AGN Space Telescope and Optical Reverberation Mapping (STORM):

Optical Emission-Line Analysis of NGC 5548

Liuyi Pei
University of Illinois at Urbana-Champaign
Lijiang, China, October 24th, 2016

STORM Collaborators

SPACE TELESCOPE AND OPTICAL REVERBERATION MAPPING PROJECT. V. OPTICAL SPECTROSCOPIC CAMPAIGN AND EMISSION-LINE ANALYSIS FOR NGC 5548

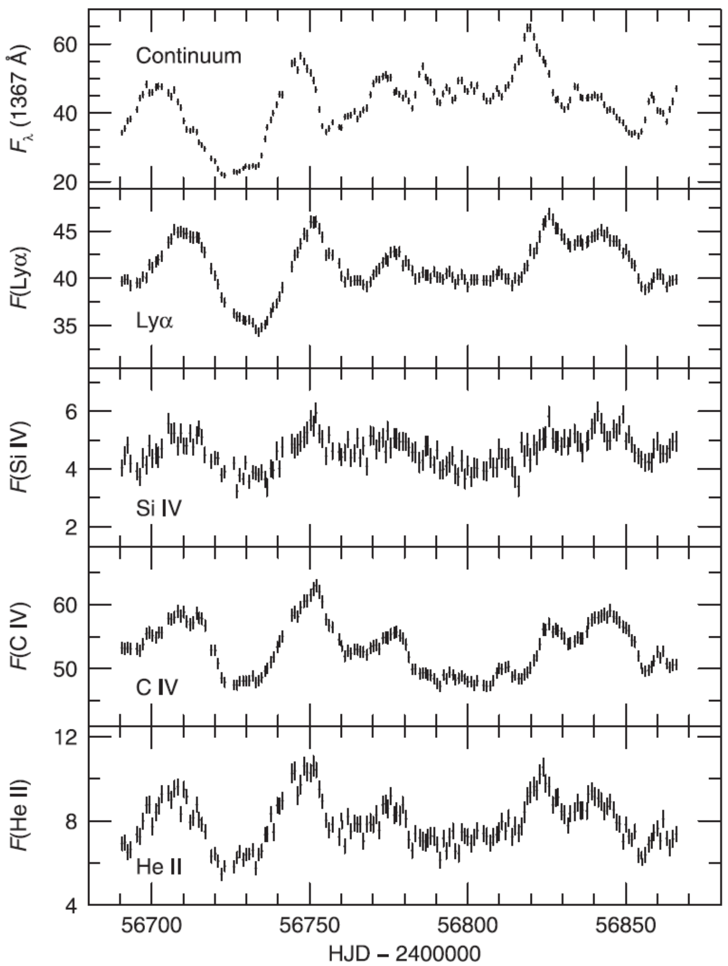
L. Pei[1,2], M. M. Fausnaugh[3], A. J. Barth[1], B. M. Peterson[3,4,5], M. C. Bentz[6], G. De Rosa[5], K. D. Denney[3,4,7], M. R. Goad[8], C. S. Kochanek[3,4], K. T. Korista[9], G. A. Kriss[5,10], R. W. Pogge[3,4], V. N. Bennert[11], M. Brotherton[12], K. I. Clubb[13], E. Dalla Bontà[14,15], A. V. Filippenko[13], J. E. Greene[16], C. J. Grier[3,17,18], M. Vestergaard[19,20], W. Zheng[13], Scott M. Adams[3,21], Thomas G. Beatty[3,17,22], A. Bigley[13], Jacob E. Brown[23], Jonathan S. Brown[3], G. Canalizo[24], J. M. Comerford[25], Carl T. Coker[3], E. M. Corsini[14,15], S. Croft[13], K. V. Croxall[3,4], A. J. Deason[26], Michael Eracleous[17,18,27,28], O. D. Fox[13], E. L. Gates[29], C. B. Henderson[3,30,31], E. Holmbeck[32], T. W.-S. Holoien[3,4], J. J. Jensen[19], C. A. Johnson[33], P. L. Kelly[34,35,36], S. Kim[3,4], A. King[37], M. W. Lau[26], Miao Li[38], Cassandra Lochhaas[3], Zhiyuan Ma[23], E. R. Manne-Nicholas[6], J. C. Mauerhan[13], M. A. Malkan[32], R. McGurk[26,39], L. Morelli[14,15], Ana Mosquera[3,40], Dale Mudd[3], F. Muller Sanchez[25], M. L. Nguyen[12], P. Ochner[14,15], B. Ou-Yang[6], A. Pancoast[41,42,43], Matthew T. Penny[3,44], A. Pizzella[14,15], Radosław Poleski[3], Jessie Runnoe[45], B. Scott[24], Jaderson S. Schimoia[3,46], B. J. Shappee[47,48], I. Shivvers[13], Gregory V. Simonian[3], A. Siviero[14], Garrett Somers[3,49], Daniel J. Stevens[3], M. A. Strauss[16], Jamie Tayar[3], N. Tejos[50,51], T. Treu[32,41,52], J. Van Saders[47], L. Vican[32], S. Villanueva Jr.[3], H. Yuk[13], N. L. Zakamska[10], W. Zhu[3], M. D. Anderson[6], P. Arévalo[53], C. Bazhaw[6], S. Bisogni[3,54], G. A. Borman[55], M. C. Bottorff[56], W. N. Brandt[17,18,57], A. A. Breeveld[58], E. M. Cackett[59], M. T. Carini[60], D. M. Crenshaw[6], A. De Lorenzo-Cáceres[61], M. Dietrich[62,63], R. Edelson[64], N. V. Efimova[65], J. Ely[5], P. A. Evans[8], G. J. Ferland[66] K. Flatland[67], N. Gehrels[68], S. Geier[69,70,71], J. M. Gelbord[72,73], D. Grupe[74], A. Gupta[3], P. B. Hall[75], S. Hicks[60], D. Horenstein[6], Keith Horne[61], T. Hutchison[56], M. Im[76], M. D. Joner[77], J. Jones[6], J. Kaastra[78,79,80], S. Kaspi[81,82] B. C. Kelly[41], J. A. Kennea[17], M. Kim[83], S. C. Kim[83], S. A. Klimanov[66], J. C. Lee[83], D. C. Leonard[67], P. Lira[84], F. MacInnis[56], S. Mathur[3,4], I. M. McHardy[85], C. Montouri[86], R. Musso[56], S. V. Nazarov[55], H. Netzer[81], R. P. Norris[6], J. A. Nousek[17], D. N. Okhmat[55], I. Papadakis[87,88], J. R. Parks[6], J.-U. Pott[39], S. E. Rafter[82,89], H.-W. Rix[39], D. A. Saylor[6], K. Schnülle[39], S. G. Sergeev[55], M. Siegel[90], A. Skielboe[19], M. Spencer[77], D. Starkey[61], H.-I. Sung[83], K. G. Teems[6], C. S. Turner[6], P. Uttley[91], C. Villforth[92], Y. Weiss[82], J.-H. Woo[76], H. Yan[23], S. Young[64], and Y. Zu[93,4]

International collaboration with 150+ co-authors

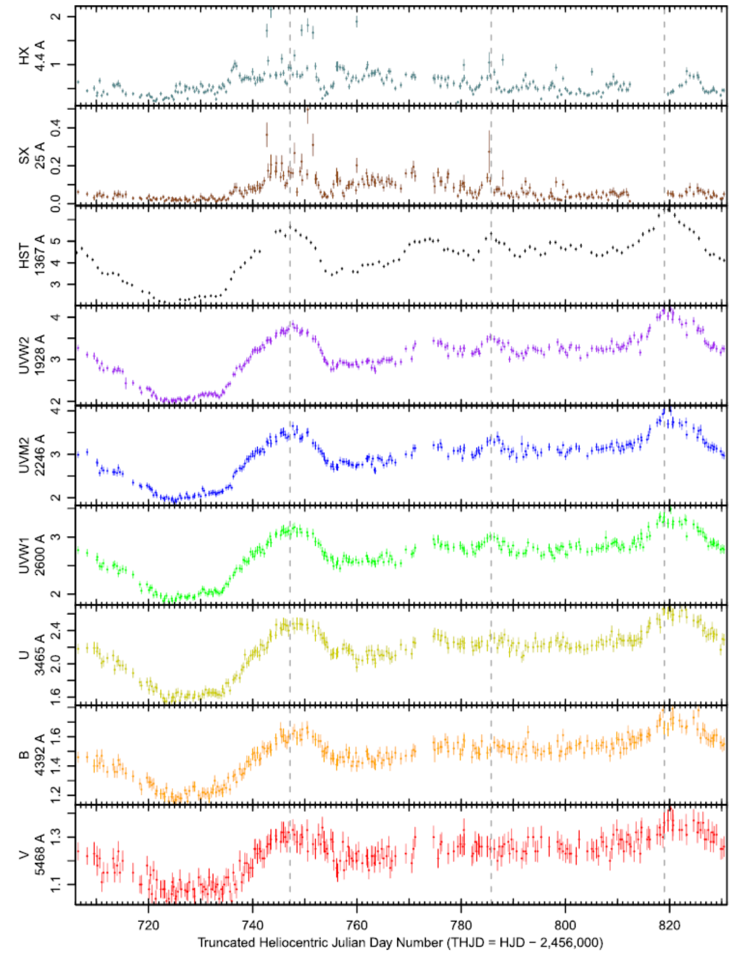
Goals and Project Components

- Carry out a detailed study of the BLR in NGC 5548 over a wide wavelength range
  - Obtain high-quality **velocity-delay maps** for multiple emission lines
  - Improve our understanding of the **BLR—continuum relationship**
- *Simultaneous* multi-wavelength monitoring
  - UV spectroscopy: *Hubble Space Telescope* (*HST*)
  - UV/X-ray photometry: *Swift*
  - Optical photometry: *Swift*, LCOGT, MLO, WMO, etc.
  - Optical spectroscopy: MDM, APO, Asiago, Lick, WIRO

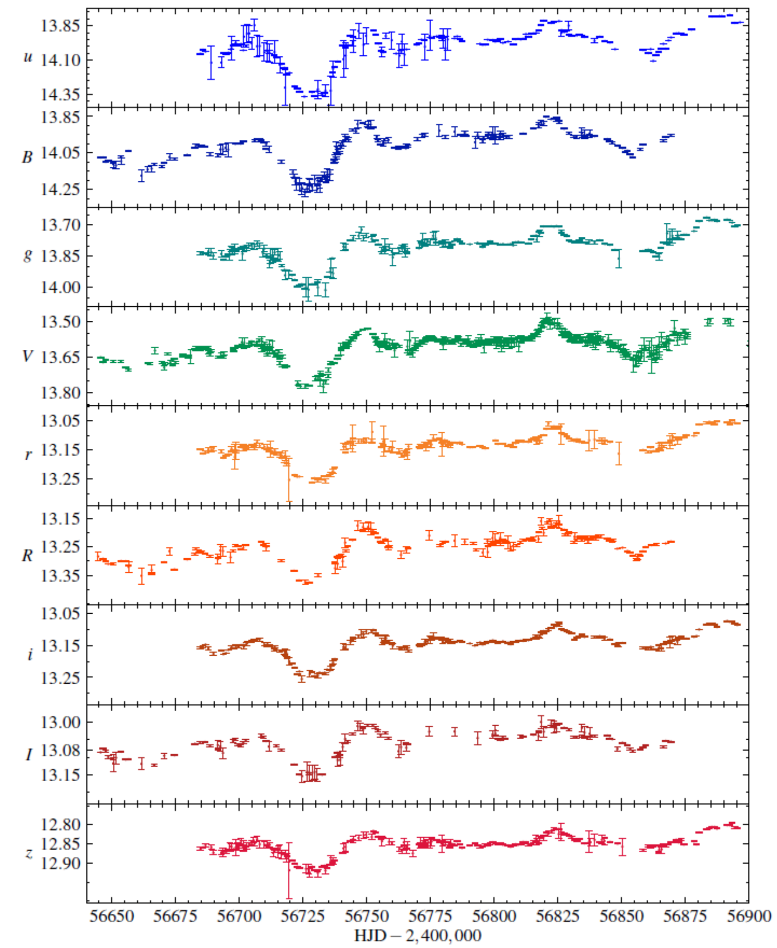
Data Papers



De Rosa et al. 2015
(*HST* data)



Edelson et al. 2015
(*Swift* data)



Fausnaugh et al. 2016
(Ground-based photometry)

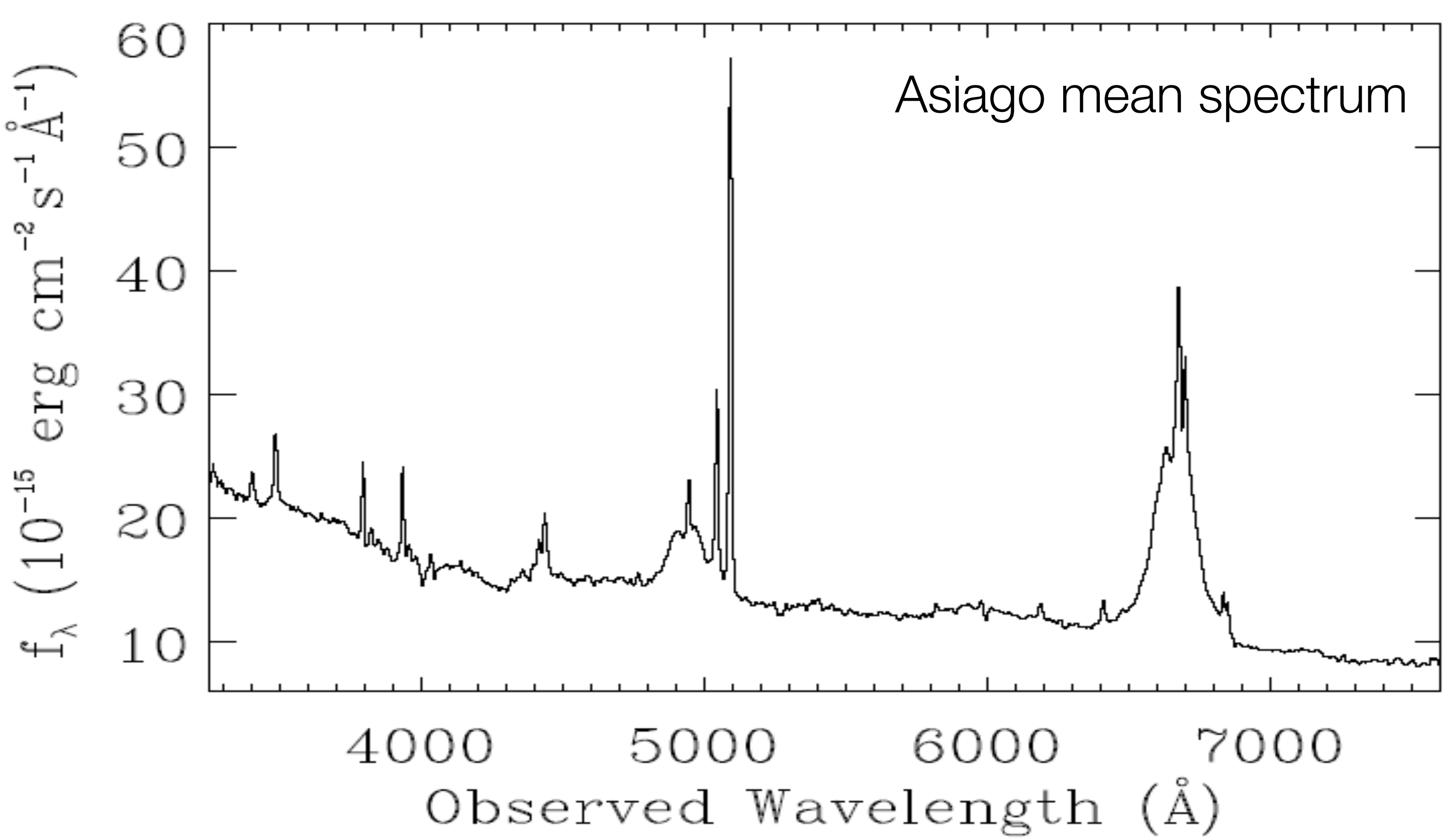
Optical spectroscopy: Pei et al, submitted

Also Goad et al. 2016, Starkey et al. submitted

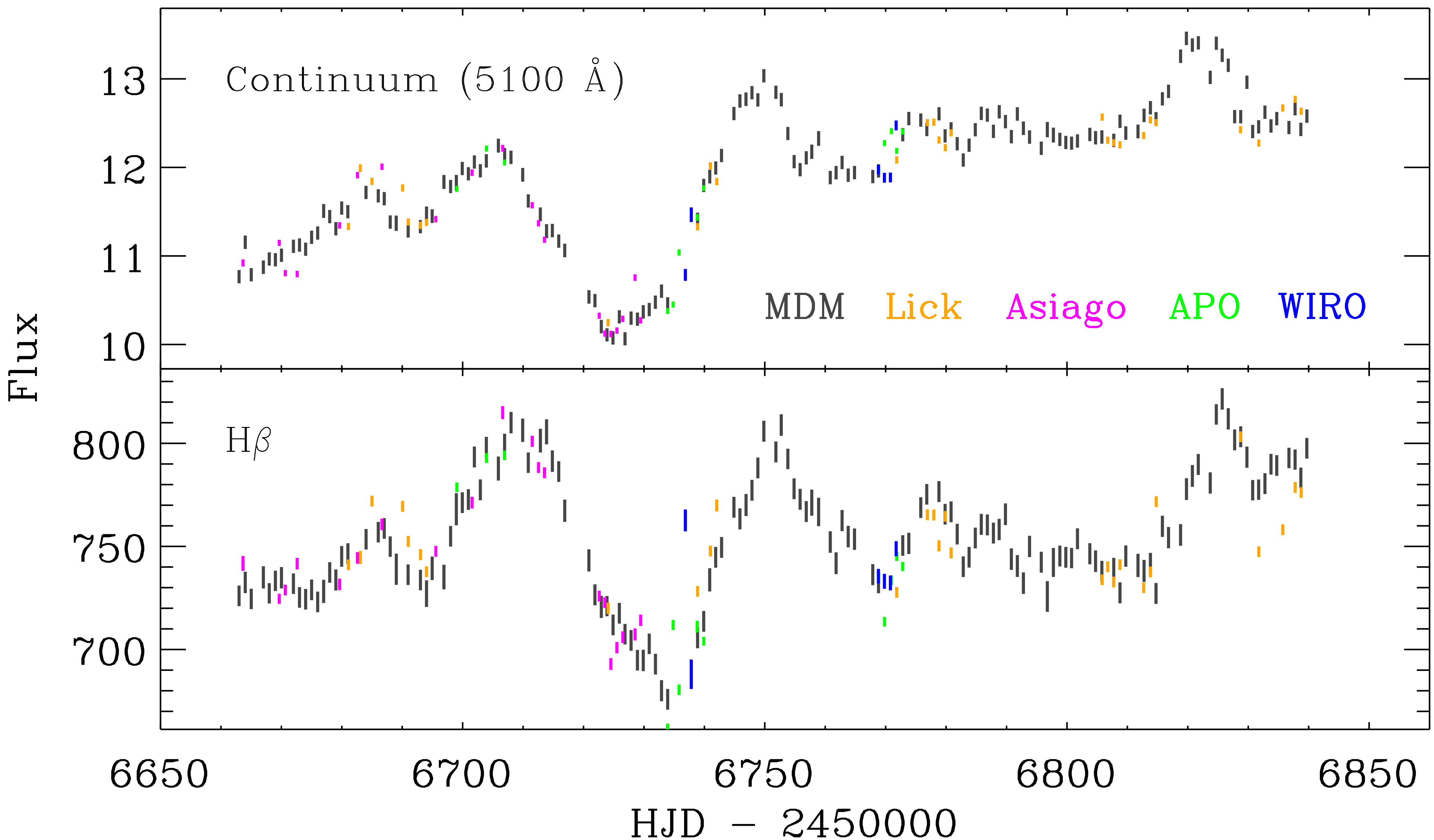
Observations and Reductions

Spectroscopic Dataset

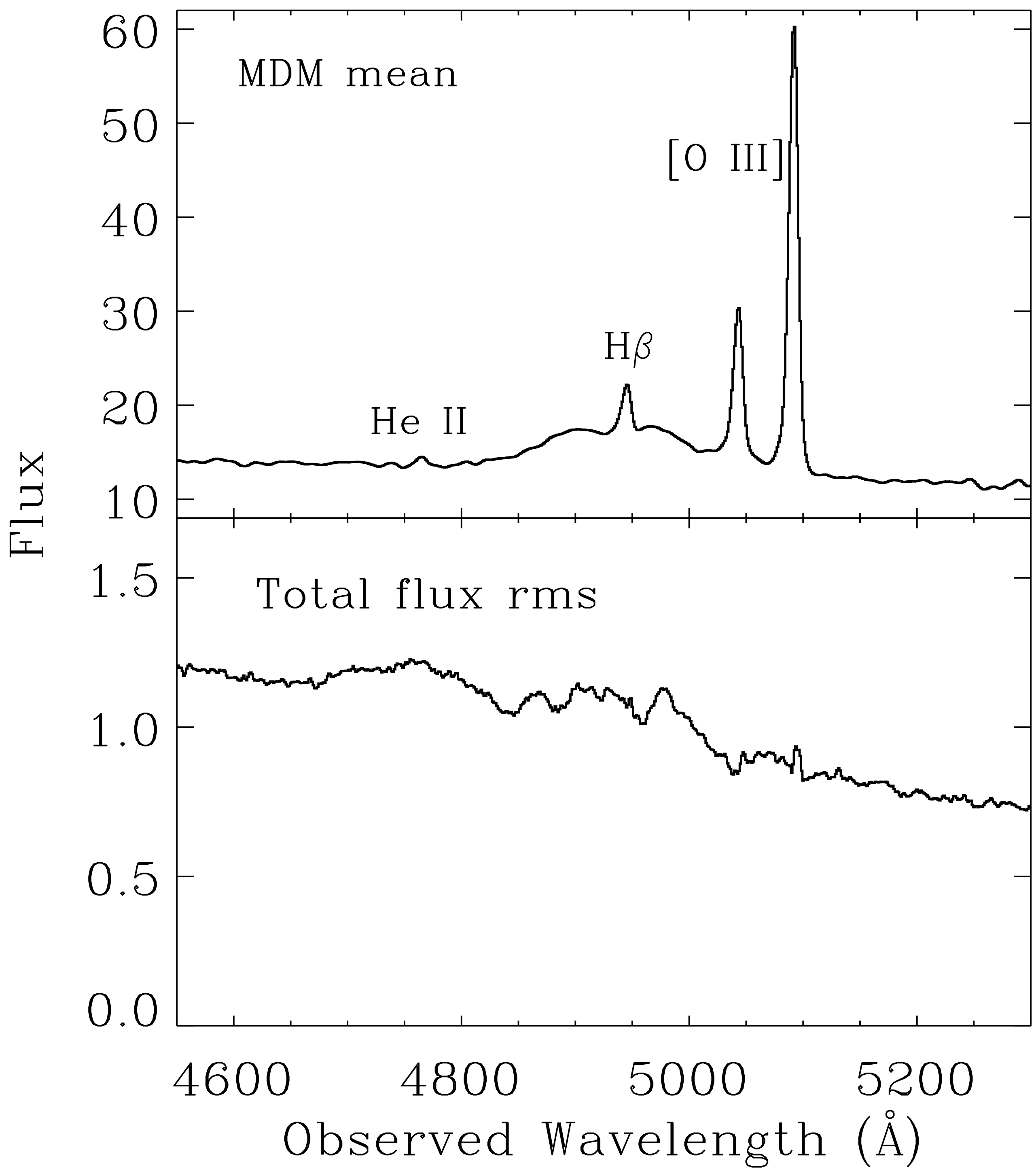
Telescope	Number of Epochs	Median Seeing ($''$)	Wavelength Dispersion (Å pixel^{-1})	Pixel Scale ($''$ pixel^{-1})	Median SNR	[O III] $F_{\rm var}$ (%)
MDM	143	1.7	1.25	0.75	118	0.62
Lick	35	1.5	1.02	0.43	194	0.32
Asiago	21	4.0	1.00	1.00	160	0.27
APO	13	1.4	1.00	0.41	160	0.28
WIRO	6	2.1	0.74	0.52	217	0.47



Optical Spectroscopy Light Curves



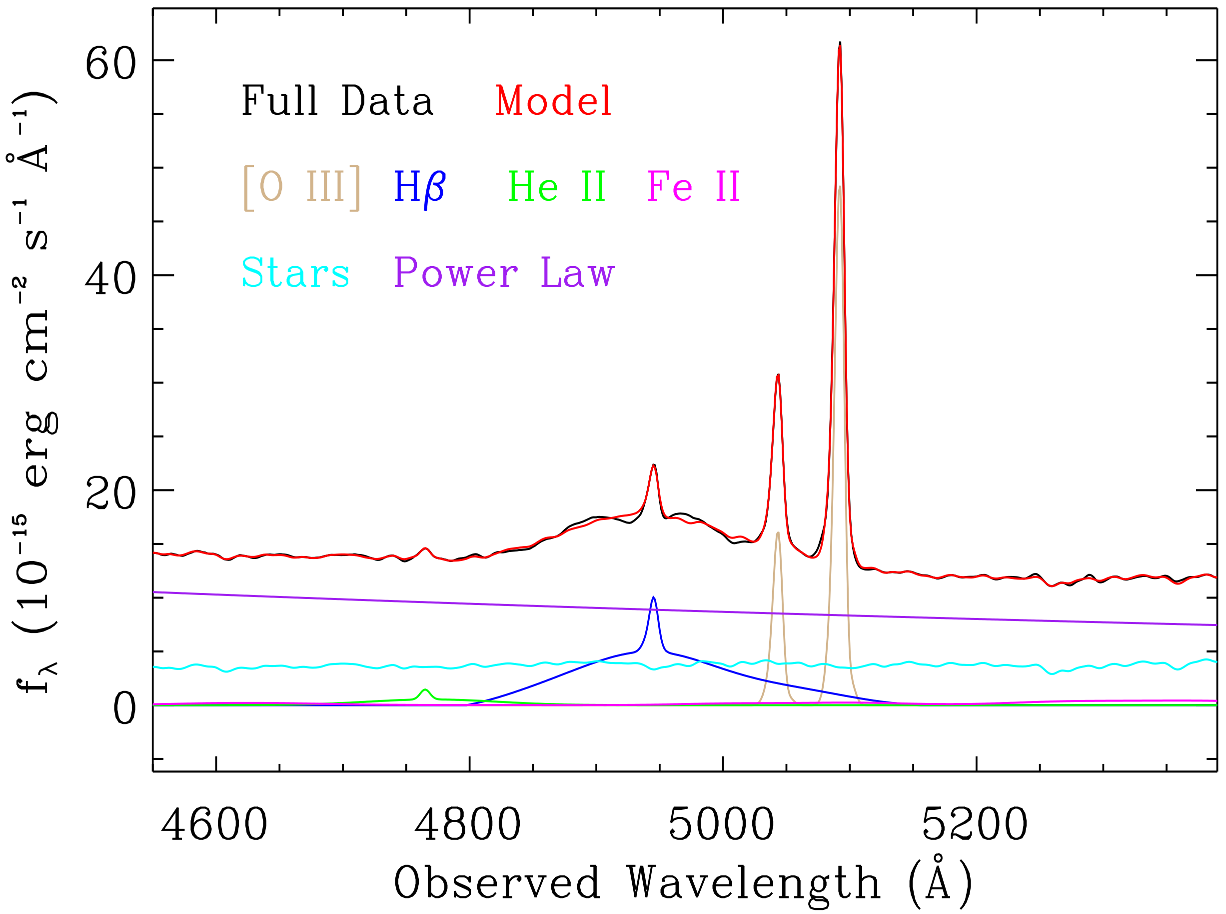
Mean and RMS



- Both Hβ and He II are highly variable
- The two broad lines are heavily blended together
- He II is very weak in the mean spectrum

Spectral Decomposition

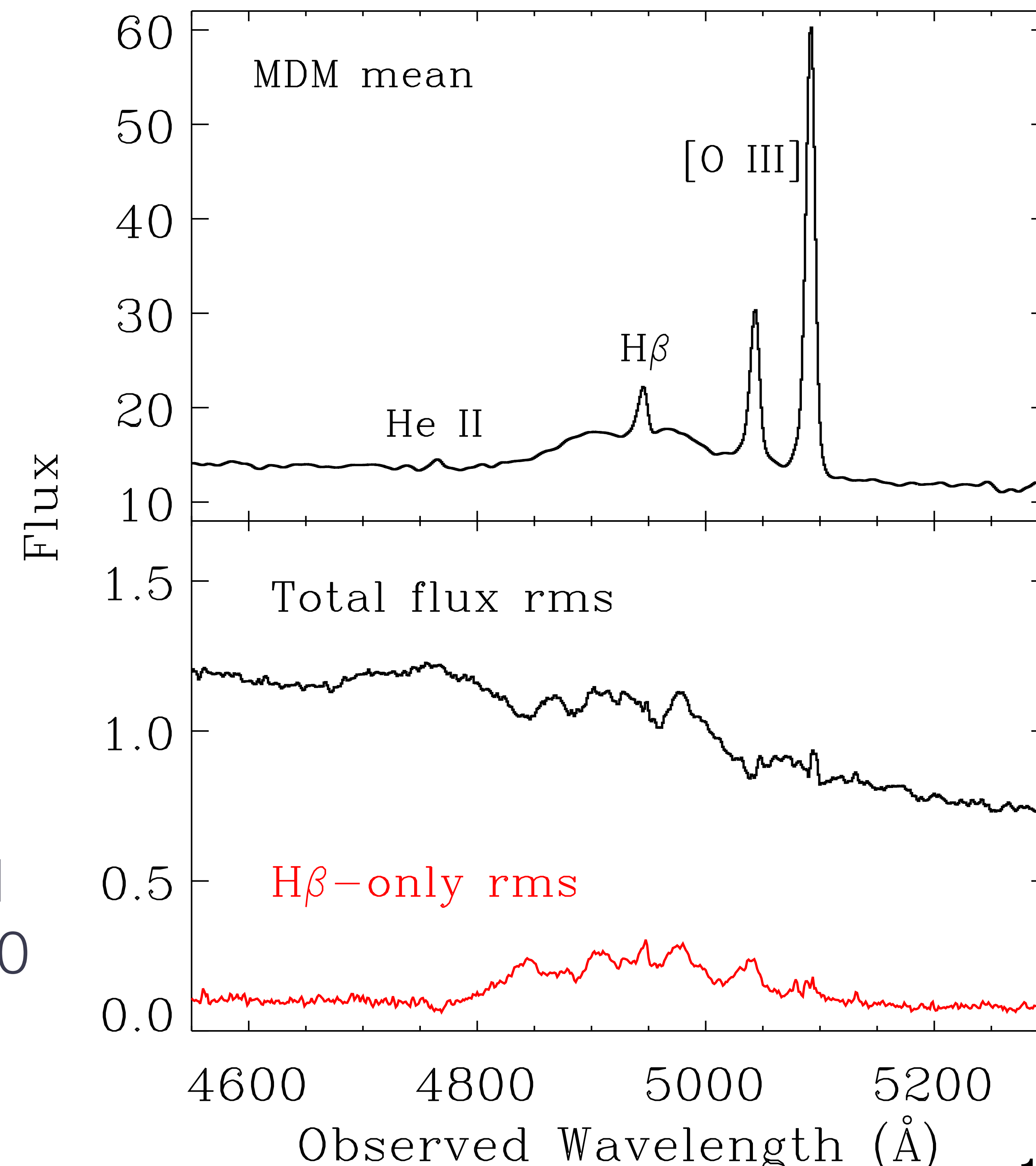
- De-blend broad lines
  - Enable measurement of He II flux
- More accurately remove the continuum
- Fitting routine:
  - Sixth order Gauss-Hermite functions for [O III], broad and narrow Hβ
  - He II λ4686 width constrained to within 3 Å of the He II λ1640 width from the nearest *HST* epoch



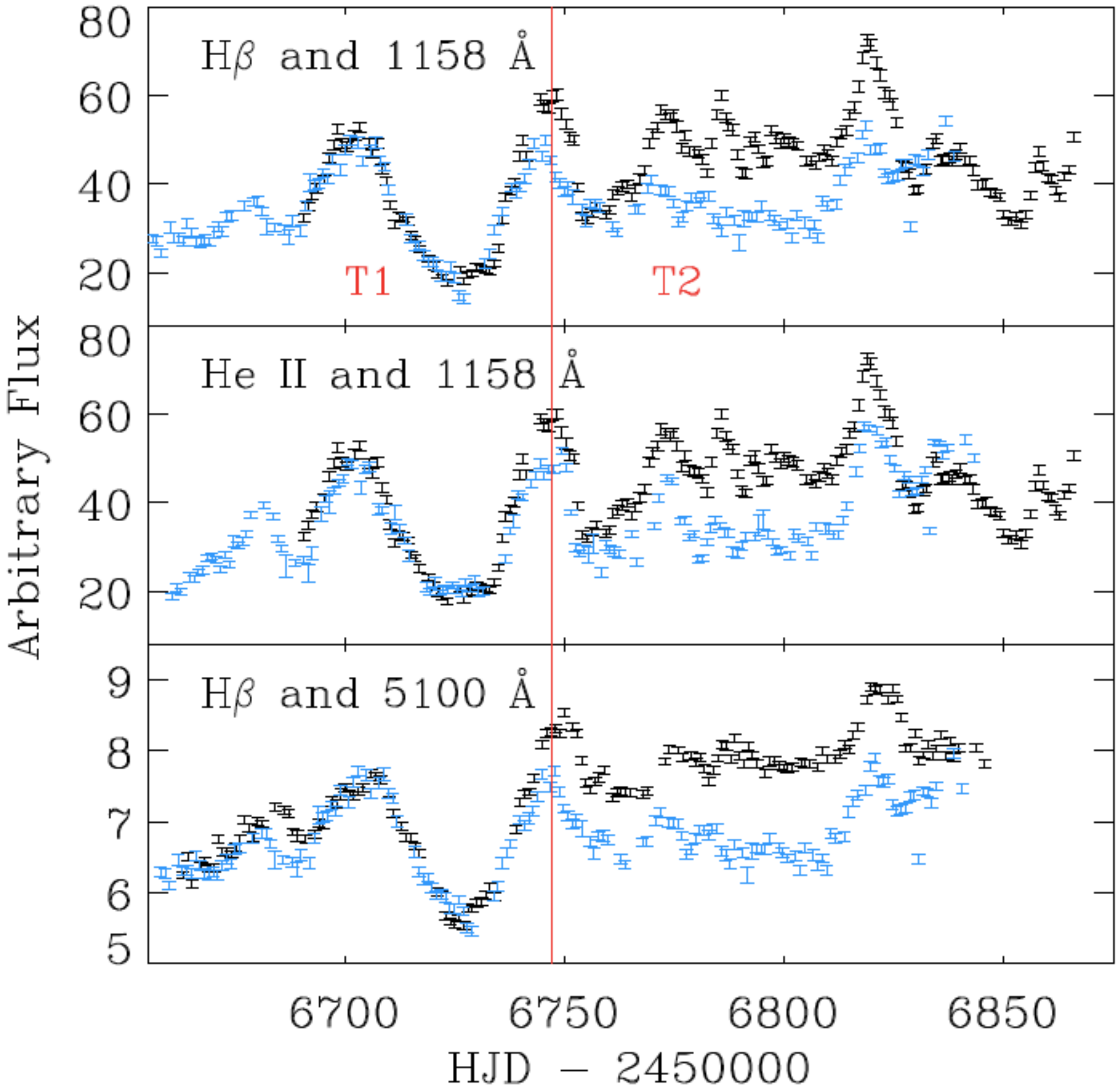
Barth+ 2015 (method)

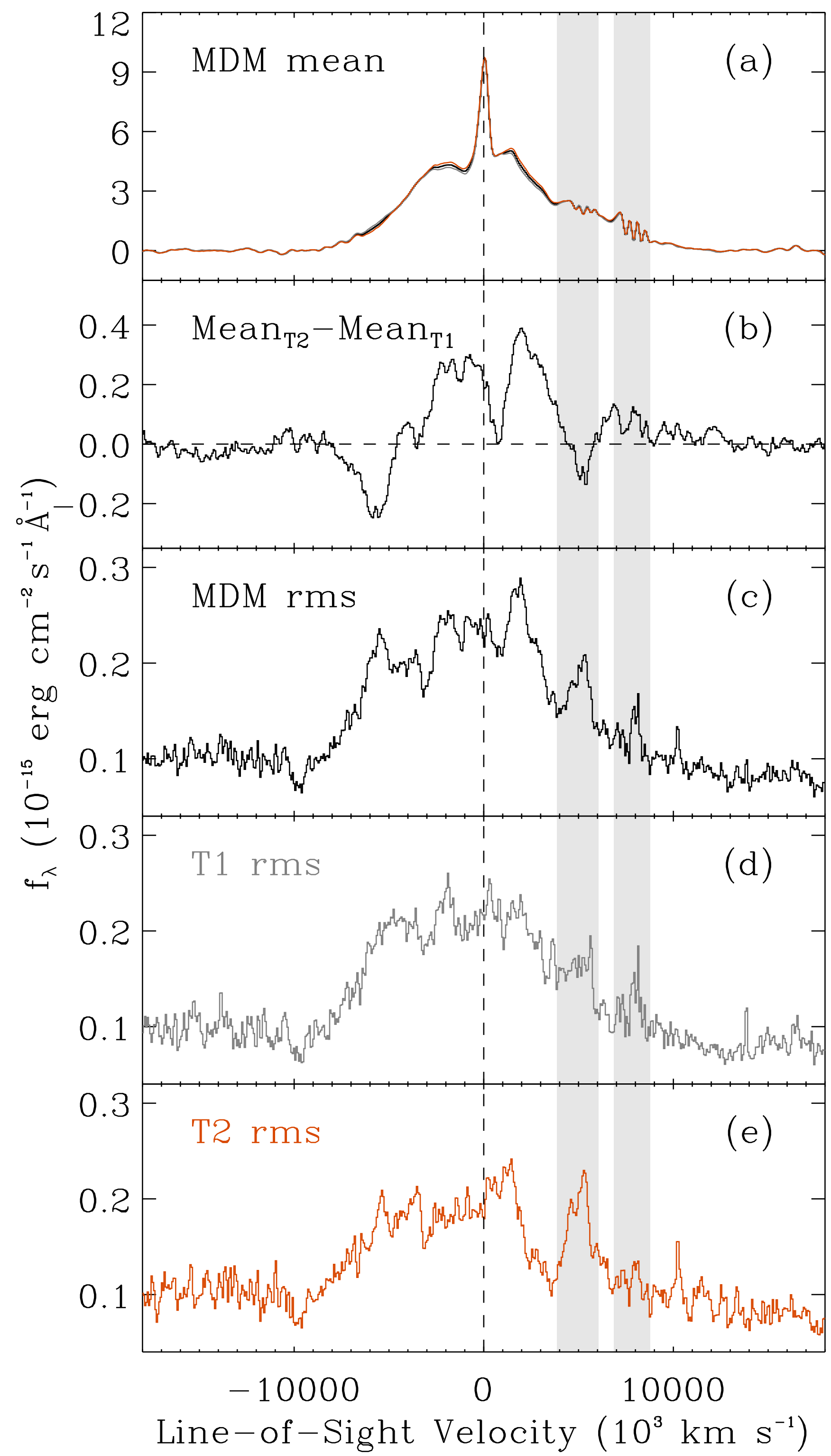
Spectral Decomposition

- De-blend broad lines
  - Enable measurement of He II flux
- More accurately remove the continuum
- Fitting routine:
  - Sixth order Gauss-Hermite functions for [O III], broad and narrow Hβ
  - He II λ4686 width constrained to within 3 Å of the He II λ1640 width from the nearest *HST* epoch



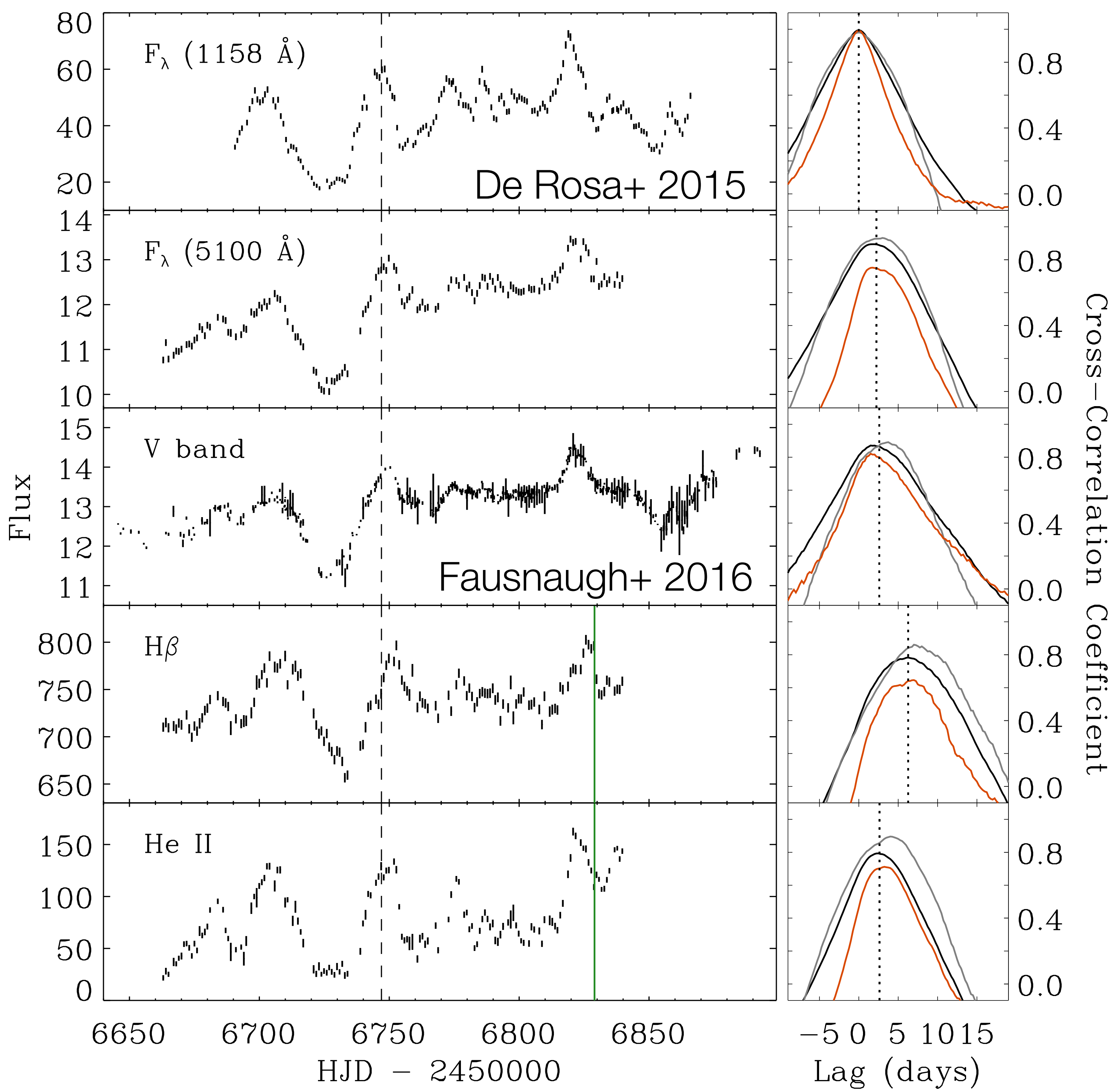
Light-Curve Decorrelation

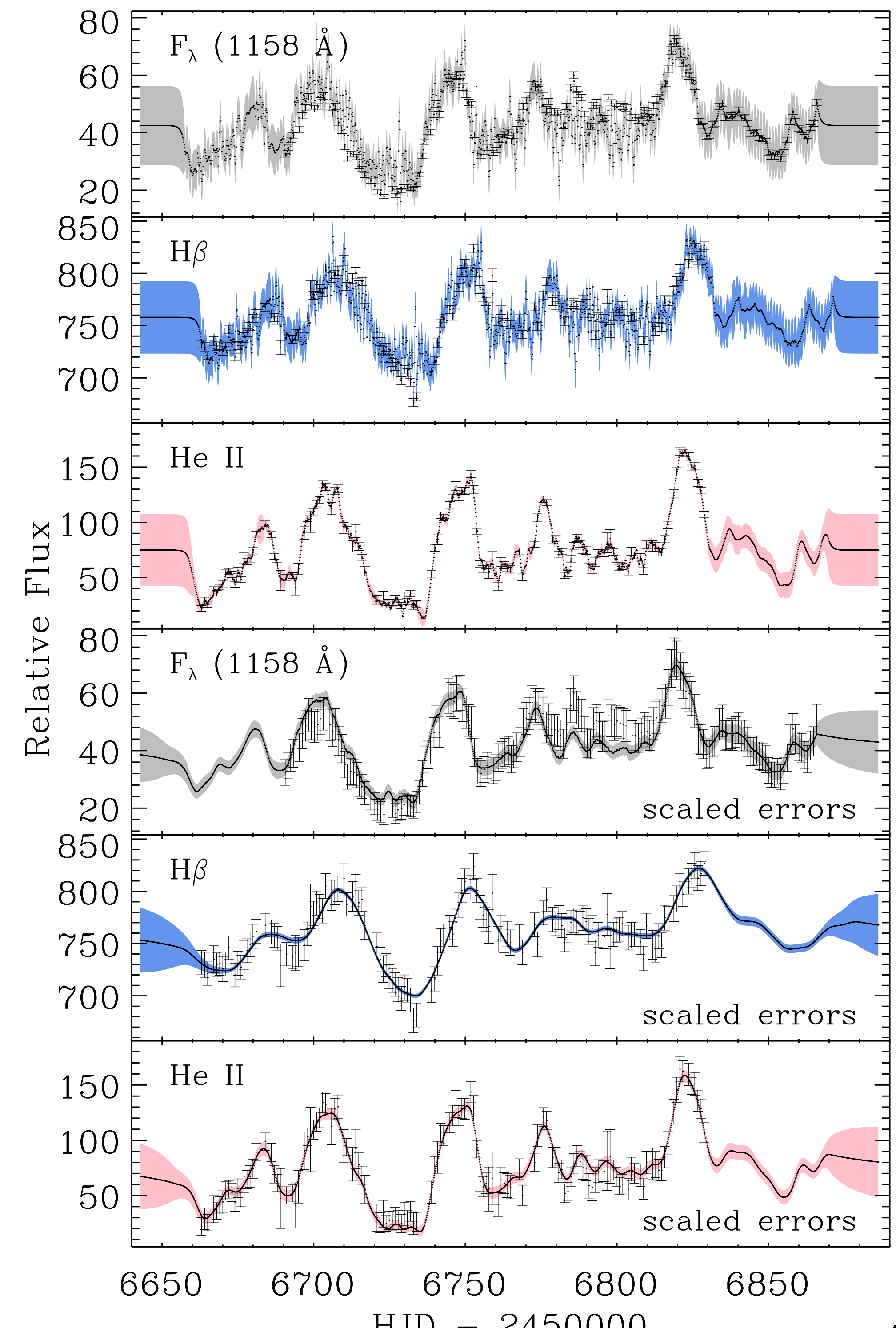




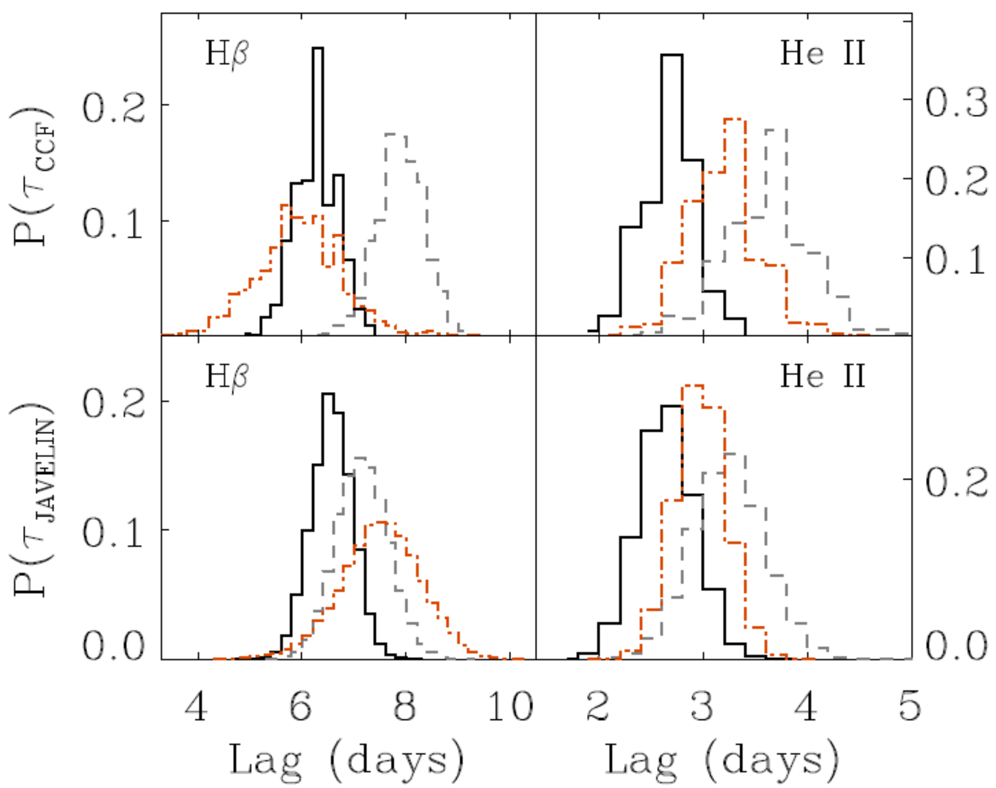
Lag Analysis

ICCF and JAVELIN

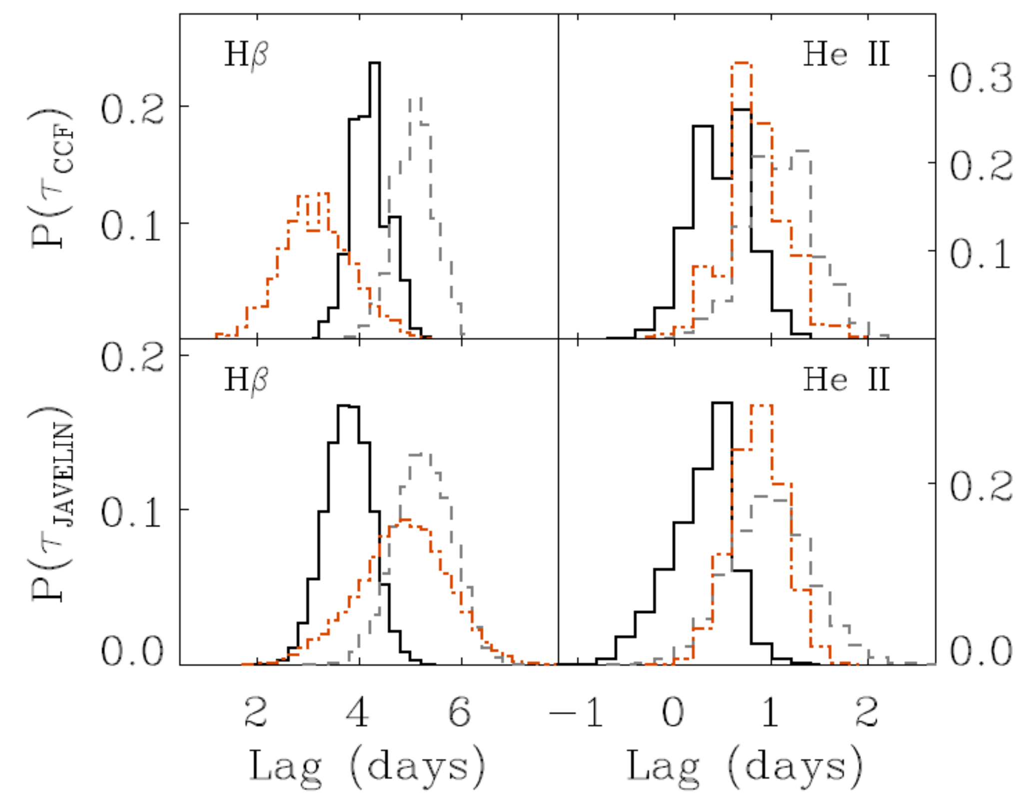




Lags w.r.t 1158 Å continuum



Lags w.r.t 5100 Å continuum



Observed-Frame Emission-Line Lags

Light Curves	τ_{cen}	$\tau_{cen,T1}$	$\tau_{cen,T2}$	$\tau_{JAVELIN}$	$\tau_{JAVELIN,T1}$	$\tau_{JAVELIN,T2}$
Hβ vs. F_λ(1158 Å)	$6.34^{+0.40}_{-0.45}$	$7.75^{+0.50}_{-0.50}$	$6.09^{+0.72}_{-0.76}$	$6.67^{+0.49}_{-0.50}$	$7.03^{+0.65}_{-0.64}$	$7.55^{+0.99}_{-1.09}$
Hβ vs. F_λ(1367 Å)	$5.99^{+0.38}_{-0.38}$	$7.36^{+0.50}_{-0.49}$	$6.09^{+0.77}_{-0.83}$	$6.23^{+0.47}_{-0.48}$	$6.63^{+0.61}_{-0.58}$	$7.23^{+1.05}_{-1.08}$
Hβ vs. F_λ(5100 Å)	$4.24^{+0.37}_{-0.37}$	$5.08^{+0.41}_{-0.48}$	$3.15^{+0.78}_{-0.81}$	$3.91^{+0.58}_{-0.60}$	$5.24^{+0.69}_{-0.70}$	$4.86^{+1.15}_{-1.19}$
Hβ vs. V band	$3.86^{+0.38}_{-0.35}$	$3.89^{+0.58}_{-0.48}$	$4.20^{+0.56}_{-0.59}$	$3.60^{+0.46}_{-0.47}$	$4.97^{+0.67}_{-0.72}$	$4.12^{+0.95}_{-0.79}$
He II vs. F_λ(1158 Å)	$2.74^{+0.24}_{-0.25}$	$3.77^{+0.40}_{-0.39}$	$3.24^{+0.37}_{-0.36}$	$2.70^{+0.27}_{-0.27}$	$3.33^{+0.36}_{-0.36}$	$3.04^{+0.25}_{-0.26}$
He II vs. F_λ(1367 Å)	$2.49^{+0.25}_{-0.24}$	$3.49^{+0.37}_{-0.44}$	$3.21^{+0.29}_{-0.34}$	$2.45^{+0.25}_{-0.26}$	$3.09^{+0.36}_{-0.37}$	$2.84^{+0.25}_{-0.25}$
He II vs. F_λ(5100 Å)	$0.80^{+0.36}_{-0.35}$	$1.23^{+0.28}_{-0.37}$	$0.86^{+0.37}_{-0.37}$	$0.16^{+0.38}_{-0.38}$	$1.15^{+0.52}_{-0.49}$	$0.86^{+0.39}_{-0.36}$
He II vs. V band	$0.51^{+0.35}_{-0.26}$	$0.41^{+0.44}_{-0.40}$	$1.48^{+0.35}_{-0.27}$	$0.45^{+0.23}_{-0.23}$	$0.64^{+0.38}_{-0.37}$	$0.93^{+0.23}_{-0.21}$

Pei et al. *submitted*

Hβ UV & Optical Lags

Light Curves	$\tau_{\rm cen}$
Hβ vs. $F_\lambda(1158\ \text{Å})$	$6.34^{+0.40}_{-0.45}$
Hβ vs. $F_\lambda(1367\ \text{Å})$	$5.99^{+0.38}_{-0.38}$
Hβ vs. $F_\lambda(5100\ \text{Å})$	$4.24^{+0.37}_{-0.37}$
Hβ vs. V band	$3.86^{+0.38}_{-0.35}$

The Hβ—UV lag is 1.5 times longer than the Hβ—optical lag

- RM usually uses the optical continuum as proxy for the ionizing continuum

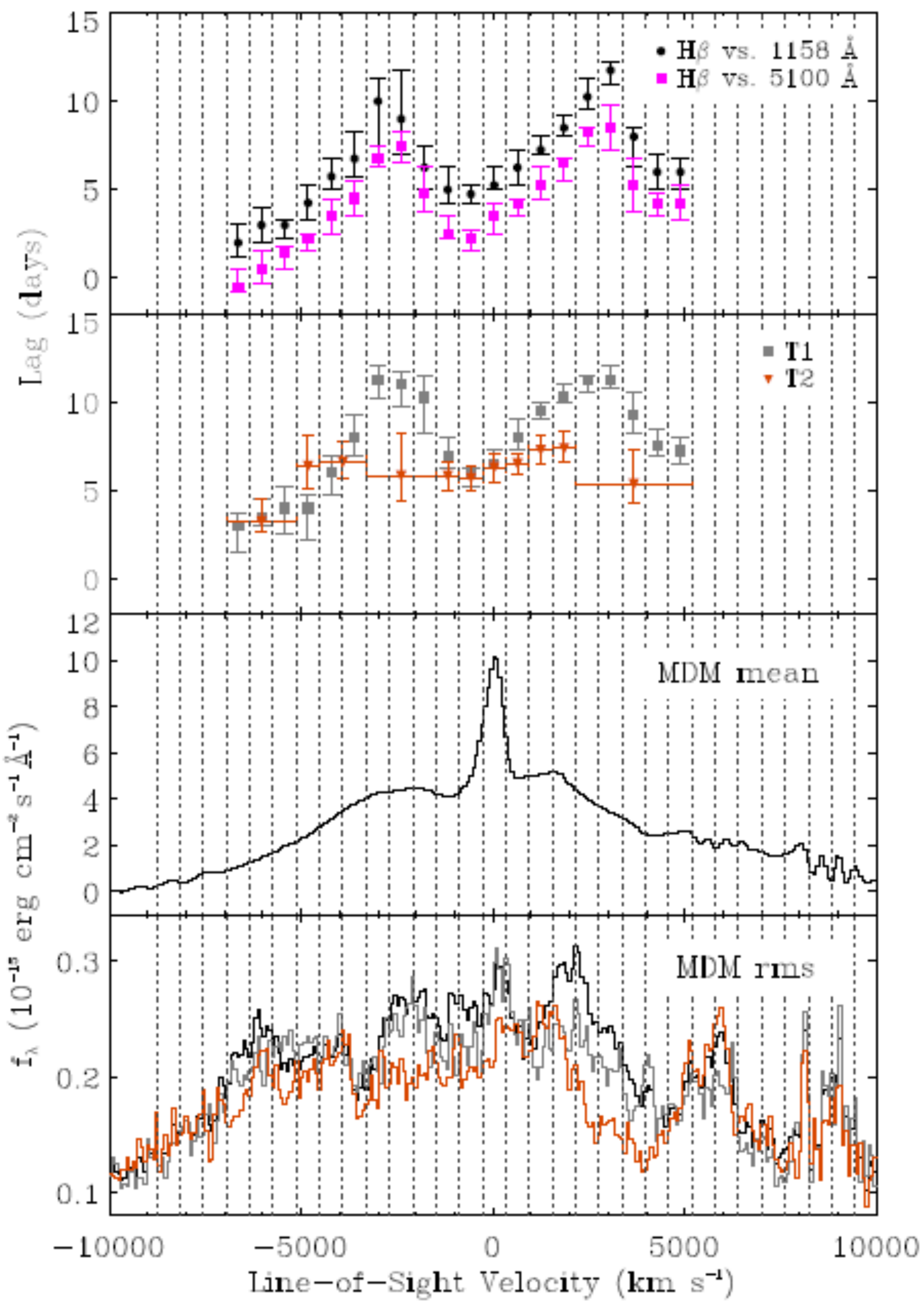
$$M_{\rm BH} = f\frac{c\tau\sigma^2}{G},\ R_{\rm BLR} = c\tau$$

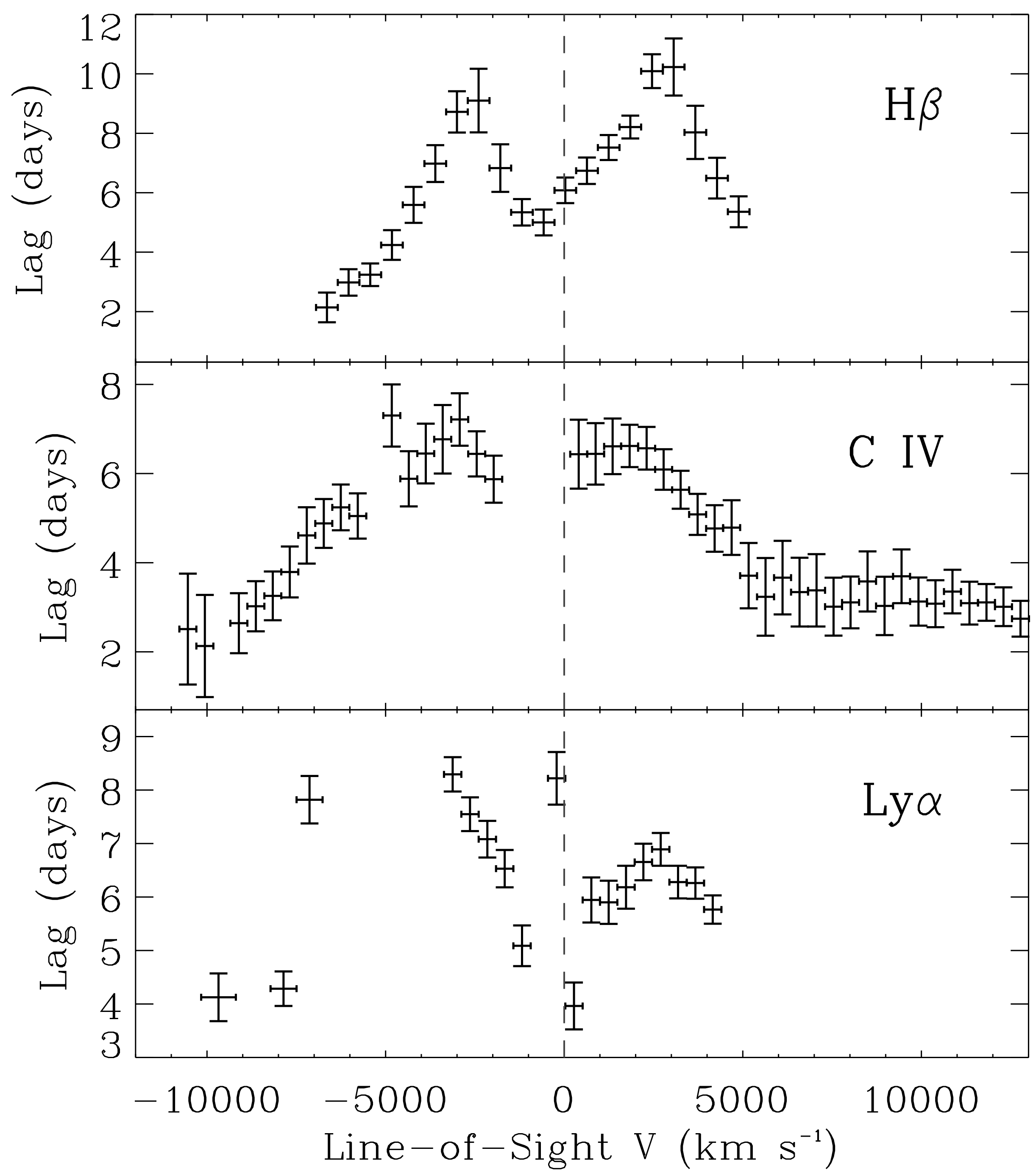
- Shorter lag ⇒ $R_{\rm BLR}$ underestimated by 50%!
- What about the BH mass?

Implications of UV & Optical Lags

- Is τ_{UV}/τ_{opt} constant for all AGNs?
  - **Yes ➙** M_{BH} values aren't affected since virial products are calibrated to quiescent galaxy $M_{BH} - \sigma_{\star}$ relation, so $\langle f \rangle$ absorbed this constant shift.
  - **No ➙** the slope or even shape of the R_{BLR} — L_{AGN} can change. This would affect all single-epoch BH masses!
- Directly affects velocity-delay maps and dynamical models obtained using only optical data

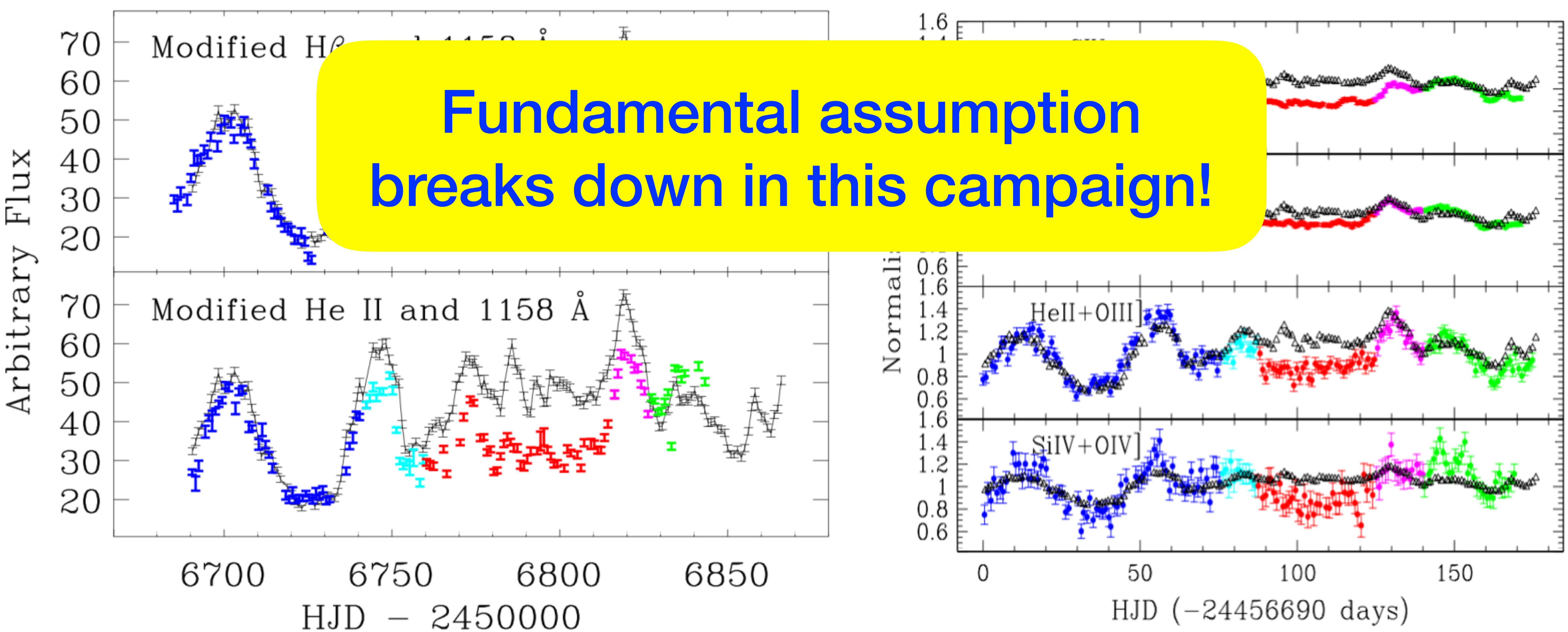
Velocity-Resolved Hβ Analysis





Anomalous Emission-Line Variability

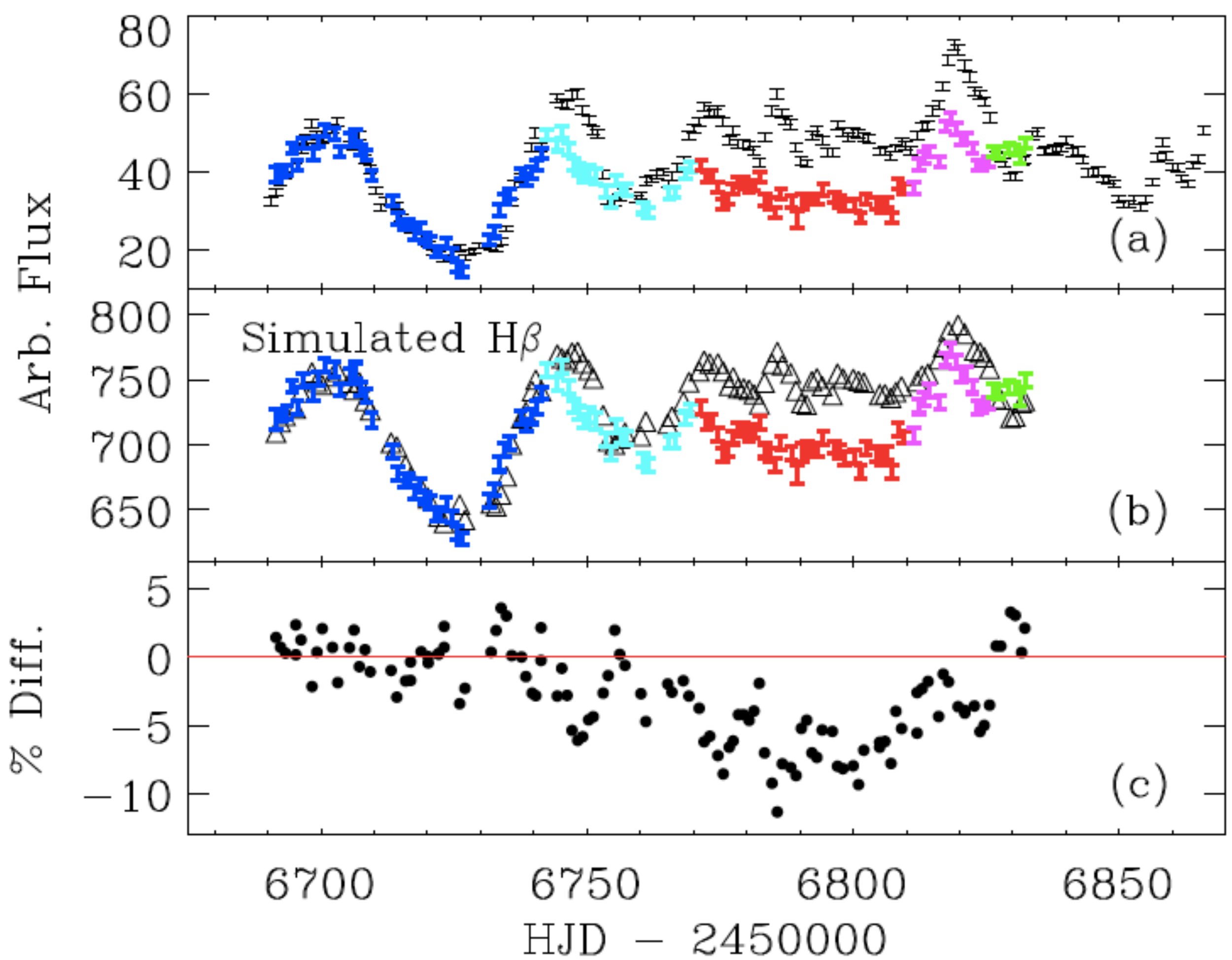
- A fundamental assumption of RM is that the line light curve is a smoothed, scaled, and shifted version of the continuum light curve

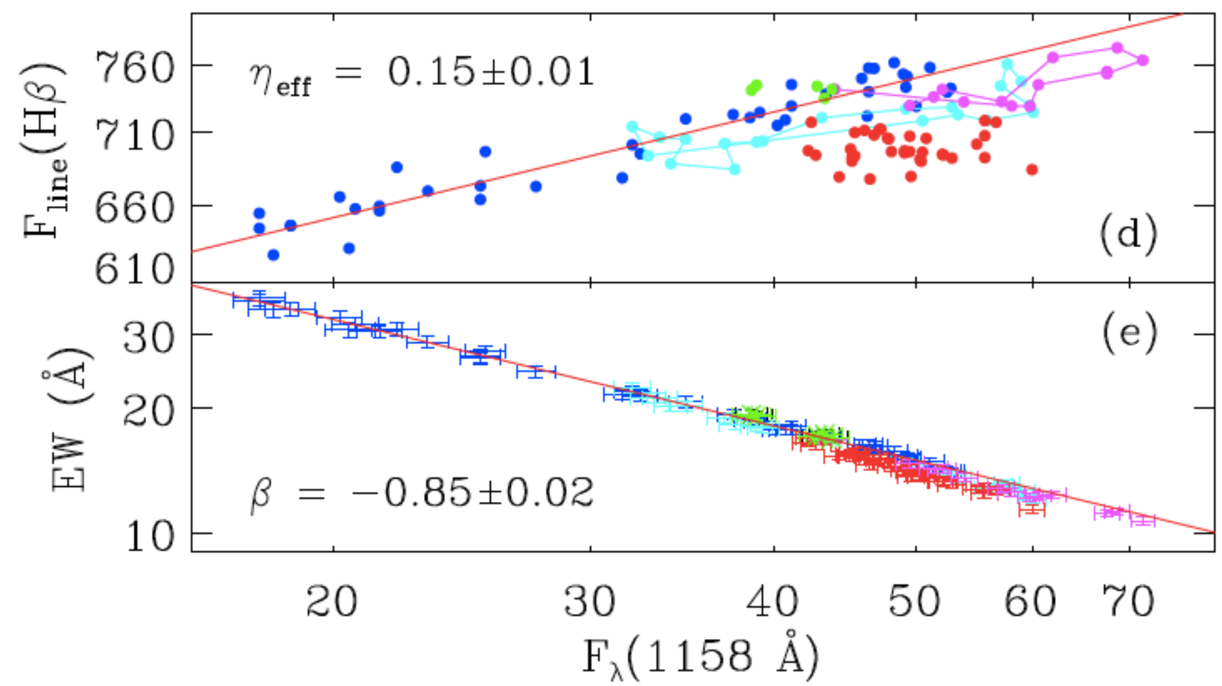


Fundamental assumption breaks down in this campaign!

Goad et al., 2016

Anomalous Emission-Line Variability





$$EW = \frac{F_{line}}{F_{cont}}$$

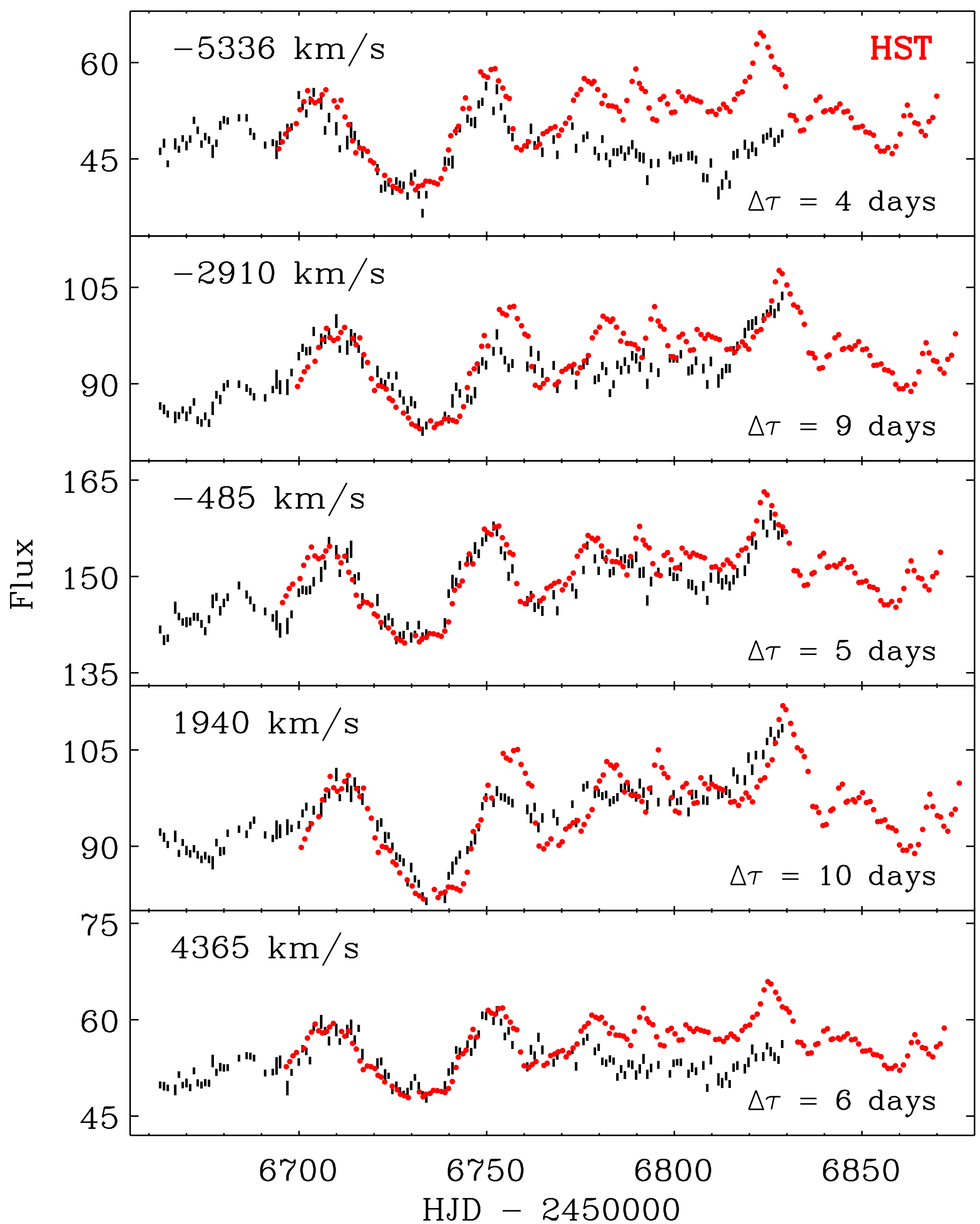
$$\log\ F_{line} = A + \eta_{eff}[\log\ F_{cont}]$$

$$\log\ EW_{line} = B + \beta[\log\ F_{cont}]$$

Broad-Line Responsivity

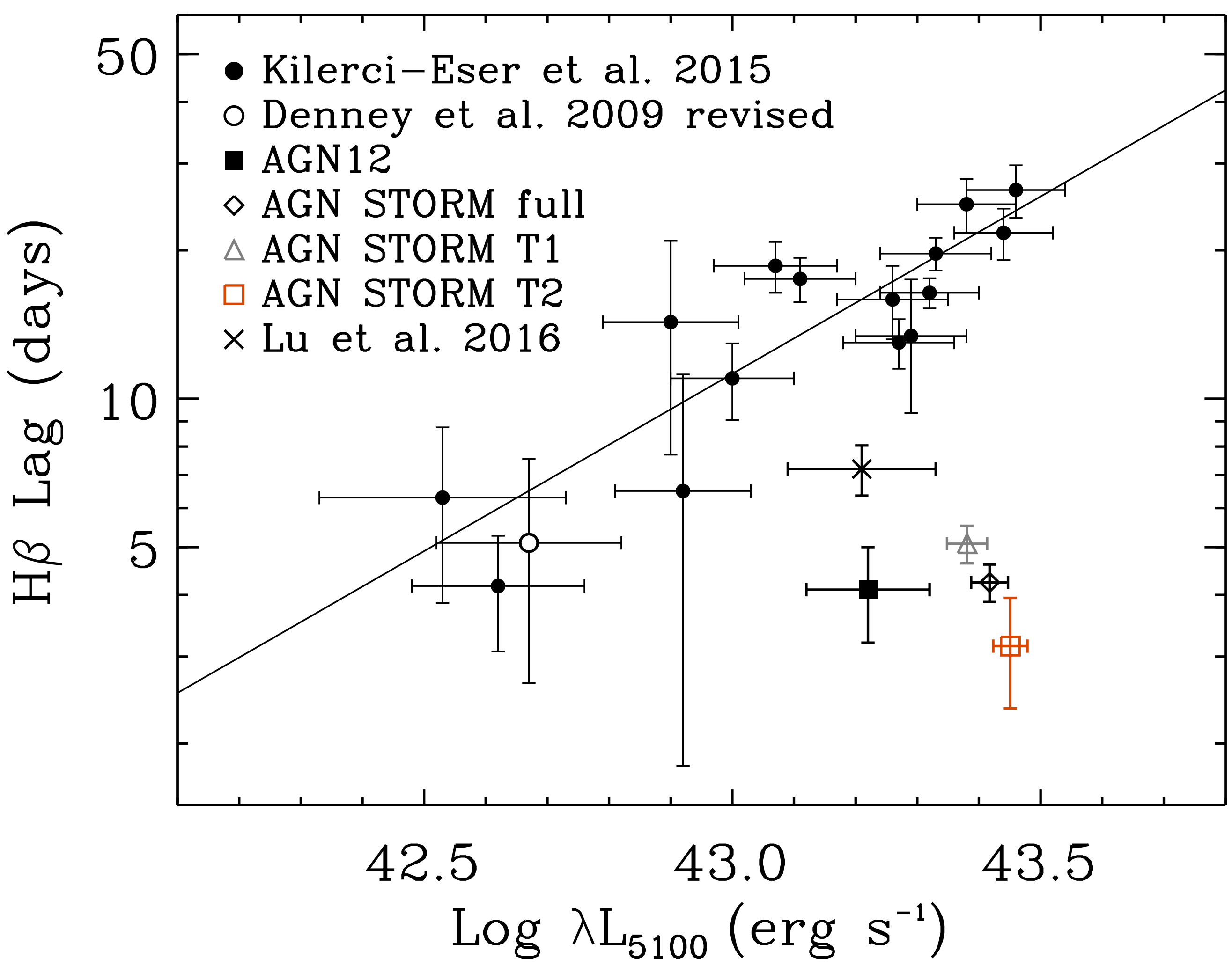
Line ID	η_{eff}	β	f_{lost}
Lyα	0.30 ± 0.01	-0.73 ± 0.02	9%
Si IV+O IV]	0.45 ± 0.01	-0.58 ± 0.03	23%
C IV	0.25 ± 0.01	-0.75 ± 0.01	18%
He II+O III]	0.58 ± 0.04	-0.48 ± 0.04	21%
Hβ	0.15 ± 0.01	-0.85 ± 0.02	6%

Anomalous Emission-Line Variability



- ✦ The anomaly is velocity-dependent
- ✦ Some scenarios suggested by Goad+ 2016
  - Shielding material
  - Change in SED
- ✦ Further investigation required!

Single-Object R_{BLR} – L_{AGN} Relation



- The Hβ lag was unexpectedly short given its luminosity during the campaign
- Similar findings by Lu+ 2016 and recent campaigns
- Explanations:
  - Partially obscured BLR backside (Peterson)
  - Continuum probes only inner part of BLR (Goad & Korista 2014)

Major Results

- We measured optical emission-line lags for NGC 5548 w.r.t. simultaneous UV and optical continua
  - Using optical continuum as proxy for driving continuum systematically results in smaller R_{BLR}; BH masses **may** be affected
- We measured velocity-resolved lags for Hβ; double-peaked lag profile similar to C IV and Ly α
- Optical emission line light curves show same anomalous behavior as UV lines, and the Hβ response during the anomaly is time-dependent
- Given the AGN's luminosity, the Hβ lag is a factor of 5 shorter than expected from its previous $R_{BLR} - L_{AGN}$ relation

Lots of puzzles, what's next?

- Velocity-delay maps and dynamical modeling of UV and optical lines (Keith's talk, Pancoast+)
- More detailed velocity-resolved studies of the BLR anomaly (Goad+)
- Future campaigns
  - More simultaneous UV and optical RM monitoring
  - More LONG campaigns to check for BLR anomaly
  - Revisit NGC 5548 to check on its R—L relation