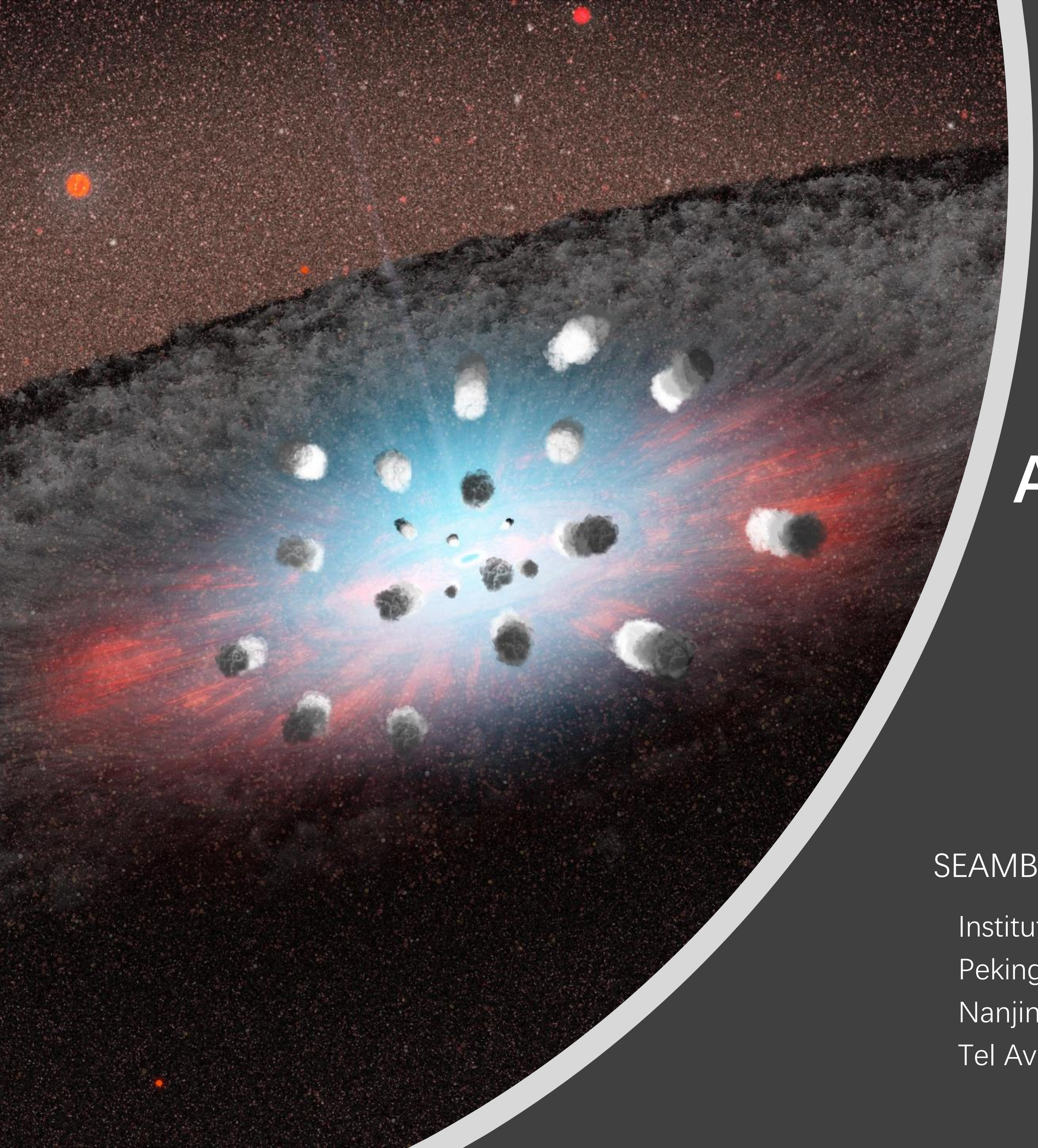


Reverberation Mapping of AGNs with High Accretion Rates

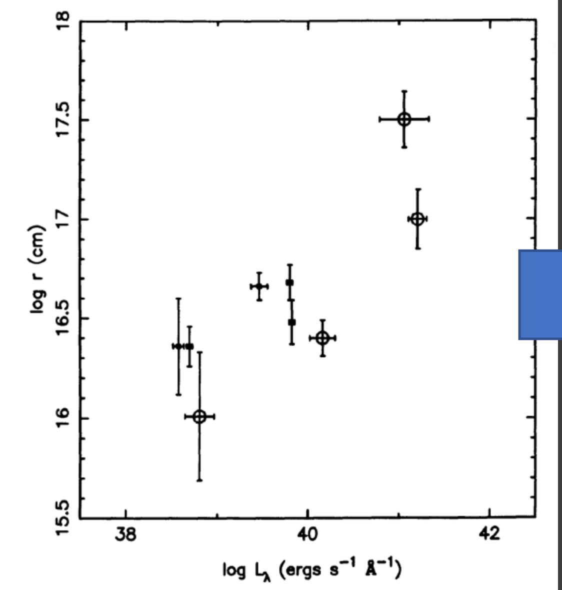
Pu Du

Institute of High Energy Physics (IHEP), CAS

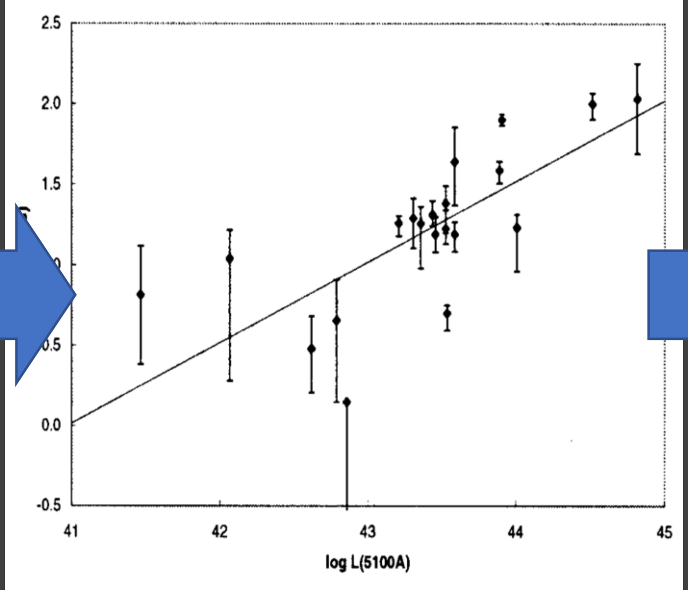
SEAMBH collaboration (PI: Jian-Min Wang)

Institute of High Energy Physics
Peking University
Nanjing Normal University
Tel Aviv University (2012-2015)
Yunnan Observatories
University of Science and Technology of China
Nanjing University

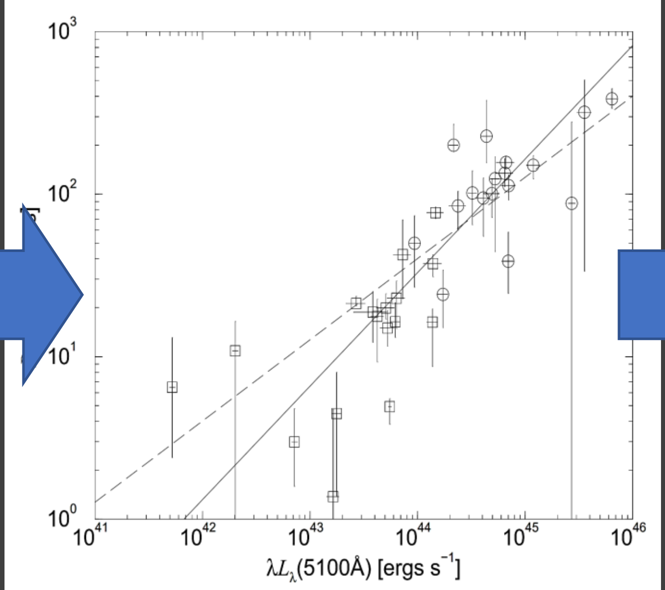
R-L relationship



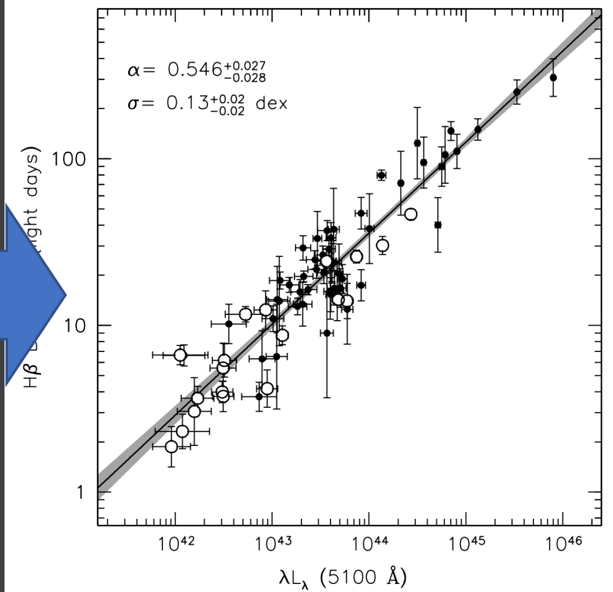
Peterson (1993)



Wandel, Peterson, Malkan (1999)

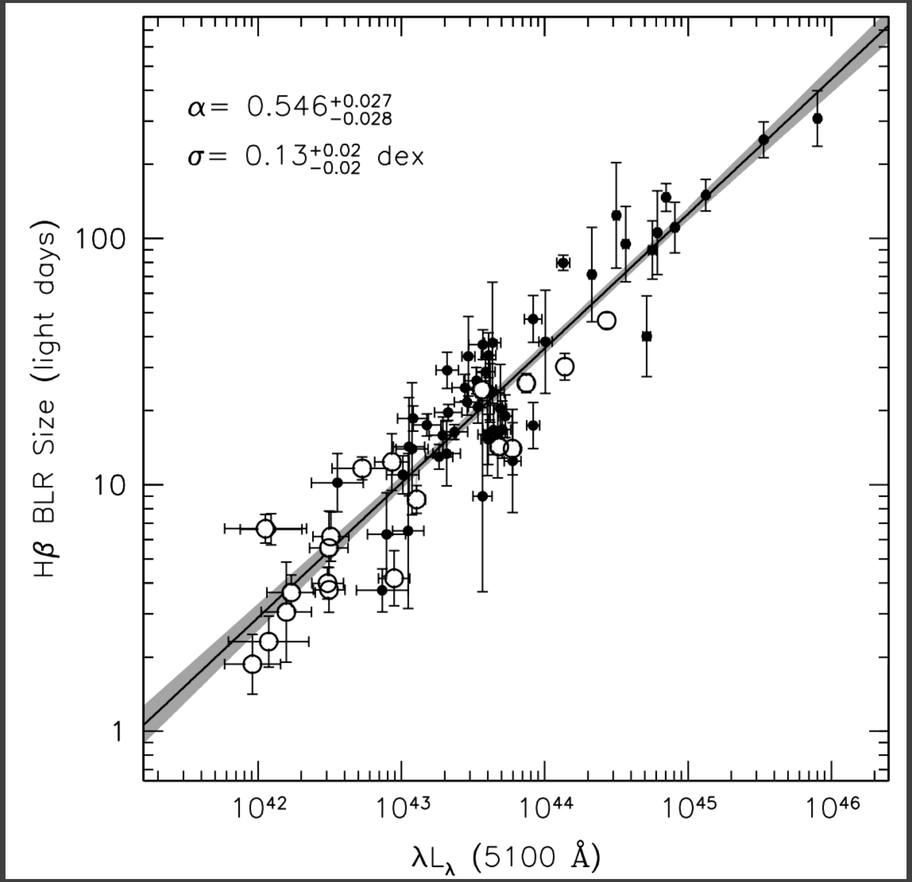


Kaspi et al. (2000)



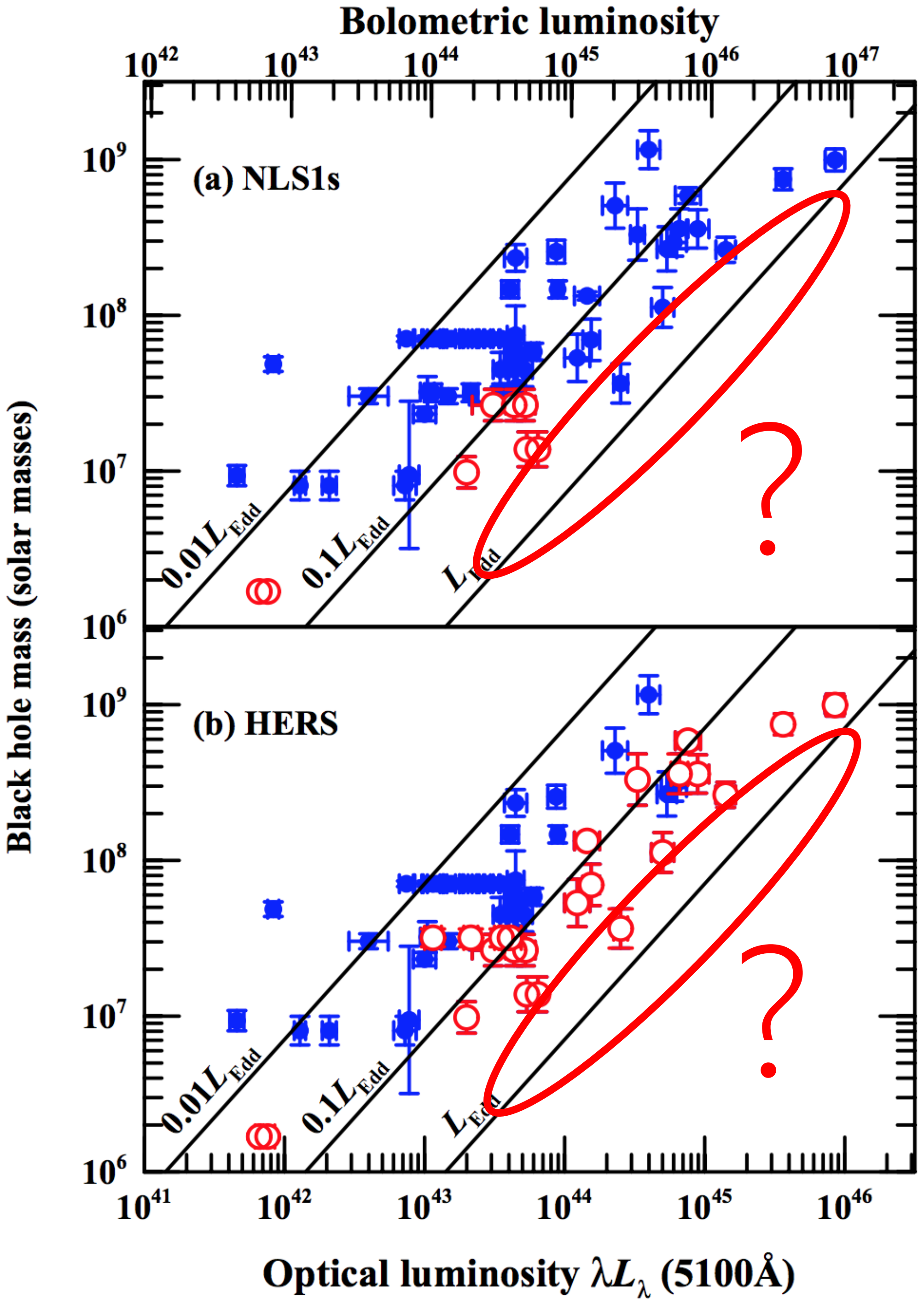
Bentz et al. (2013)

R-L relationship



Bentz et al. 2013

?



High accretion rate AGNs?

- Lack of AGNs with high accretion rates
- High-accretion-rate AGNs are more abundant in high-z universe
- Different or not?

Peterson (2011)

Accretion regimes?

Low accretion disks
(ADAF; ADIOs)

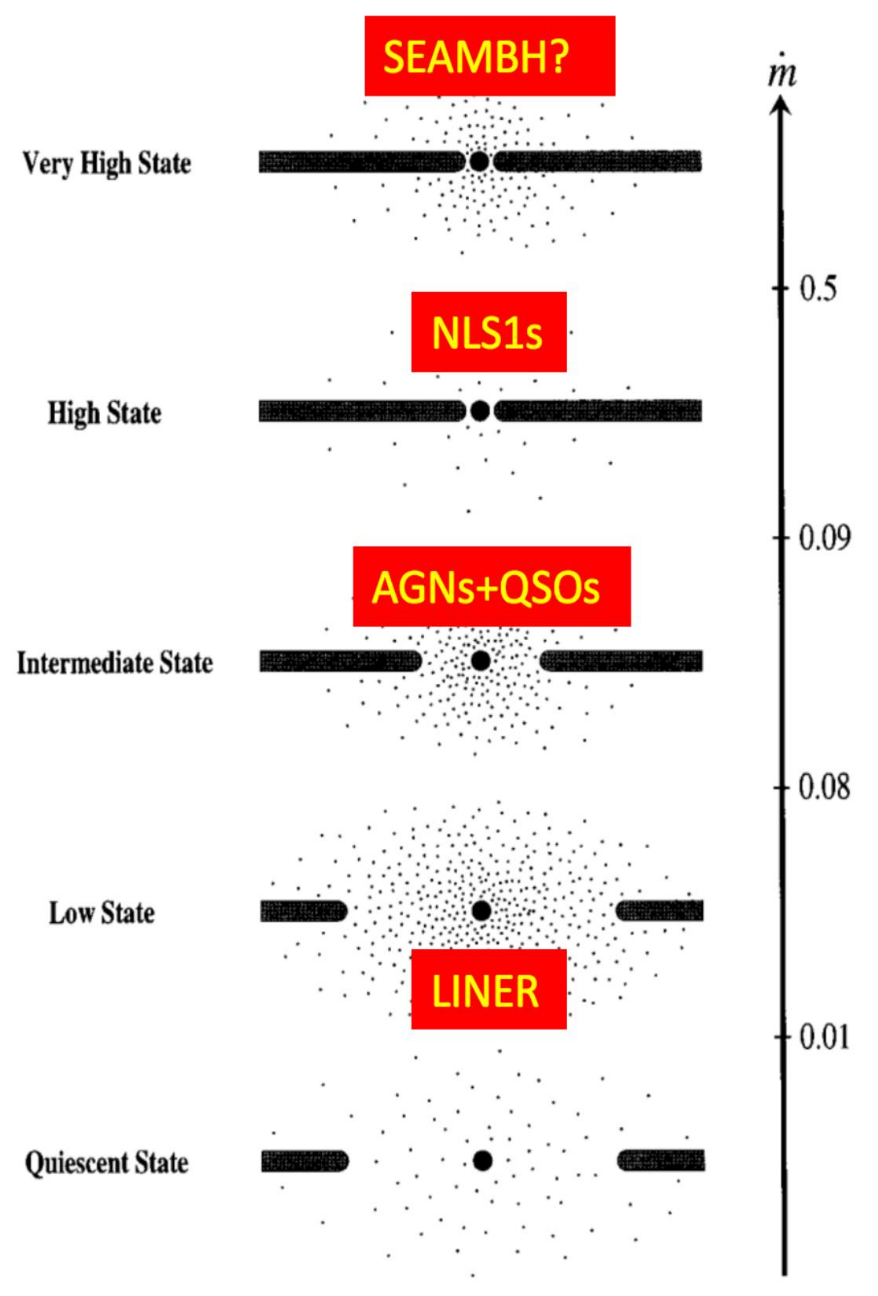
$$L_{\rm rad} \propto \dot{M}^2$$

Shakura-Sunyaev disk
(intermediate rates)

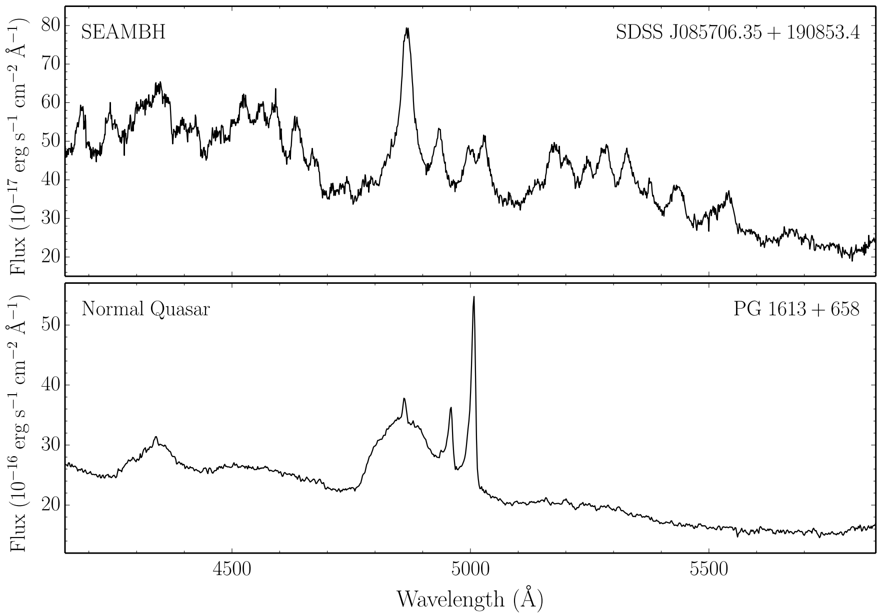
$$L_{\rm rad} \propto \dot{M}$$

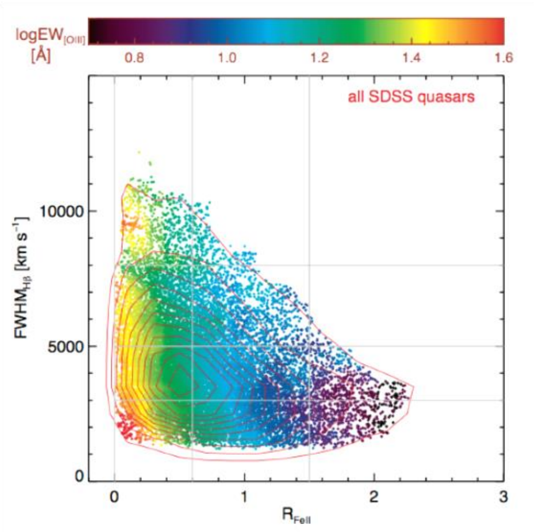
Slim disks
(high accretion rates)

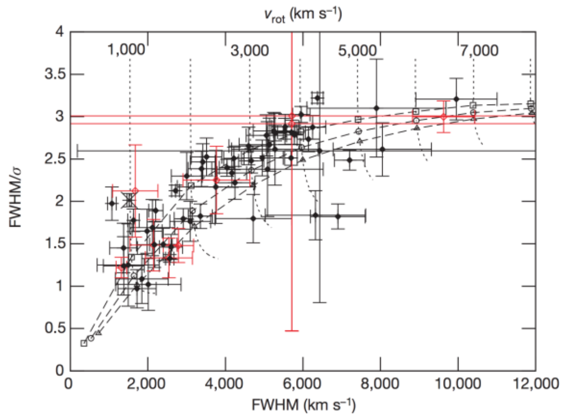
$$L_{\bullet} = l_0 (1 + a \ln \dot{M}_{\bullet}) M_{\bullet}$$



BLR Physics: different







SEAMBH project

- a RM campaign targeting

  Super-Eddington Accreting Massive Black Holes (SEAMBHs)

- to understand:

  1. the physics of the SEAMBHs
  2. SEAMBHs as cosmological distances

Sample selection

- Strong Fe II emission
- Single-epoch spectroscopy based on

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

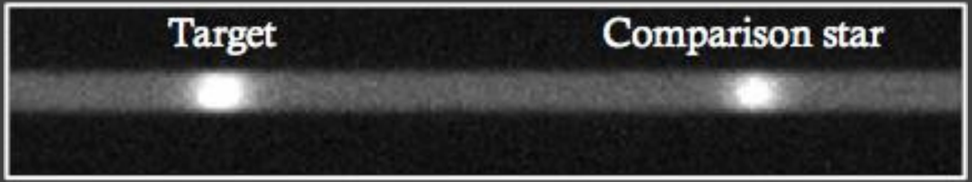
$$\dot{\mathscr{M}} = \dot{M}_\bullet / L_{\mathrm{Edd}} c^{-2}$$

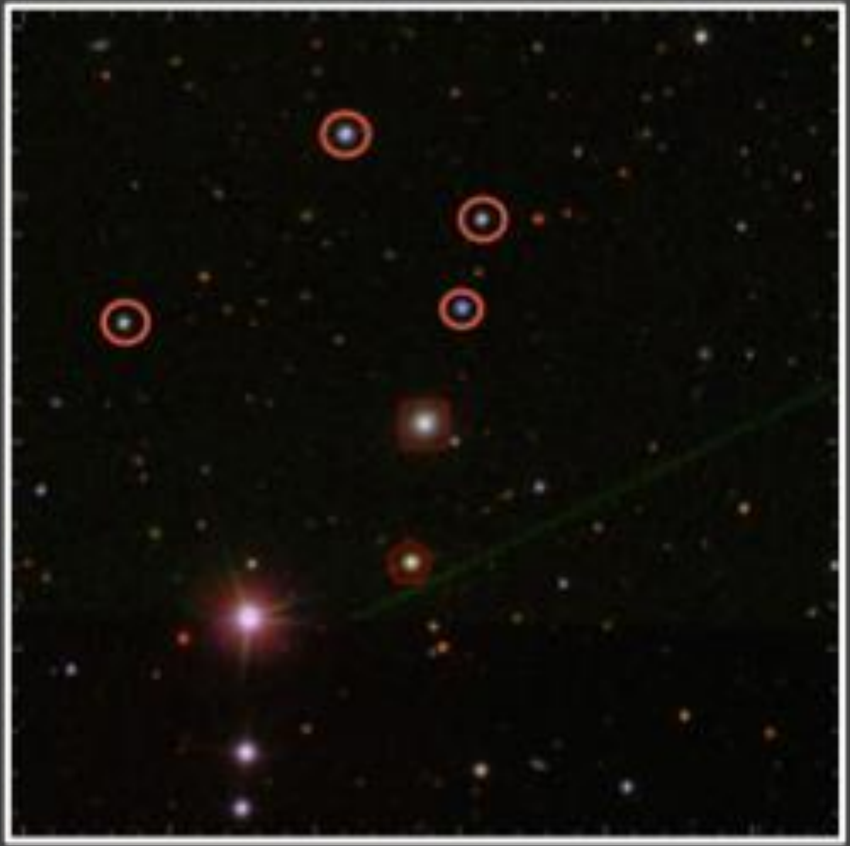
Sample

- SEAMBH2012:
  9 of 10 objects (z<0.1)
- SEAMBH2013:
  5 of 8 objects (0.1<z<0.2)
- SEAMBH2014:
  5 of 10 objects (0.1<z<0.3)
- SEAMBH2015-2016:
  10 of 10 objects (0.1<z<0.4)
- SEAMBH2017-2018:
  SEAMBHs with longer lags & Mg II

Observing strategy

- Observe a nearby comparison star along the slit simultaneously
- Photometry to test the variation
- [OIII] too weak!





Observation

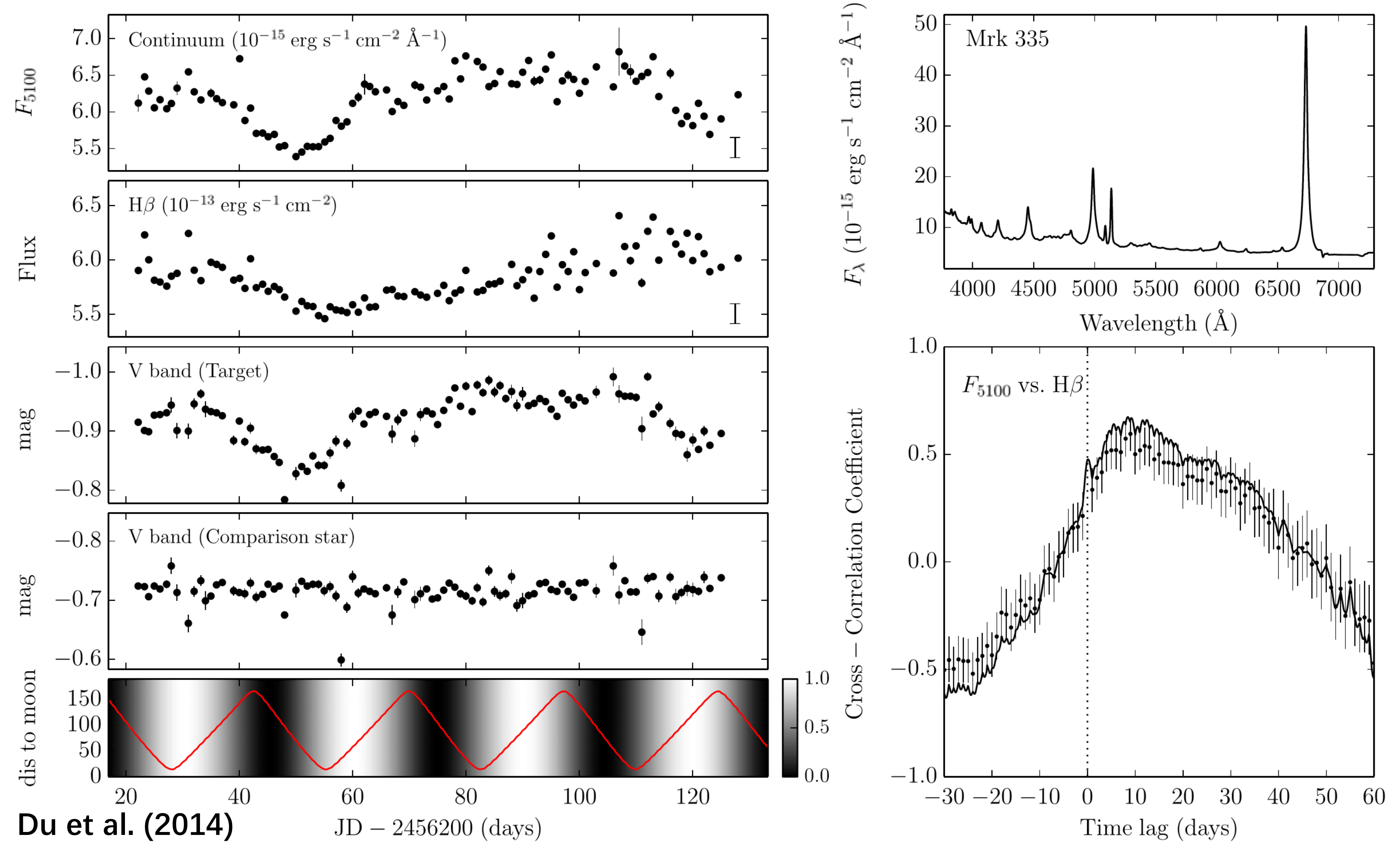
- Sampling interval
- 2012: 1~2 d (τ~7-15 d)
- 2013: 5~6 d (τ~15-40 d)
- 2014: 6~7 d (τ~15-60 d)
- 15-16: 5~7 d (τ~25-100 d)
- 17-18: 5~7 d (τ~50-150 d)

- Observational period
- 2012: 110~200 d
- 2013: 160~200 d
- 2014: 150~200 d
- 15-16: 180~600 d
- 17-18: 400~600 d

Famous objects: Mrk 335, Mrk 142, Mrk 1044, Mrk 382,
Mrk 493, KUG 1031+398, Ark 564,
some PG quasars, ……

Mrk 335

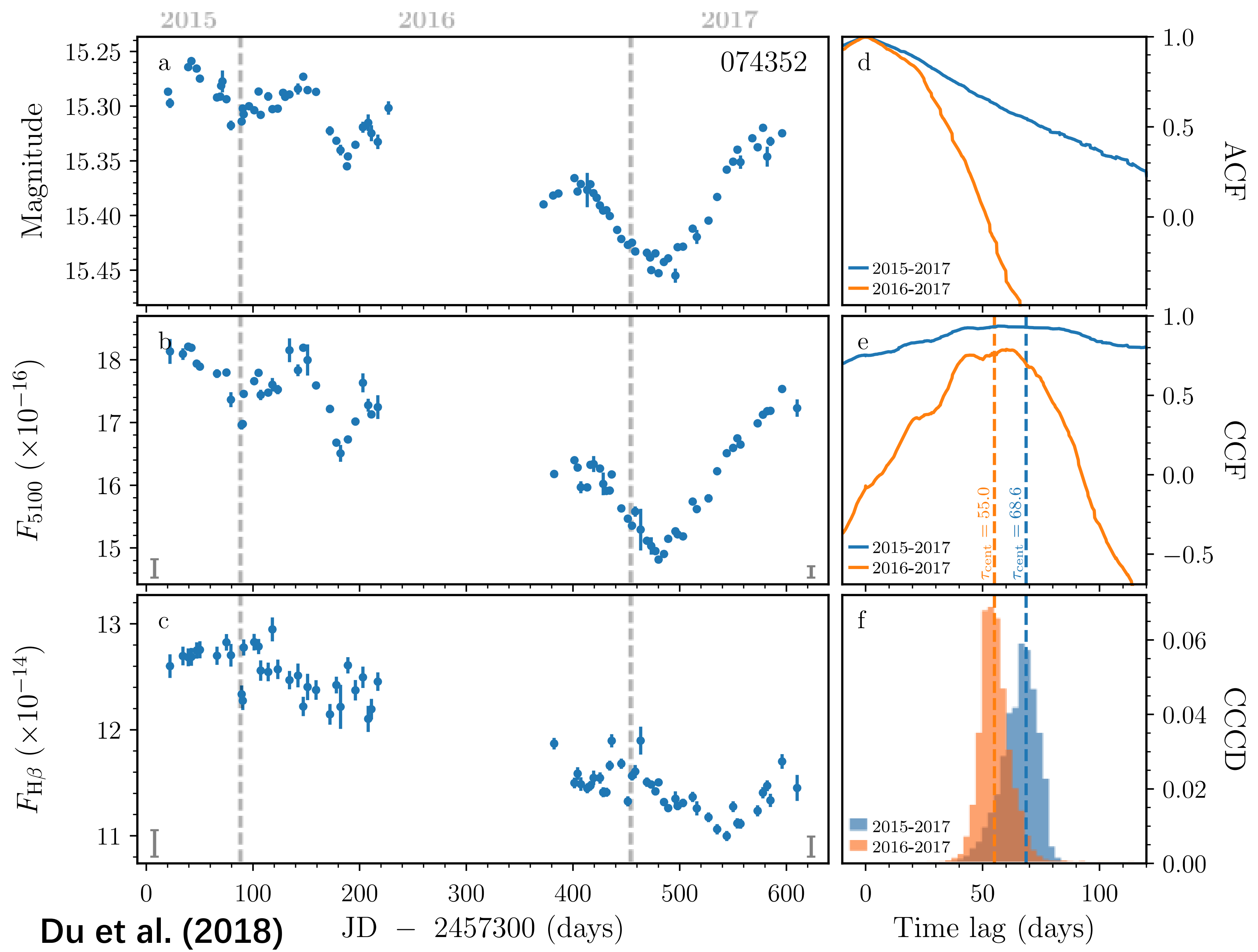
14.0 mag



Du et al. (2014)

SDSSJ074352

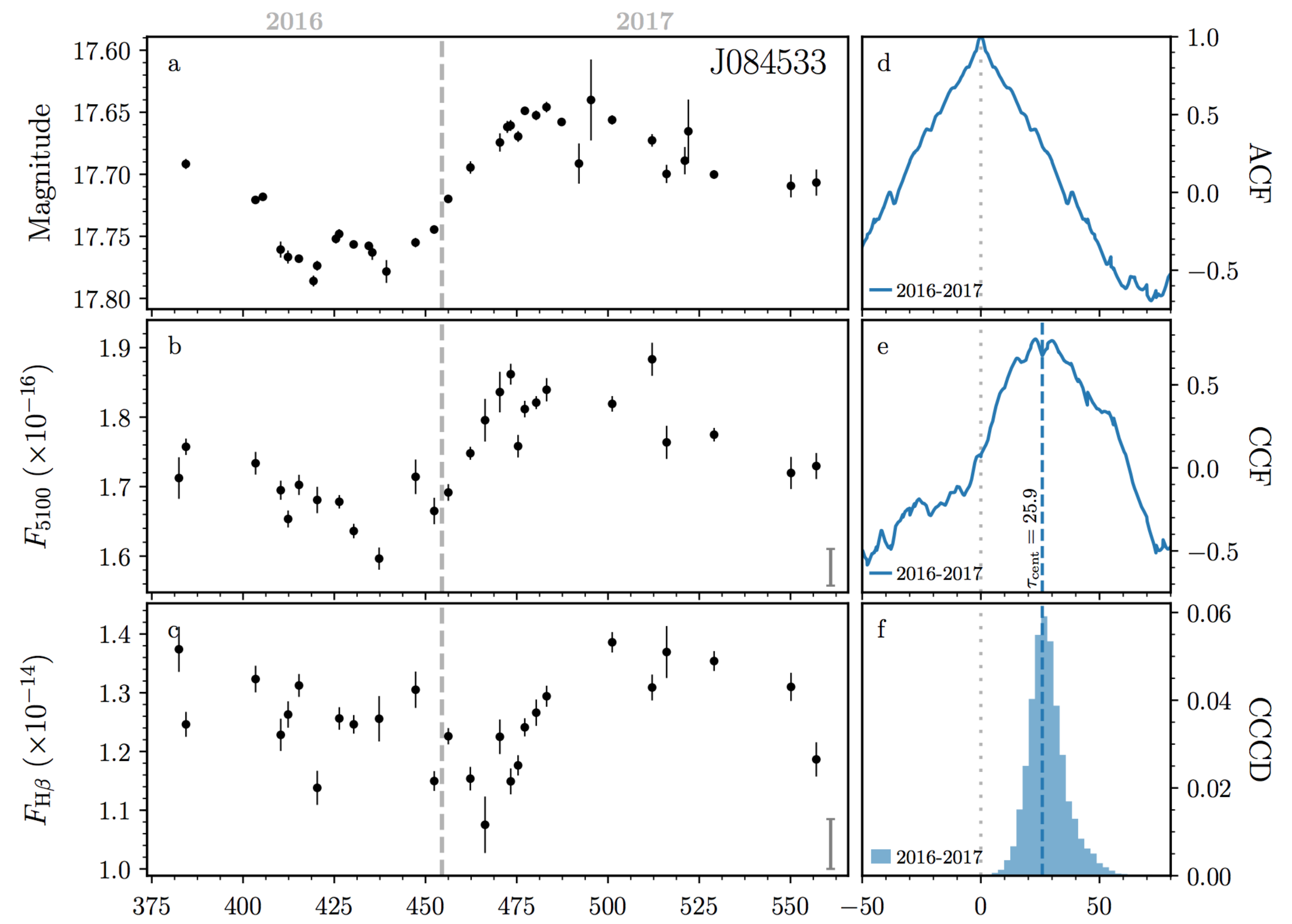
15.4 mag



Du et al. (2018)

SDSSJ084533

17.7 mag



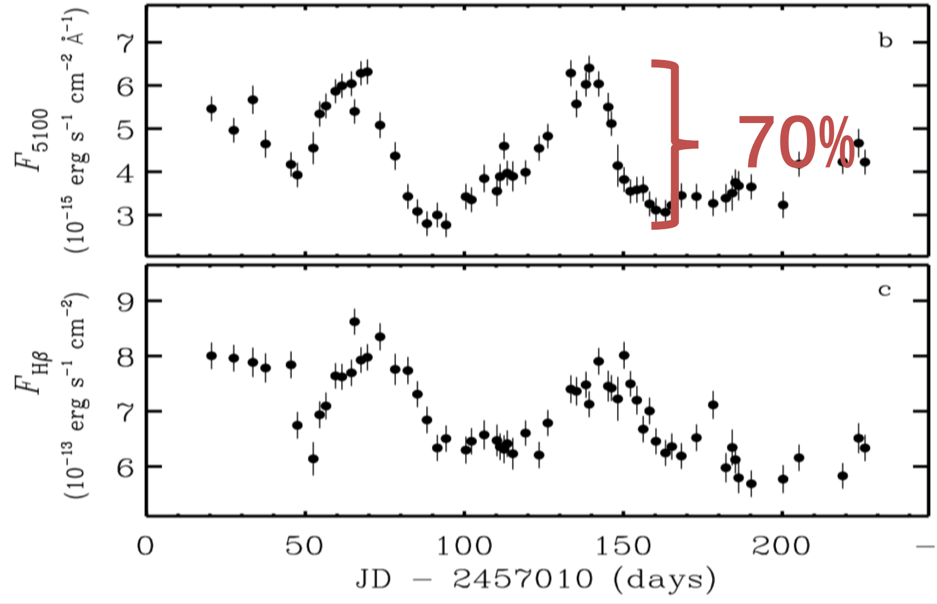
Du et al. (2018)

Variation amplitude

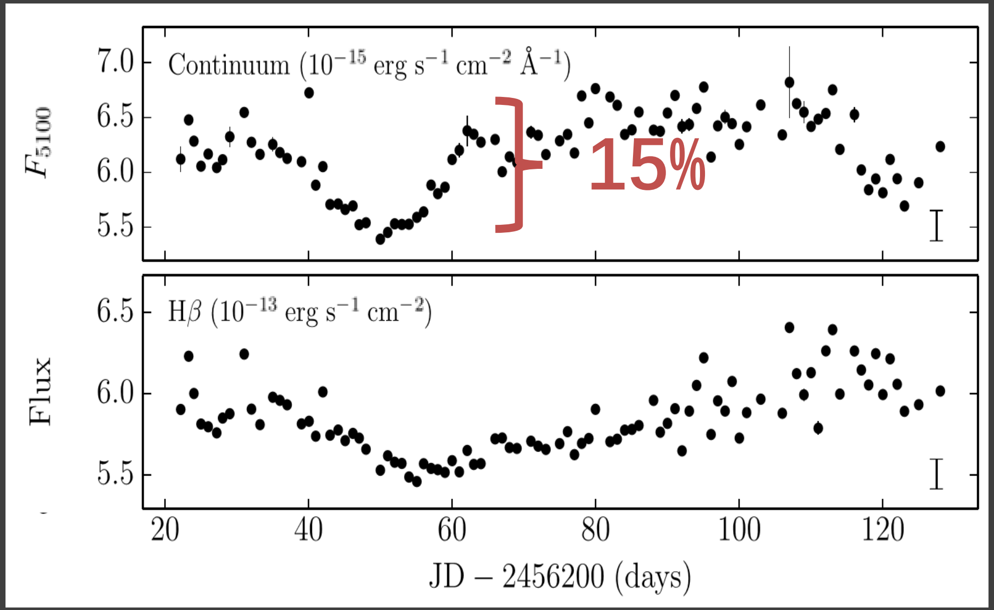
- non-SEAMBHs: NGC 5548, 3C 120, Mrk 110, ⋯ $F_{\rm var}$= 15–35%
- **SEAMBHs:** Mrk 335, Mrk 142, Mrk 493, ⋯ $F_{\rm var}$= 3-10%

$$F_{\rm var} = \frac{(\sigma^2 - \Delta^2)^{1/2}}{\langle F \rangle},$$

NGC 5548 (non-SEAMBH)

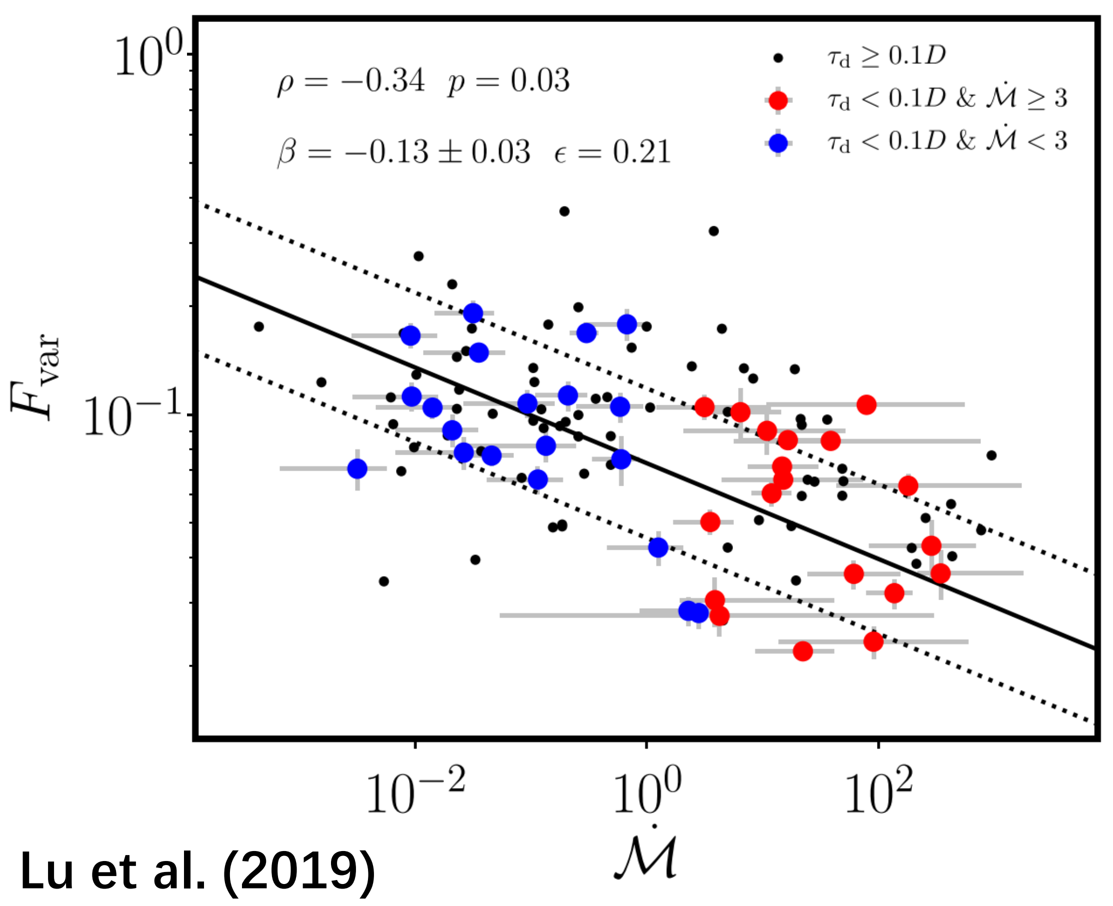


Mrk 335 (SEAMBH)

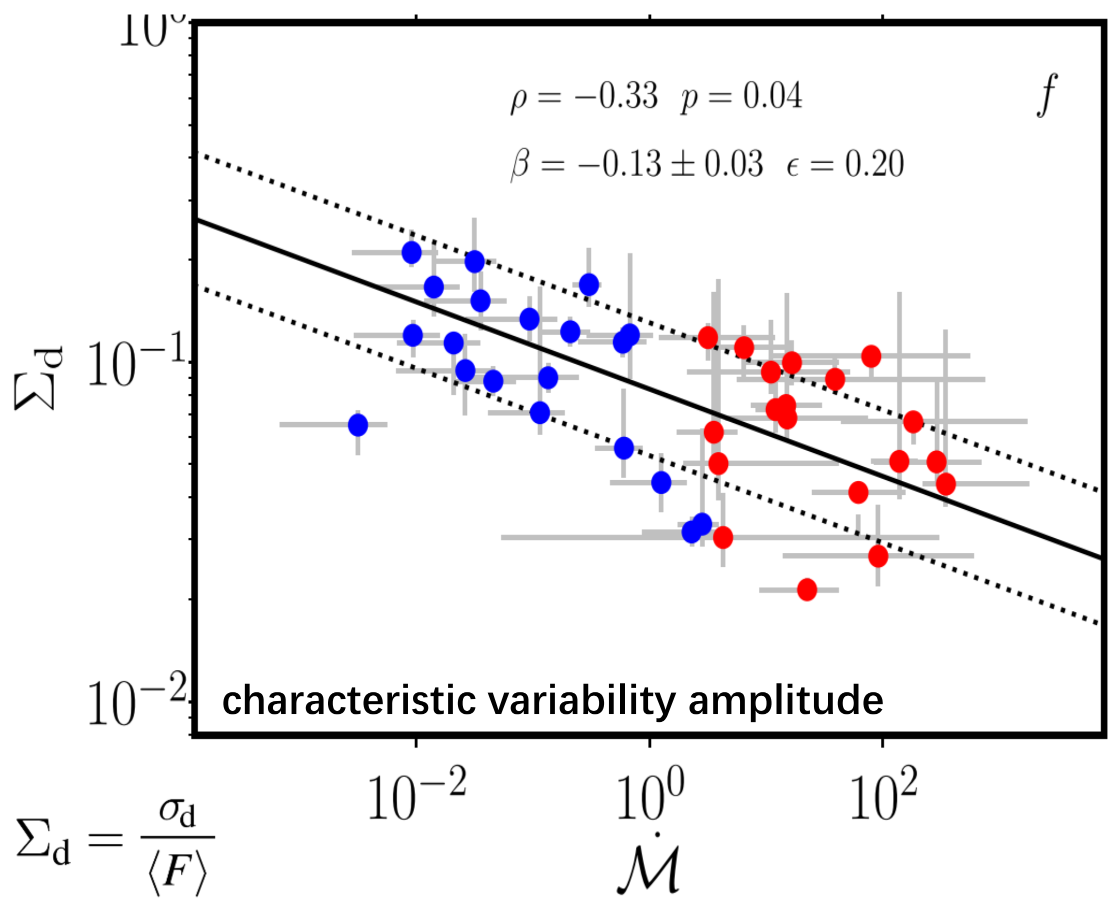


Need high calibration accuracy!

Variation amplitude



Lu et al. (2019)

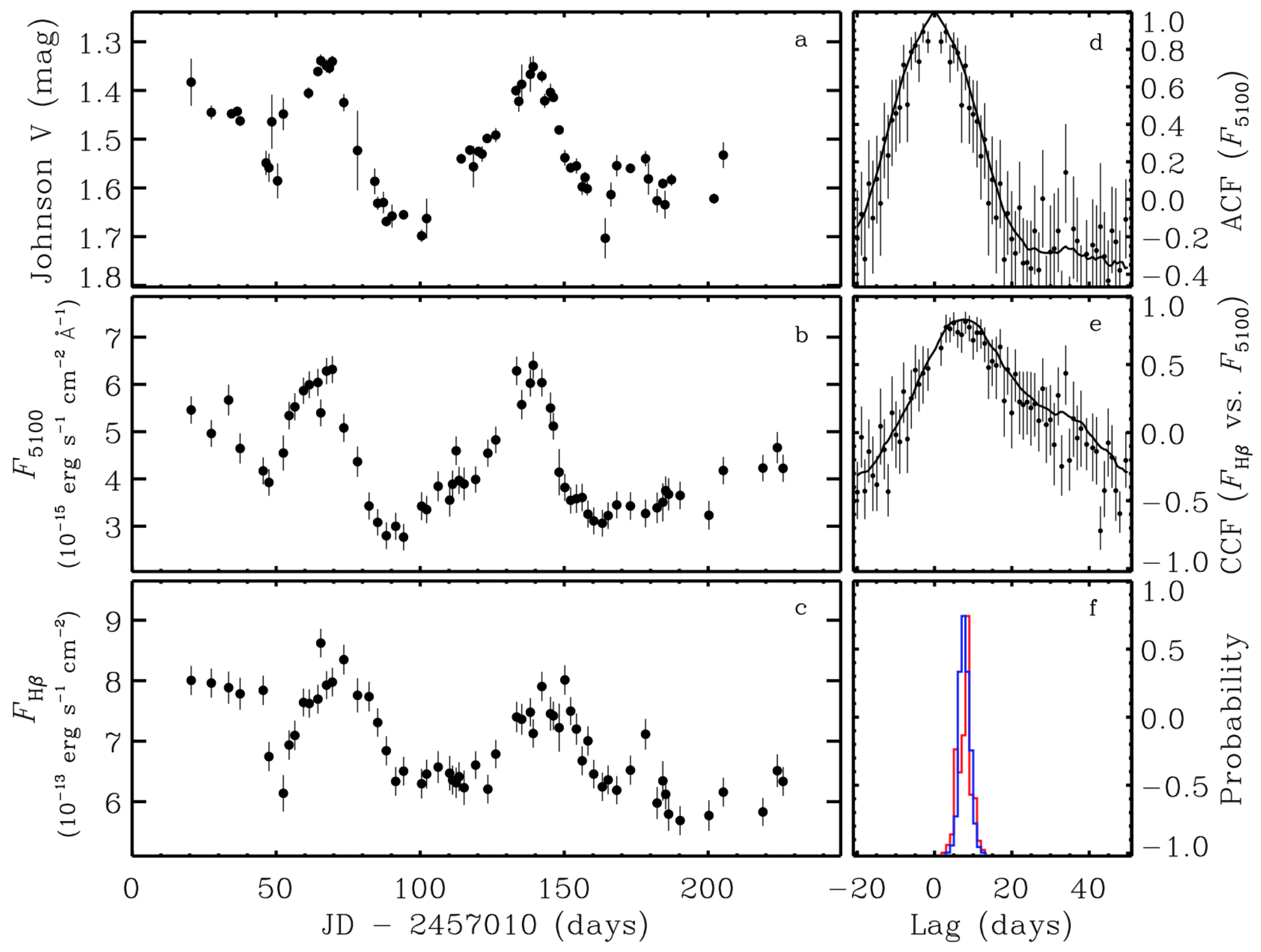


characteristic variability amplitude

$$\Sigma_{\rm d} = \frac{\sigma_{\rm d}}{\langle F \rangle}$$

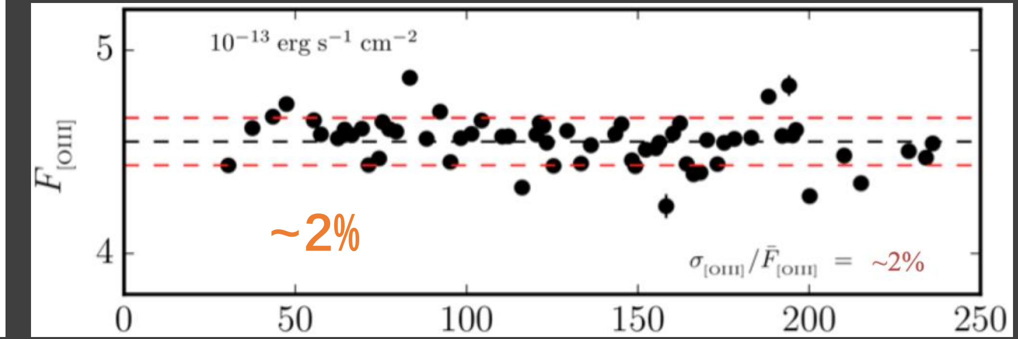
Need high calibration accuracy!

Accuracy: NGC 5548 (Lu et al. 2016)



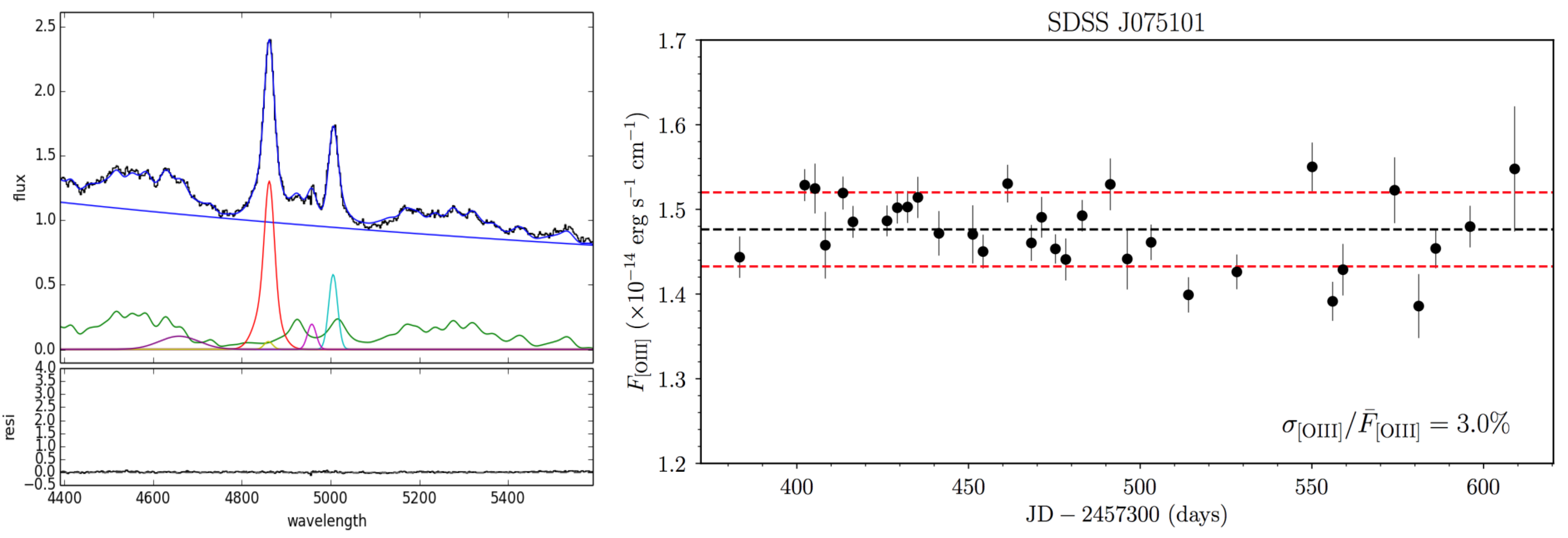
Scatter of LC
1~2%

Std of [OIII]
~2%



~2%

Accuracy evaluation: SDSSJ075101



Std of [OIII] ~3%

Accuracy evaluation

comparison-star based calibration

Accuracy ~2%

Host subtraction

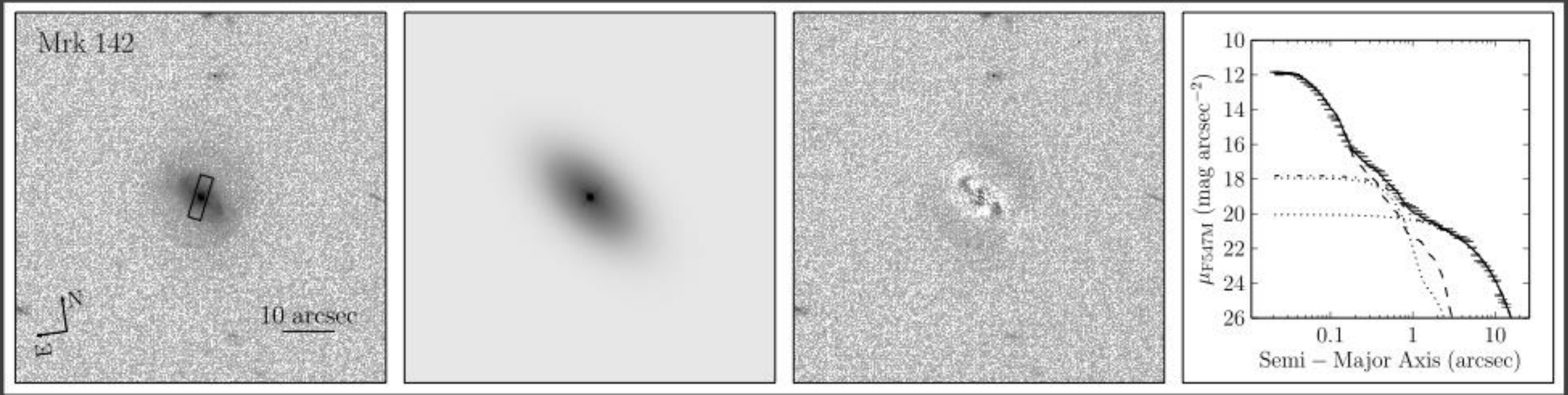


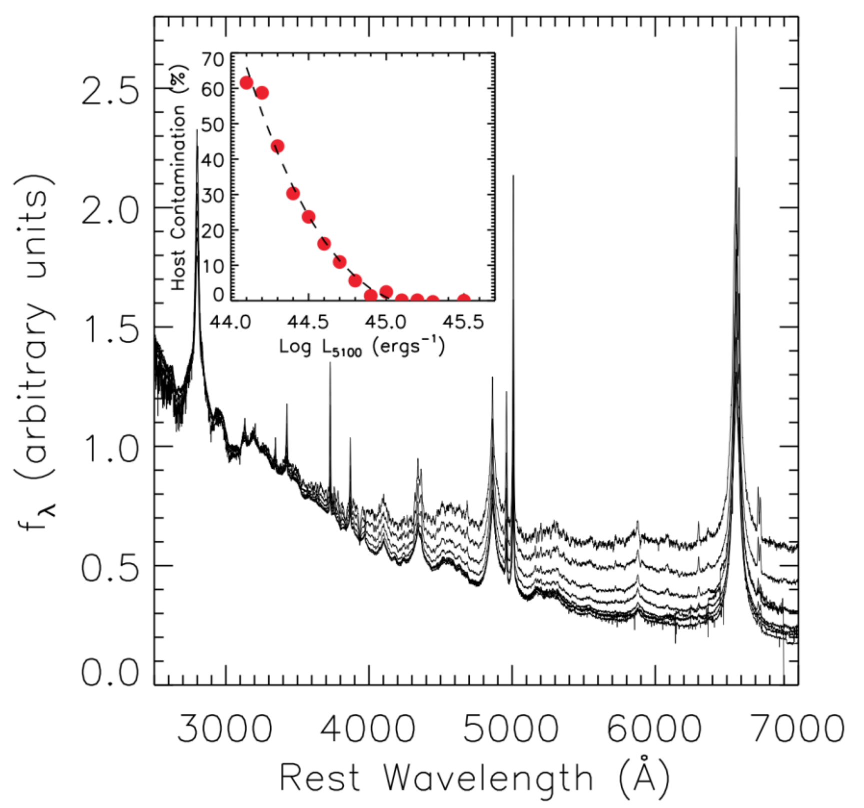
image decomposition for the objects with HST obs.

Host subtraction

- Otherwise, an empirical relationship

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

$$\frac{L_{5100,\rm host}}{L_{5100,\rm QSO}} = 0.8052 - 1.5502x + 0.9121x^2 - 0.1577x^3$$

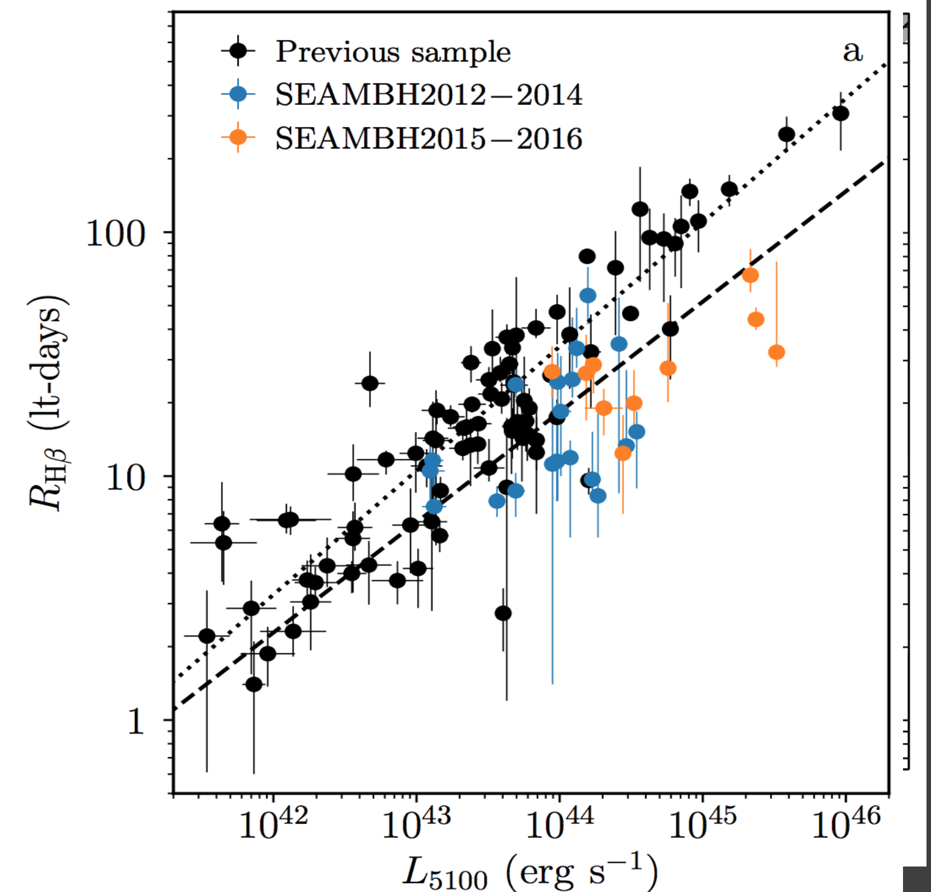


(Shen et al. 2011)

- host fraction (@5100A) **15% - 40%**
- consistent with the spectral fitting results.

Let’s come back to the R-L relationship

R-L relationship

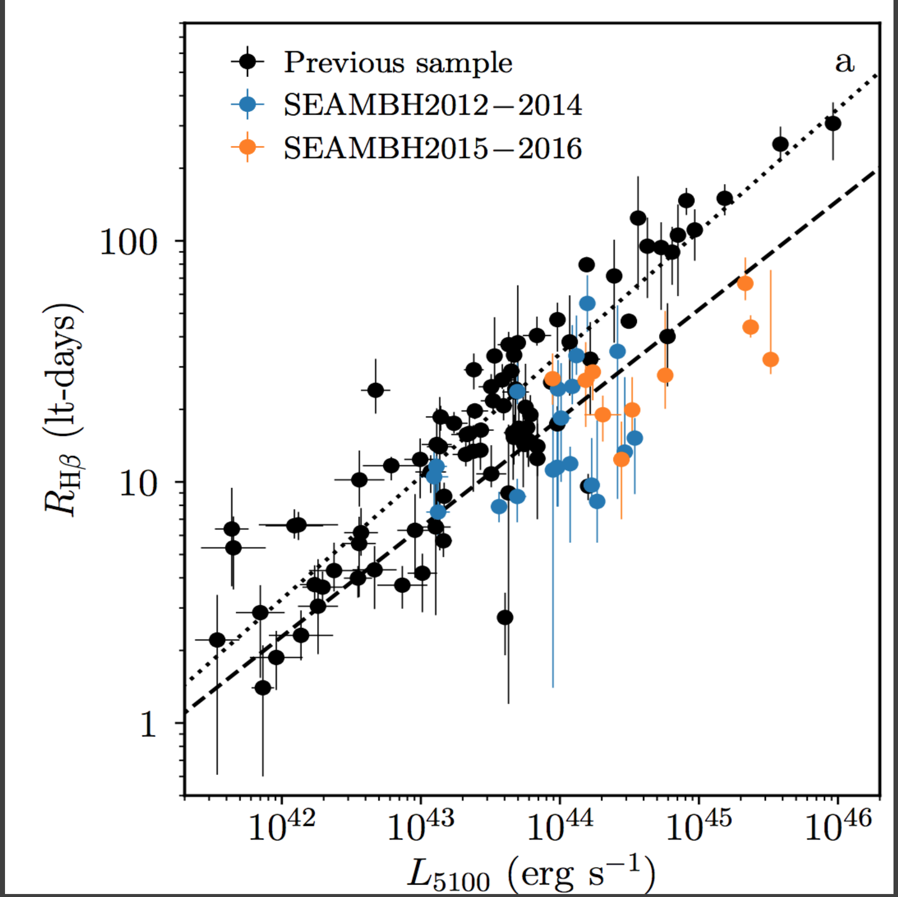


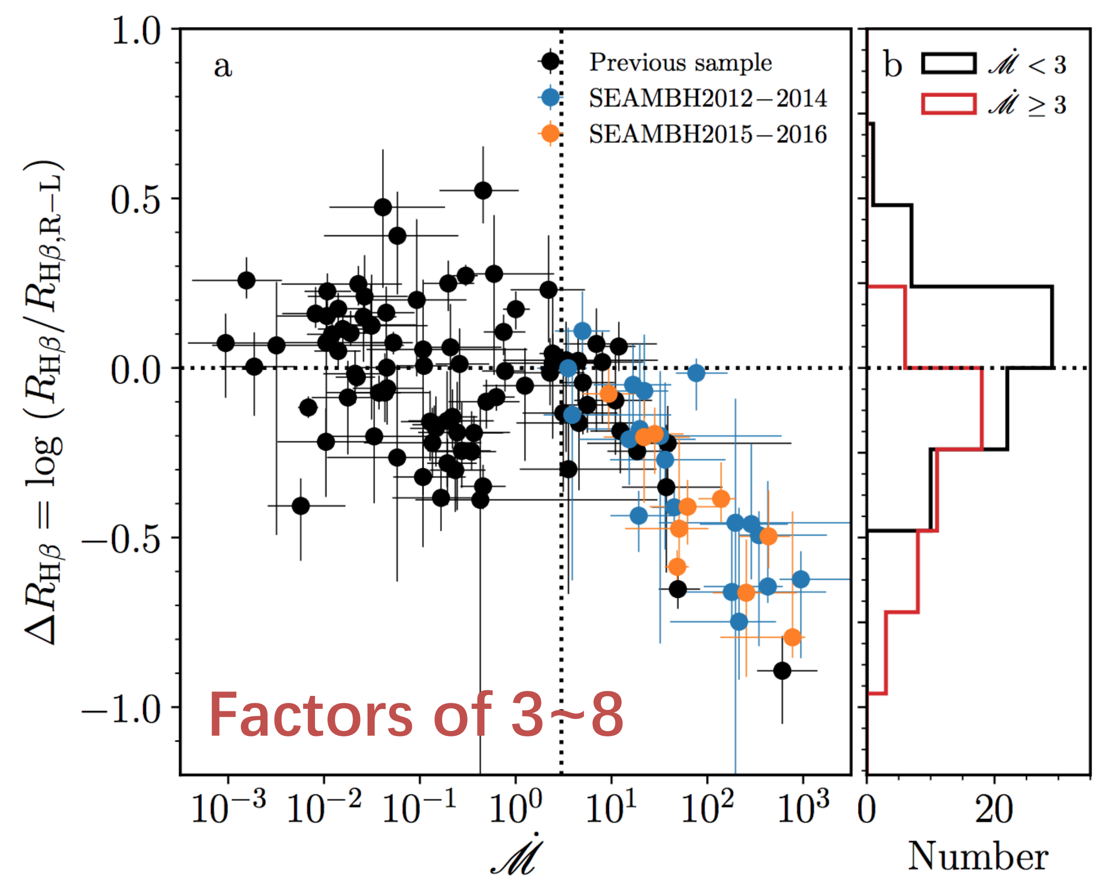
Bentz et al. 2013

?

Du et al. (2014; 2015; 2016a; 2018),
Wang et al. (2014), Hu et al. (2015)

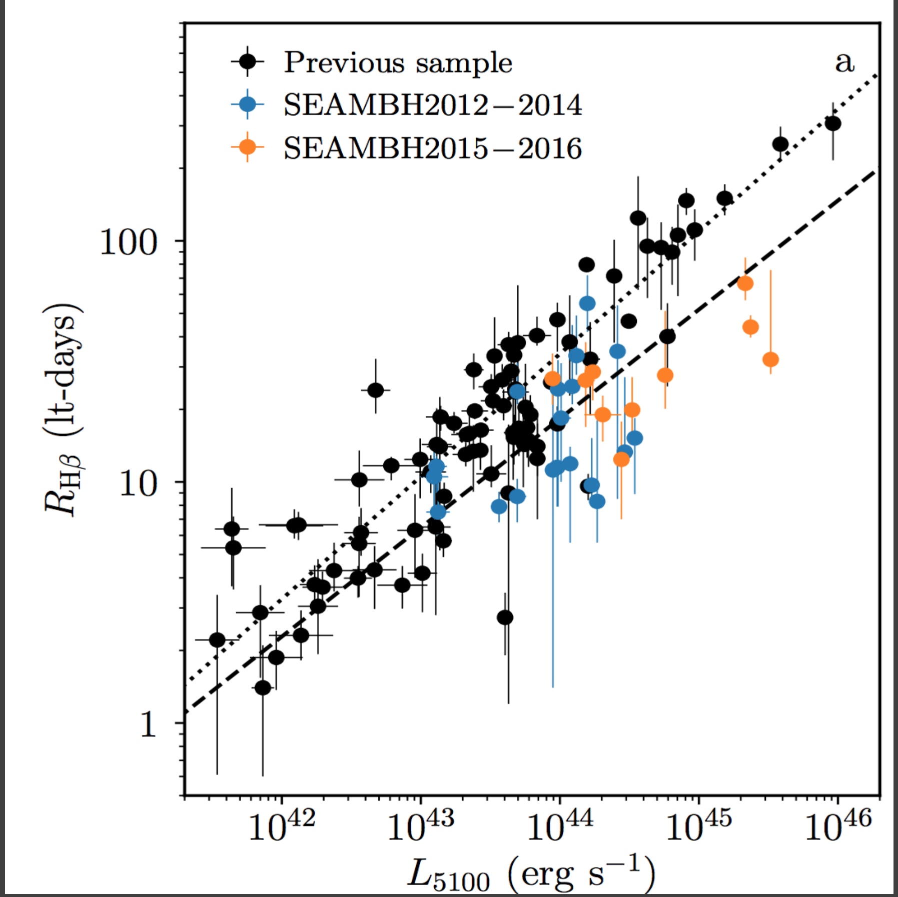
R-L relationship



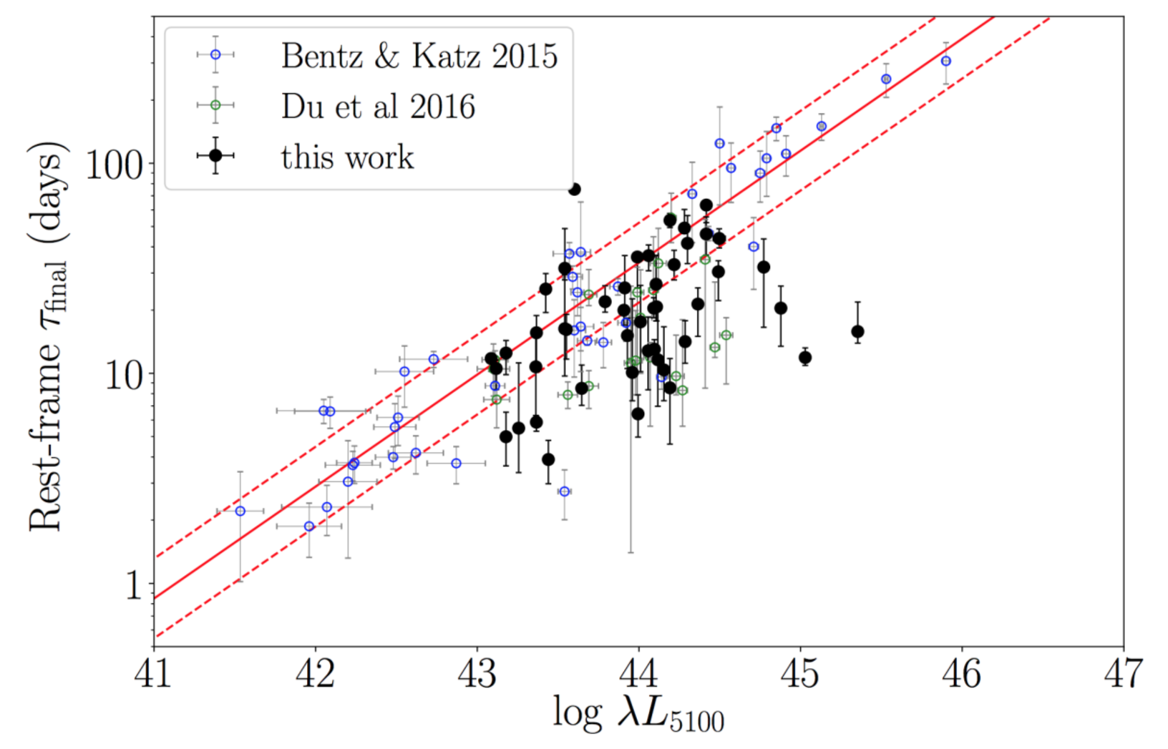


Du et al. (2014; 2015; 2016a; 2018),
Wang et al. (2014), Hu et al. (2015)

R-L relationship



Du et al. (2014; 2015; 2016a; 2018), Wang et al. (2014), Hu et al. (2015)



Grier et al. (2017)

Is accretion rate a primary driver?

We collect 8 different spectral parameters:

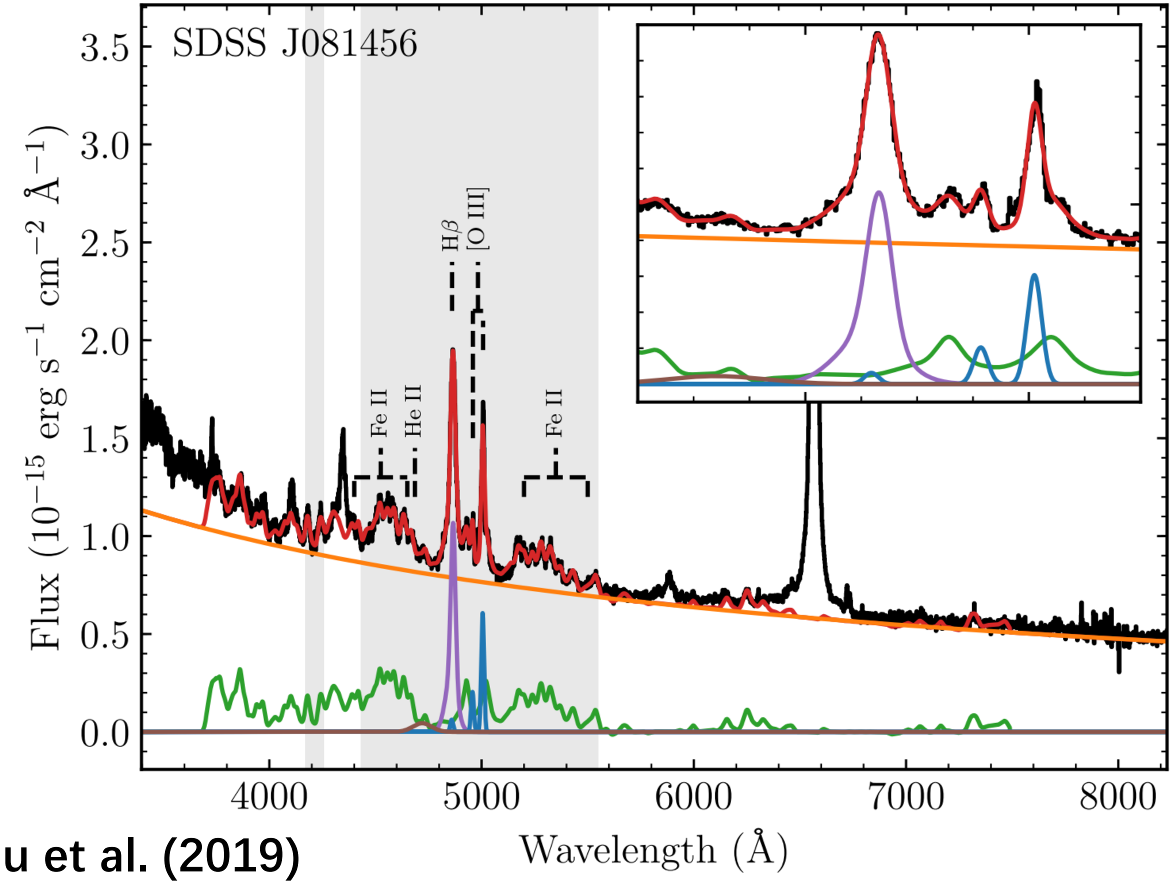
- $\mathcal{R}_{\rm Fe} = F_{\rm Fe}/F_{\rm H\beta}$
- $\rm FWHM_{H\beta}$
- $\rm EW_{[OIII]}$
- $\mathcal{D}_{\rm H\beta} = {\rm FWHM_{H\beta}}/\sigma_{\rm H\beta}$
- $\rm FWHM_{Fe\ II}/FWHM_{H\beta}$
- $A = [\lambda_c(3/4) - \lambda_c(1/4)]/{\rm FWHM_{H\beta}}$
- $\rm EW_{H\beta}$
- $\rm EW_{HeII}$

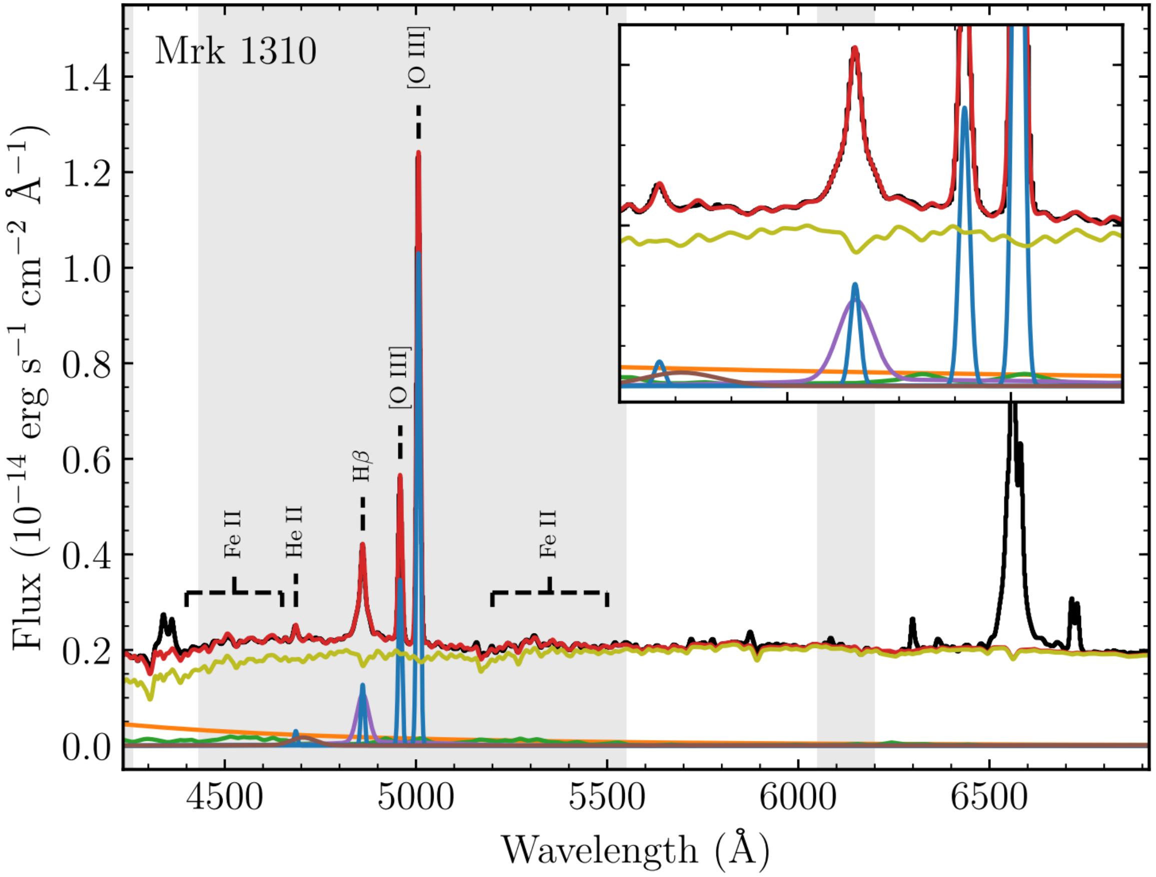
All of them can be measured from single-epoch spectral

Du et al. (2019)

Is accretion rate a primary driver?

- **The parameters are measured by multi-component fitting or from literatures:**

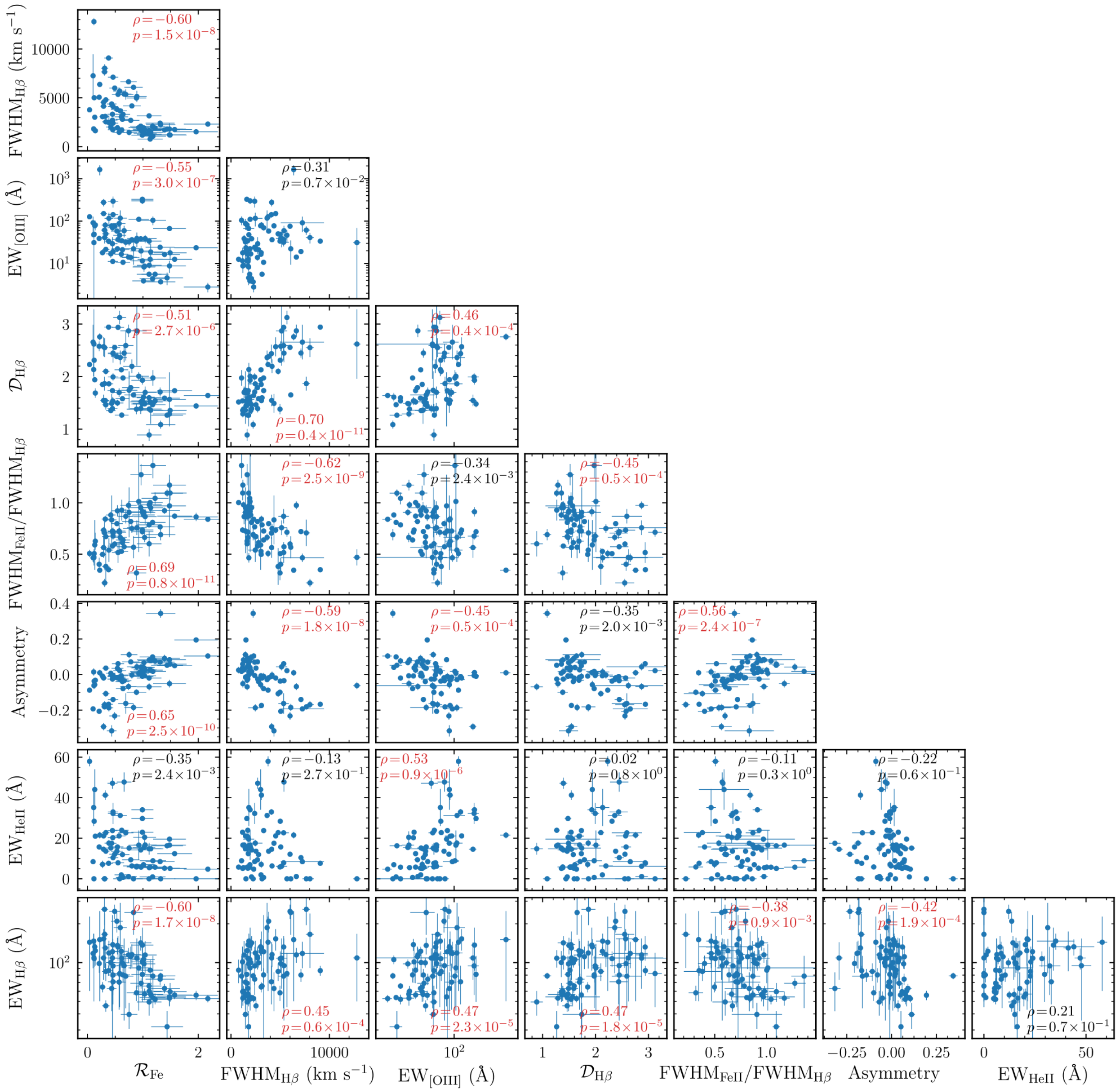




Du et al. (2019)

Pairwise correlations

- Interesting to check for the present RM sample
- Completeness of the RM sample
- Samples:
  - Bentz et al. 2013
  - SEAMBH campaign
  - some other objects



Du et al. (2019)

Pairwise correlations

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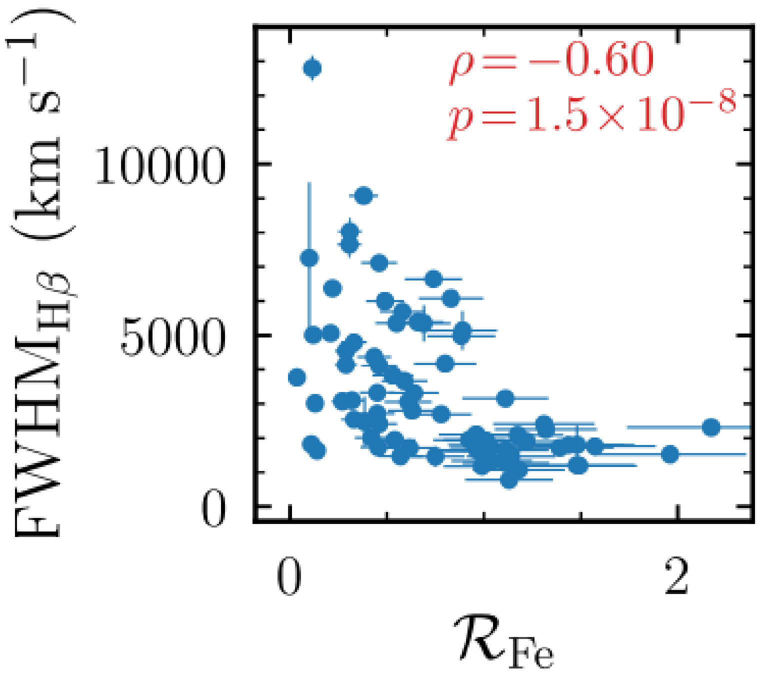
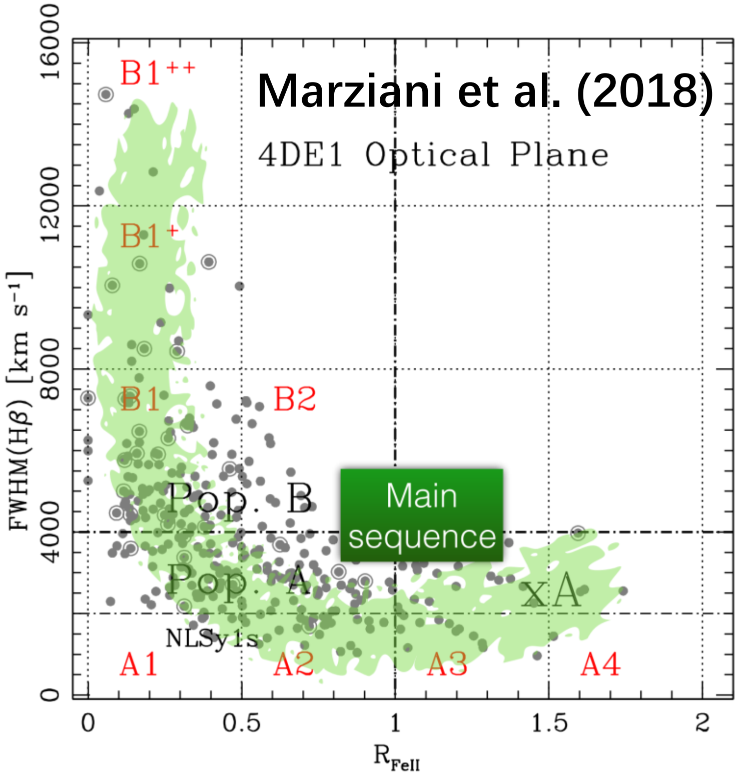
Du et al. (2019)

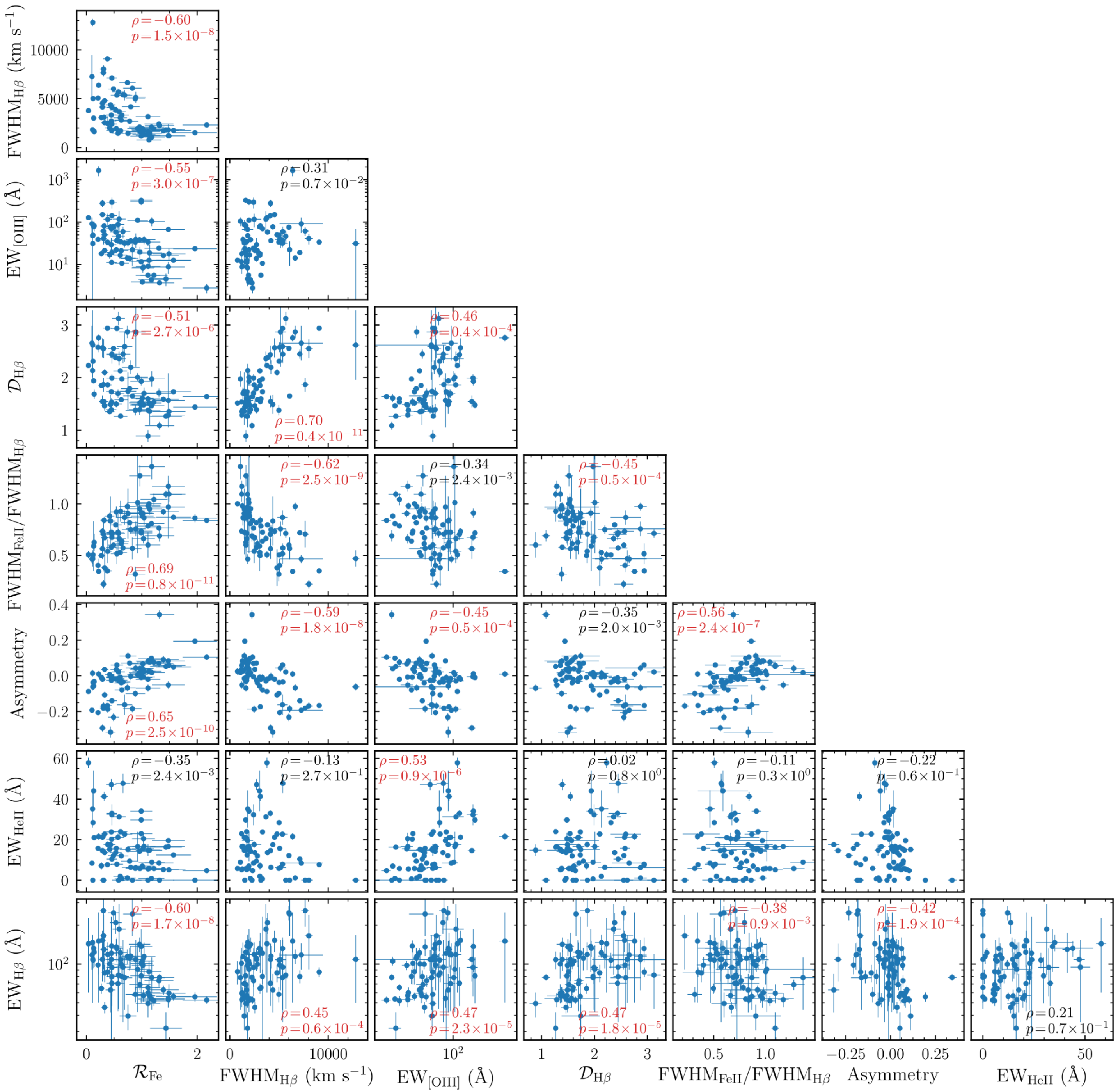


Still incomplete, but not too bad


Marziani et al. (2018)

Pairwise correlations

- Some highlights

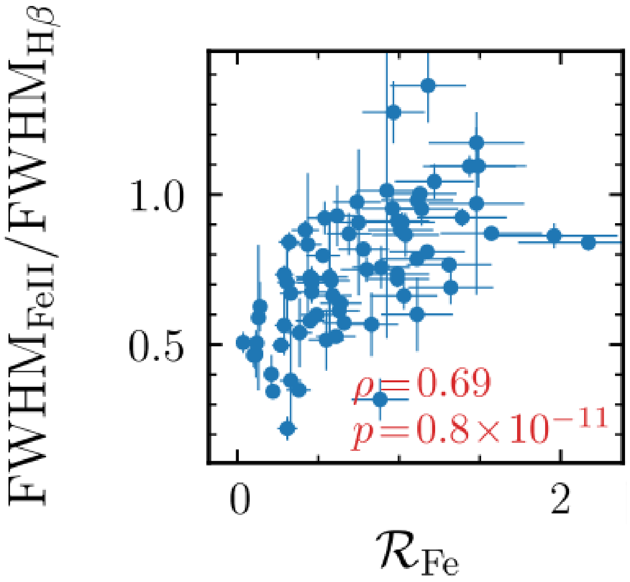


Du et al. (2019)

Pairwise correlations

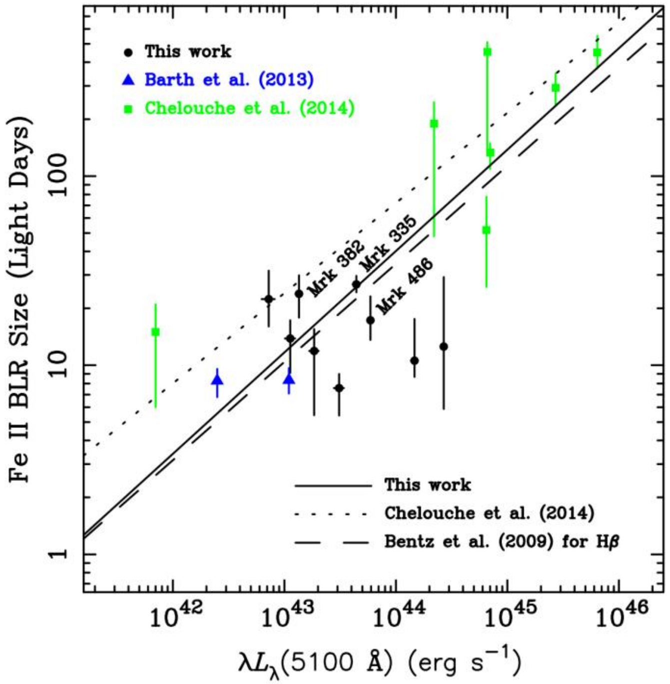
- Some highlights

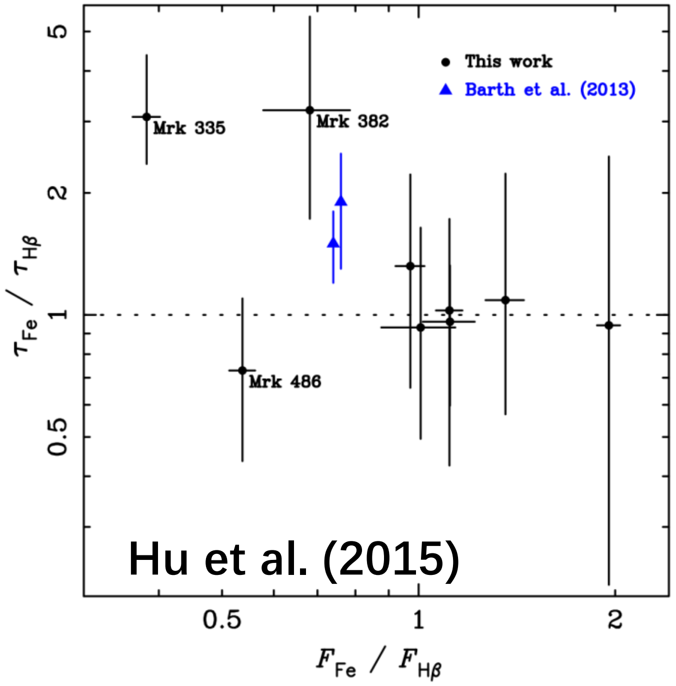
Du et al. (2019)



If Fe II is stronger:

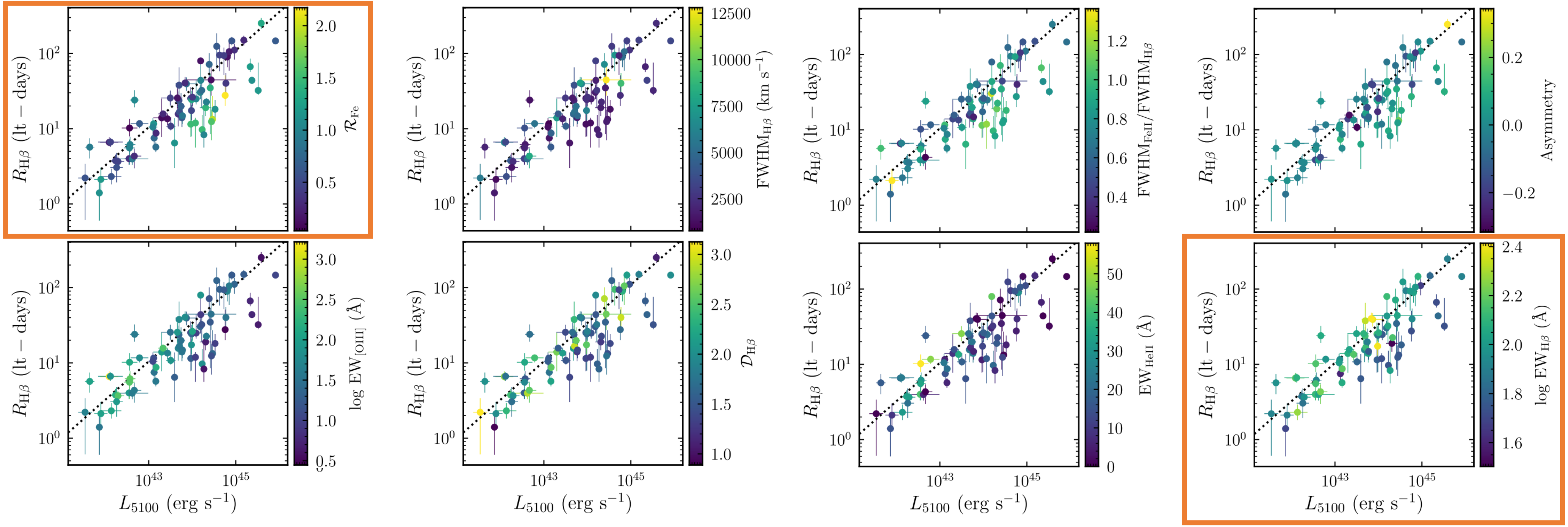
- Fe II-emitting region is closer to Hβ region
- The width ratio → 1





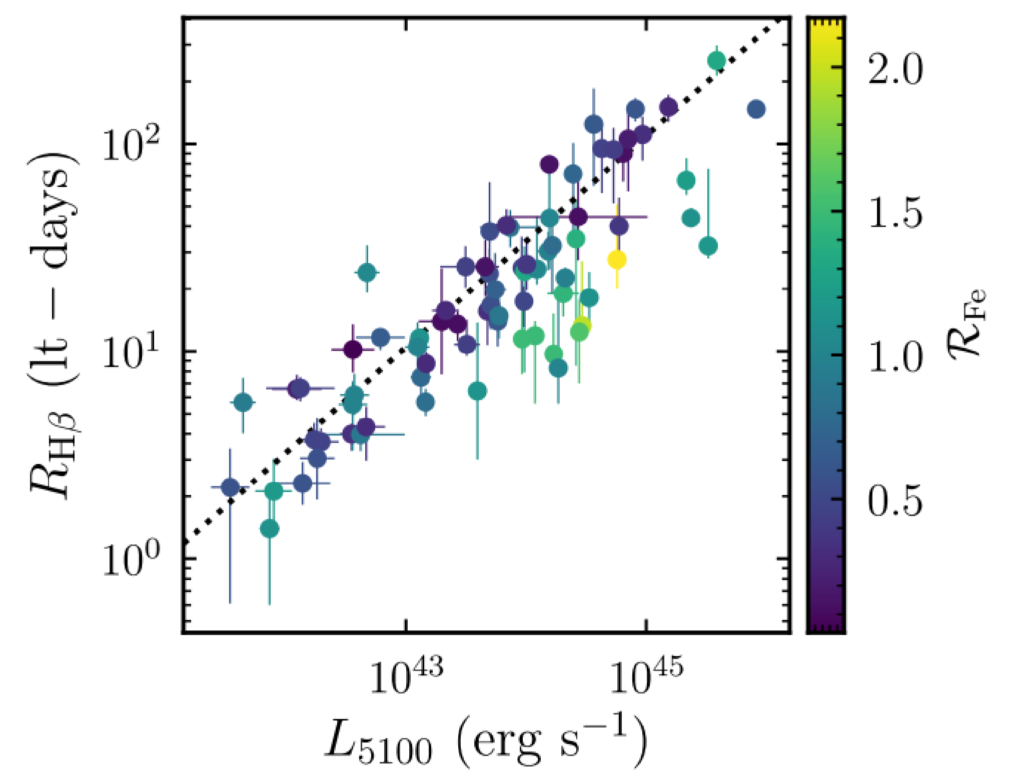
Hu et al. (2015)

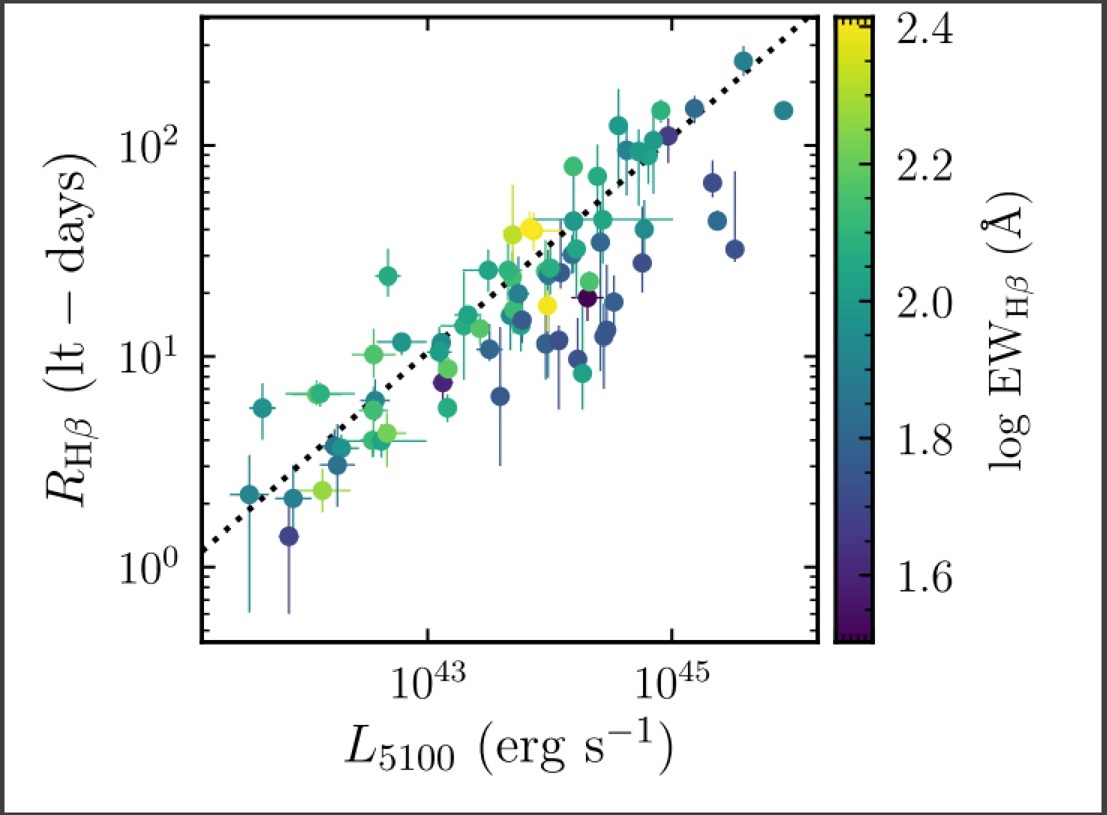
R-L relation color-coded by different parameters



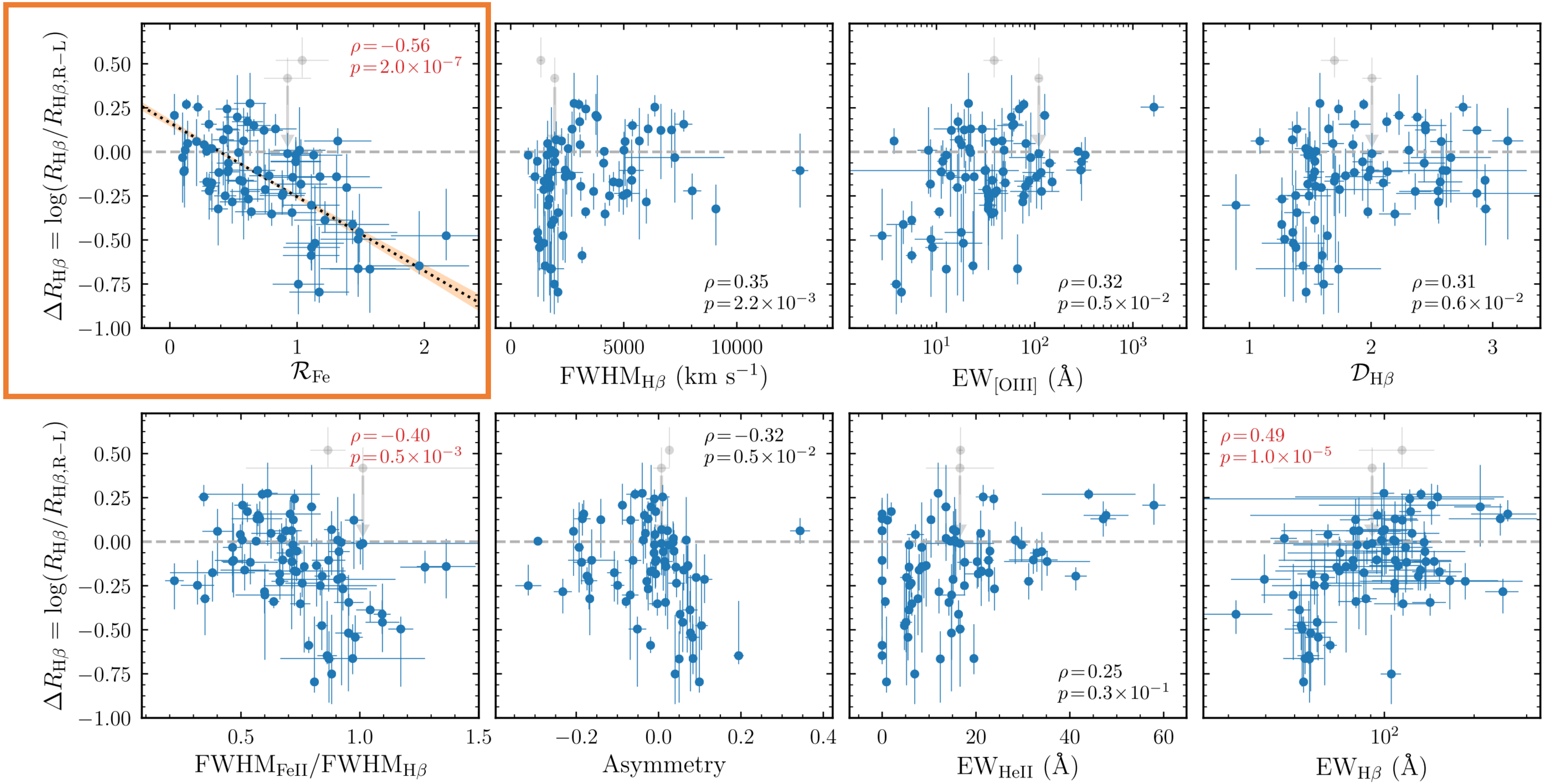
Du et al. (2019)

R-L relation color-coded by different parameters

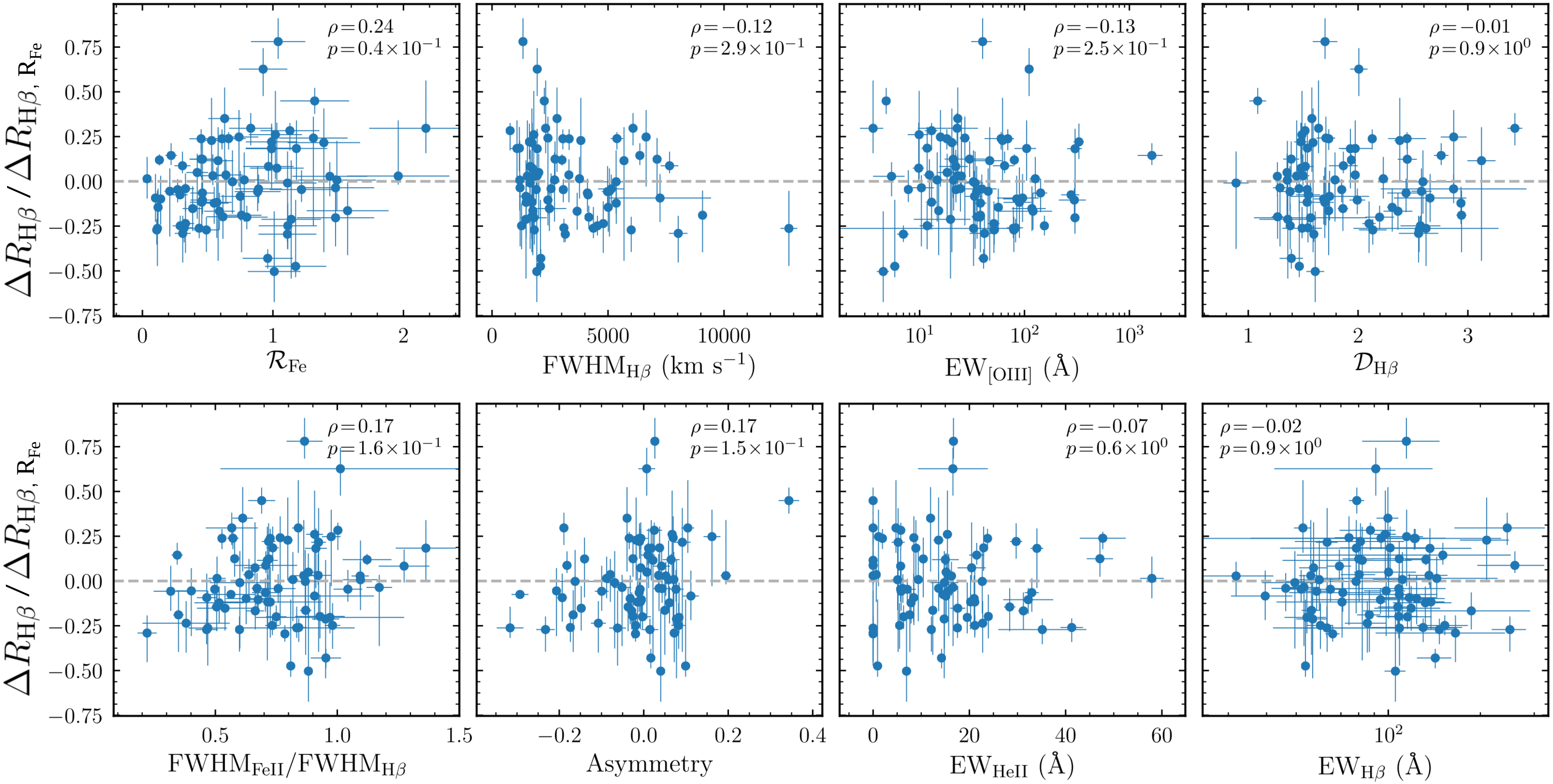




Du et al. (2019)

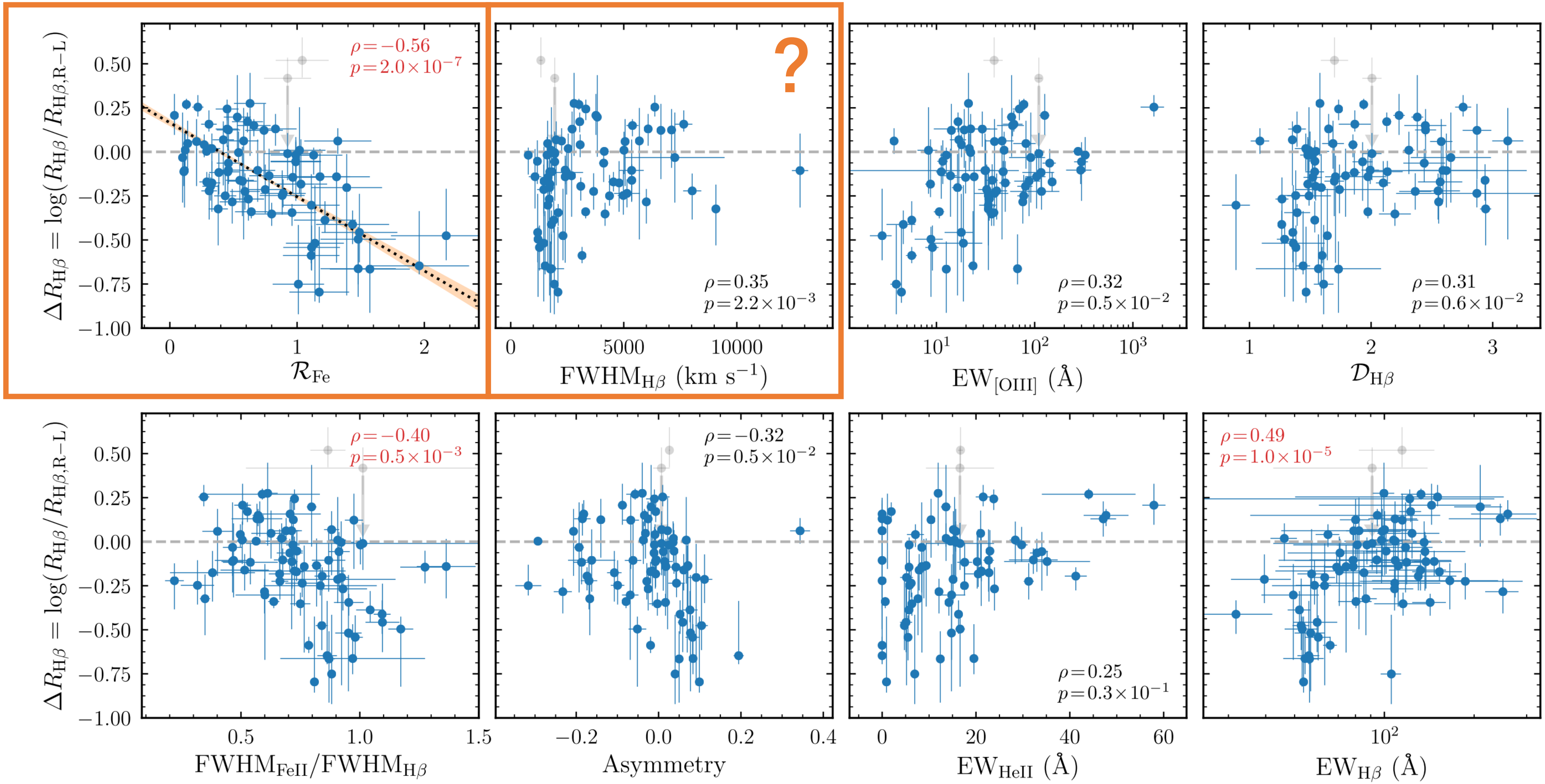

$\Delta R_{\mathrm{H}\beta} = \log(R_{\mathrm{H}\beta}/R_{\mathrm{H}\beta,\mathrm{R-L}})$
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\rho = -0.56$
$p = 2.0 \times 10^{-7}$
0
1
2
$\mathcal{R}_{\mathrm{Fe}}$
$\rho = 0.35$
$p = 2.2 \times 10^{-3}$
0
5000
10000
$\mathrm{FWHM}_{\mathrm{H}\beta}$ (km s^{-1})
$\rho = 0.32$
$p = 0.5 \times 10^{-2}$
10^1
10^2
10^3
$\mathrm{EW}_{[\mathrm{OIII}]}$ (Å)
$\rho = 0.31$
$p = 0.6 \times 10^{-2}$
1
2
3
$\mathcal{D}_{\mathrm{H}\beta}$
$\Delta R_{\mathrm{H}\beta} = \log(R_{\mathrm{H}\beta}/R_{\mathrm{H}\beta,\mathrm{R-L}})$
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\rho = -0.40$
$p = 0.5 \times 10^{-3}$
0.5
1.0
1.5
$\mathrm{FWHM}_{\mathrm{FeII}}/\mathrm{FWHM}_{\mathrm{H}\beta}$
$\rho = -0.32$
$p = 0.5 \times 10^{-2}$
−0.2
0.0
0.2
0.4
Asymmetry
$\rho = 0.25$
$p = 0.3 \times 10^{-1}$
0
20
40
60
$\mathrm{EW}_{\mathrm{HeII}}$ (Å)
$\rho = 0.49$
$p = 1.0 \times 10^{-5}$
10^2
$\mathrm{EW}_{\mathrm{H}\beta}$ (Å)

Du et al. (2019)



Du et al. (2019)

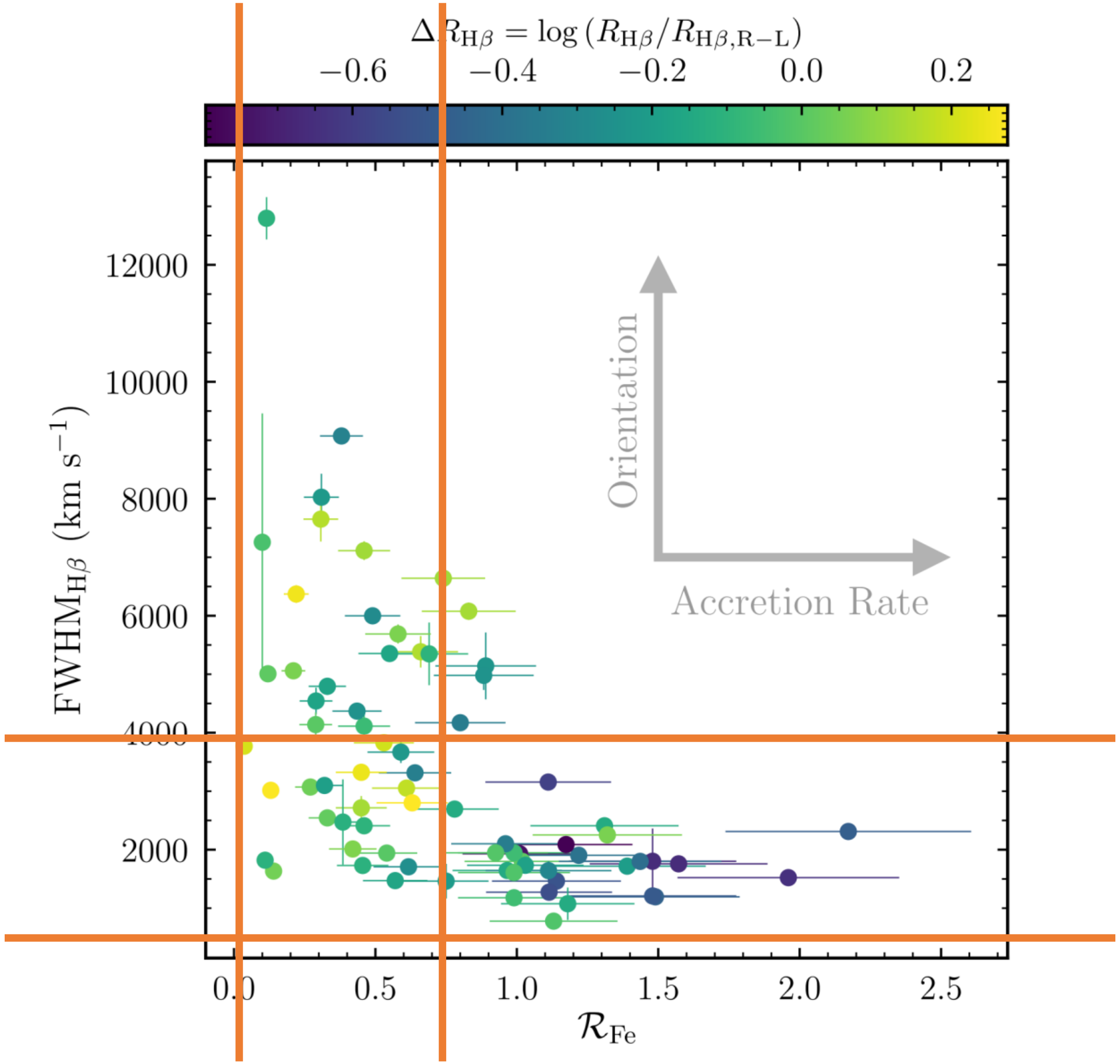
$R_{\rm Fe}$ is definitely the primary driver for the shortened lags!


?
ρ = −0.56
p = 2.0 × 10⁻⁷
ρ = 0.35
p = 2.2 × 10⁻³
ρ = 0.32
p = 0.5 × 10⁻²
ρ = 0.31
p = 0.6 × 10⁻²
ρ = −0.40
p = 0.5 × 10⁻³
ρ = −0.32
p = 0.5 × 10⁻²
ρ = 0.25
p = 0.3 × 10⁻¹
ρ = 0.49
p = 1.0 × 10⁻⁵
ΔR_Hβ = log(R_Hβ/R_Hβ,R−L)
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
R_Fe
0
1
2
FWHM_Hβ (km s⁻¹)
0
5000
10000
EW_[OIII] (Å)
10¹
10²
10³
D_Hβ
1
2
3
FWHM_FeII/FWHM_Hβ
0.5
1.0
1.5
Asymmetry
−0.2
0.0
0.2
0.4
EW_HeII (Å)
0
20
40
60
EW_Hβ (Å)
10²

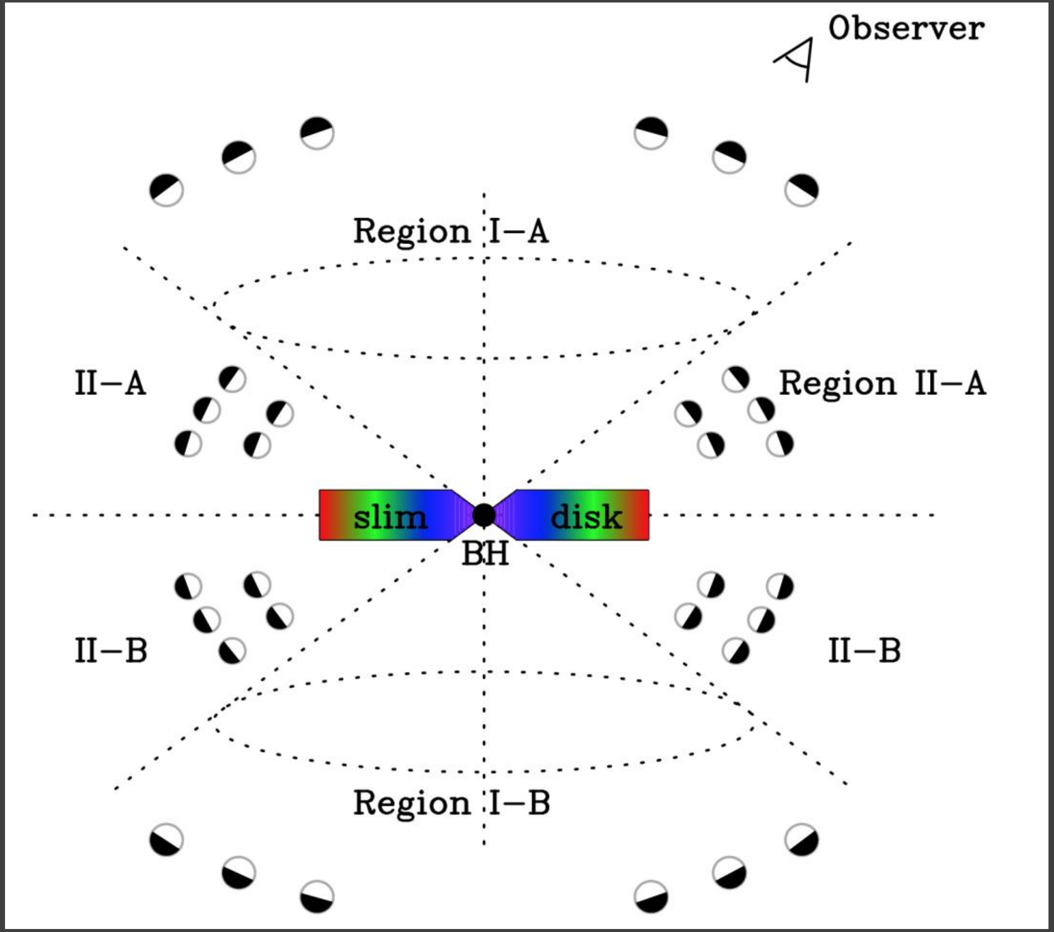
Du et al. (2019)

Eigenvector 1 sequence can break the degeneracy!

- Accretion rate is the primary driver
- The influence of orientation is not obvious



Self-shadowing effect of slim accretion disk



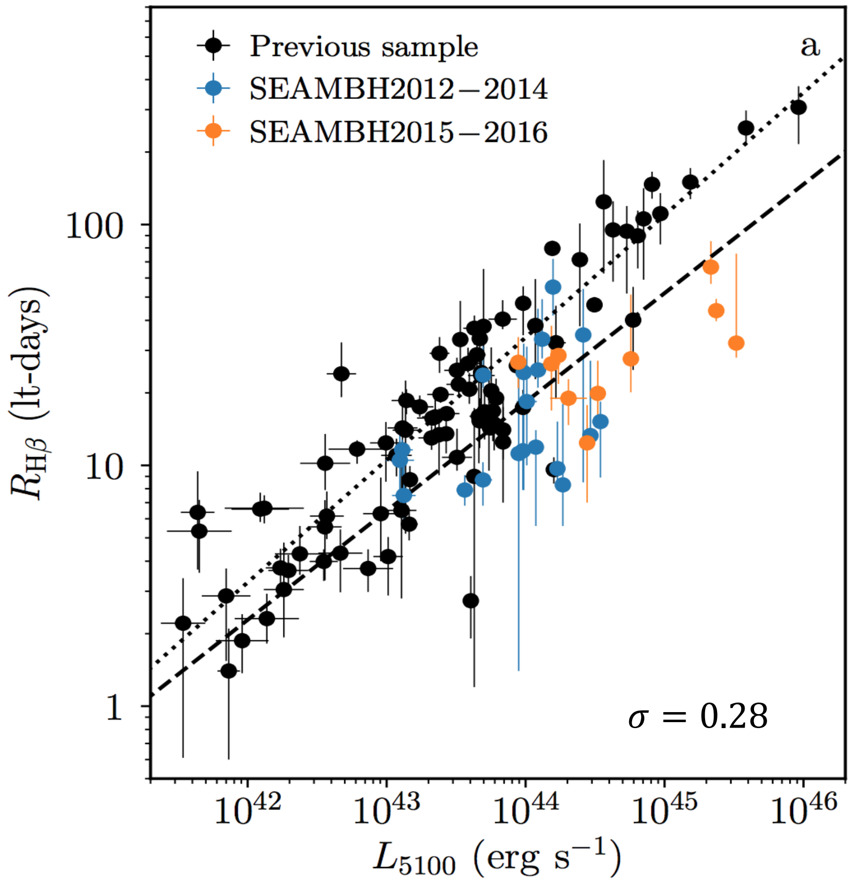
the self-shadowing effect (Wang et al. 2014):

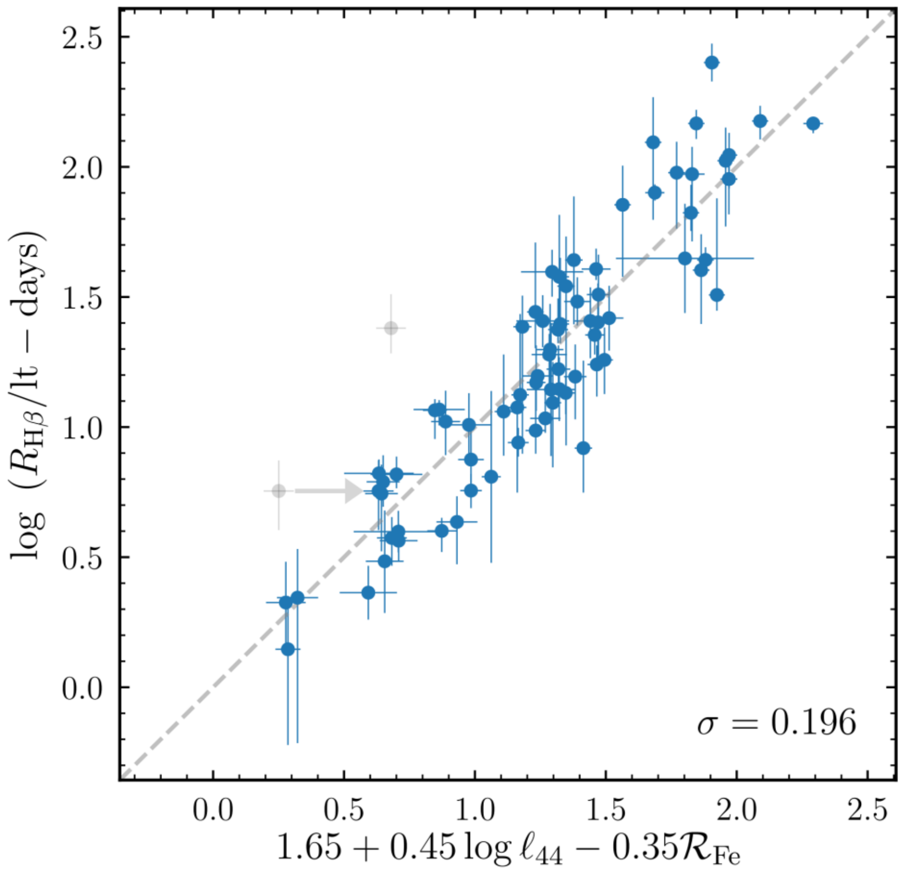
Clouds (Region II) are closer to BH

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

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

A new scaling relation: $\log\left(R_{\mathrm{H}\beta}/\mathrm{lt\!-\!days}\right) = \alpha + \beta \log \ell_{44} + \gamma \mathcal{R}_{\mathrm{Fe}}$

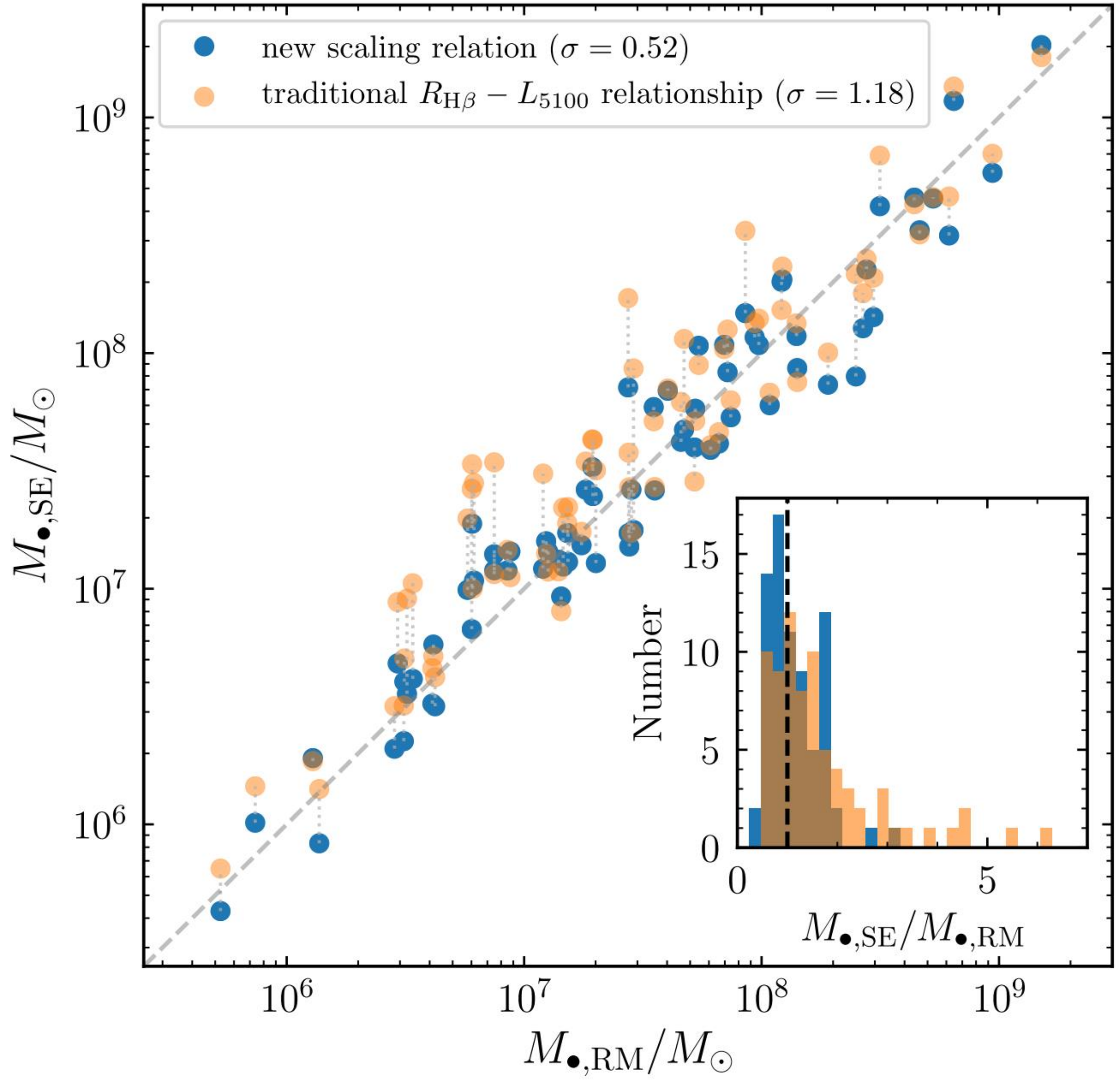




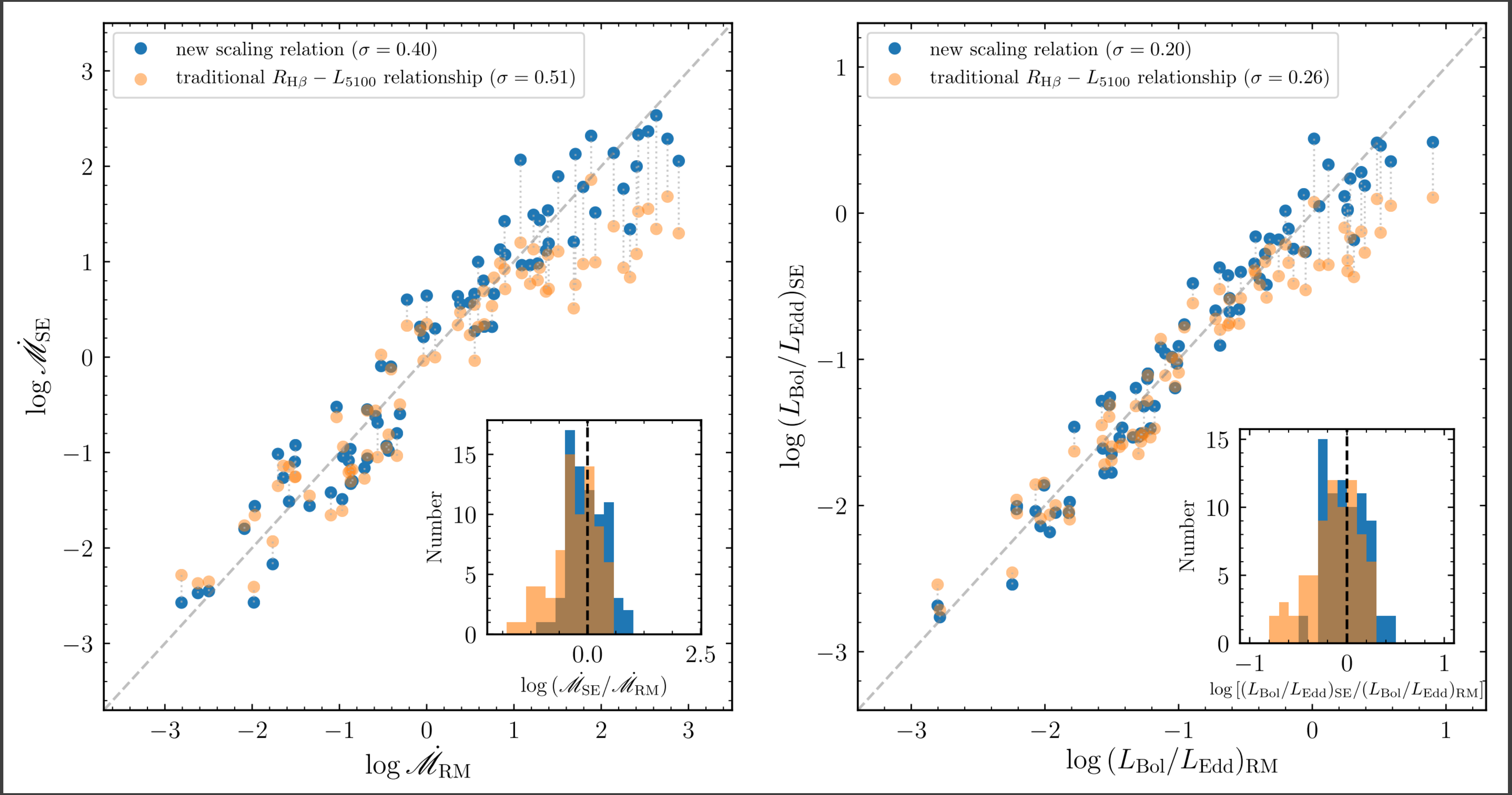
Du et al. (2019)

The new scaling relation
&
BH mass measurement

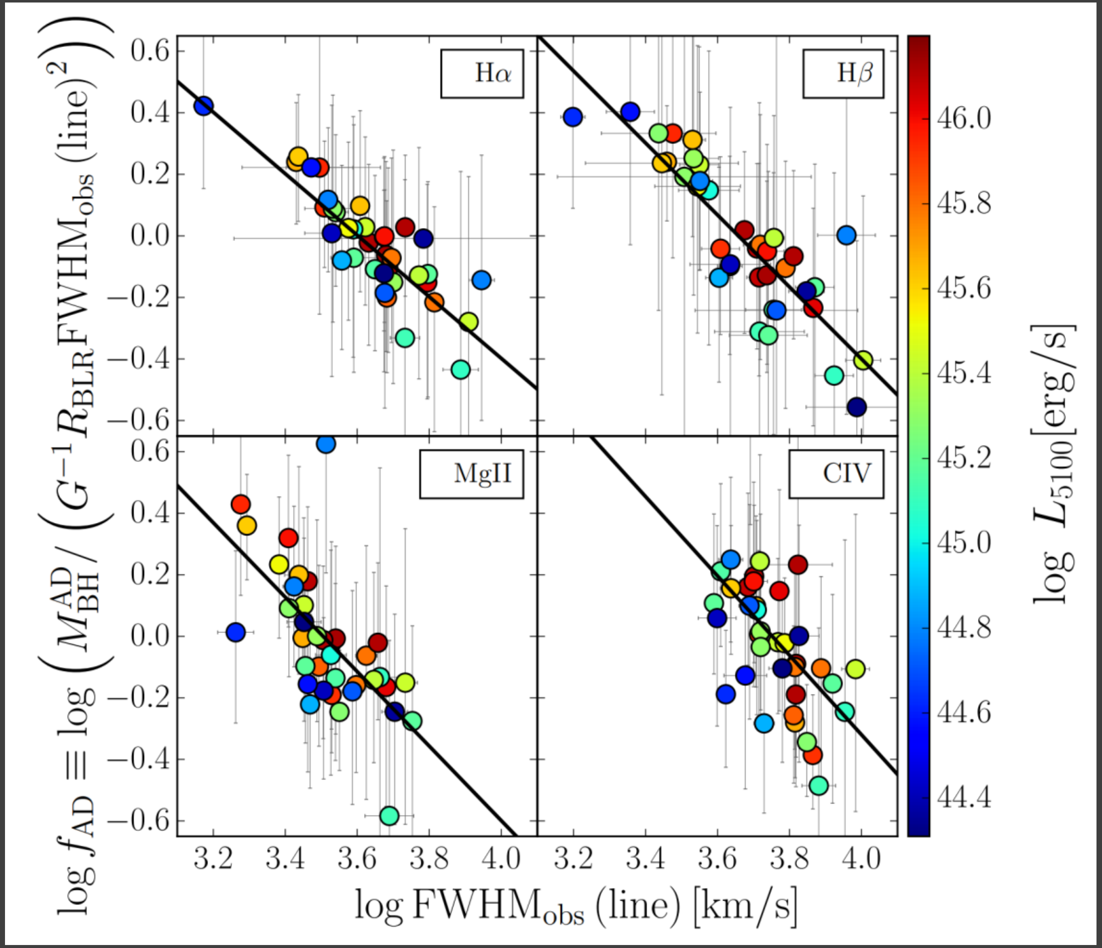
If there is no difference for *f* factor



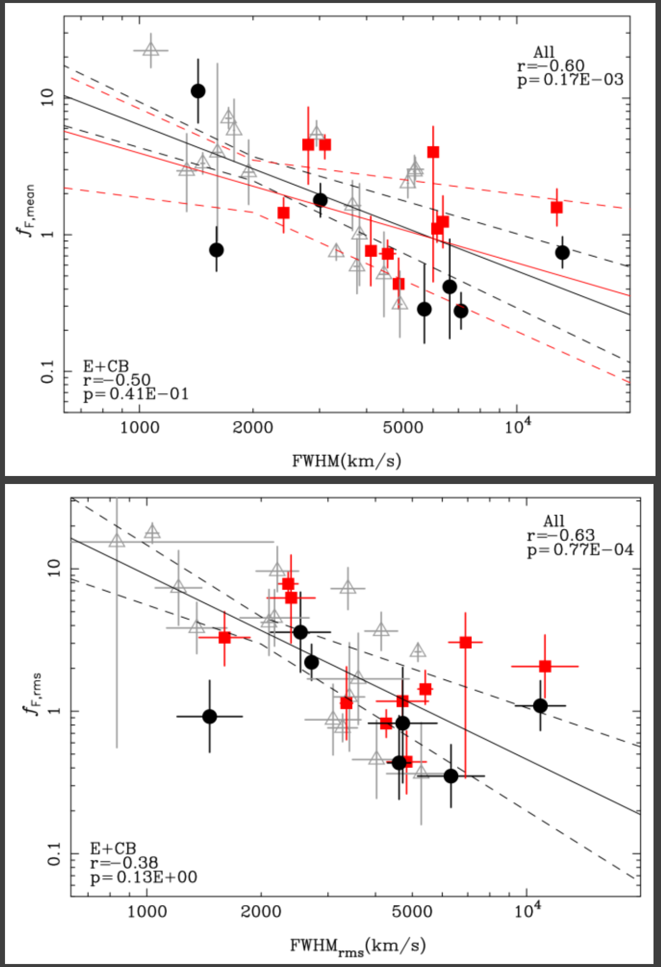
Accretion Rate and Eddington Ratio



f factor?



Accretion-disk based BH mass vs. single-epoch BH mass based R-L relation (Mejia-Restrepo et al. 2018)



M-sigma based BH mass vs. RM BH mass (Yu et al. 2019)
Pseudobulge?

Summary

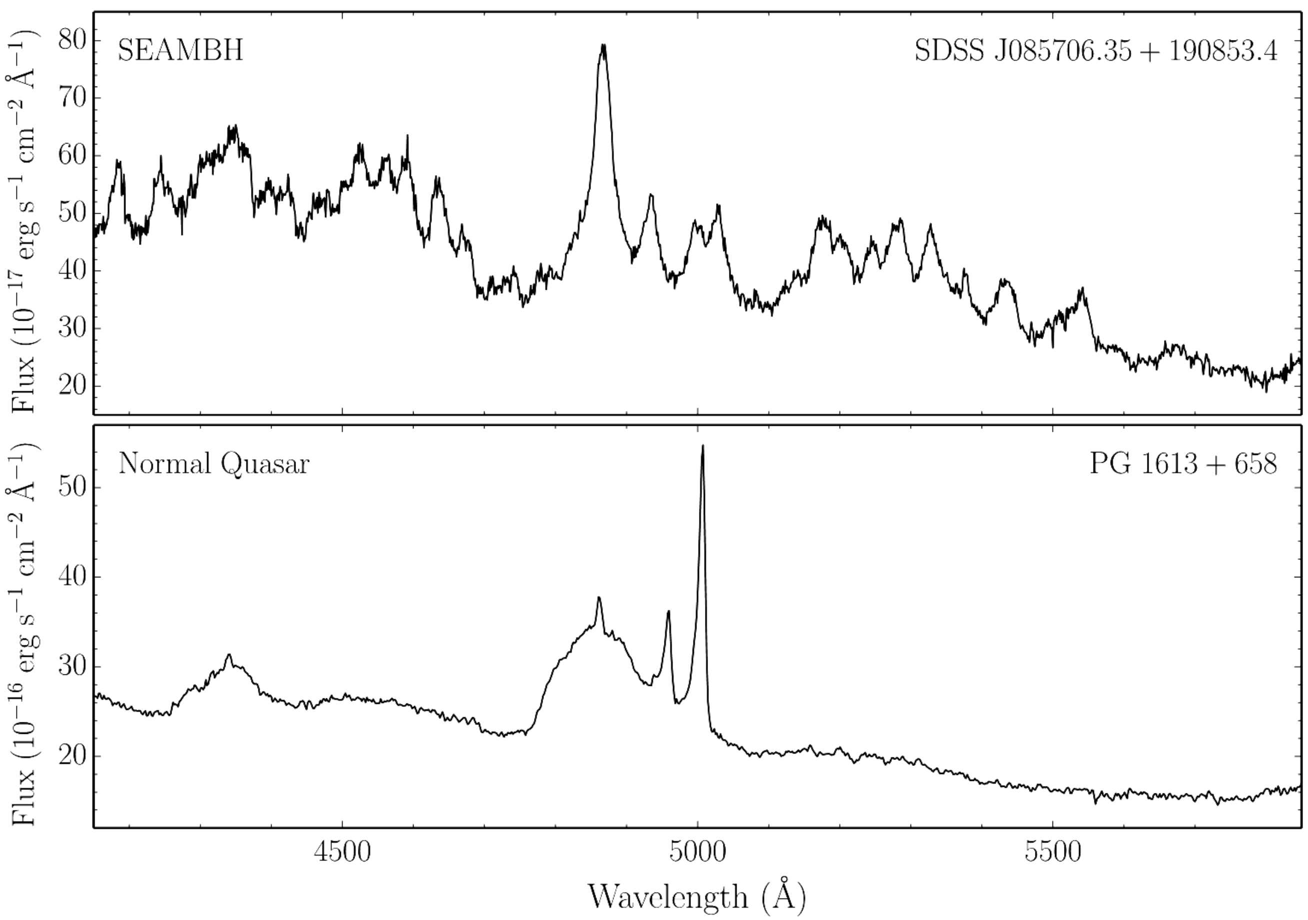
- SEAMBHs: shortened Hβ time lags
- R_{Fe} is the primary driver for the shortened lags
- A new scaling relation

$$\log\left(R_{\mathrm{H}\beta}/\mathrm{lt\!-\!days}\right) = \alpha + \beta\log\ell_{44} + \gamma\mathcal{R}_{\mathrm{Fe}}$$

Thanks!

SEAMBHs: candidates

- Strong Fe II
- Narrow Hβ
- weak [O III]



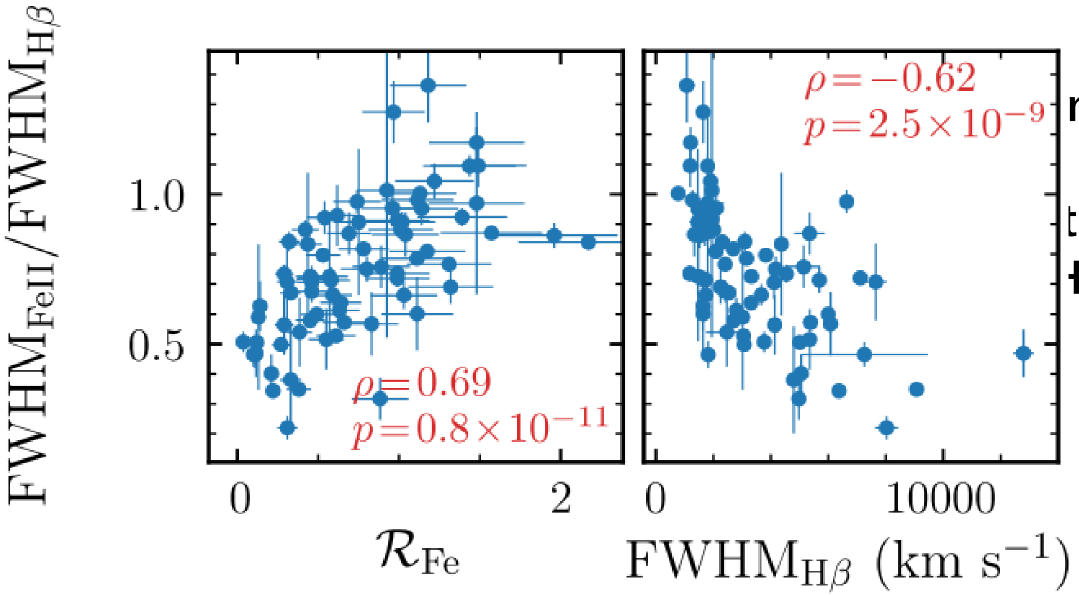
Pairwise correlations

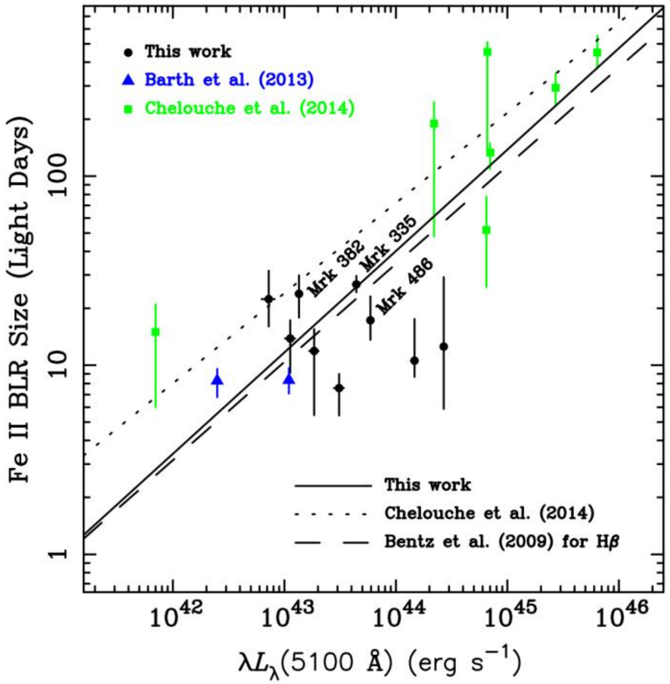
- Some highlights

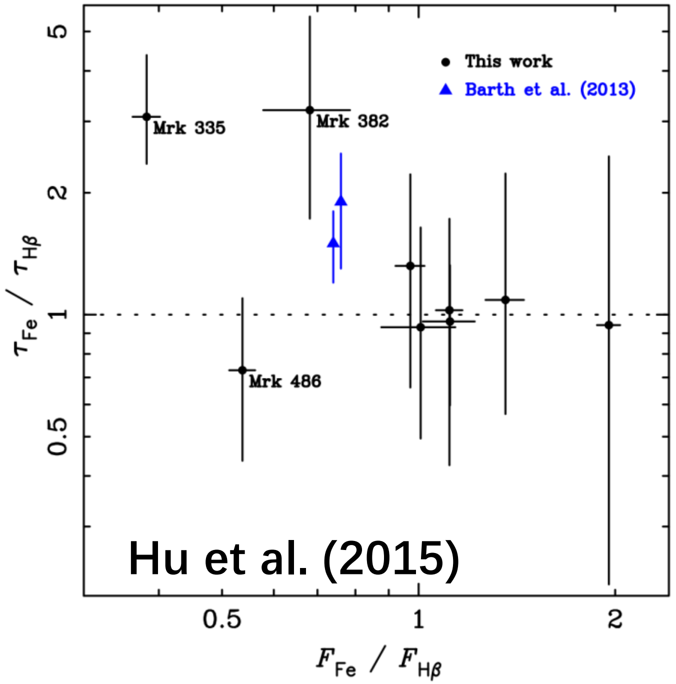
nger:

ting region is
Hβ region

ratio → 1



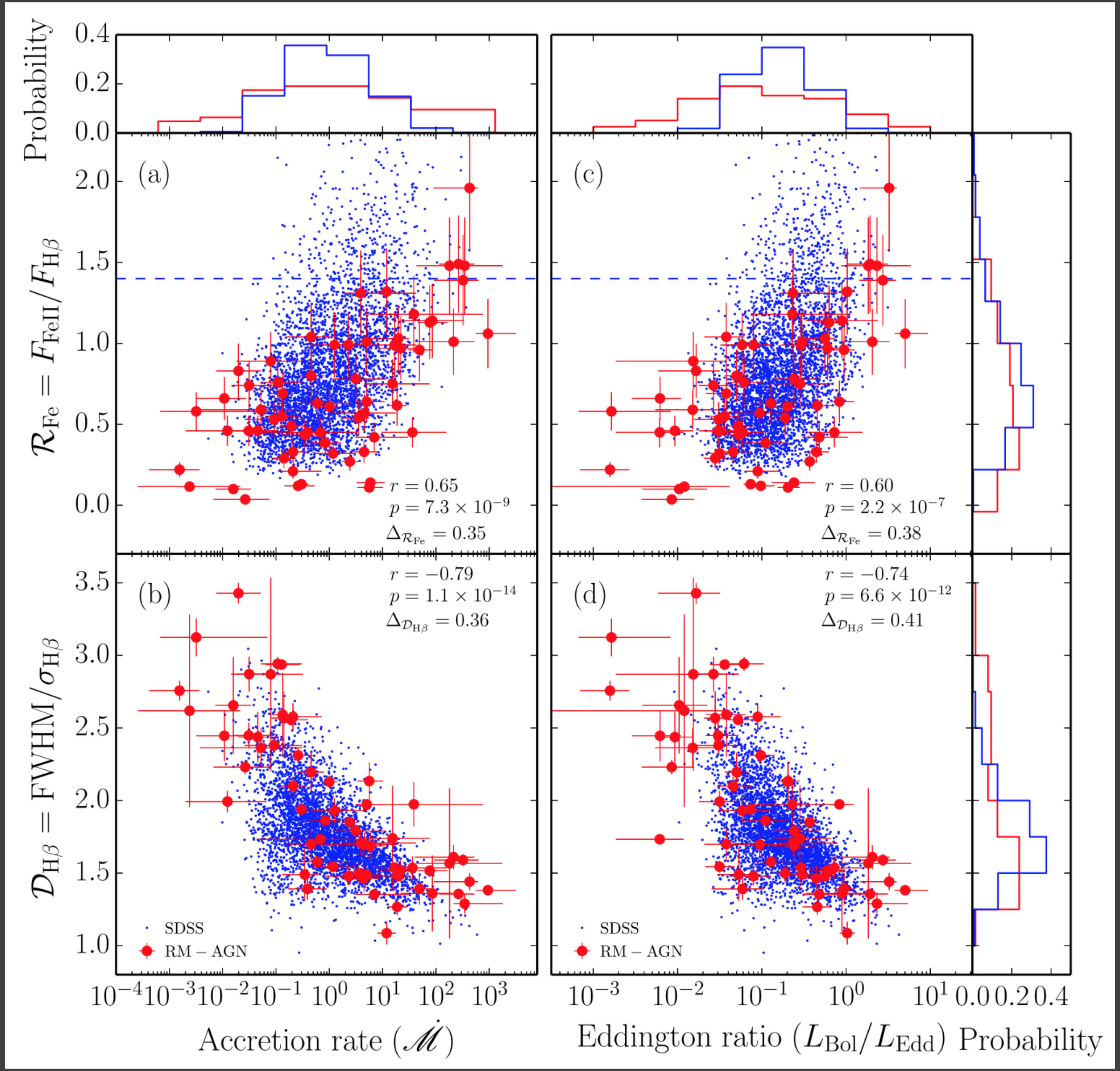




Hu et al. (2015)

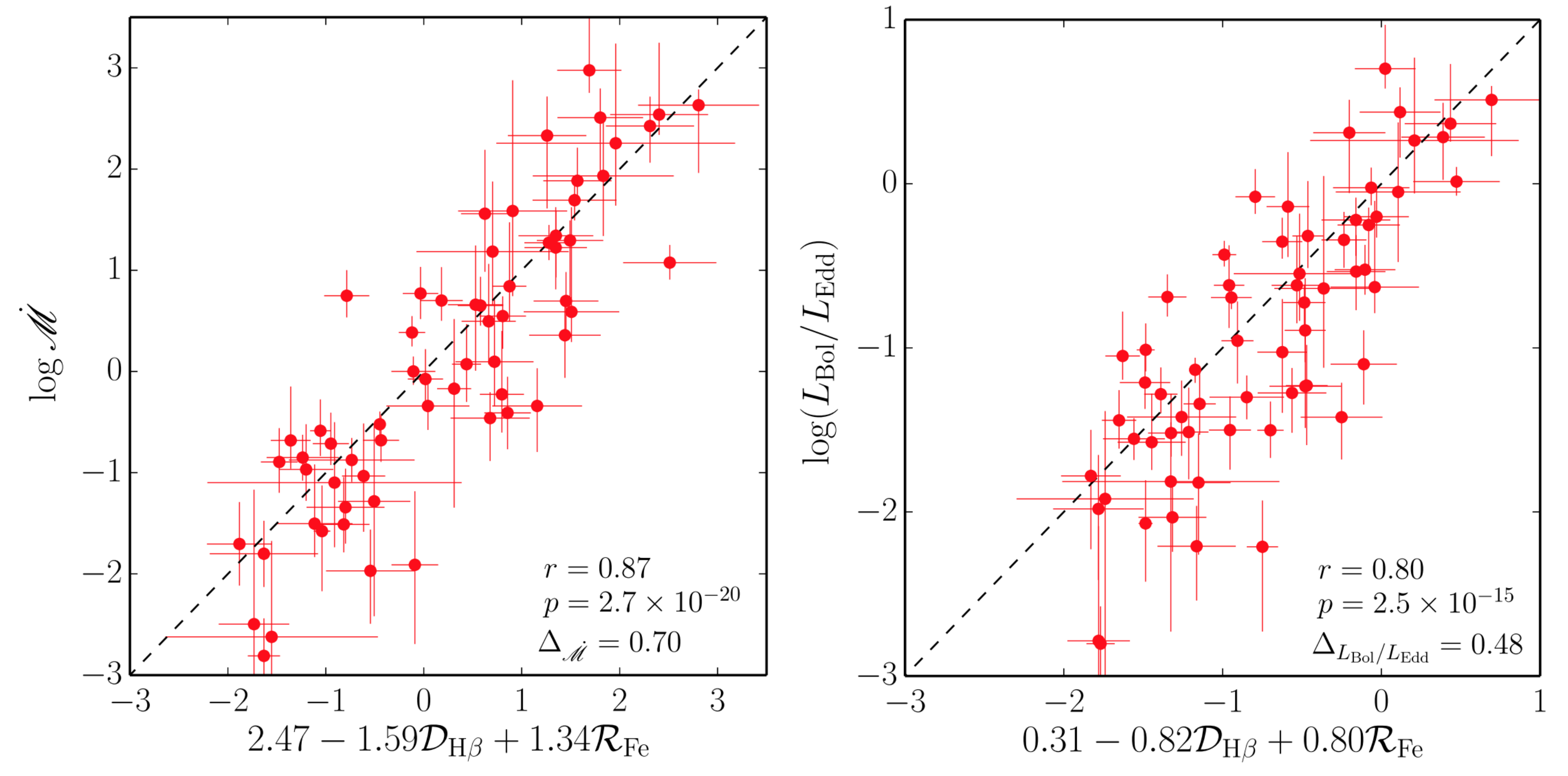
Du et al. (2019)

In 2016, we established a bivariate correlation: BLR fundamental plane



Du et al. (2016b)

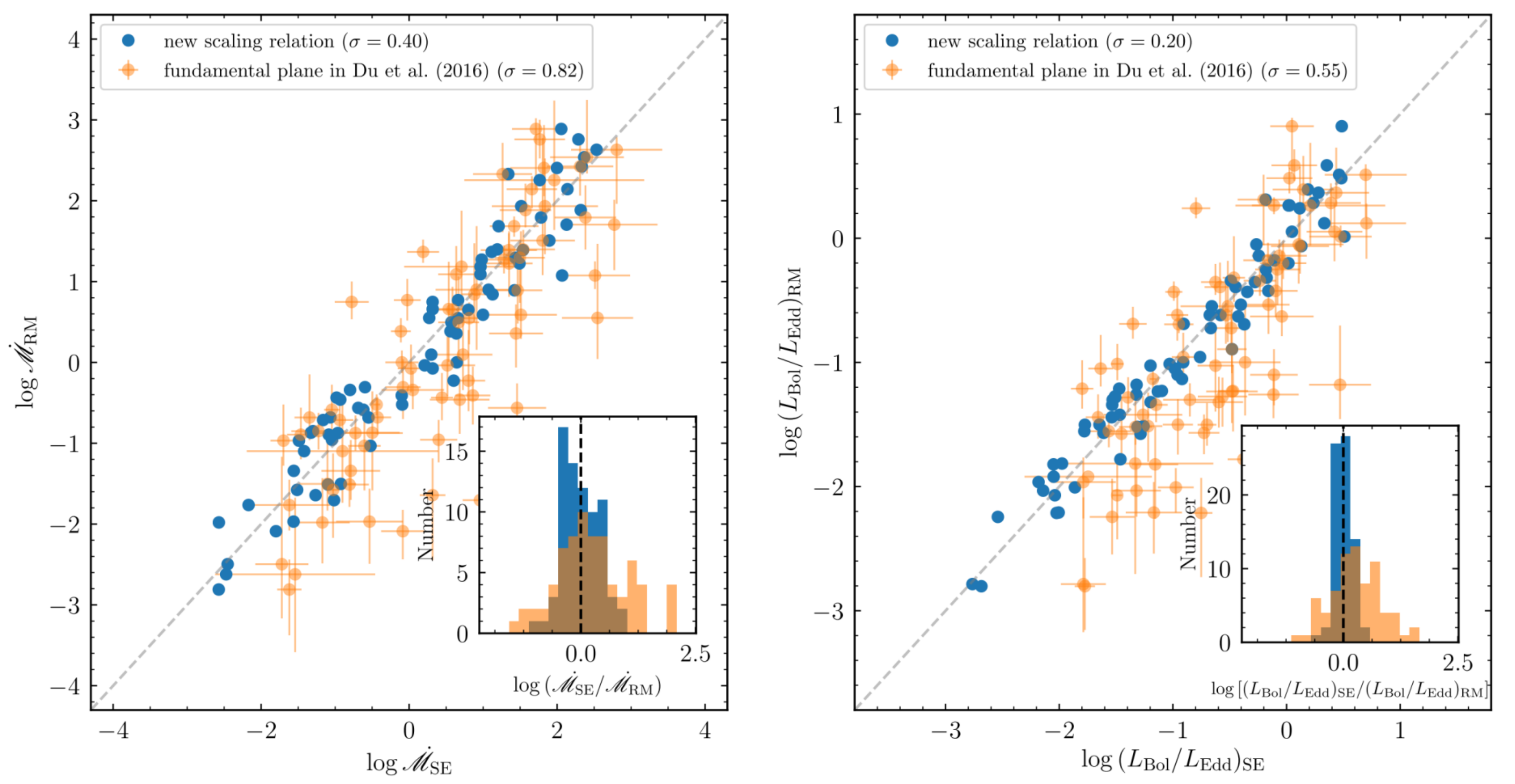
In 2016, we established a bivariate correlation: BLR fundamental plane



- A good beginning for direct indicator of accretion rate
- Do NOT need any information of luminosity!

Du et al. (2016b)

In 2016, we established a bivariate correlation: BLR fundamental plane



The scatter of FP need to be improved by including more single-epoch properties

Du et al. (2019)

Calibration: pros and cons

- [OIII]-based

Pros:

no need to rotate the slit

Cons:

Spectral slope issue

- Comparison-star-based

Pros:

Spectral slope calibration

Cons:

Inaccurate slit rotate -> calibration issue