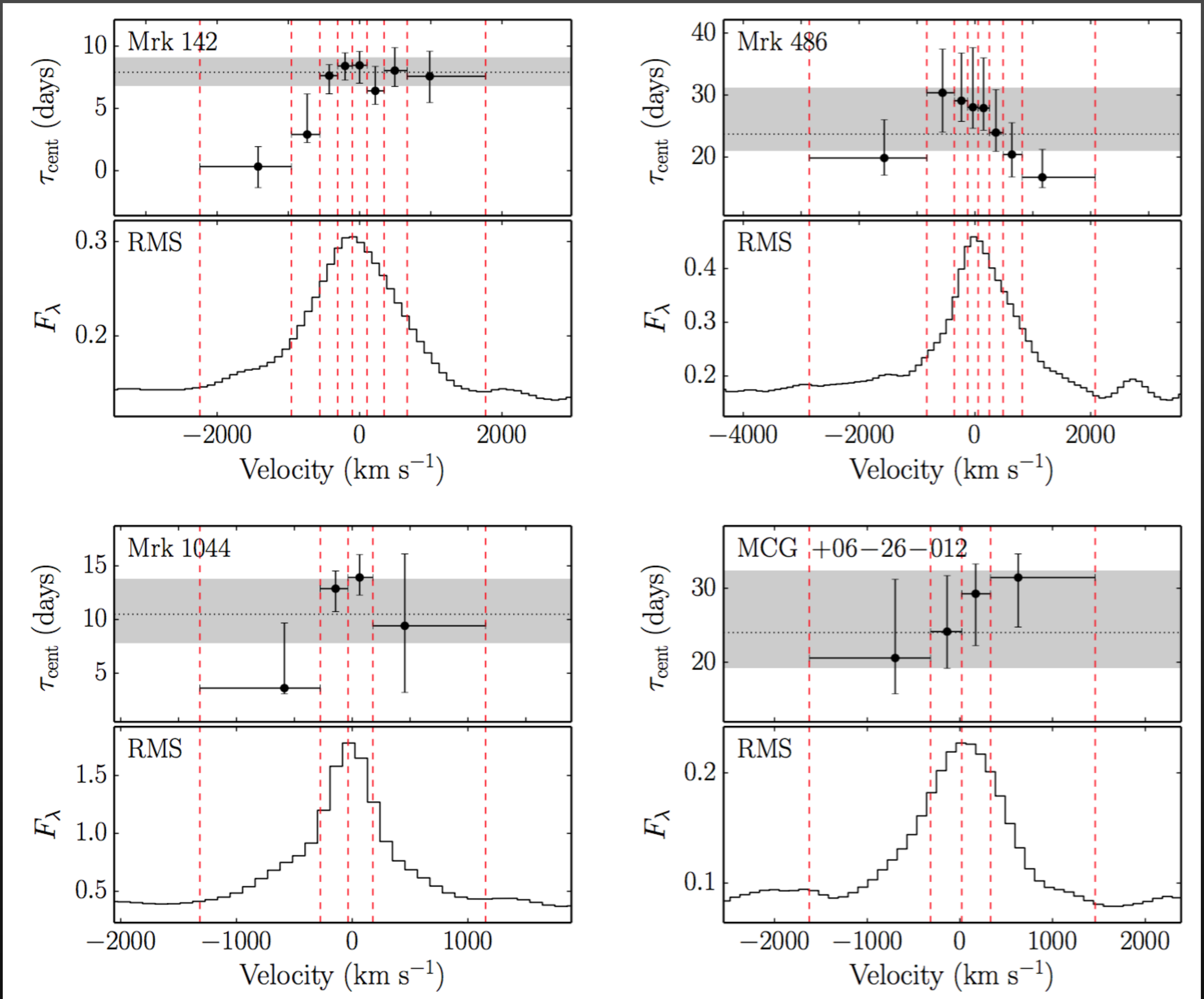


Du et al. 2016c

Before and after the deconvolution



Du et al. 2016c



Du et al. 2016c

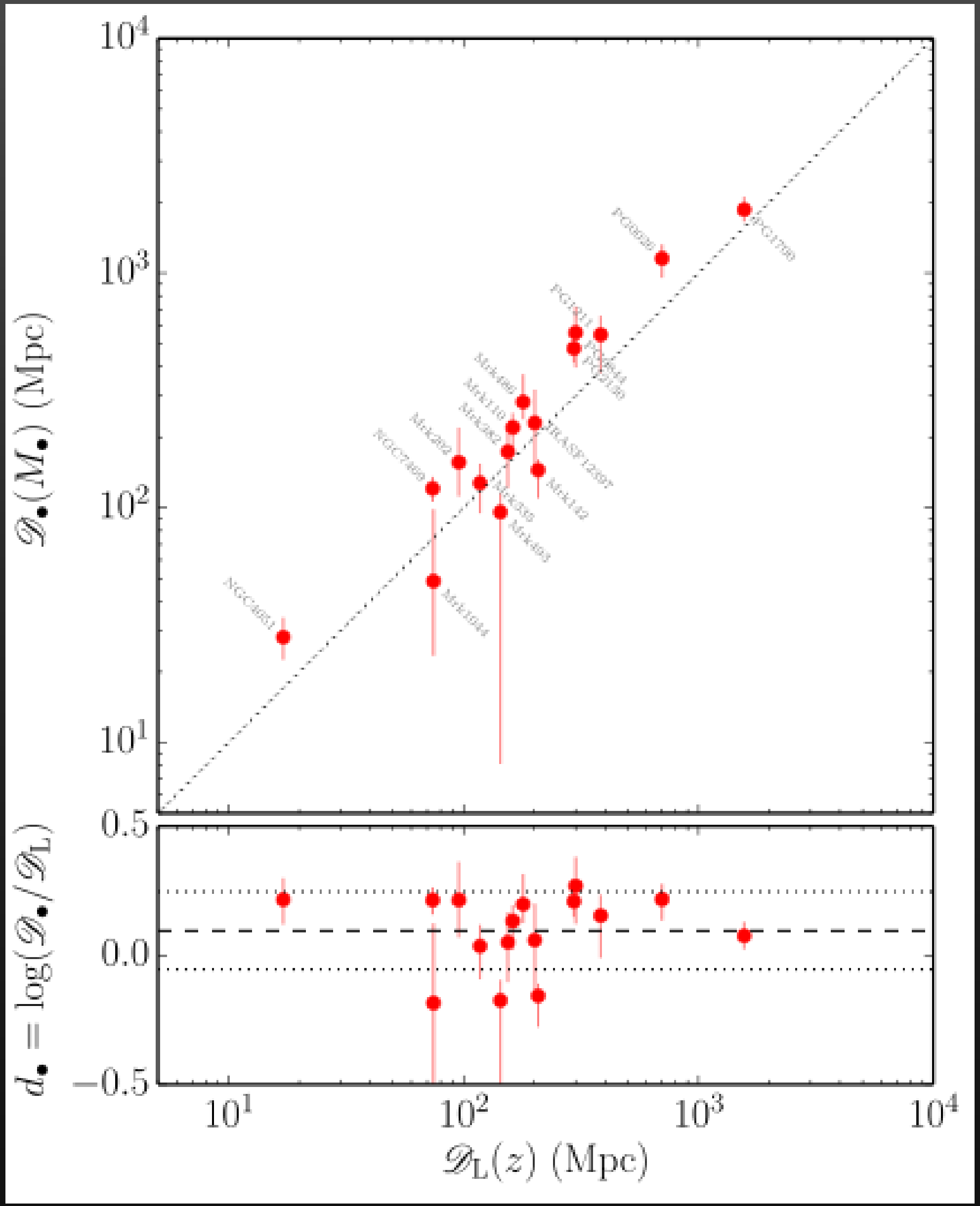
How precise if SEAMBHs are distance probes?

luminosity distance

$$\mathscr{D}_\bullet = 250.3\, \ell_\kappa^{1/2} m_7^{2/3} F_{11}^{-1/2}\ \mathrm{Mpc}\,,$$

$$\ell_\kappa = \xi \ell_\odot / \kappa_{40}$$

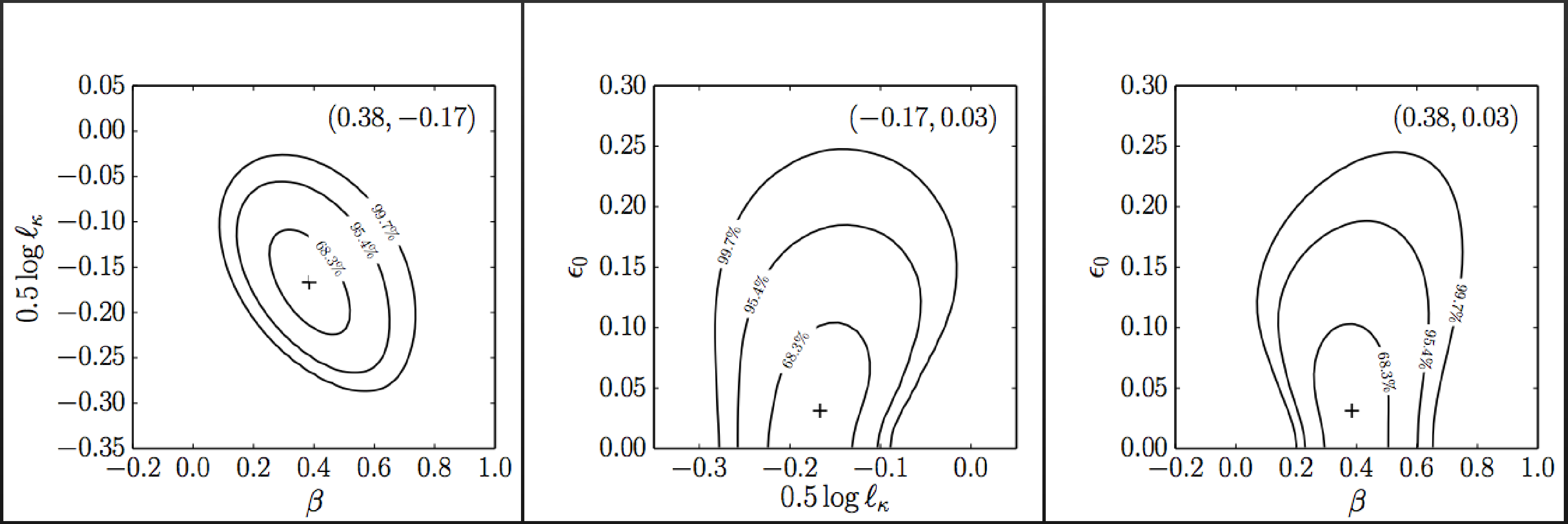
$$\kappa_{\mathrm{Bol}} \approx \kappa_0 m_7^{-1/3},$$



calibration

$$\mathscr{D}_\bullet = 250.3\, \ell_\kappa^{1/2} m_7^{2/3} F_{11}^{-1/2}\ \mathrm{Mpc}\,, \quad \rightarrow \quad \mathscr{D}_\bullet = 250.3\, \ell_\kappa^{1/2} m_7^{(1+\beta)/2} F_{11}^{-1/2}\ \mathrm{Mpc}$$

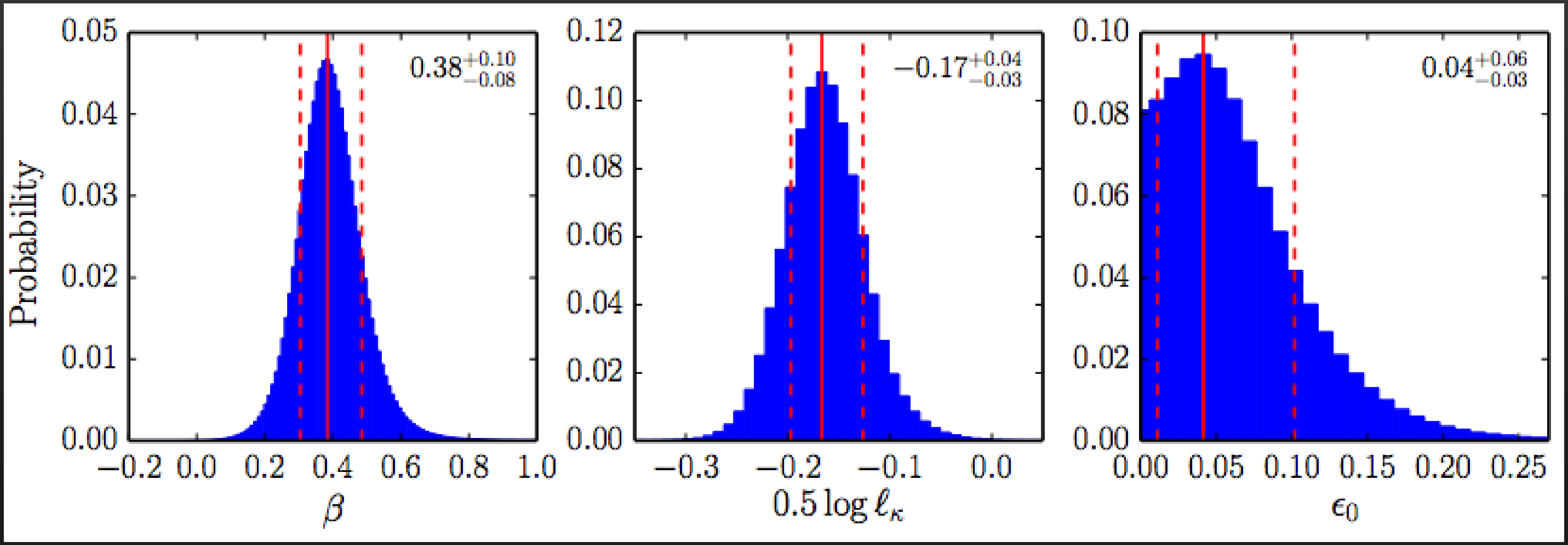
$$P(\ell, \beta, \epsilon_0 \mid \{m_i\}, \{F_i\})$$



$$\kappa_{\mathrm{Bol}} \approx \kappa_0 m_7^{-1/3}, \quad \rightarrow \quad \beta$$

calibration

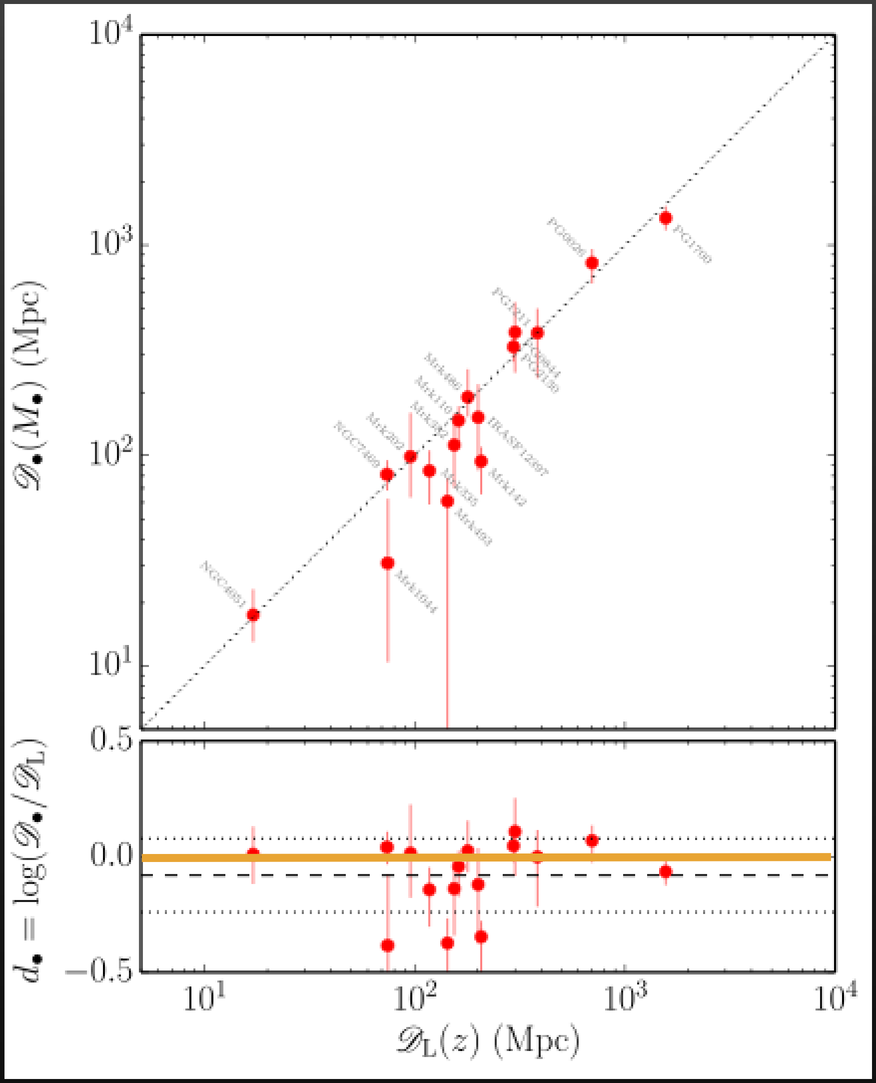
$$P(\ell, \beta, \epsilon_0 \mid \{m_i\}, \{F_i\})$$



least chisq $\ell_\kappa = 0.54$

After calibration

1st year Lijiang observations



Du et al. (2014)+Wang et al. (2014)

Observed scatter:
~0.15dex

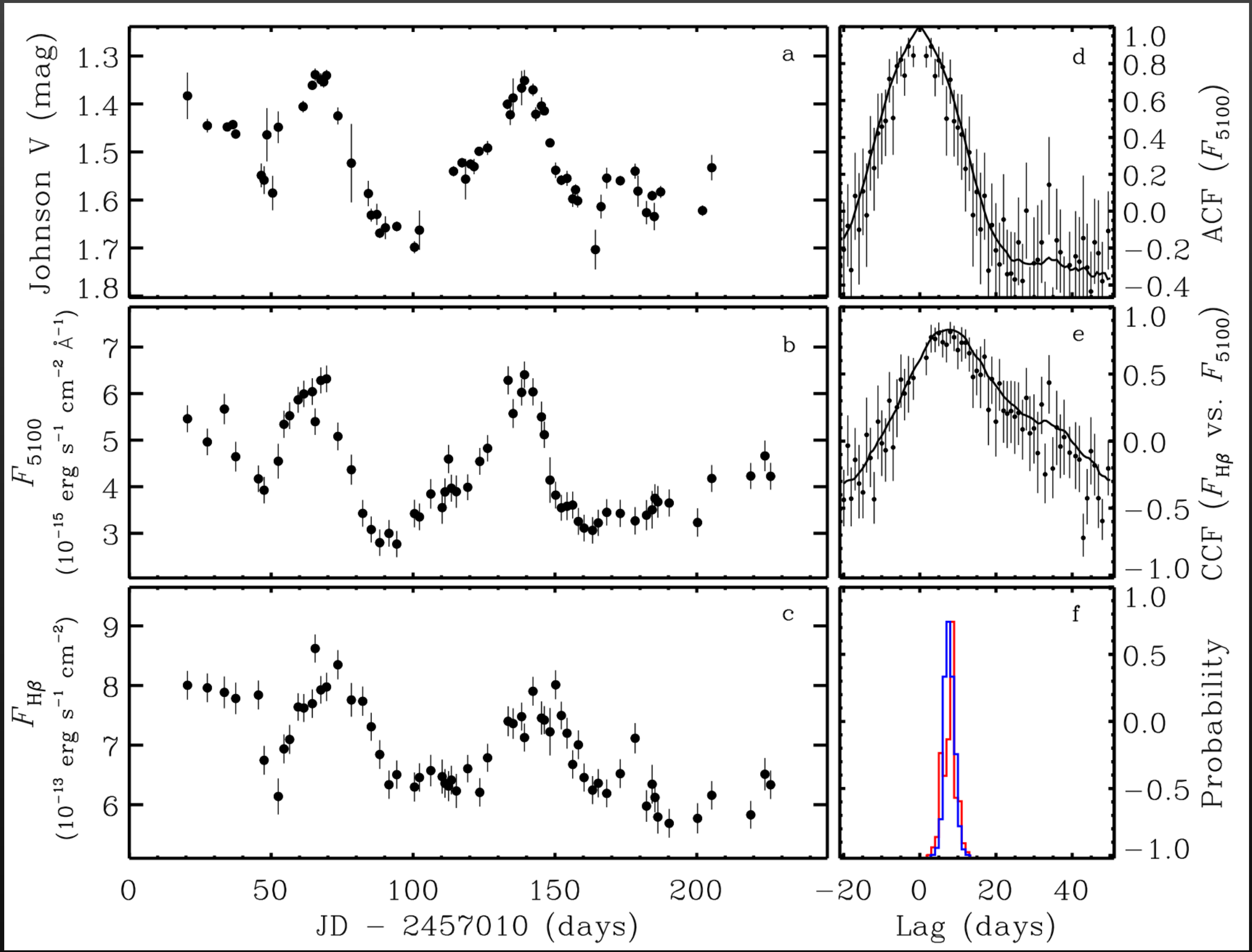
Estimated intrinsic
scatter : ~0.04 dex.

SEAMBHs:
good quality standard
candles

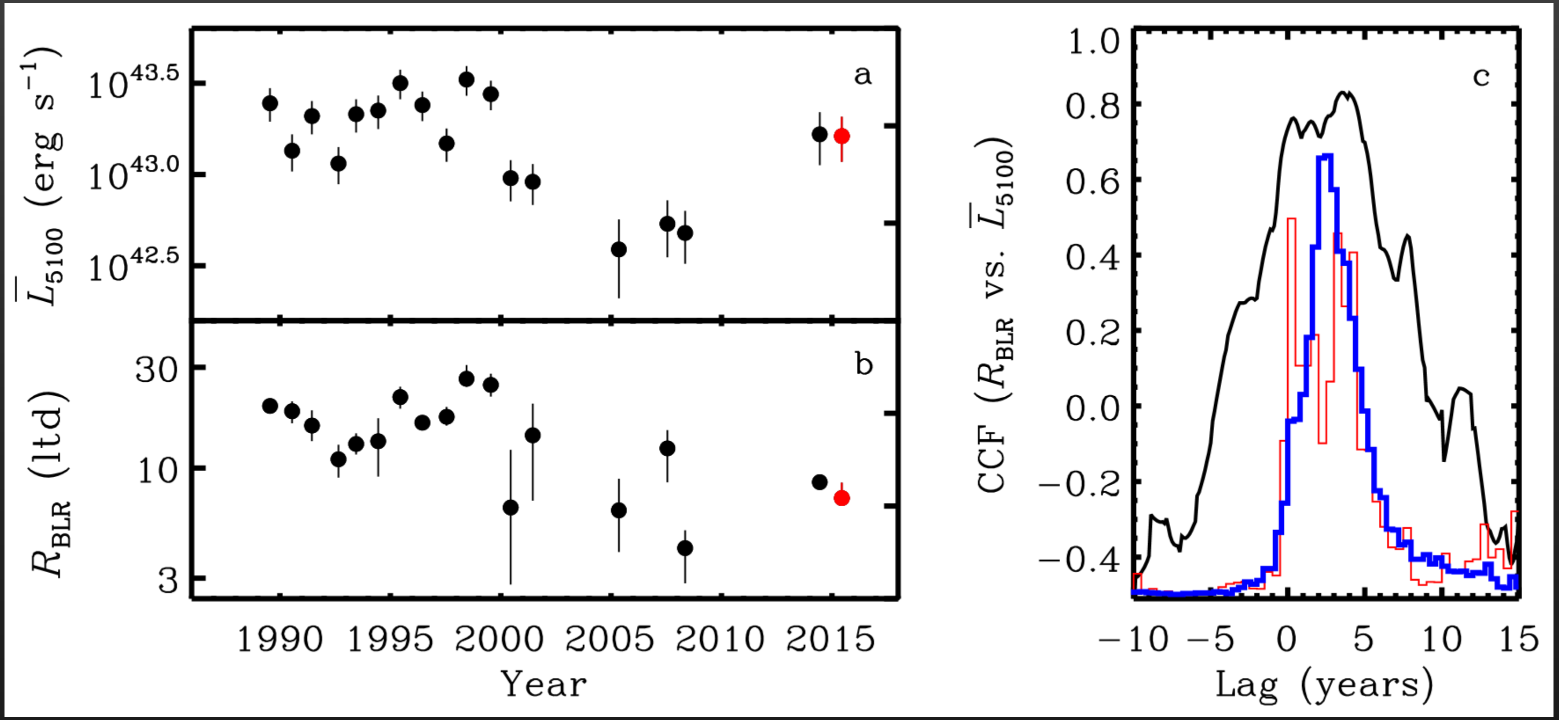
Nearby AGNs with normal accretion rates

NGC 5548

(Lu, Du et al. 2016)



NGC 5548



$$t_{\rm BLR} = \frac{c\tau_{\rm H\beta}}{V_{\rm FWHM}} = 3.36\ \tau_{20}\, V_{5000}^{-1}\ \text{years},$$

(Lu, Du et al. 2016)

Summary

- SEAMBHs: shorter Hβ time lags (by a factor 2-8);
- New scaling relation & fundamental plane: BH mass estimator
- Saturated luminosity: probe the distance in the universe
    - -The accuracy of SEAMBH candle: ~ 0.15 dex;
- Deconvolution and velocity-resolved time lags;
- NGC 5548: evidence for radiation pressure

Thanks!