Fe II Reverberation in Active Galactic Nuclei

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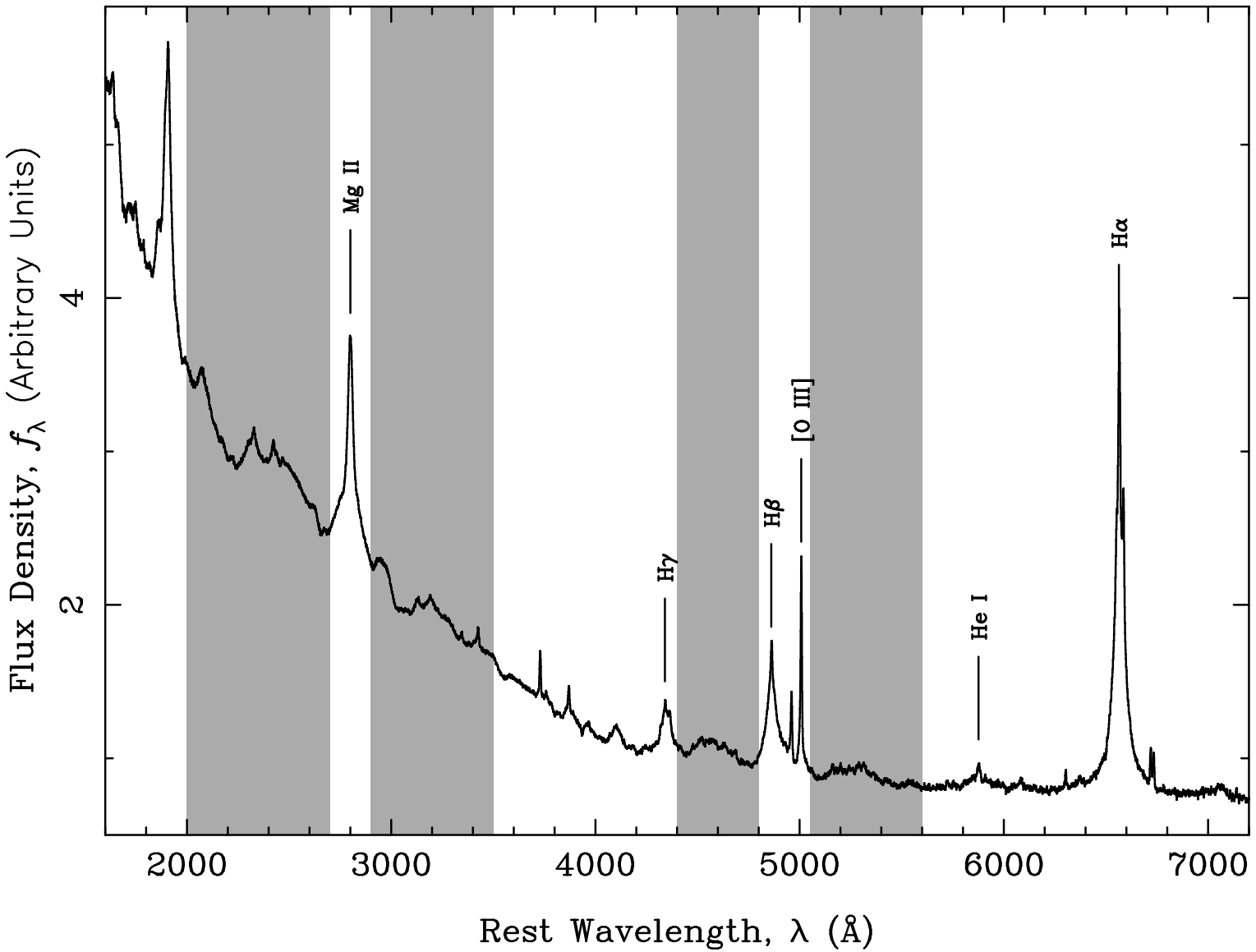
Pu Du, Kai-Xing Lu, Yan-Rong Li, Fang Wang, Jie Qiu, Jin-Ming Bai, Shai Kaspi, Luis C. Ho, Hagai Netzer, Jian-Min Wang (SEAMBH collaboration)

Hu et al. 2015, ApJ, 804, 138

Lijiang, 2016.10.24

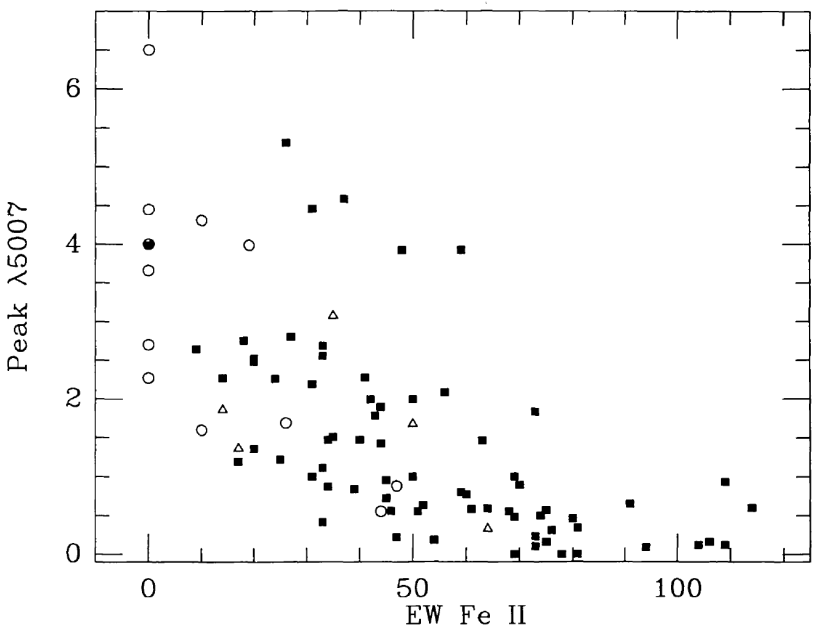
Fe II emission: pseudo-continuum

Vanden Berk et al. 2001, AJ, 122, 549

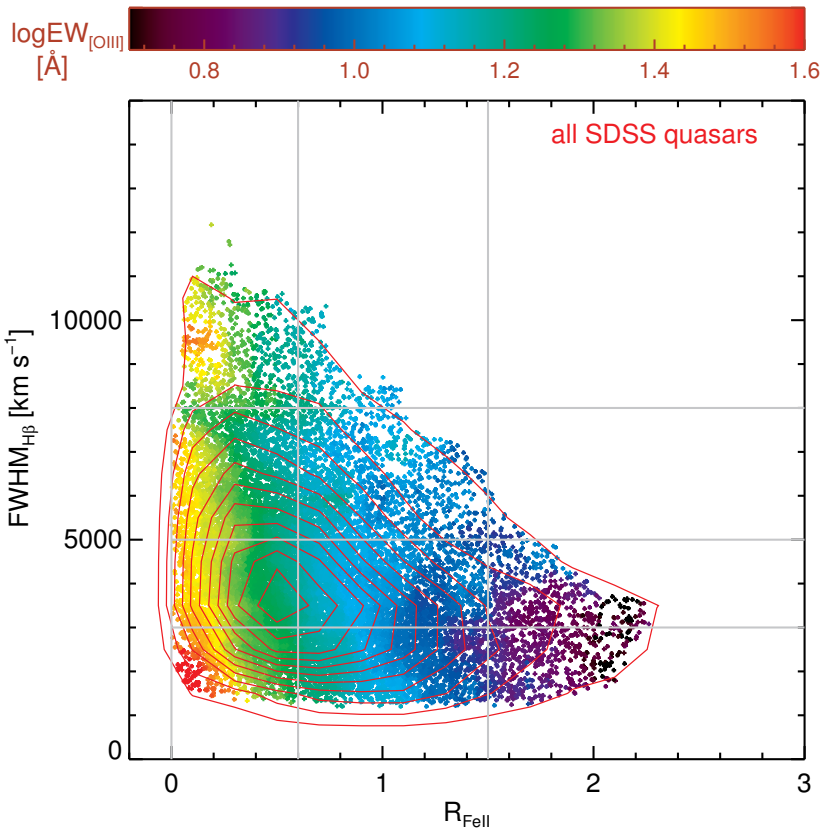


Fe II emission: eigenvector 1

Boroson & Green 1992, ApJS, 80, 109



Shen & Ho 2014, Nature, 513, 210



Fe II emission: problems

Line intensities calculated poorly agree with observations

- Collisional ionization and excitation: Collin-Souffrin et al. (1980), Netzer & Wills (1983), Sigut & Pradhan (1998), Collin & Joly (2000), Baldwin et al. (2004)
- Microturbulence: Baldwin et al. (2004)
- Anisotropy: Ferland et al. (2009)

The location of the Fe II-emitting region: same as Hβ?

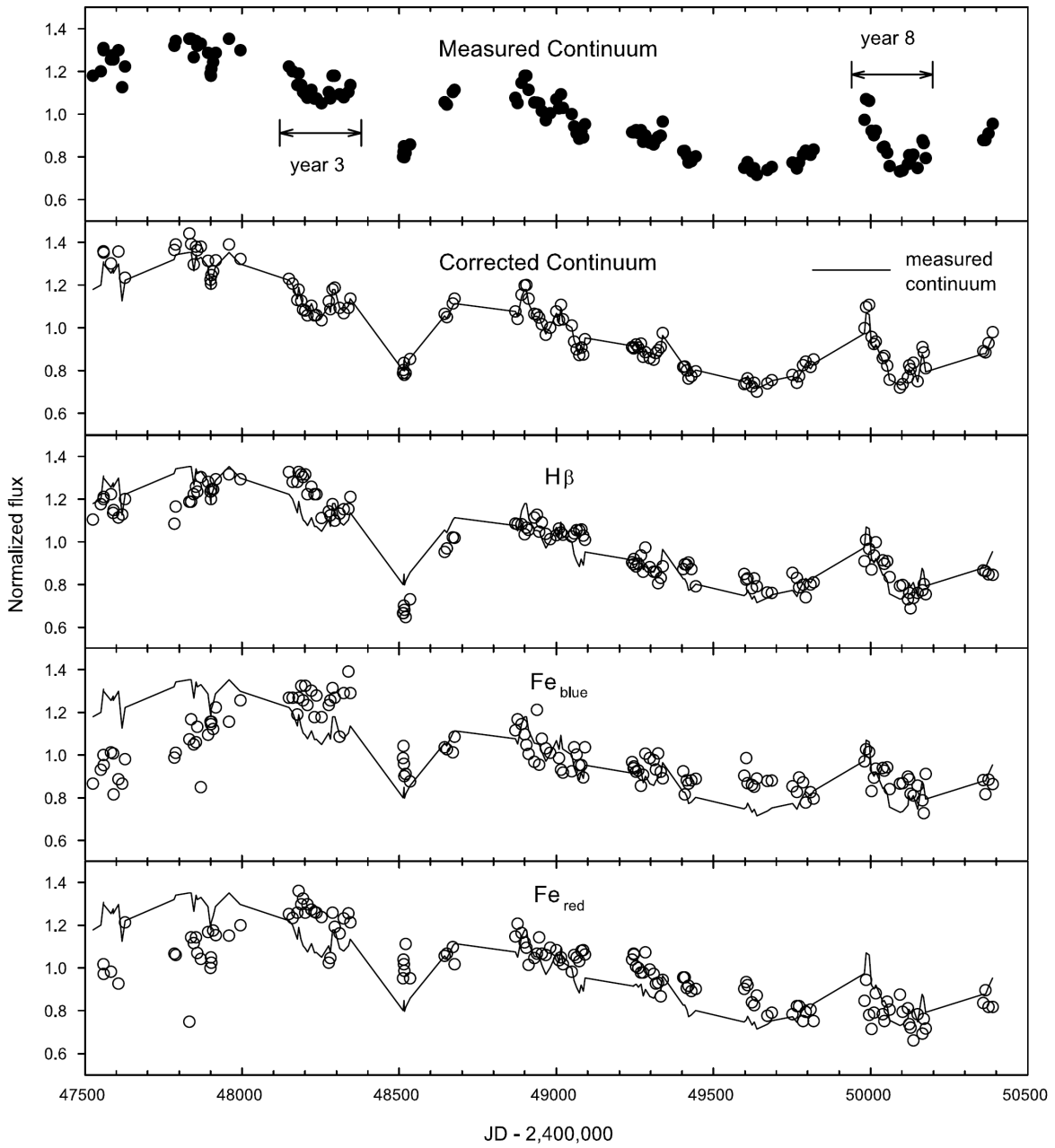
- Similar ionization energy
- Similar width: Boroson & Green (1992), Laor (1997), Veron-Cetty et al. (2004), Sulentic et al. (2012)
- Narrower: Marziani et al. (2003), Popović (2007), Hu et al. (2008)
- Intermediate-line region: Hu et al. (2012), Zhang (2013), Modzelewska et al. (2014)
- Outer part of the accretion disk: Joly (1987)

Reverberation mapping observations

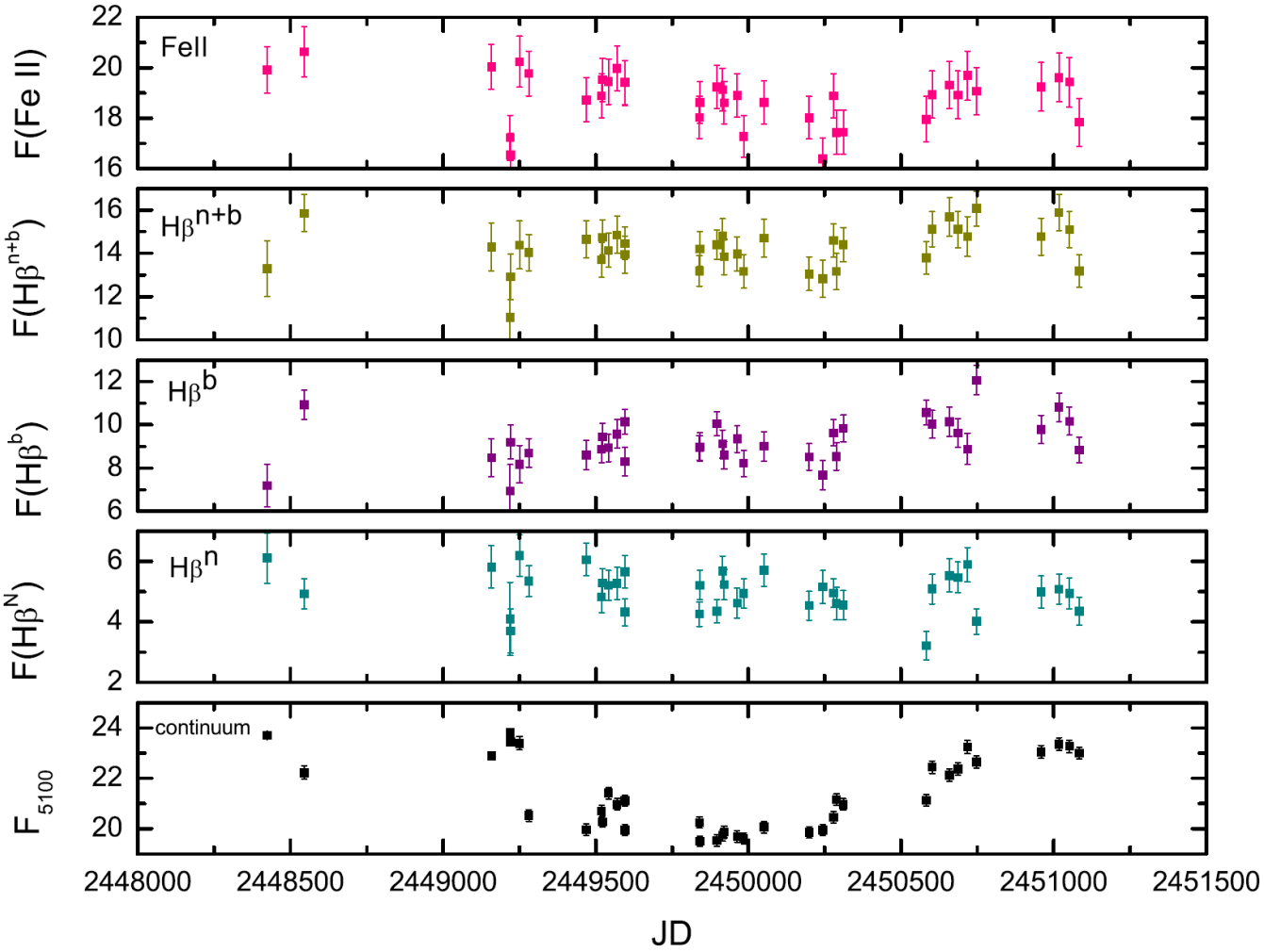
- The reverberation of the Fe II emission –> photoionization
- Time lag –> location of the Fe II-emitting region

- Show variability: Kollatschny et al. (2000), Wang et al. (2005), Shapovalova et al. (2012),
- Upper limits: Vestergaard & Peterson (2005), Kuehn et al. (2008)
- Only a few detect Fe II reverberation: Bian et al. (2010), Rafter et al. (2013), Barth et al. (2013), Chelouche et al. (2014)

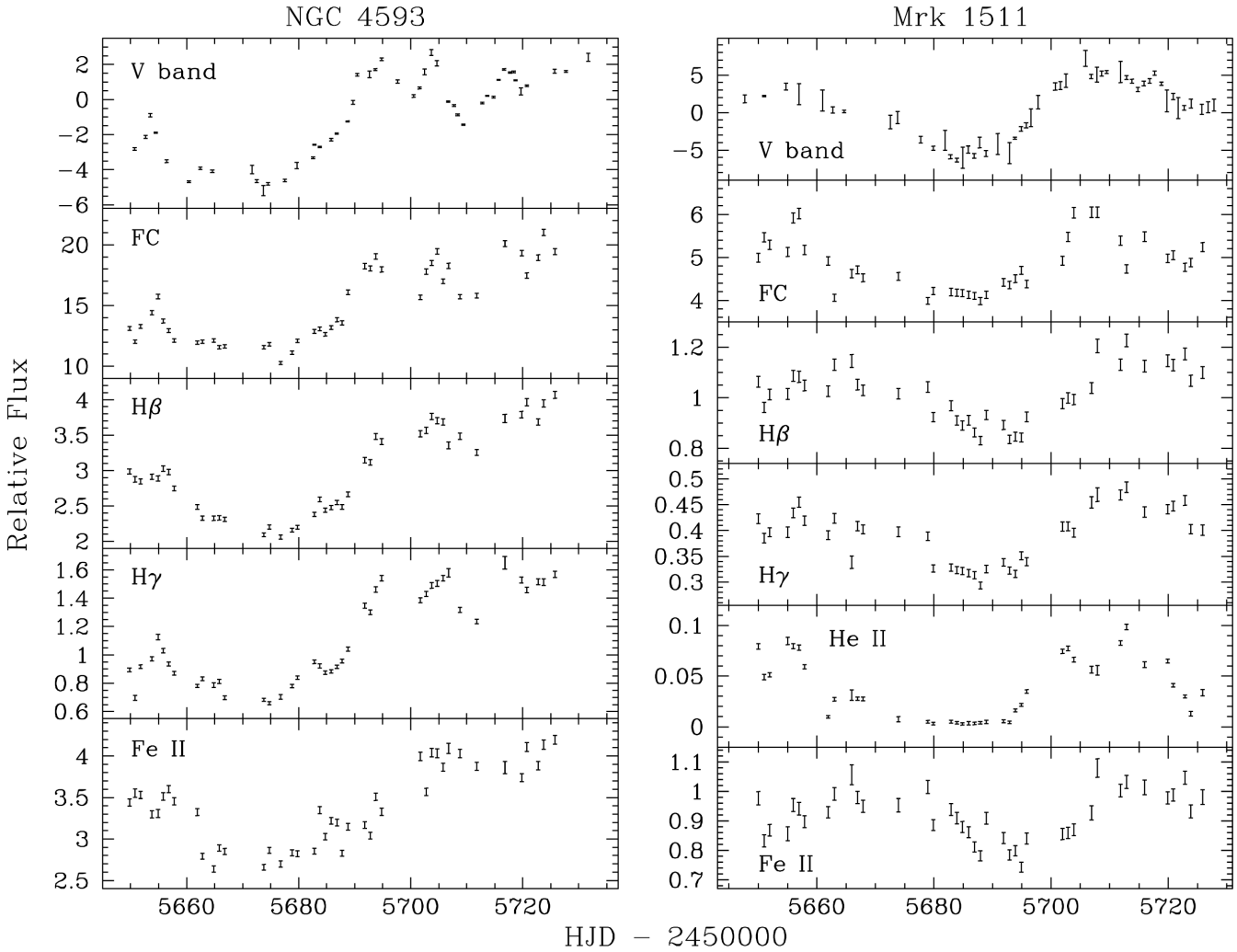
Kuehn et al. (2008): Ark 120



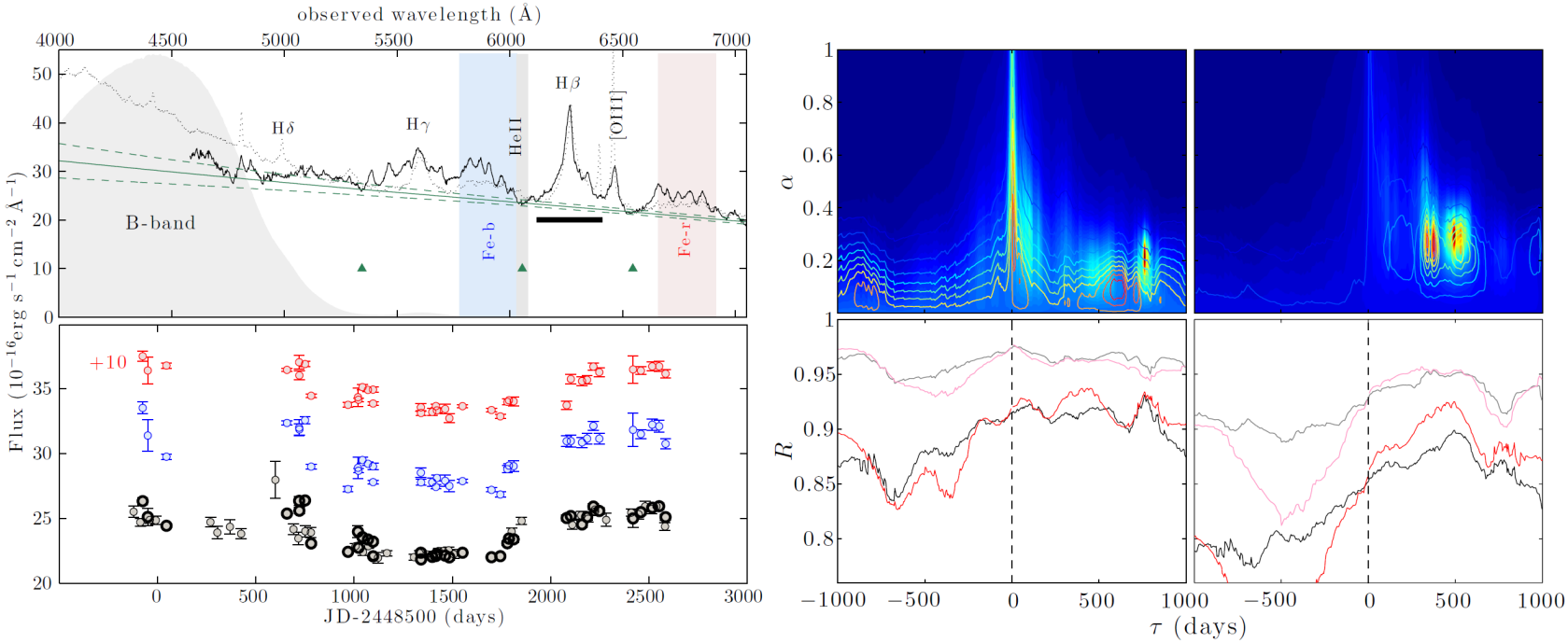
Bian et al. (2010): PG 1700+518, 209^{+100}_{-147}



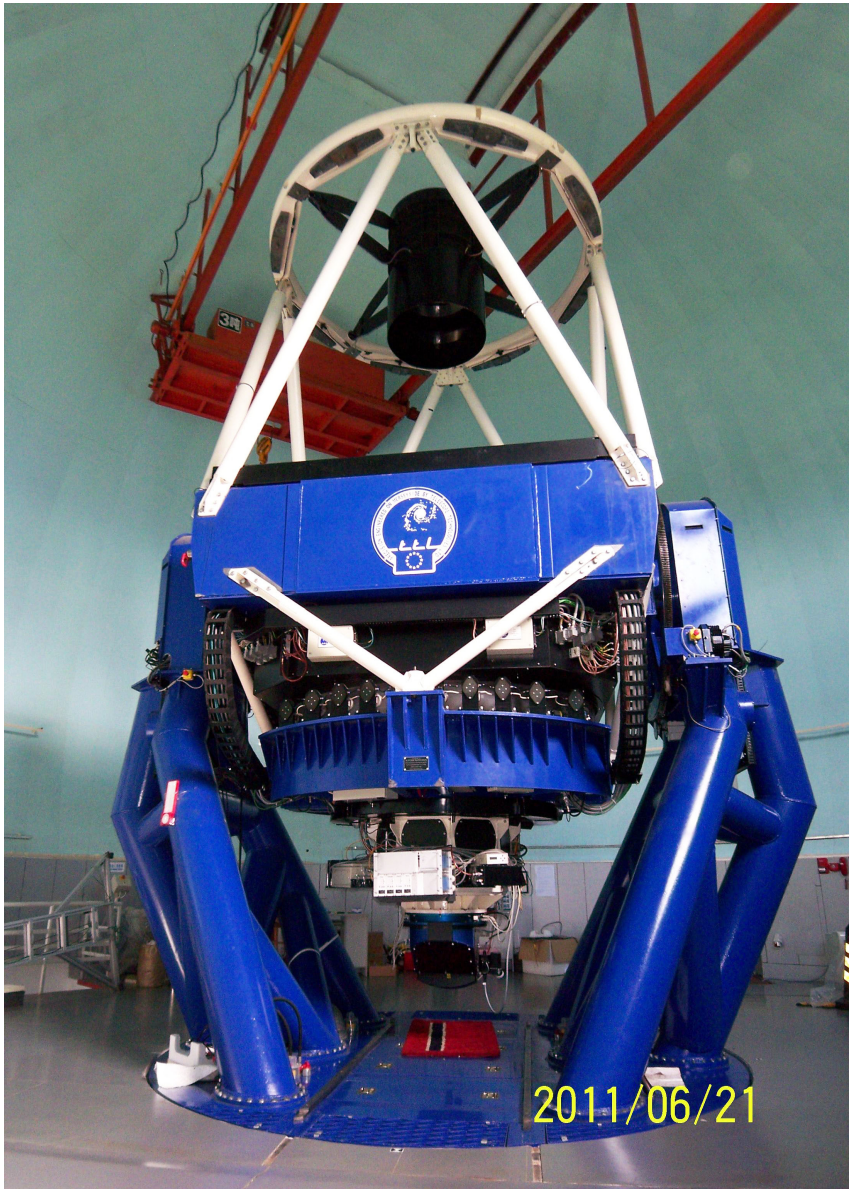
Barth et al. (2013)



Chelouche et al. (2014): multivariate correlation function



SEAMBH campaign 2012-2013

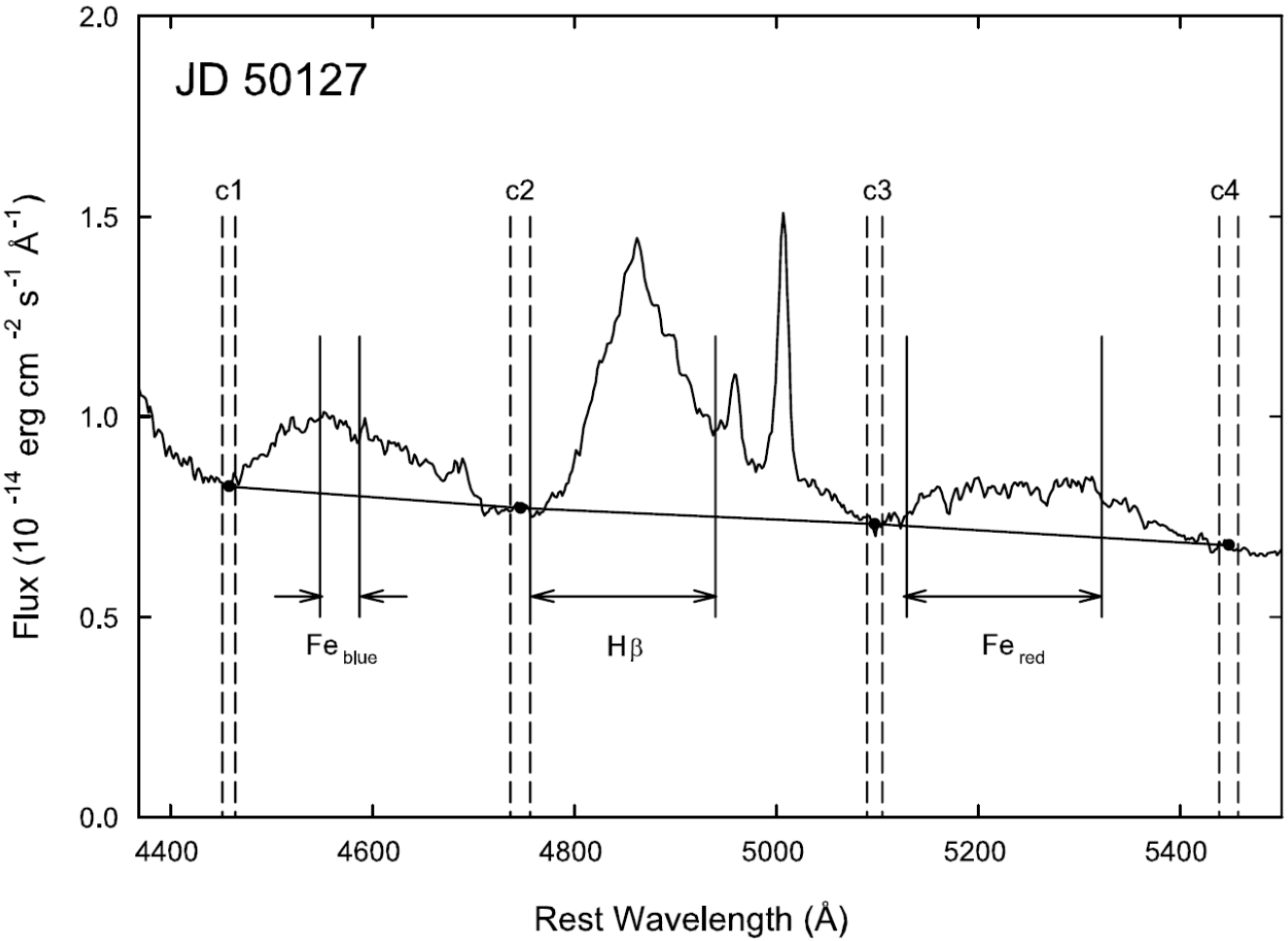


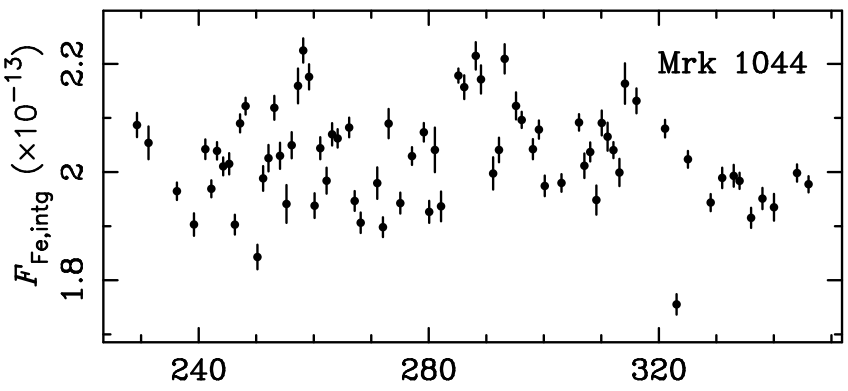
- 10 NLS1s, high-cadence observation
- Hβ time lags for 8: Du et al. (2014), Wang et al. (2014)

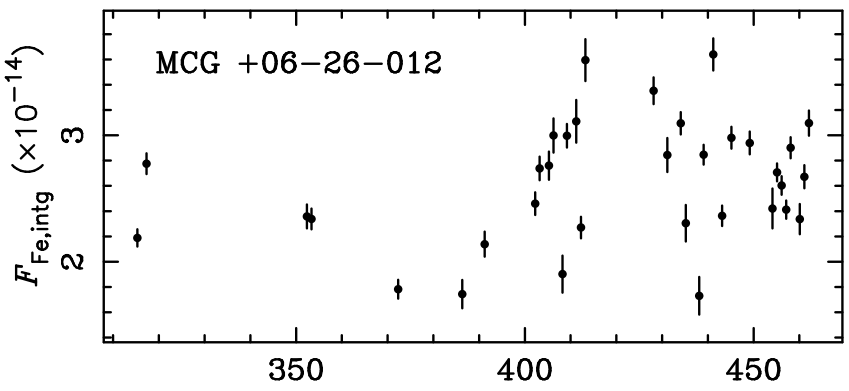
- Strong Fe II emission
- Fe II variability amplitude: only 2-5%
- Traditional integration method doesn't work well

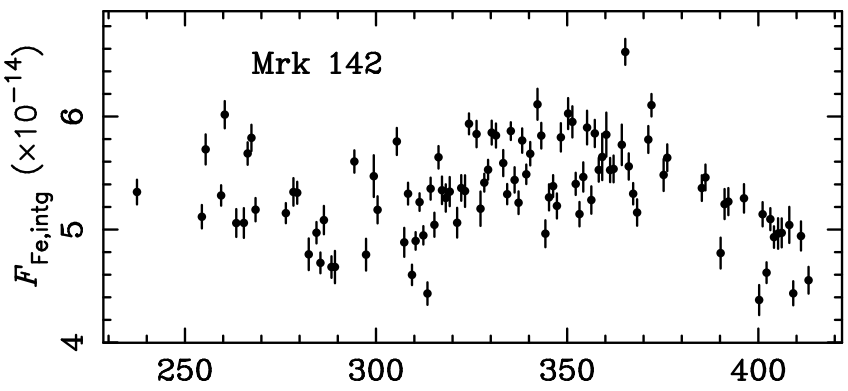
Traditional integration method

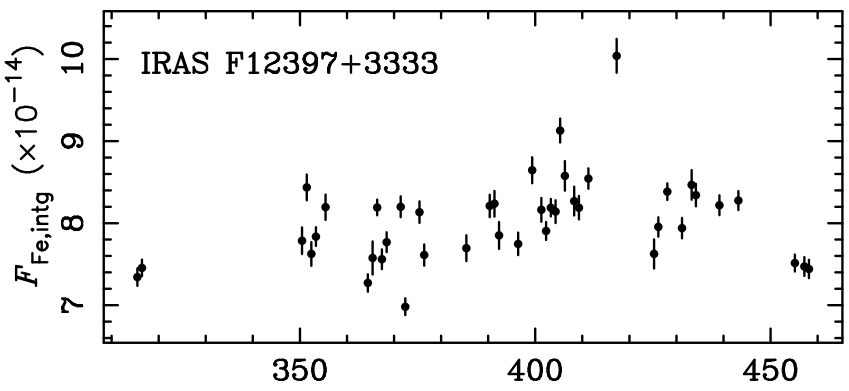
Kuehn et al. 2008, ApJ, 673, 69

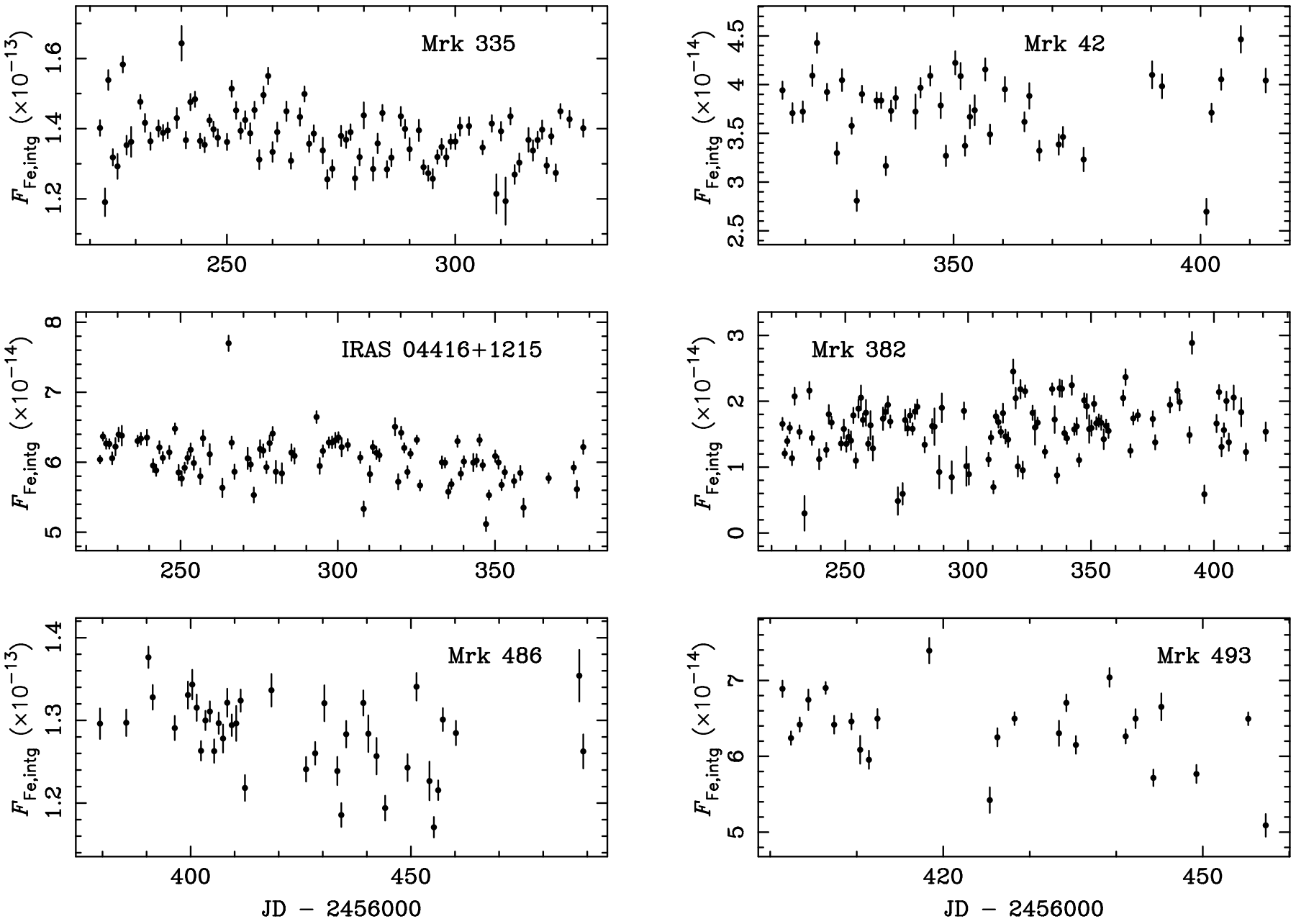



Mrk 1044
$F_{\rm Fe,intg}$ ($\times10^{-13}$)
1.8
2
2.2
240
280
320


MCG +06−26−012
$F_{\rm Fe,intg}$ ($\times10^{-14}$)
2
3
350
400
450


Mrk 142
$F_{\rm Fe,intg}$ ($\times10^{-14}$)
4
5
6
250
300
350
400

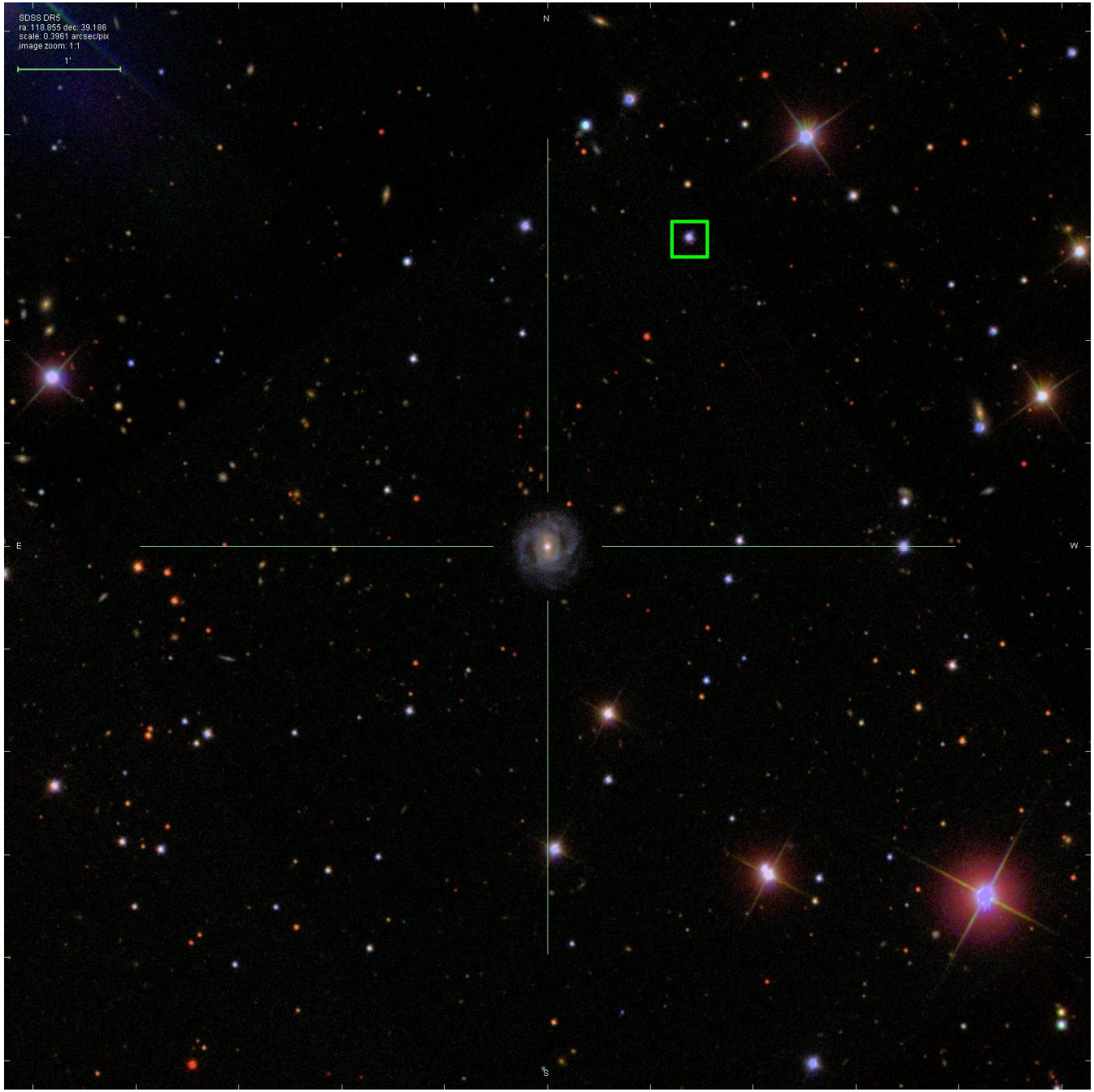

IRAS F12397+3333
$F_{\rm Fe,intg}$ ($\times10^{-14}$)
7
8
9
10
350
400
450


Mrk 335
Mrk 42
IRAS 04416+1215
Mrk 382
Mrk 486
Mrk 493
$F_{\rm Fe,intg}$ ($\times10^{-13}$)
$F_{\rm Fe,intg}$ ($\times10^{-14}$)
JD − 2456000

Why simple integration doesn't work well for Fe II?

- Works well for single strong line: Hβ
- Contamination: He II and coronal lines
- Host starlight: continuum not a straight line

- Apparent flux variation of the host galaxy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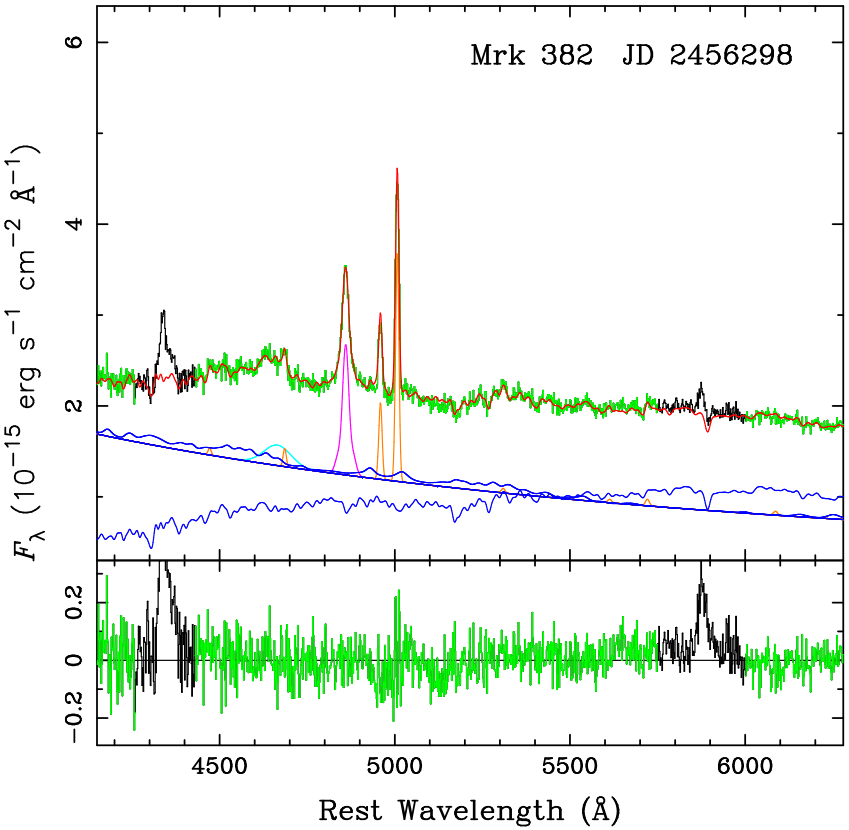
ra: 118.855 dec: 39.186
scale: 0.3961 arcsec/pix
image zoom: 1:1
1'
N
E
W
S

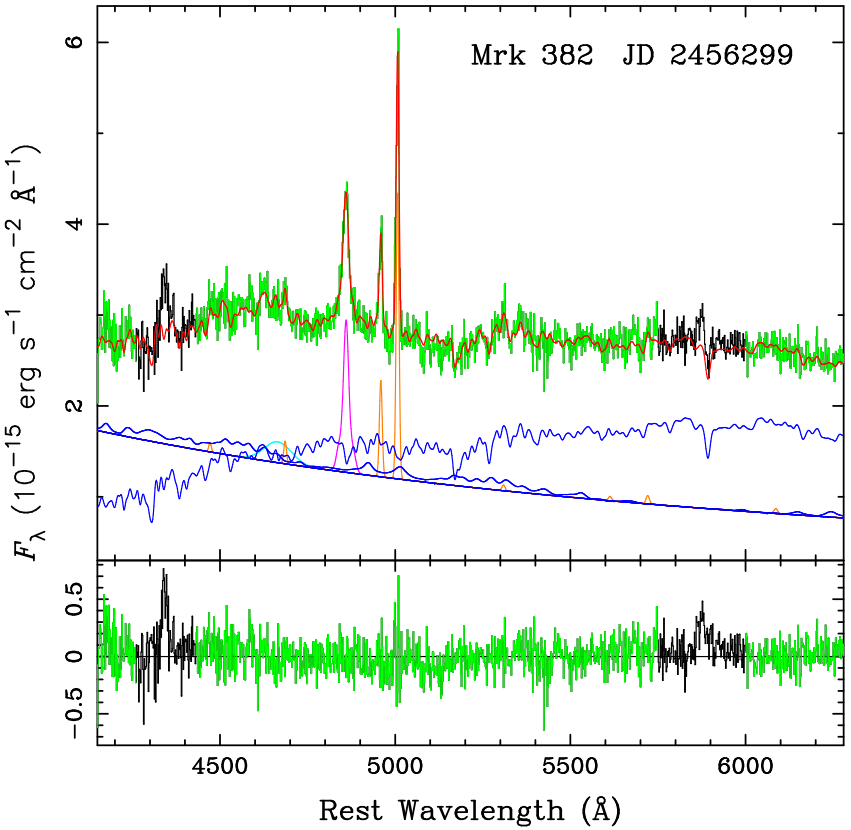
Apparent flux variation of the host galaxy

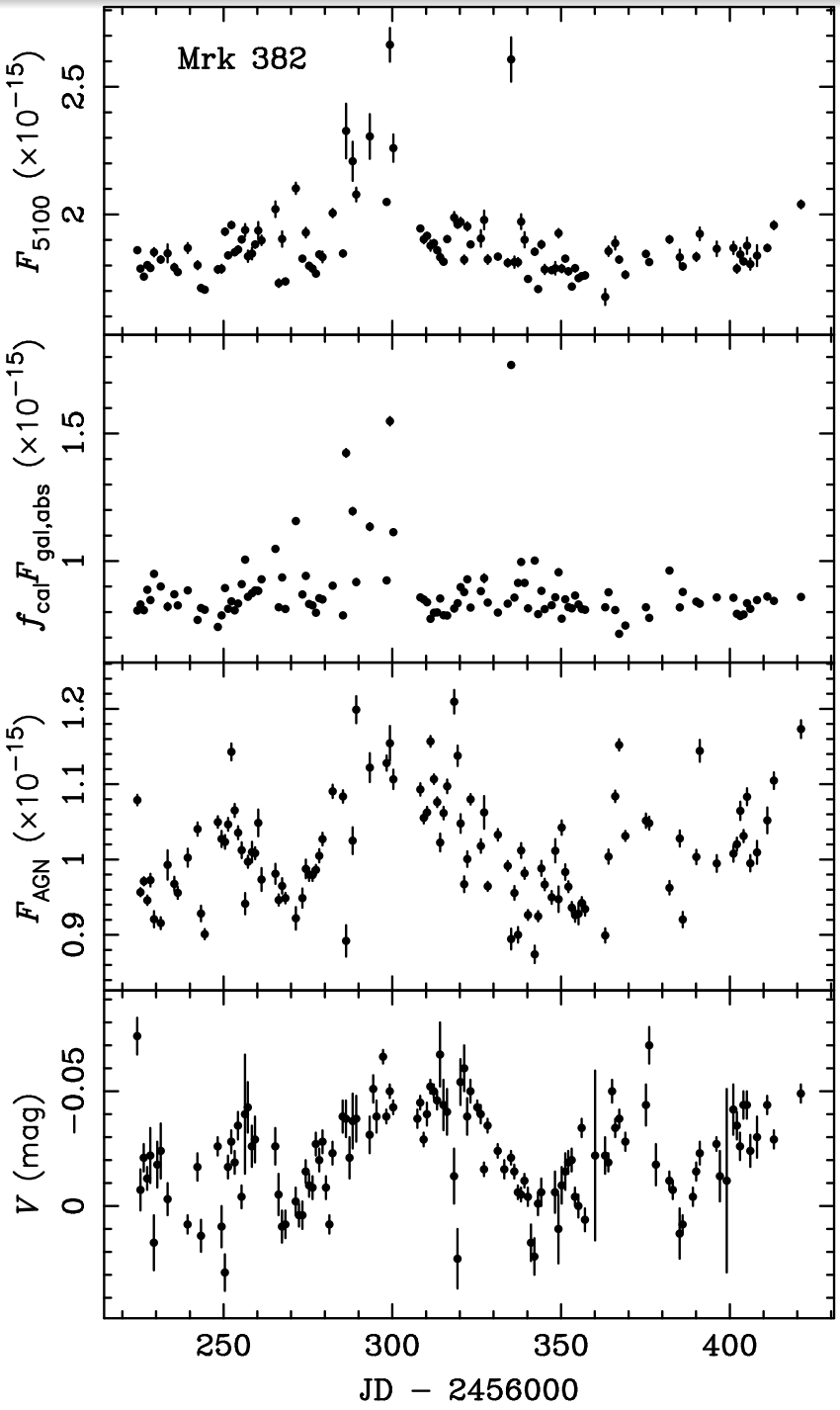
- Comparison star: differential spectrophotometry
- Works well for point source: AGN continuum, emission lines
- bad for extended host galaxy

$$F_{5100} = F_{\rm AGN} + f_{\rm cal} F_{\rm gal,abs}$$

$f_{\rm cal}$ changes due to variable seeing and mis-centering


Mrk 382 JD 2456298
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)

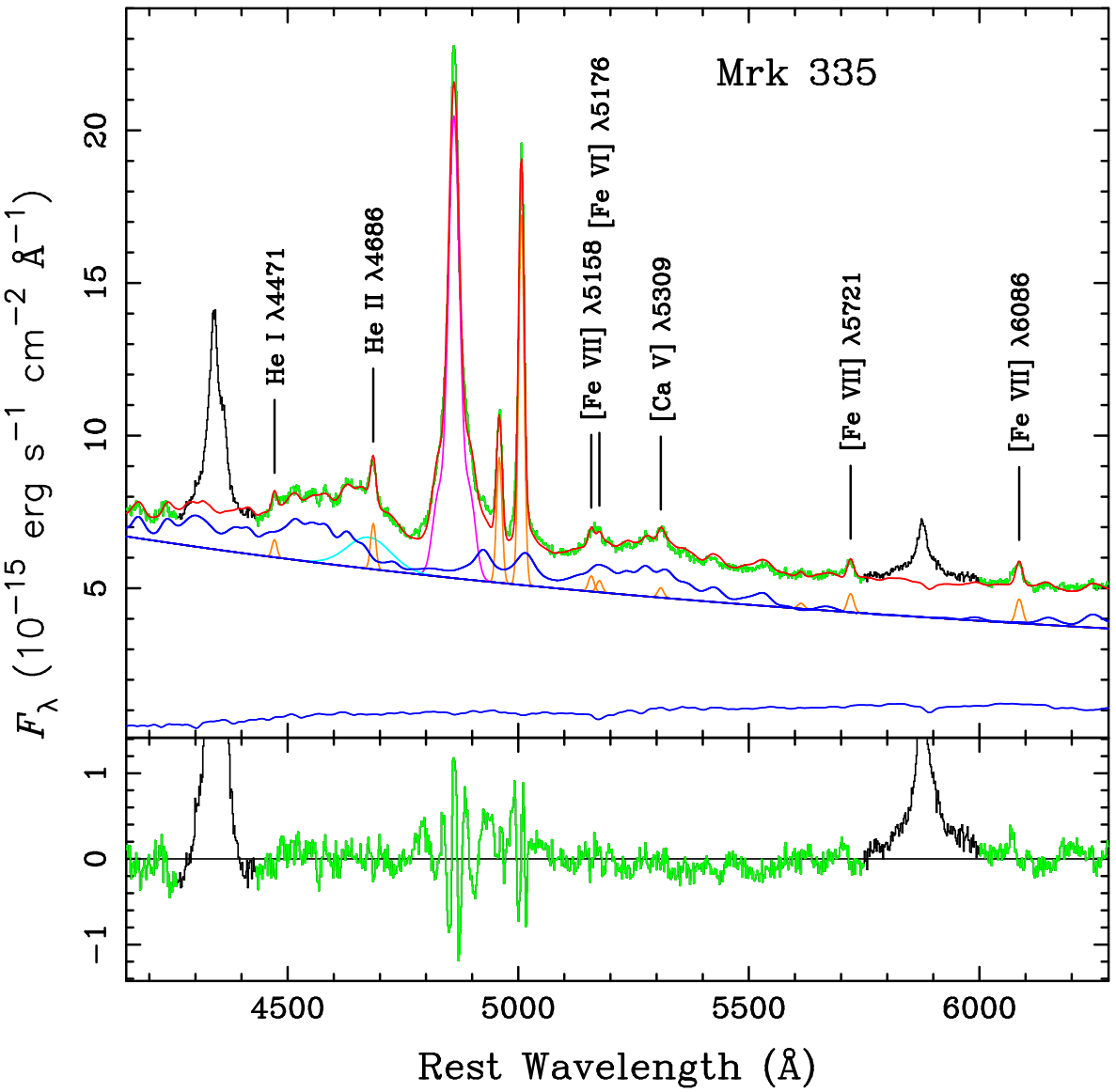

Mrk 382 JD 2456299
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)

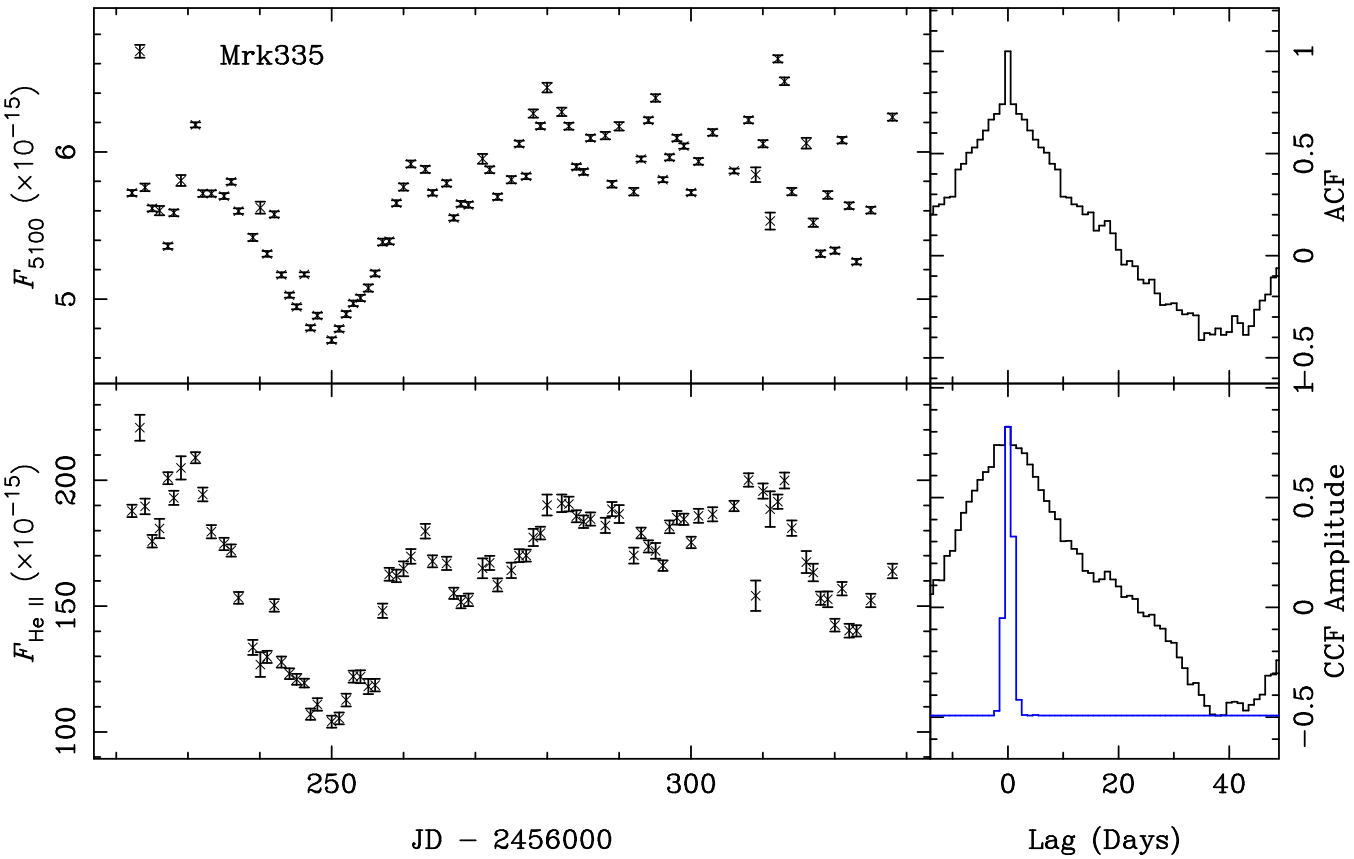


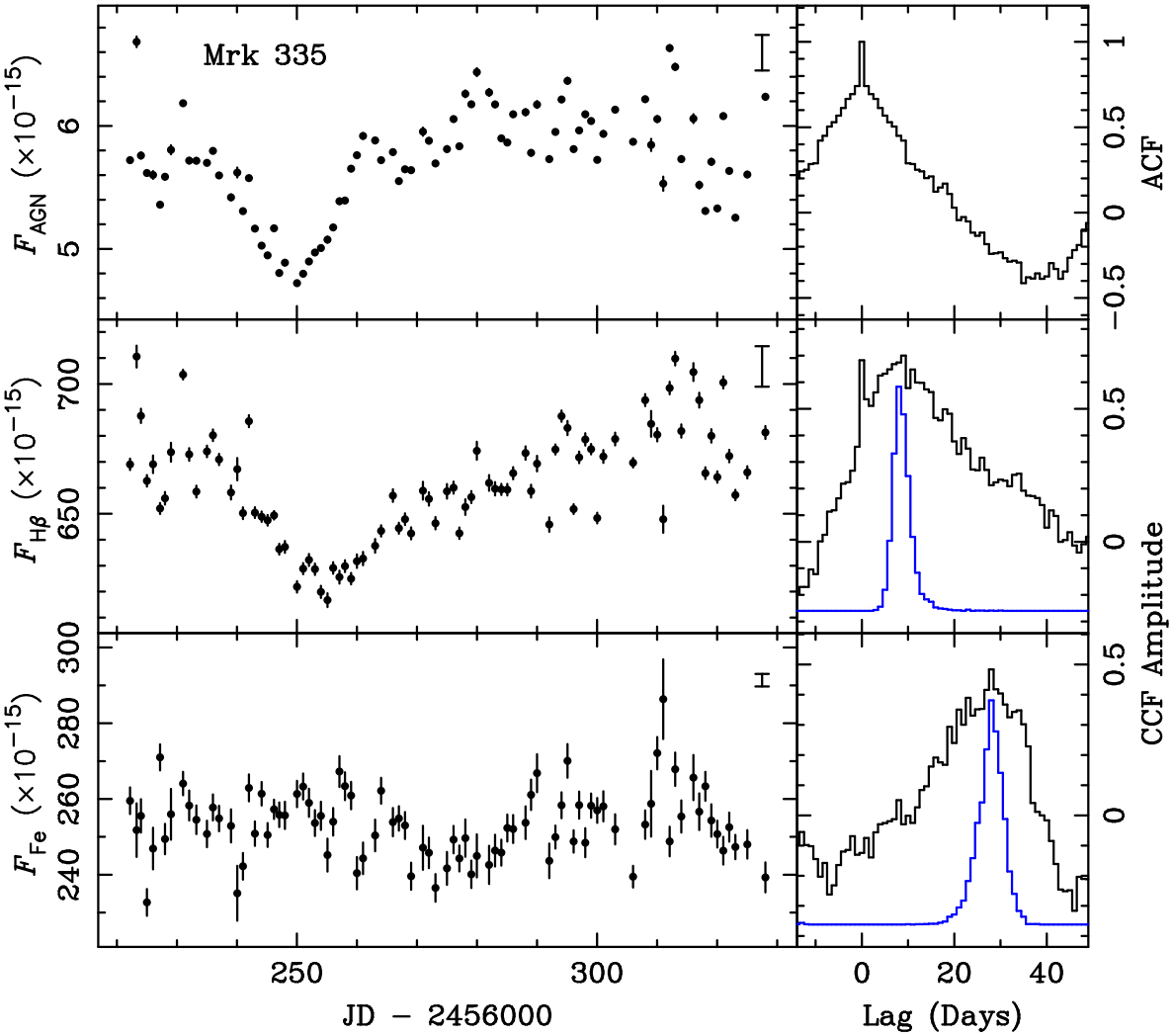
$$F_{5100} = F_{\rm AGN} + f_{\rm cal} F_{\rm gal,abs}$$

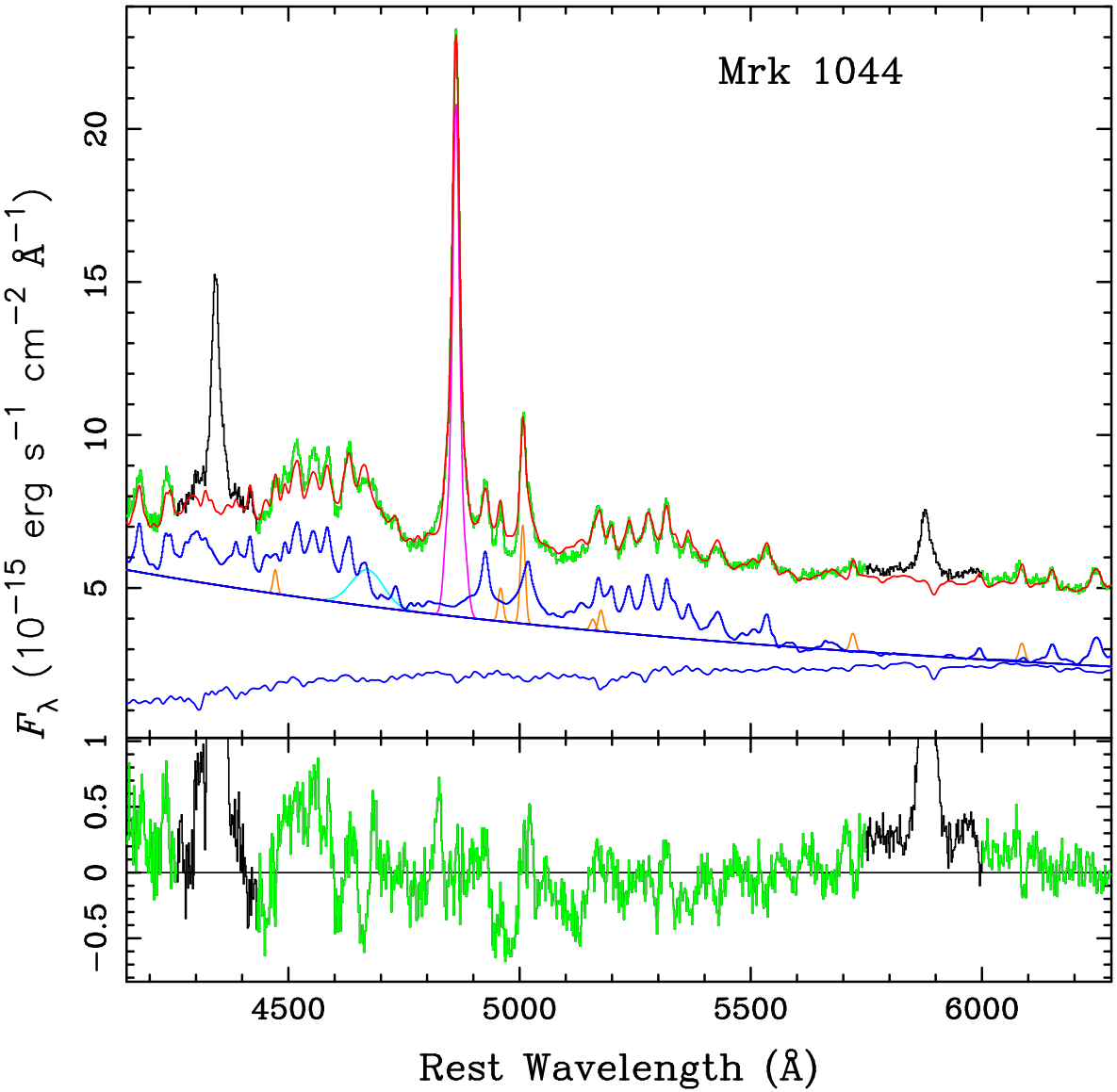
- Spectral fitting
- Fix AGN continuum slope
- Allow changes in host flux

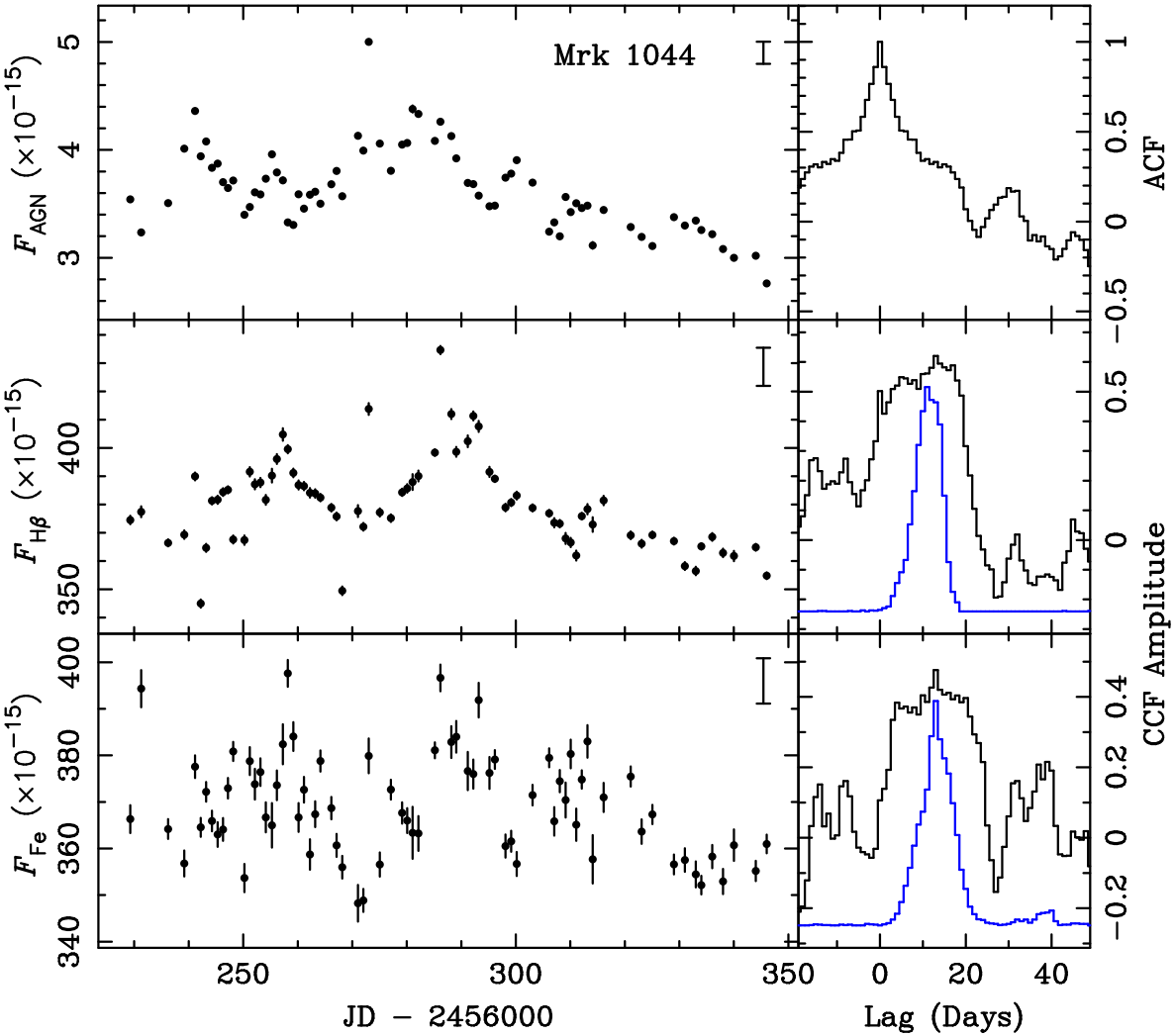
Contamination of He II and coronal lines

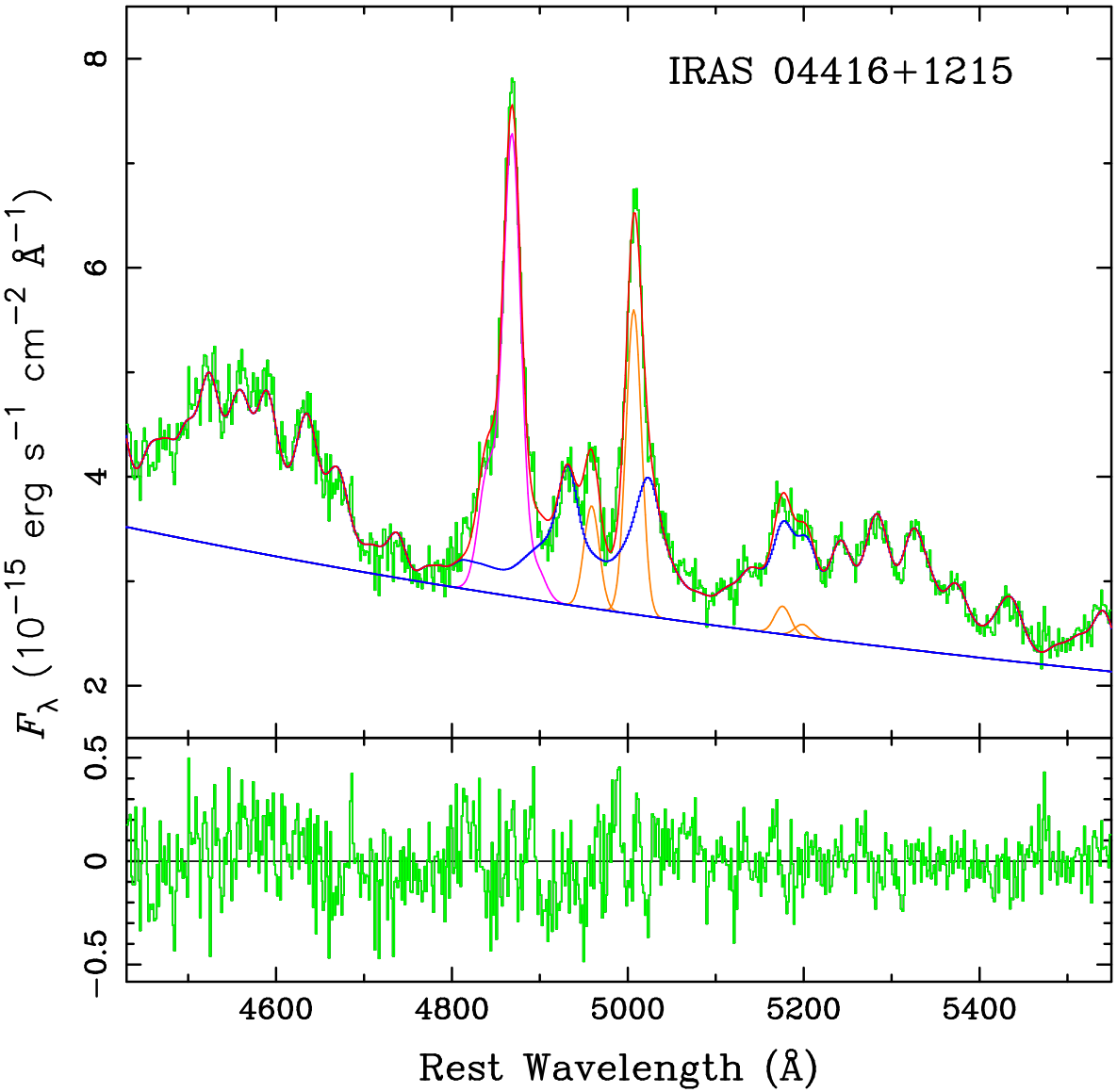


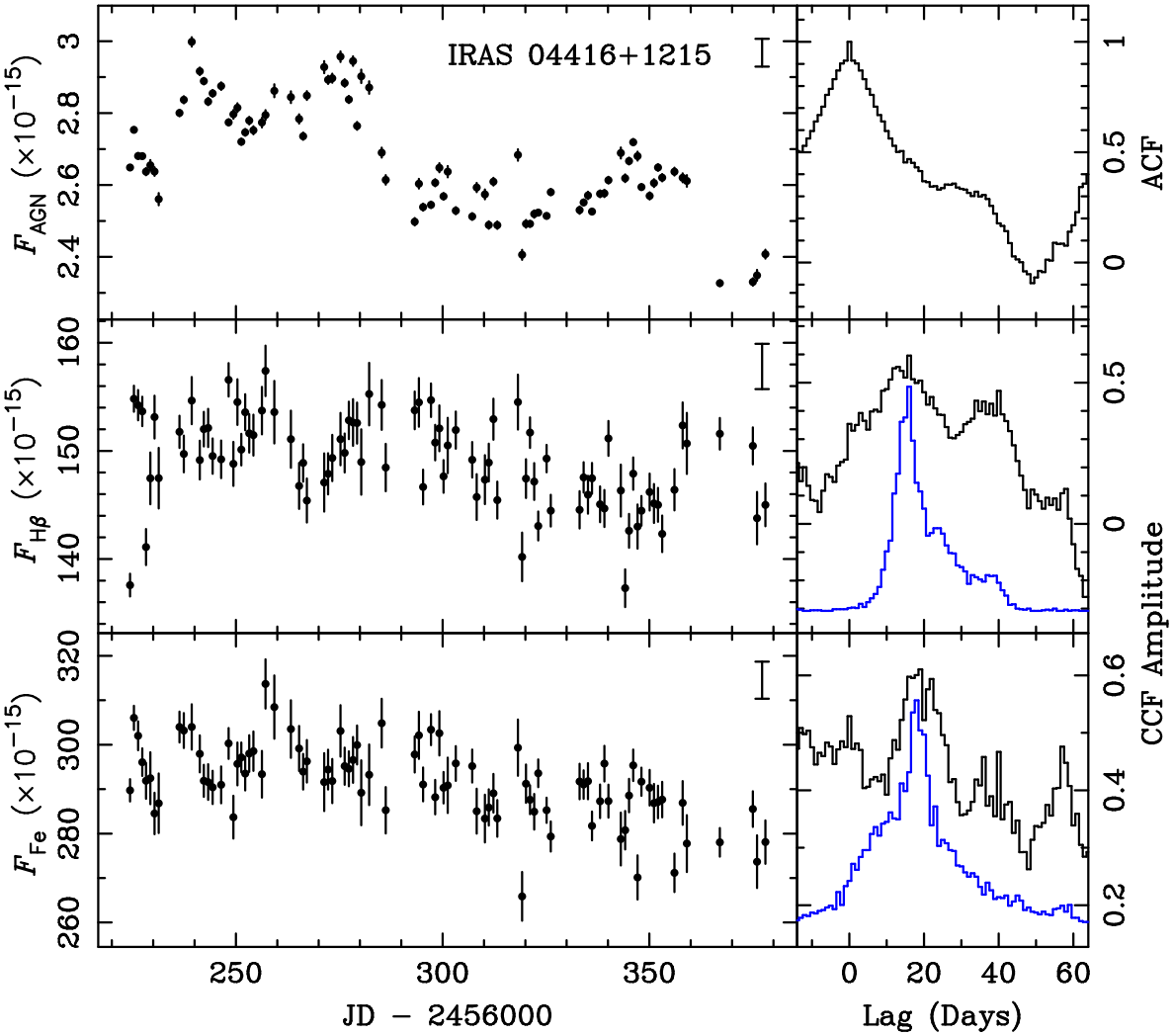

Mrk335
F_{5100} ($\times 10^{-15}$)
$F_{\rm He\ II}$ ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

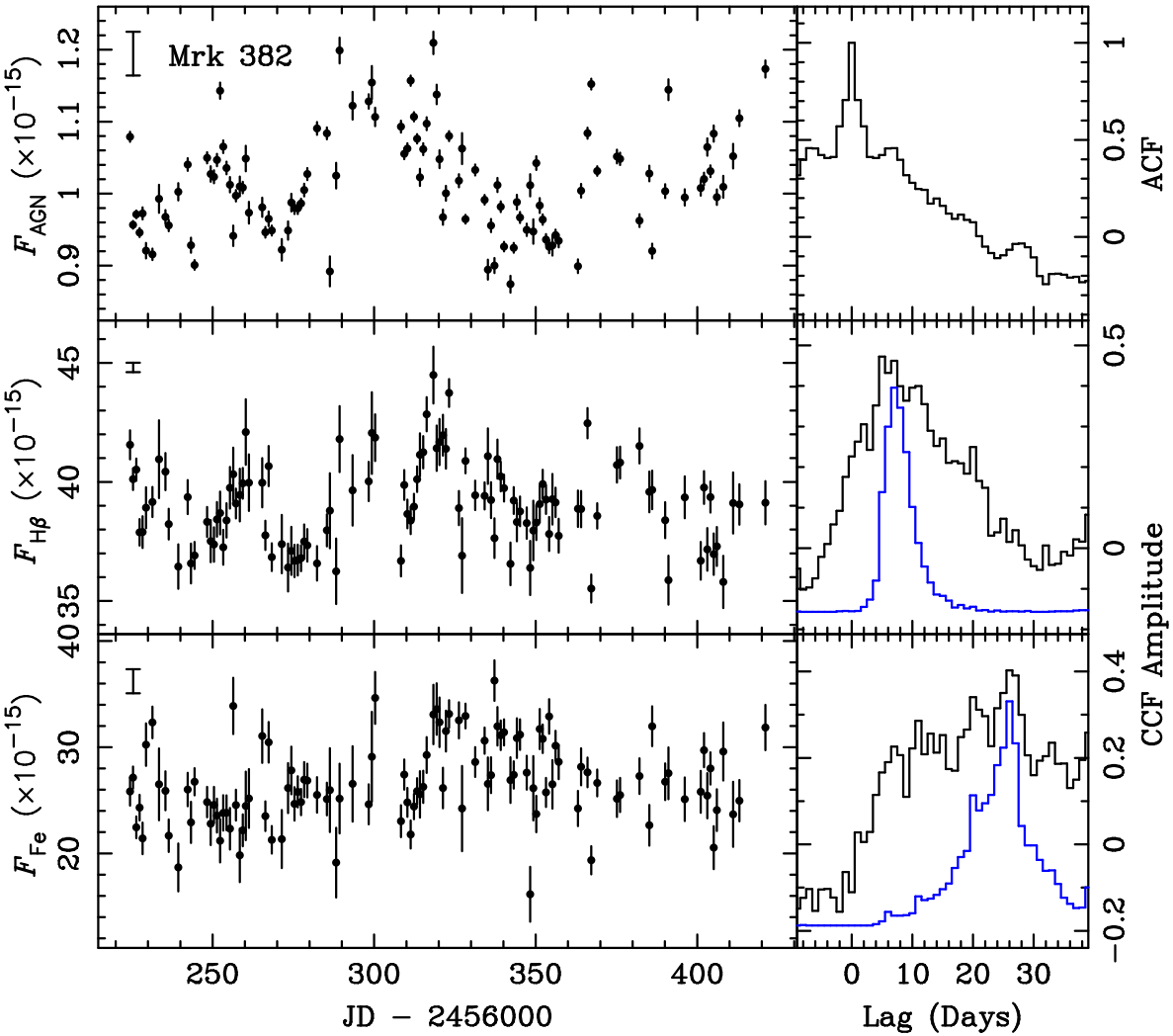

Mrk 335
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude
H

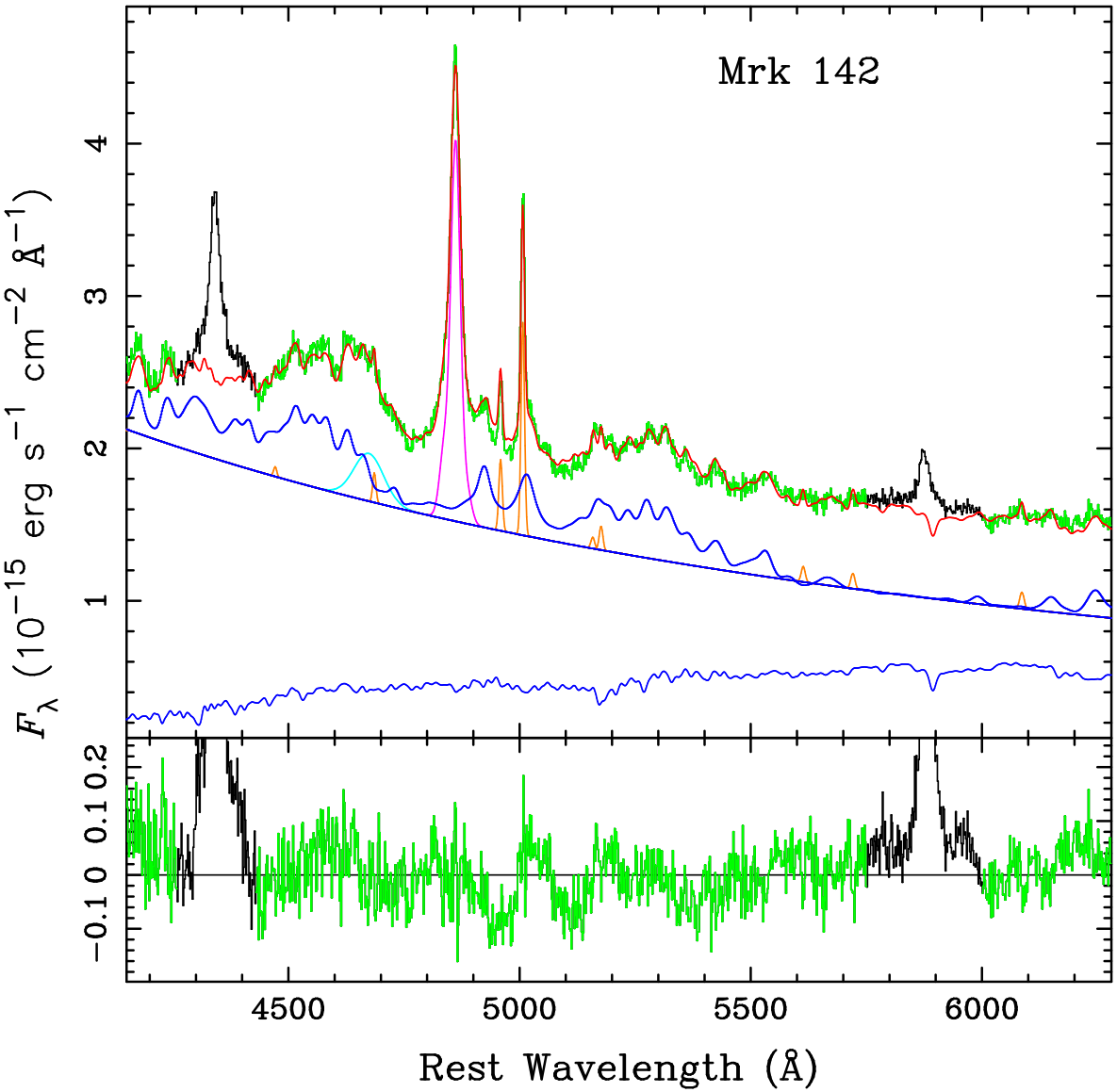

Mrk 1044
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
1
5
10
15
20
−0.5
0
0.5
1
4500
5000
5500
6000
Rest Wavelength (Å)

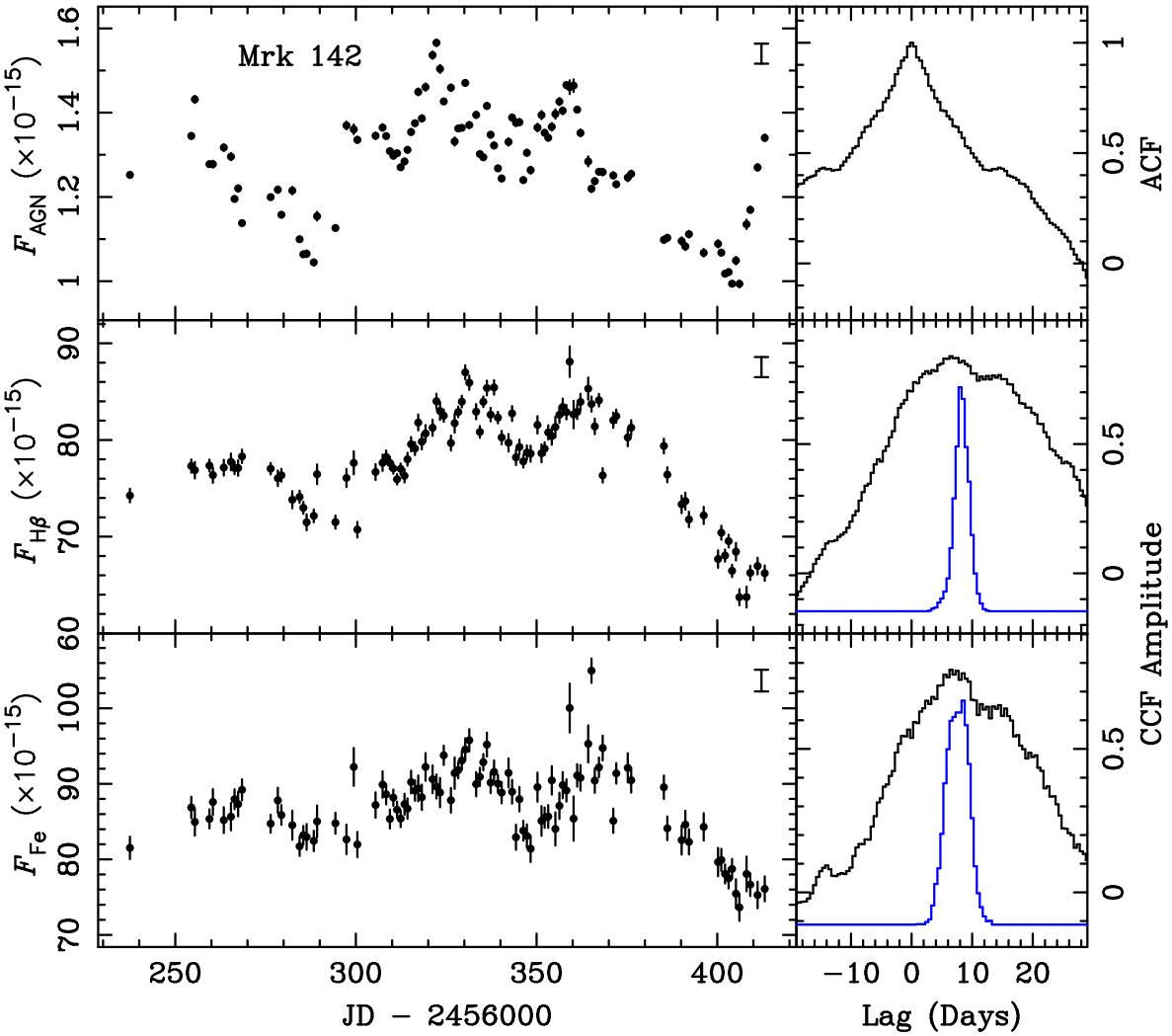

Mrk 1044
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

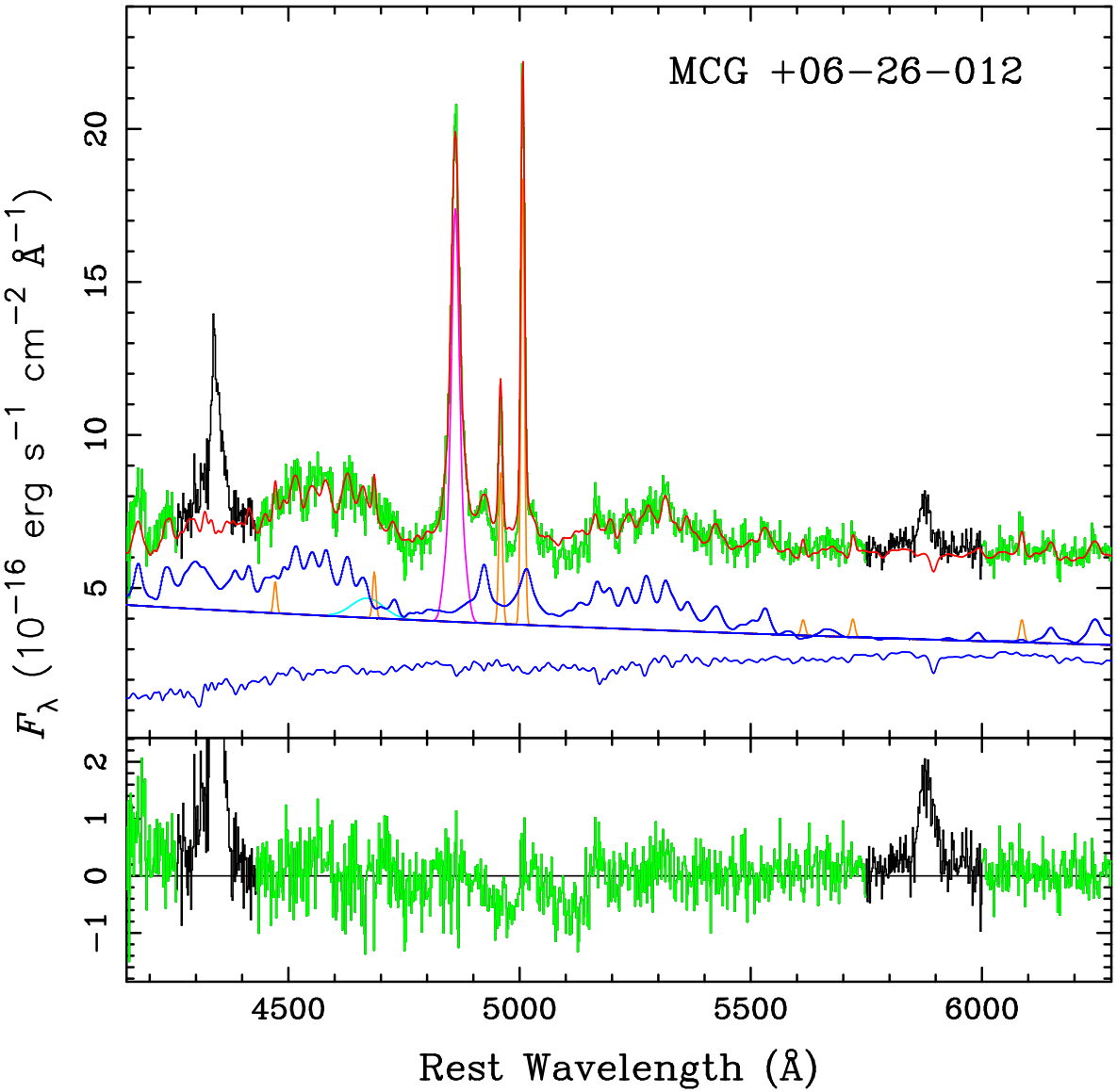

IRAS 04416+1215
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
8
6
4
2
0.5
0
−0.5
4600
4800
5000
5200
5400
Rest Wavelength (Å)

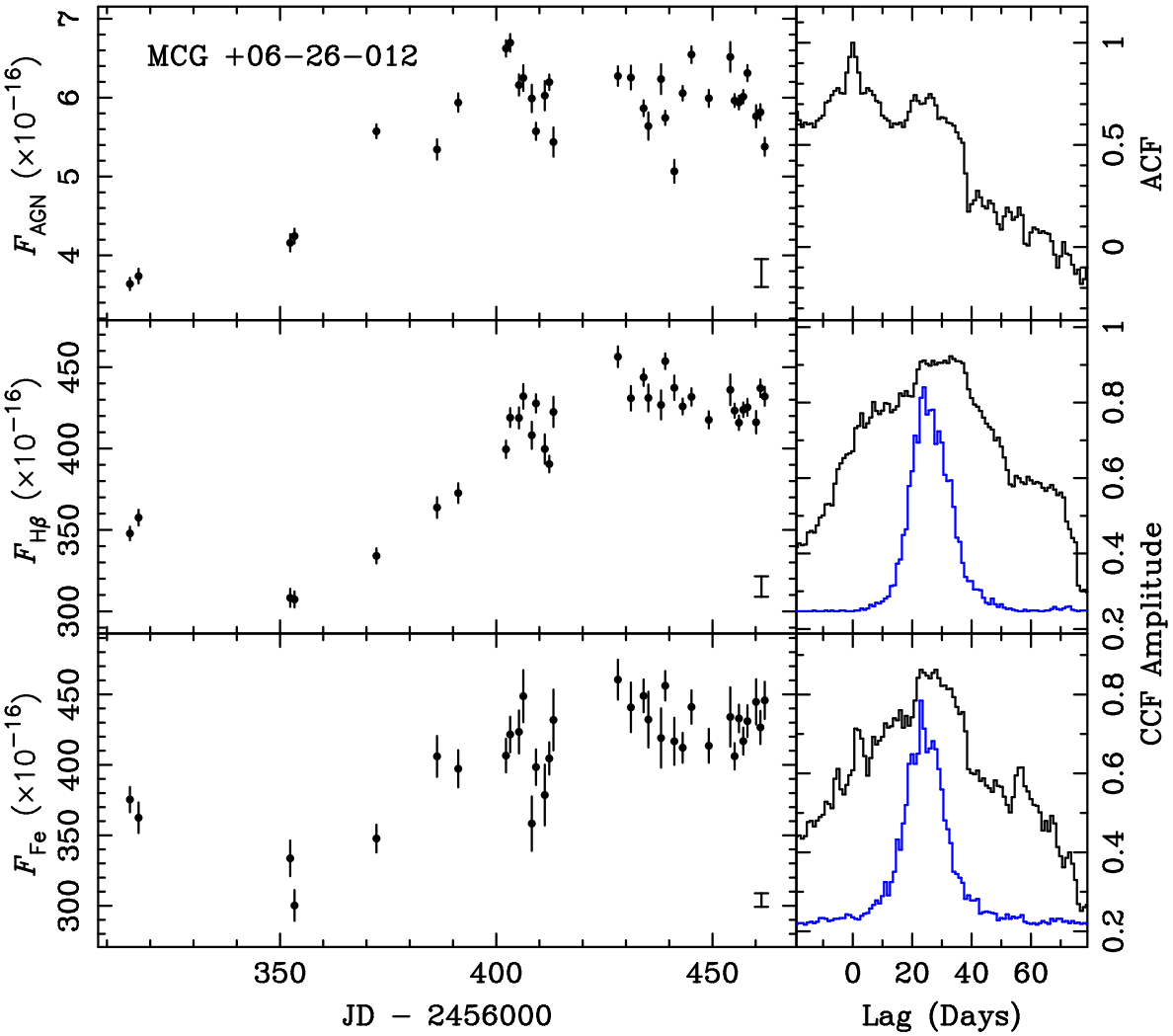

IRAS 04416+1215
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

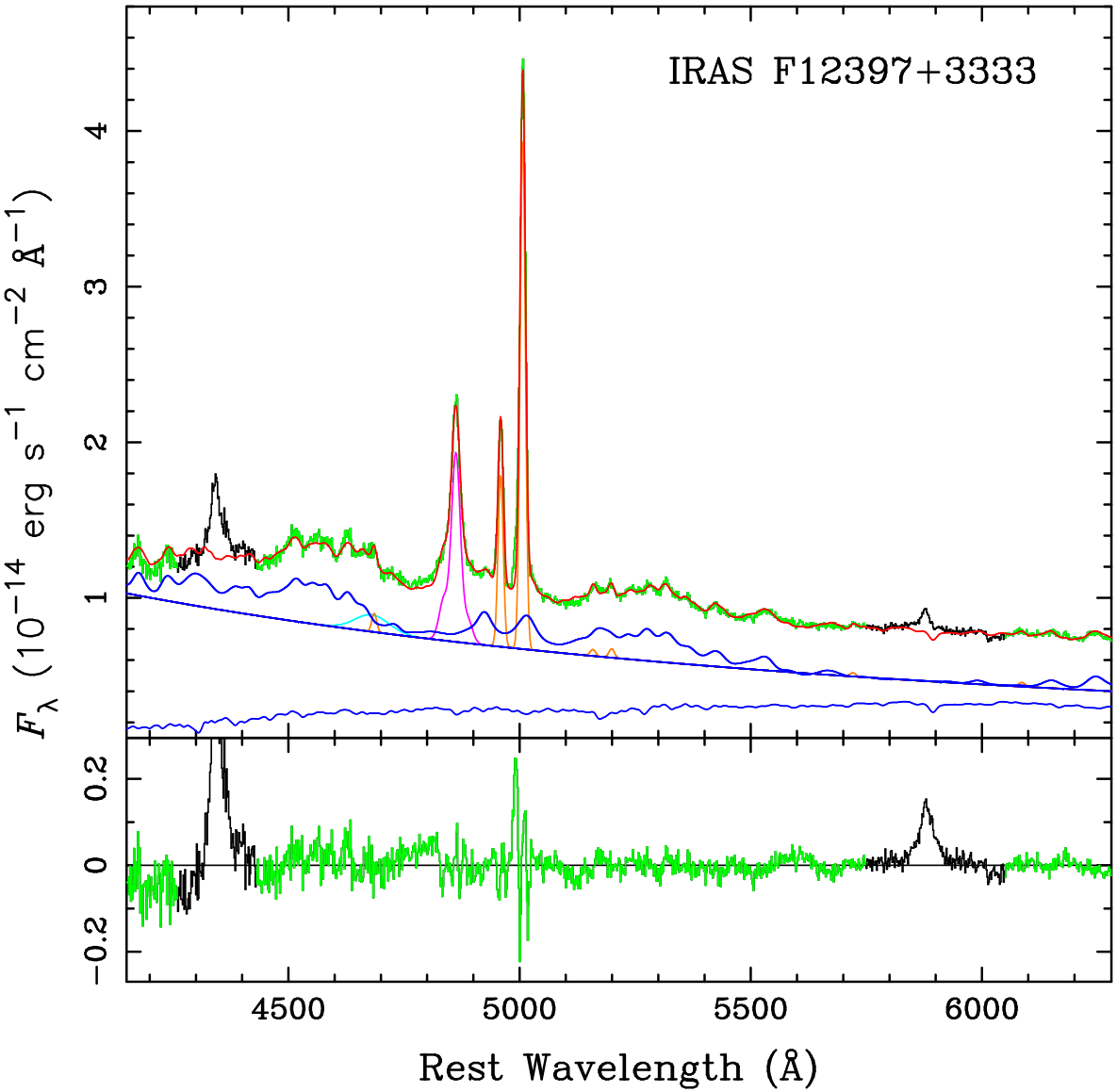

Mrk 382
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

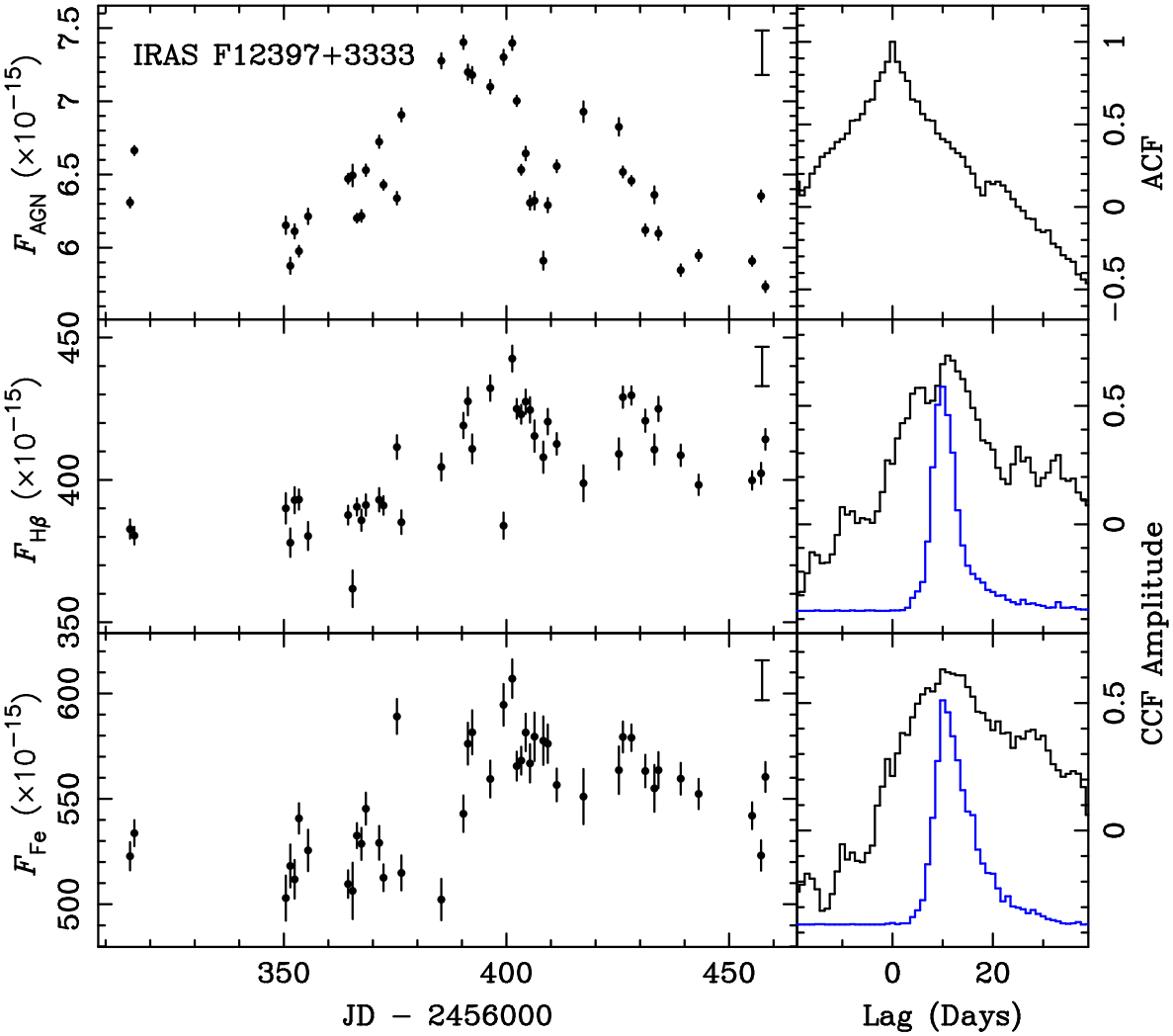

Mrk 142
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
1
2
3
4
−0.1 0 0.1 0.2
4500
5000
5500
6000
Rest Wavelength (Å)

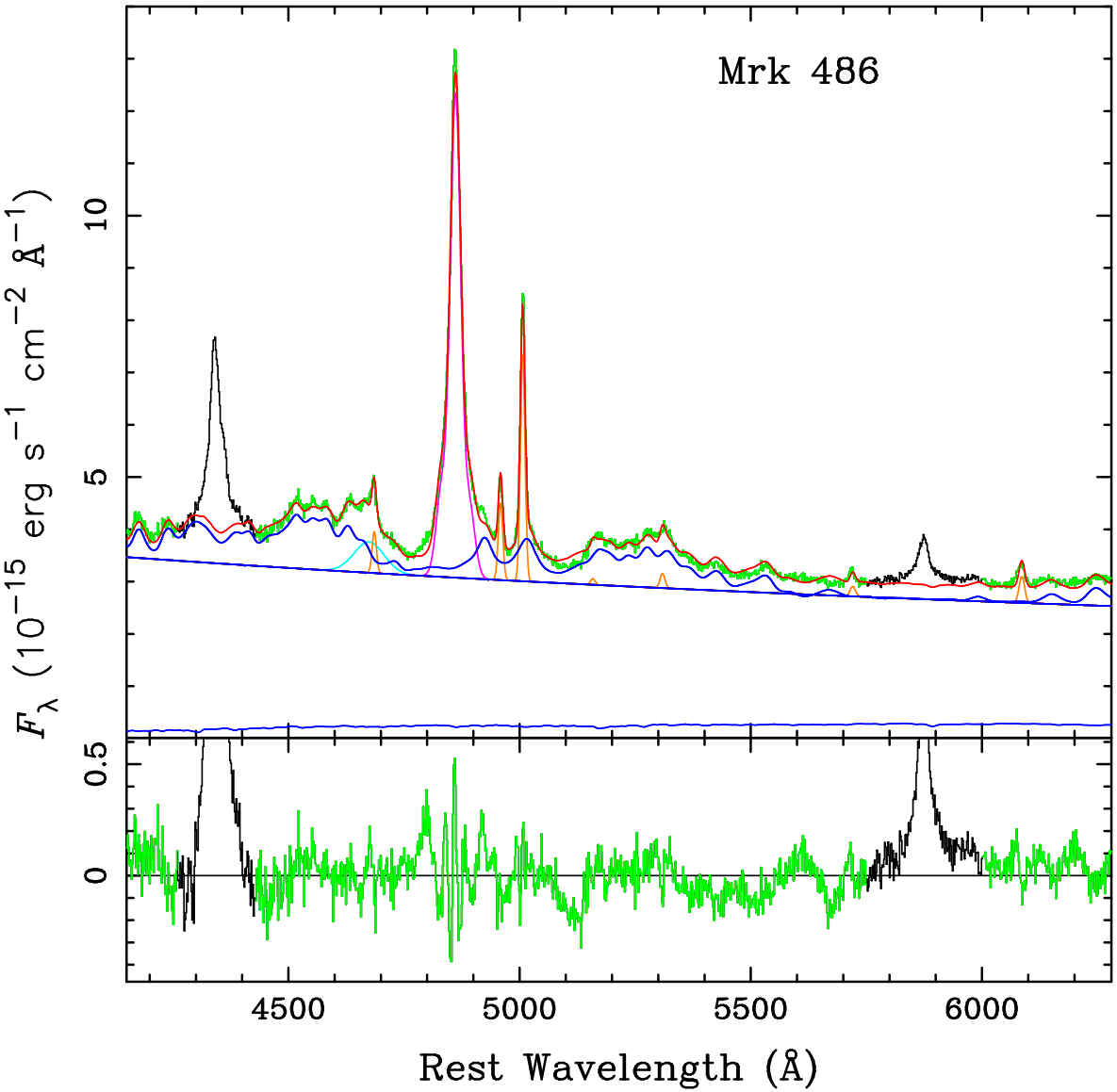

Mrk 142
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

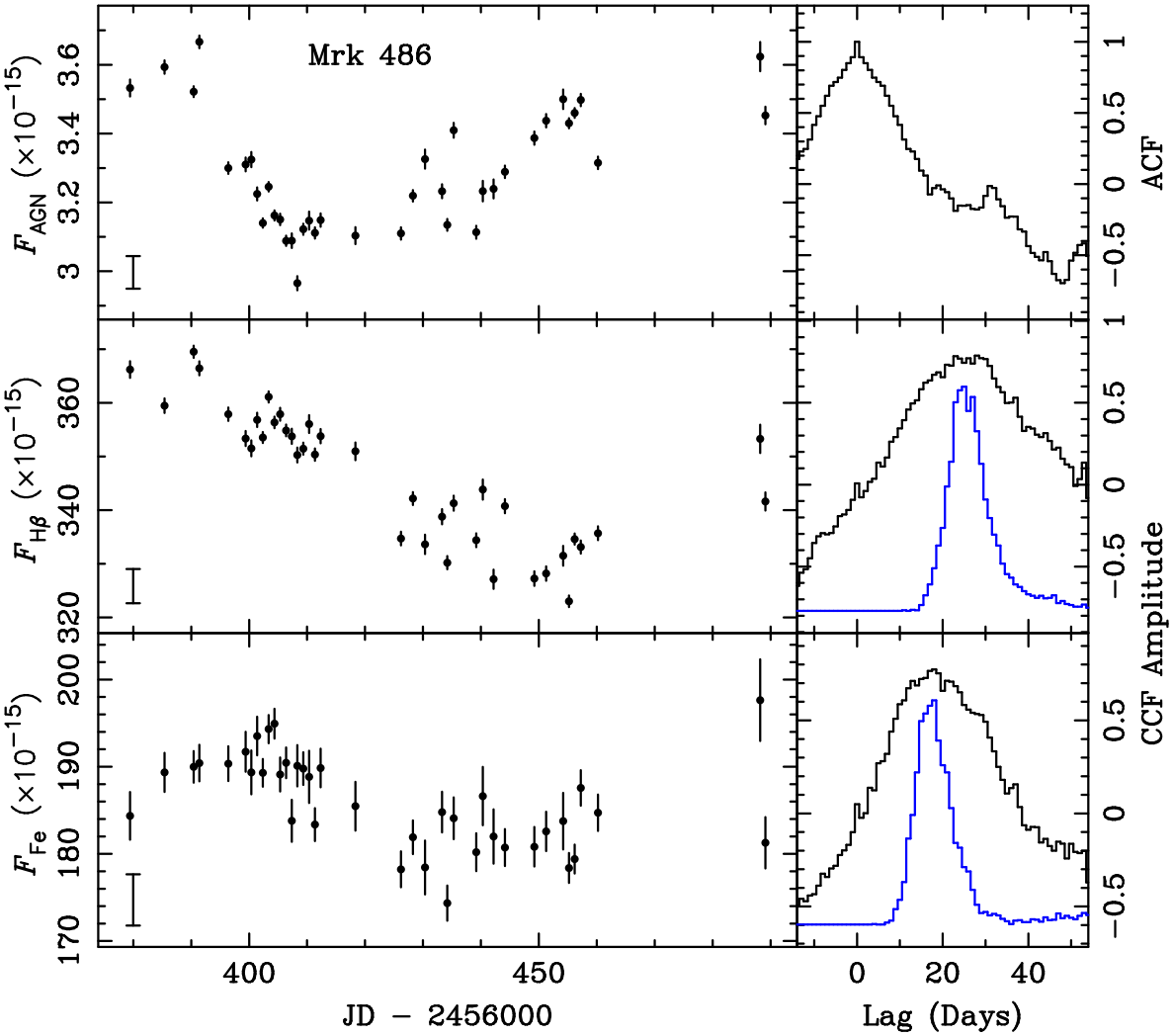

MCG +06−26−012
F_λ (10^{-16} erg s^{-1} cm^{-2} Å^{-1})
5
10
15
20
−1
0
1
2
4500
5000
5500
6000
Rest Wavelength (Å)

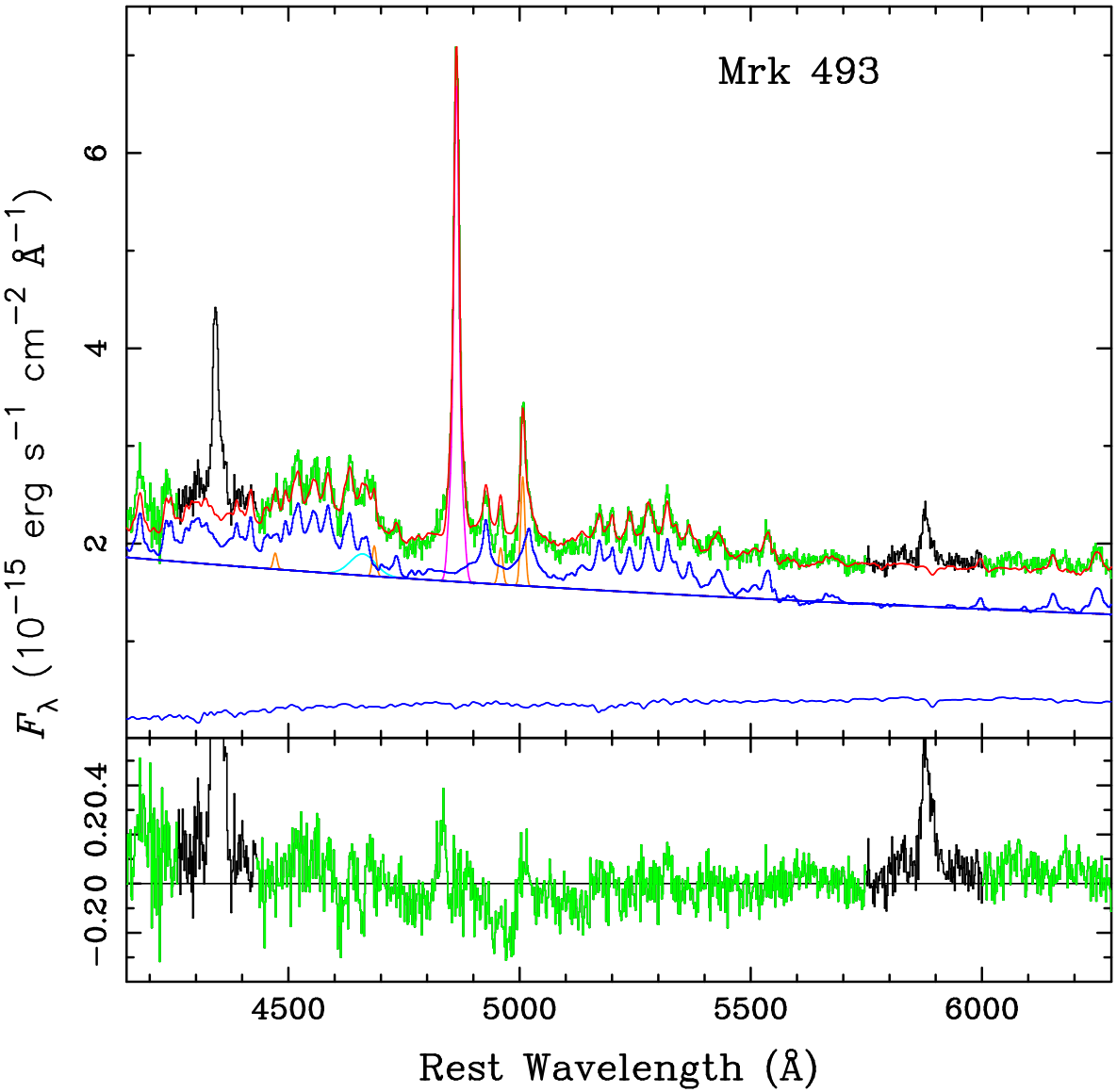

MCG +06−26−012
F_{AGN} ($\times 10^{-16}$)
$F_{H\beta}$ ($\times 10^{-16}$)
F_{Fe} ($\times 10^{-16}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

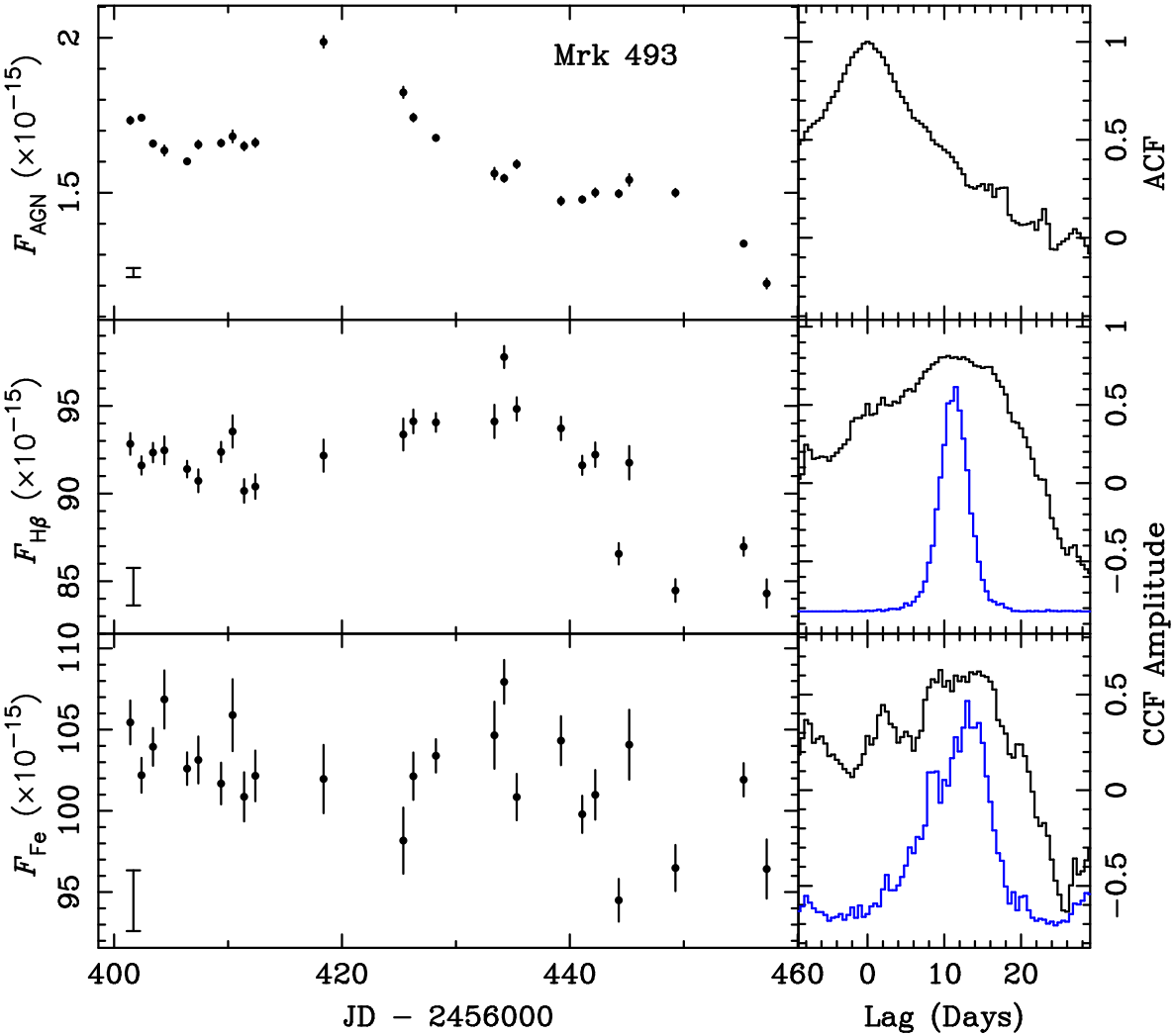

IRAS F12397+3333
F_λ (10^{-14} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)
4500
5000
5500
6000
1
2
3
4
0.2
0
−0.2

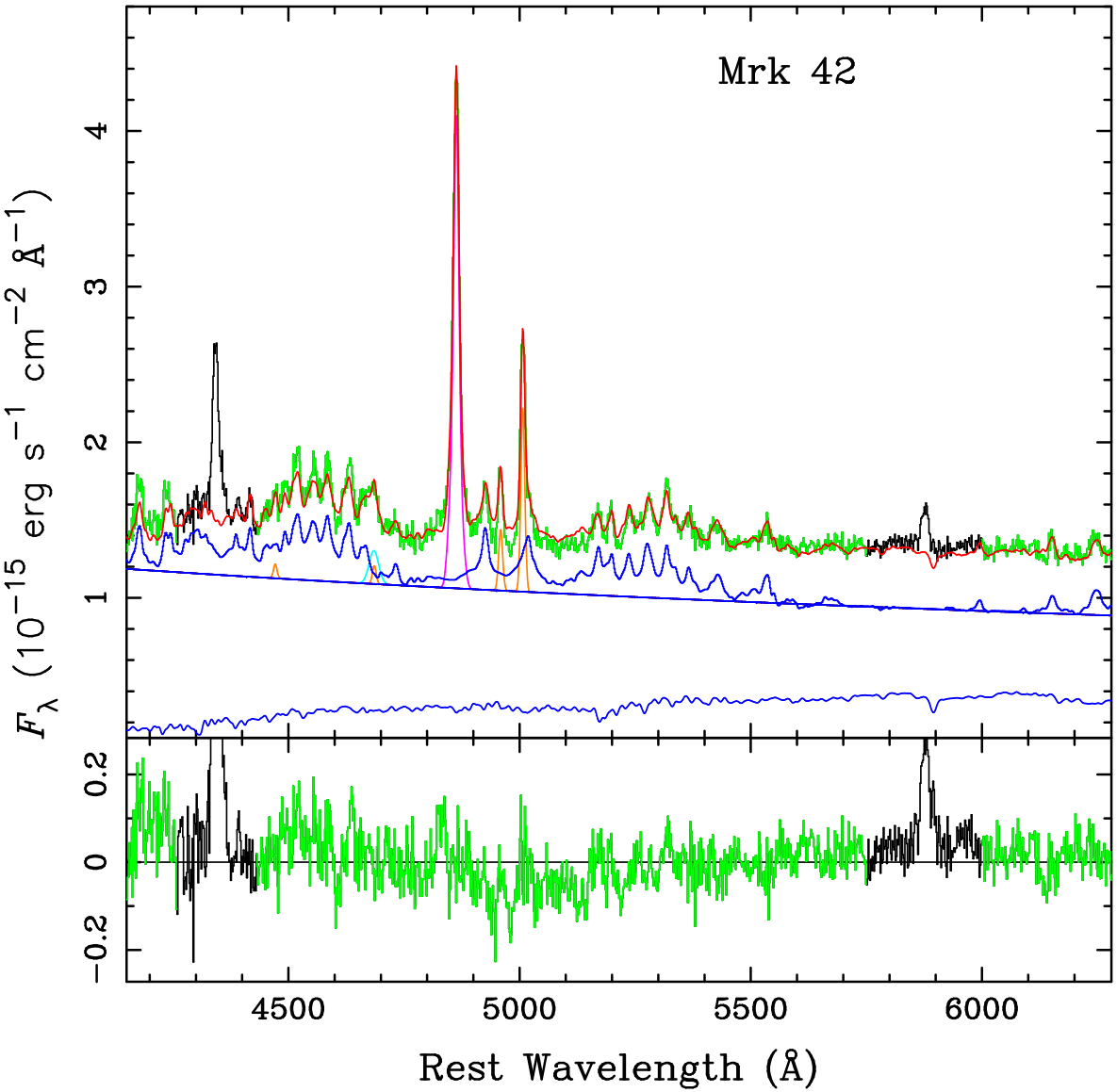

IRAS F12397+3333
F_{AGN} ($\times 10^{-15}$)
$F_{H\beta}$ ($\times 10^{-15}$)
F_{Fe} ($\times 10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

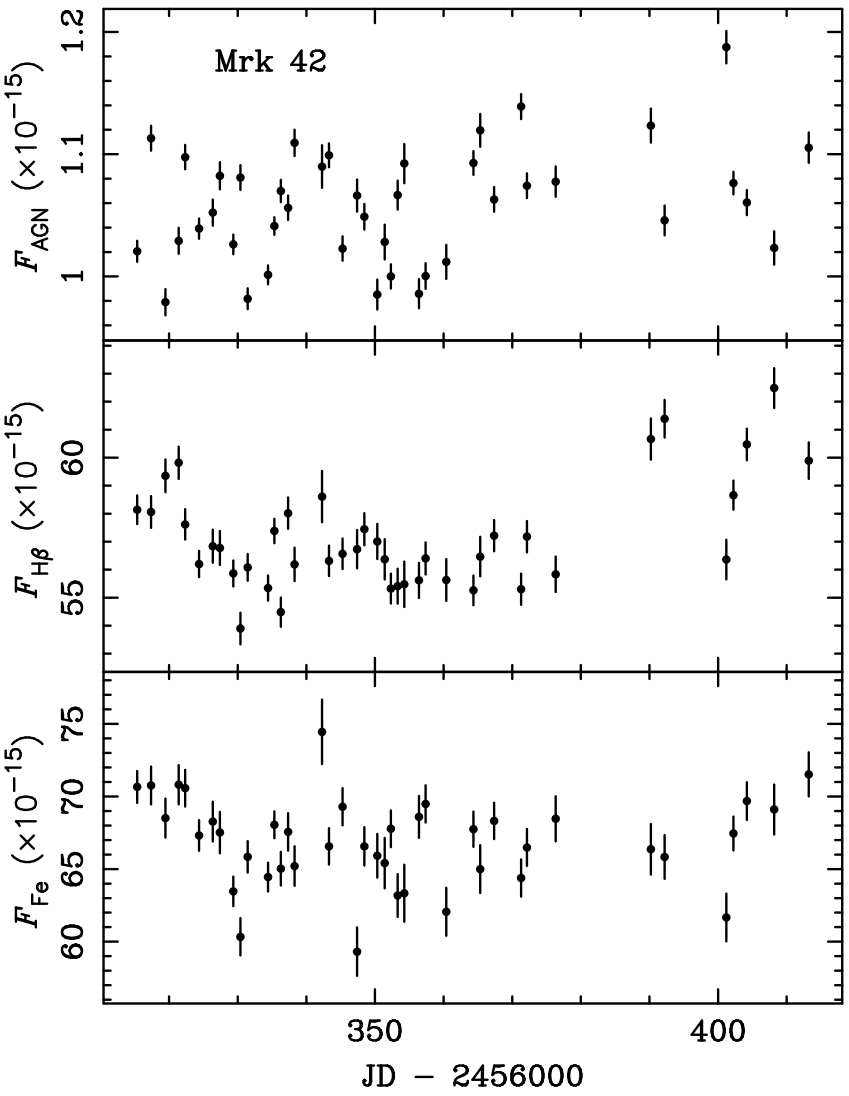

Mrk 486
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
10
5
0.5
0
4500
5000
5500
6000
Rest Wavelength (Å)


Mrk 486
F_{AGN} ($\times 10^{-15}$)
3
3.2
3.4
3.6
$F_{H\beta}$ ($\times 10^{-15}$)
320
340
360
F_{Fe} ($\times 10^{-15}$)
170
180
190
200
400
450
JD − 2456000
ACF
−0.5
0
0.5
1
CCF Amplitude
0
20
40
Lag (Days)

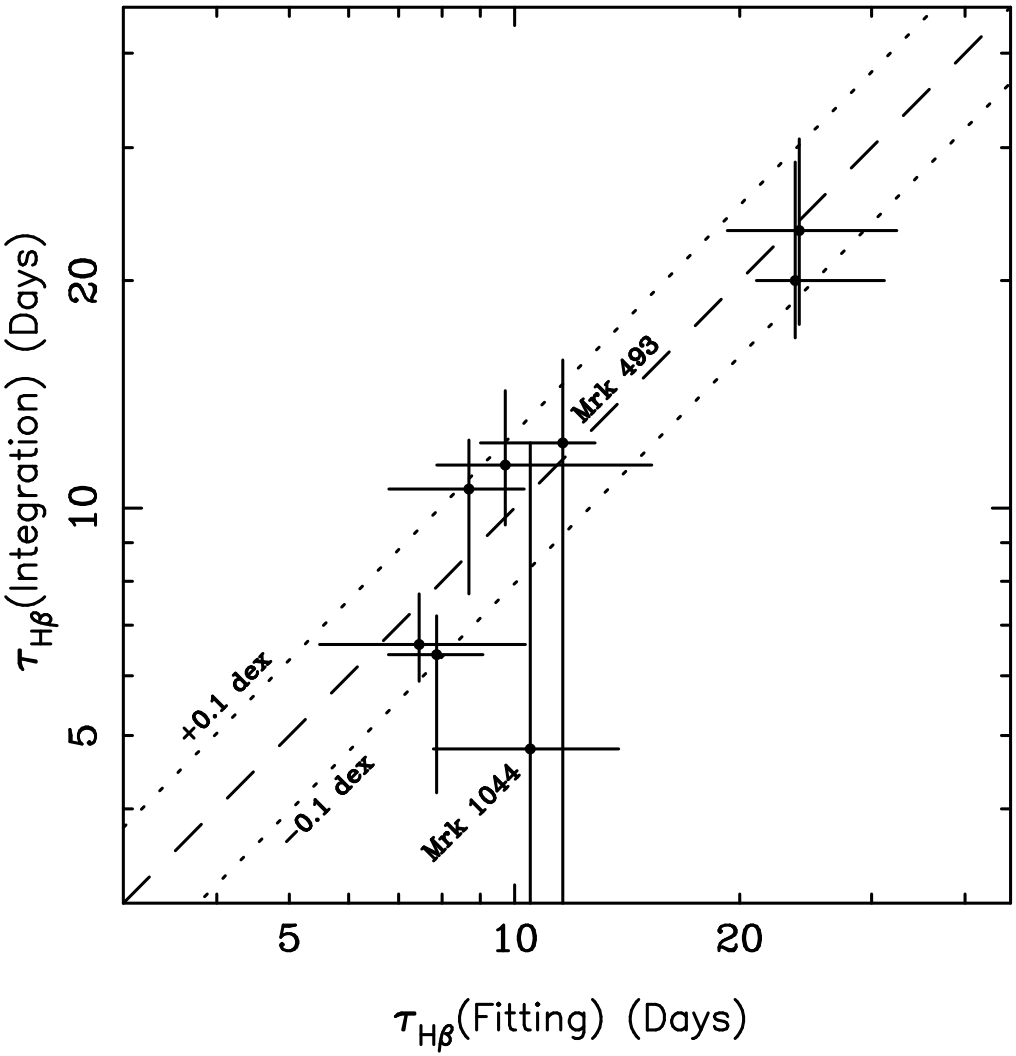

Mrk 493
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
2
4
6
−0.2 0.2 0.4
4500
5000
5500
6000
Rest Wavelength (Å)


Mrk 493
F_{AGN} ($\times10^{-15}$)
H
$F_{H\beta}$ ($\times10^{-15}$)
F_{Fe} ($\times10^{-15}$)
JD − 2456000
Lag (Days)
ACF
CCF Amplitude

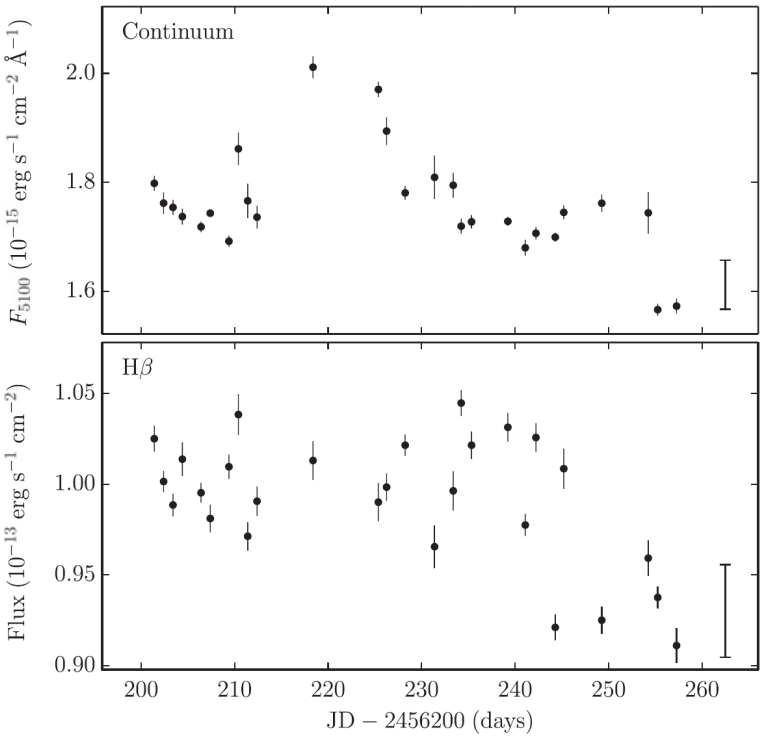

Mrk 42
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
4
3
2
1
0.2
0
−0.2
4500
5000
5500
6000
Rest Wavelength (Å)


Mrk 42
F_{AGN} ($\times 10^{-15}$)
1
1.1
1.2
$F_{H\beta}$ ($\times 10^{-15}$)
55
60
F_{Fe} ($\times 10^{-15}$)
60
65
70
75
350
400
JD − 2456000

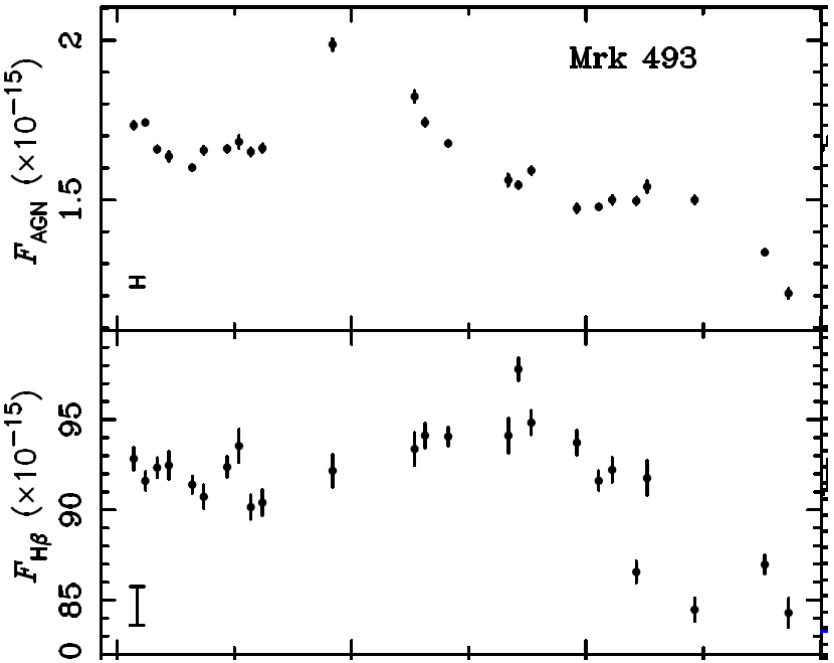
$\mathrm{H}\beta$ time lag from fitting: one more detection, two with smaller uncertainties



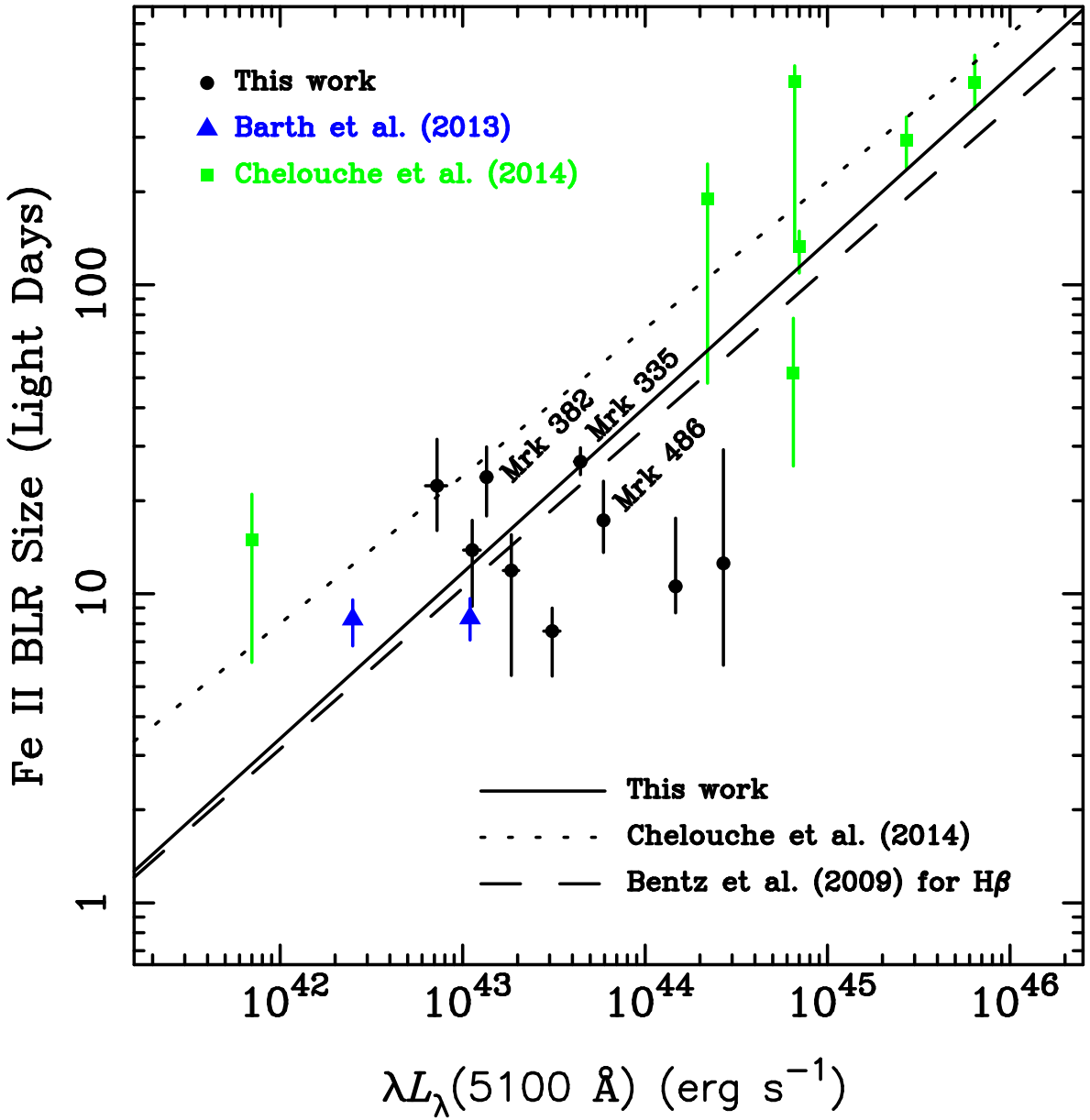
By integration



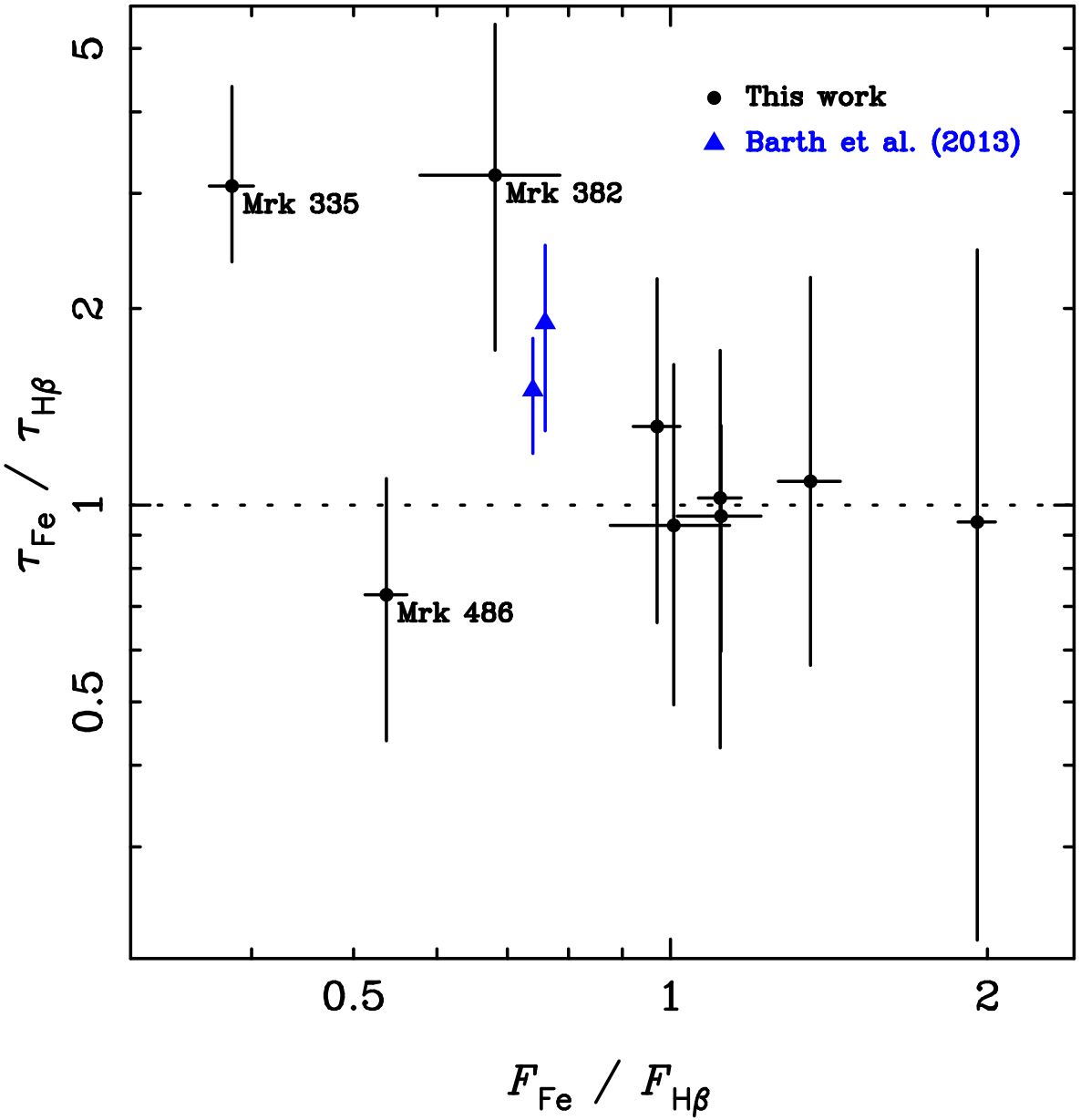
By fitting



Fe II $R_{\rm BLR}$–L relation



Comparison between Fe II and Hβ lags



Summary

- Sophisticated spectral fitting method, taking into account the apparent flux change of the host galaxy, and several narrow lines.

- Significant Fe II time lags in 9 of 10 NLS1s.
  –> Fe II emission originate in photoionized gas.

- The difference in the time lags of Fe II and $\mathrm{H}\beta$ depends on the flux ratio of Fe II to $\mathrm{H}\beta$
  –> No simple answer to where is the Fe II-emitting region.

THANK YOU!