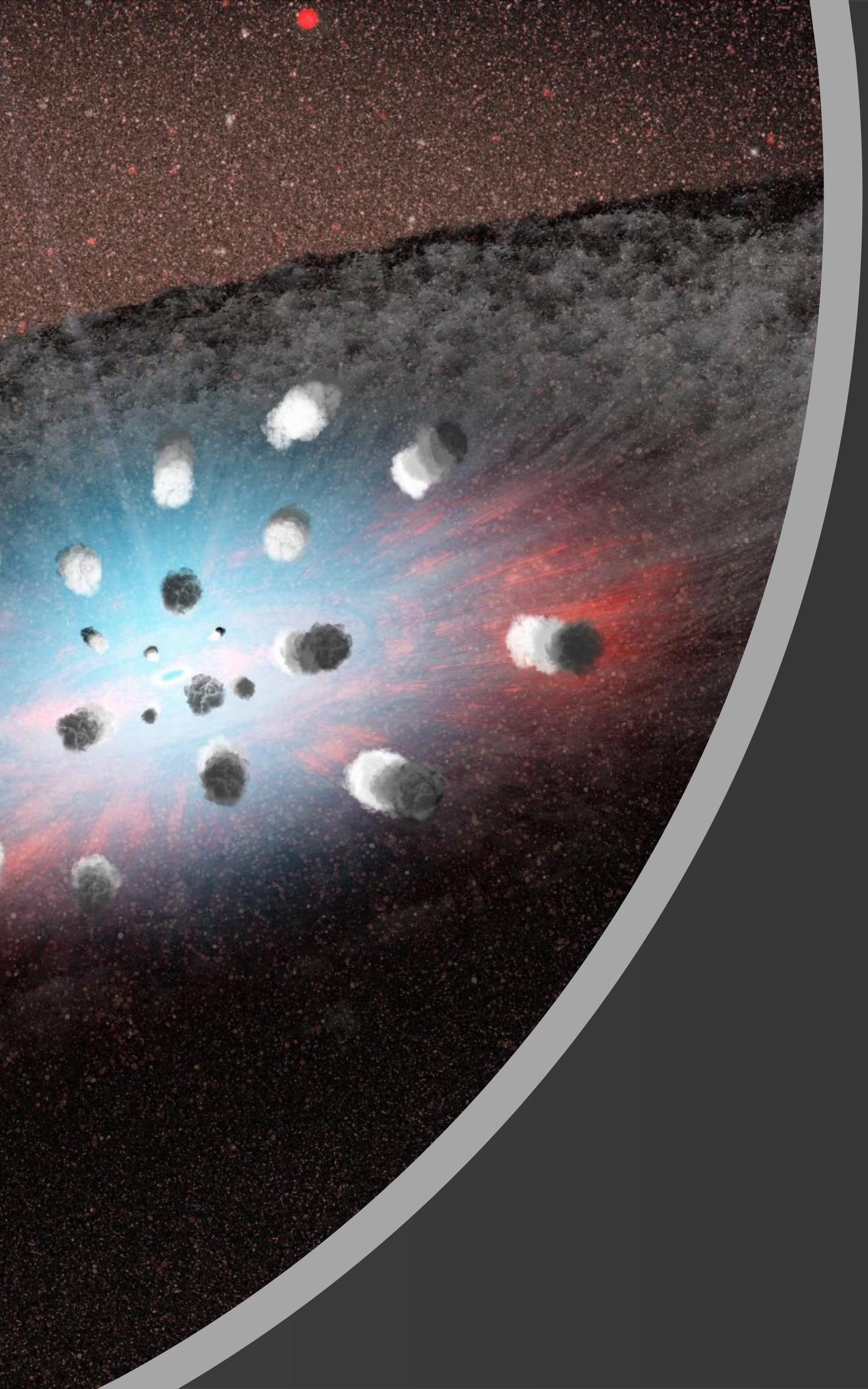


Reverberation Mapping of Emission Lines

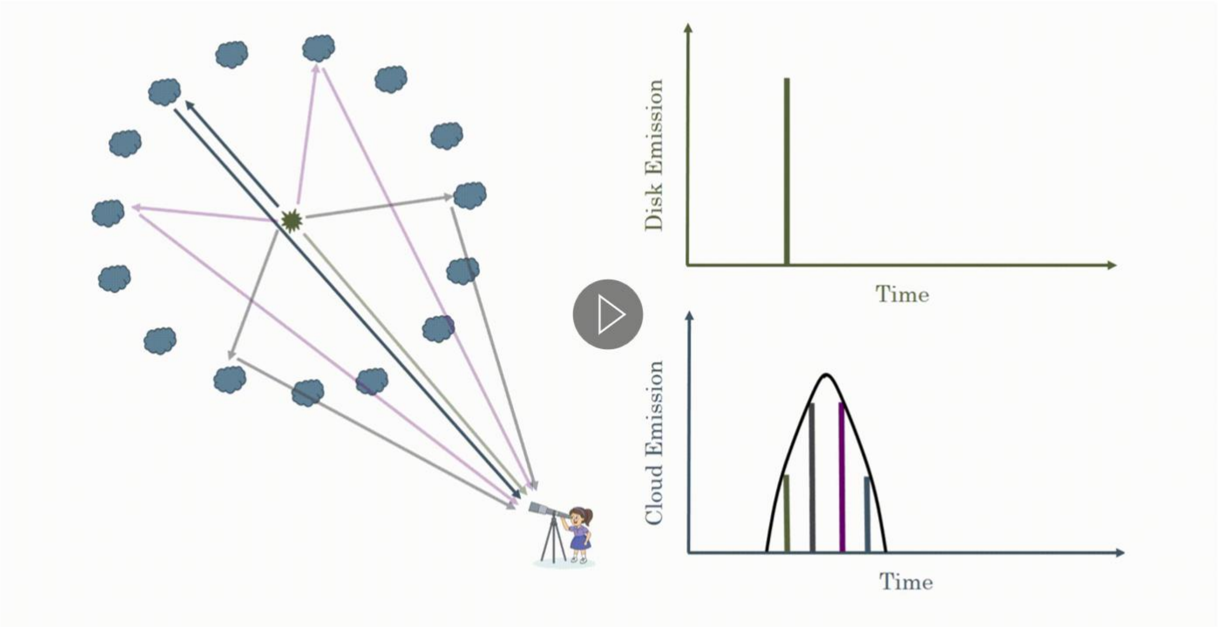
Last Decade and Future Prospects

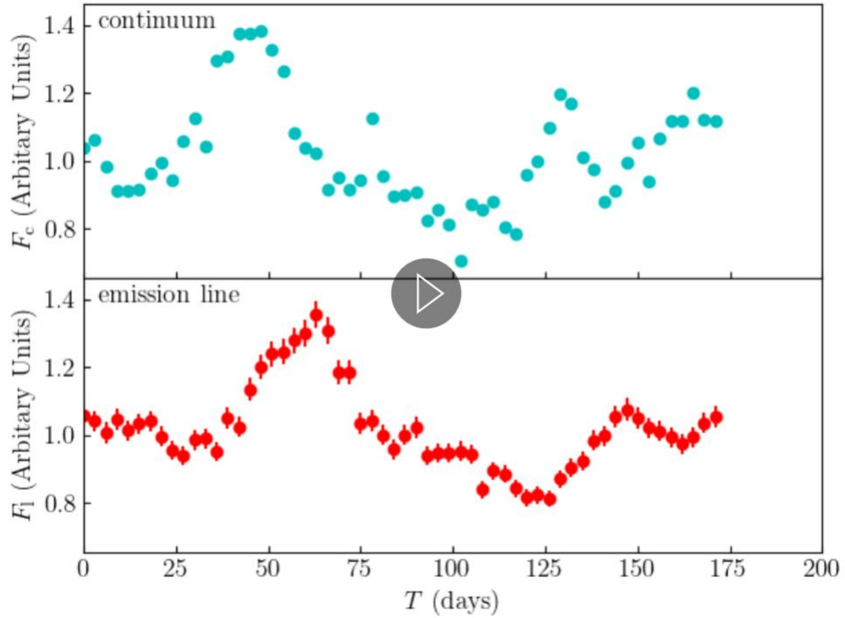
Pu Du

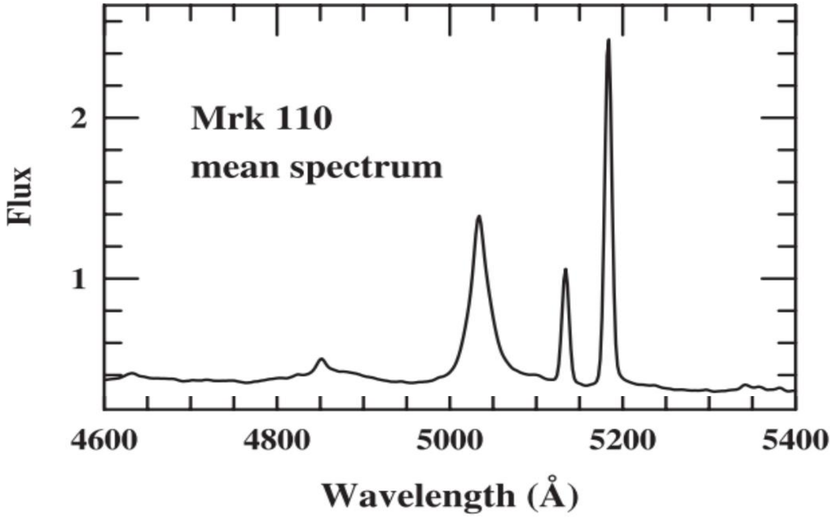
Institute of High Energy Physics,
Chinese Academy of Sciences

Naples, Italy
2023.6.27

Reverberation Mapping (RM)







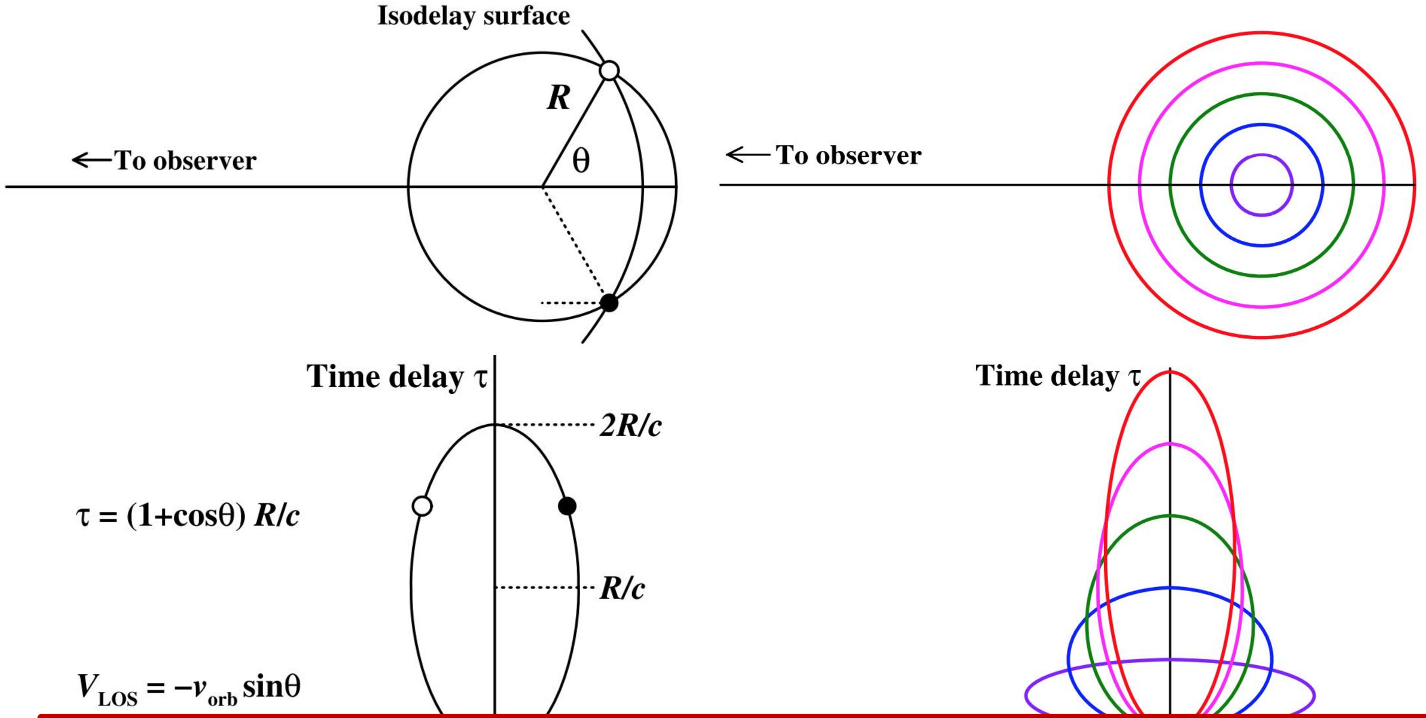
- Investigate the BLR properties in AGNs
- Measure the masses of SMBHs

$$M_{\bullet} = f\frac{c\tau \times V^2}{G}$$

Geometry and kinematics of the BLRs

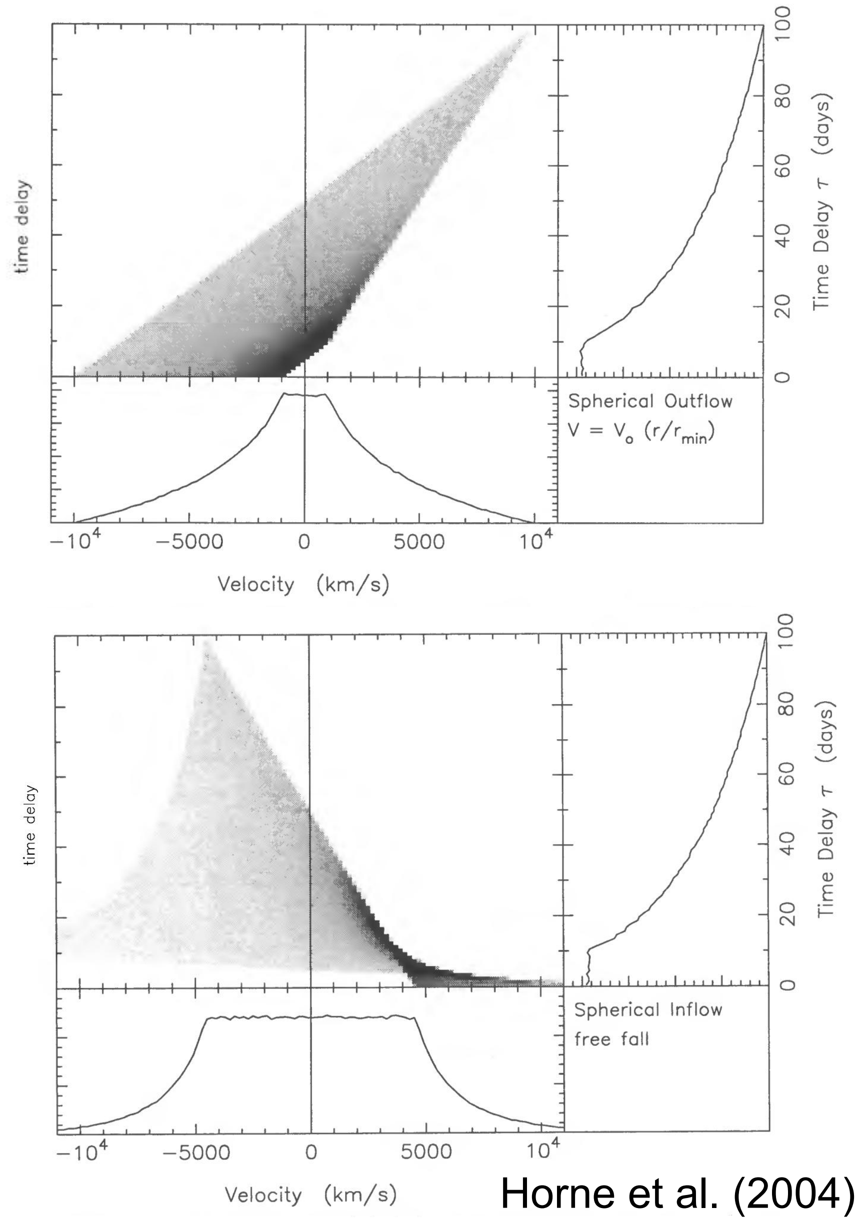
$$\Delta L(V_{\rm LOS}, t) = \int \underline{\Psi(V_{\rm LOS}, \tau)} \Delta C(t-\tau)\, d\tau,$$

Transfer function / velocity-delay map



- Maximum Entropy Method (Horne 1994)
- Subtractively Optimized Local Averages (Pijpers & Wanders 1994)
- Regularized Linear Inversion (Vio et al. 1994; Krolik & Done 1995)

Peterson & Horne (2004)



Horne et al. (2004)

RM 2013-2023

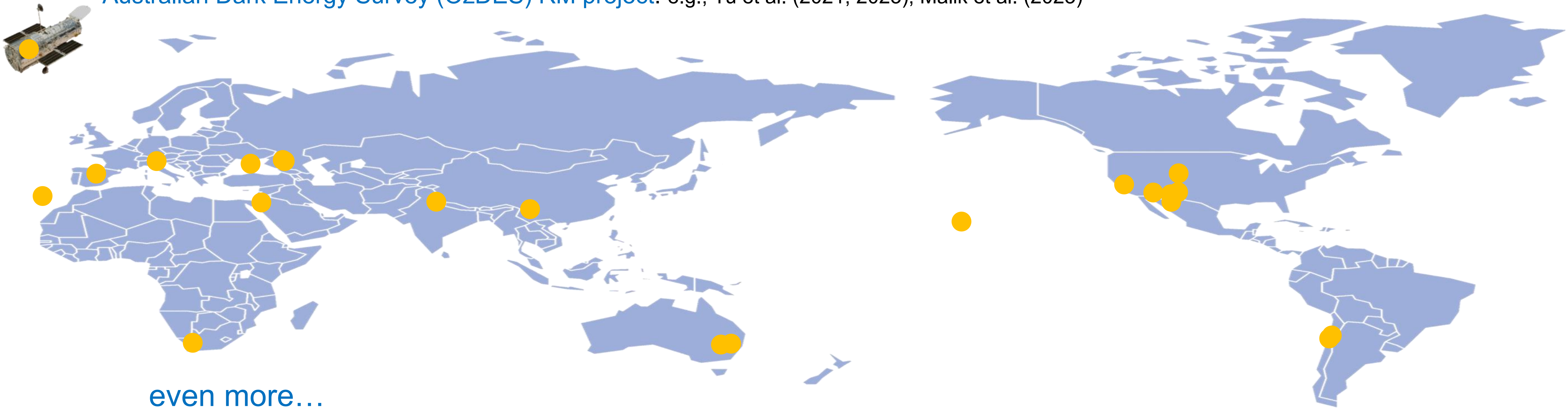
RM programs targeting specific types of AGNs or specific scientific objectives

- AGN Space Telescope and Optical Reverberation Mapping (AGN STORM) Projects 1 & 2: e.g., De Rosa et al. (2015), Kara et al. (2023)
- Lick AGN Monitoring Project (LAMP): e.g., Barth et al. (2015), U et al. (2022), Villafana et al. (2022)
- Super-Eddington Accreting Massive Black Holes (SEAMBH) project: e.g., Du et al. (2014, 2015, 2016, 2018a)
- Monitoring AGNs with Hβ Asymmetry (MAHA) project: e.g., Du et al. (2018b), Brotherton et al. (2020), Bao et al. (2022)
- Seoul National University AGN Monitoring Project (SAMP): e.g., Woo et al. (2019), Rakshit et al. (2020)
- HET long-term RM program: Kaspi et al. (2021)
- Luminous quasars RM program: Lira et al. (2018)
- SALT Mg II RM program: e.g., Czerny et al. (2019), Zajacek et al. (2020, 2021)

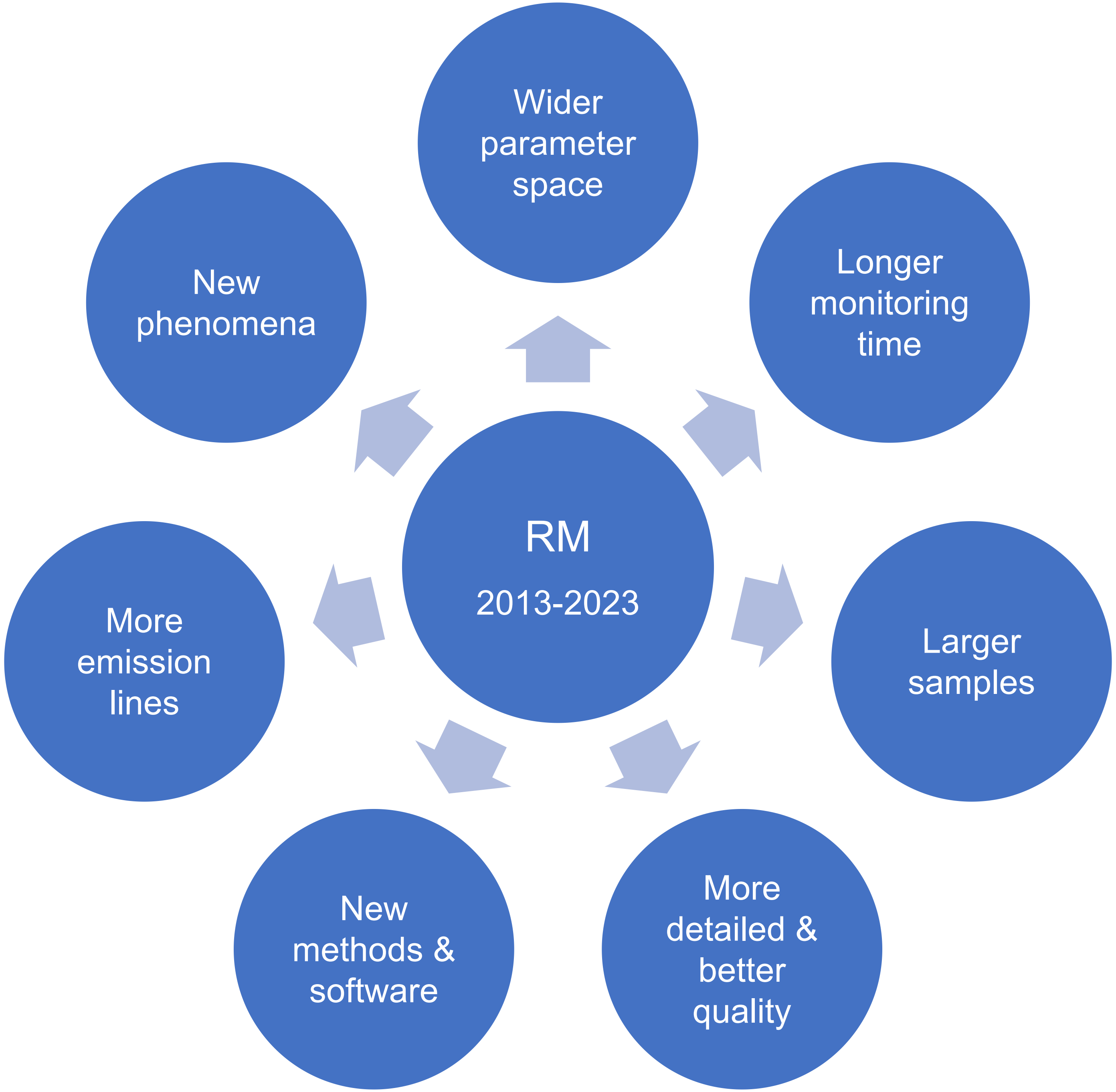
……

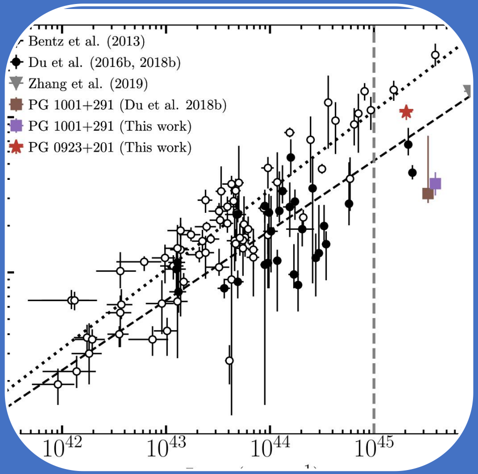
"Industrial"-scale RM programs

- Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) project: e.g., Shen et al. (2015, 2023), Grier et al. (2017)
- Australian Dark Energy Survey (OzDES) RM project: e.g., Yu et al. (2021, 2023), Malik et al. (2023)

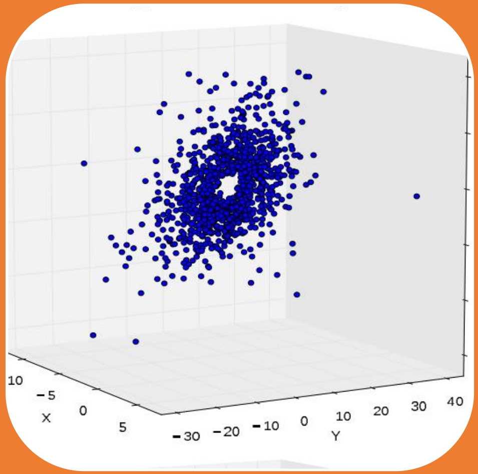


even more…

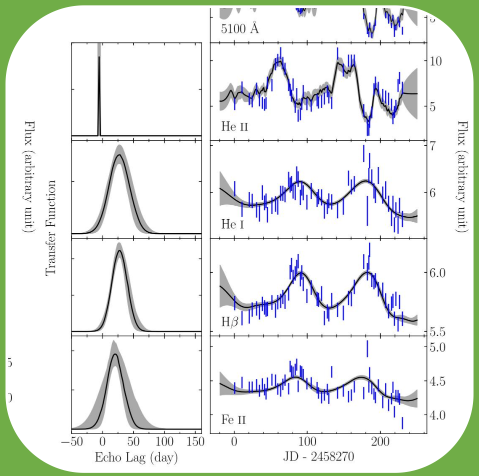

RM
2013-2023
Wider parameter space
Longer monitoring time
Larger samples
More detailed & better quality
New methods & software
More emission lines
New phenomena



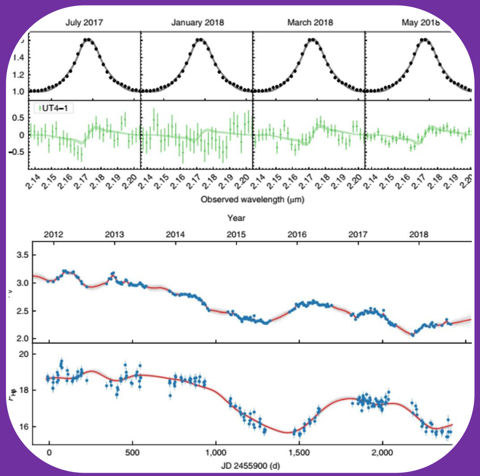
R-L relations



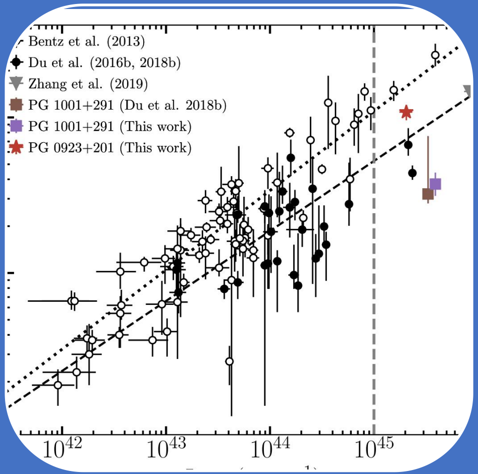
Velocity-resolved RM & BLR kinematics



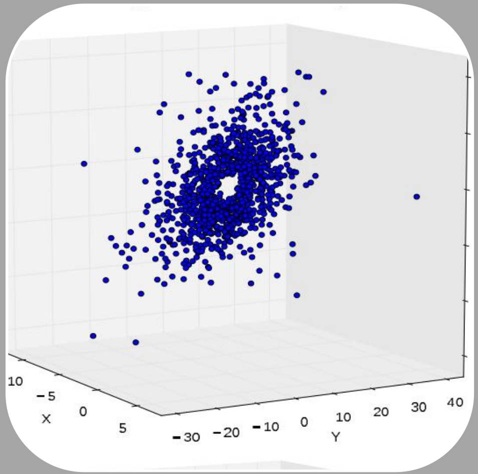
New phenomena



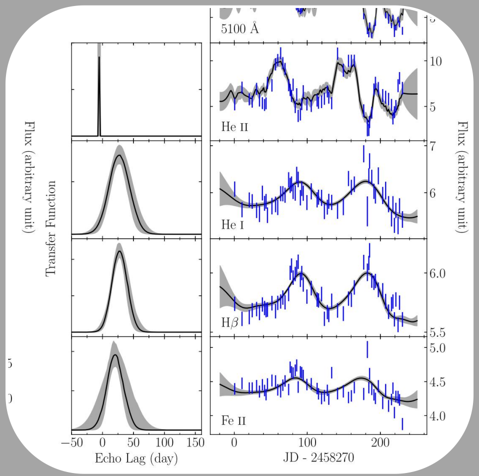
New applications



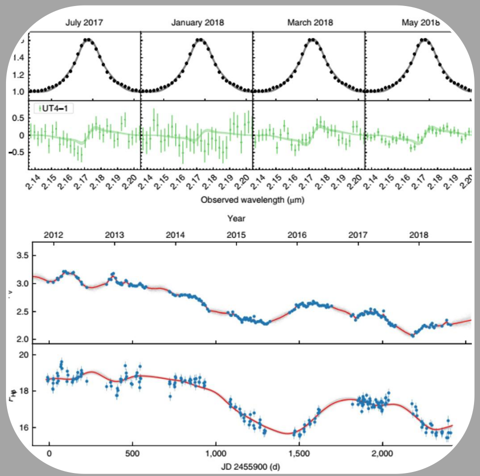
R-L relations



Velocity-resolved RM & BLR kinematics

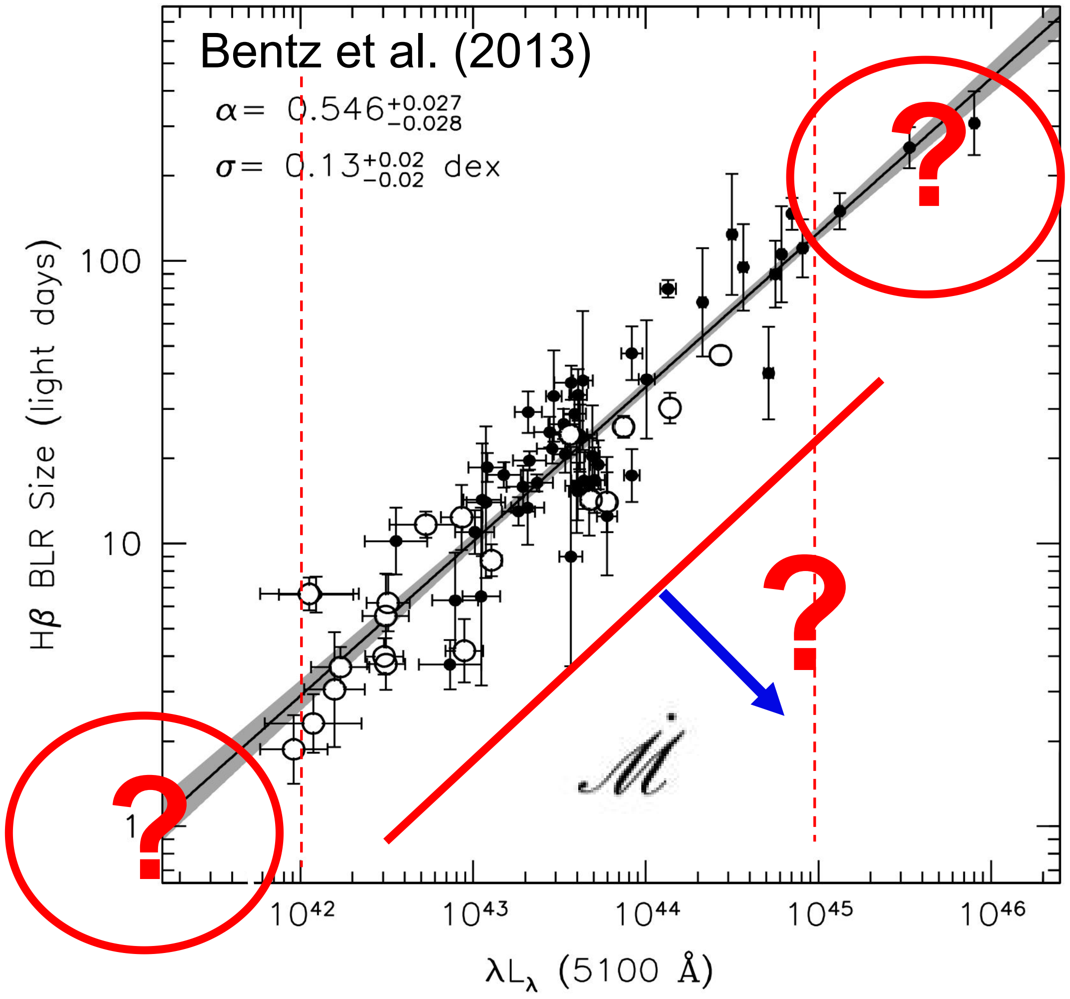


New phenomena



New applications

Wider Parameter Space

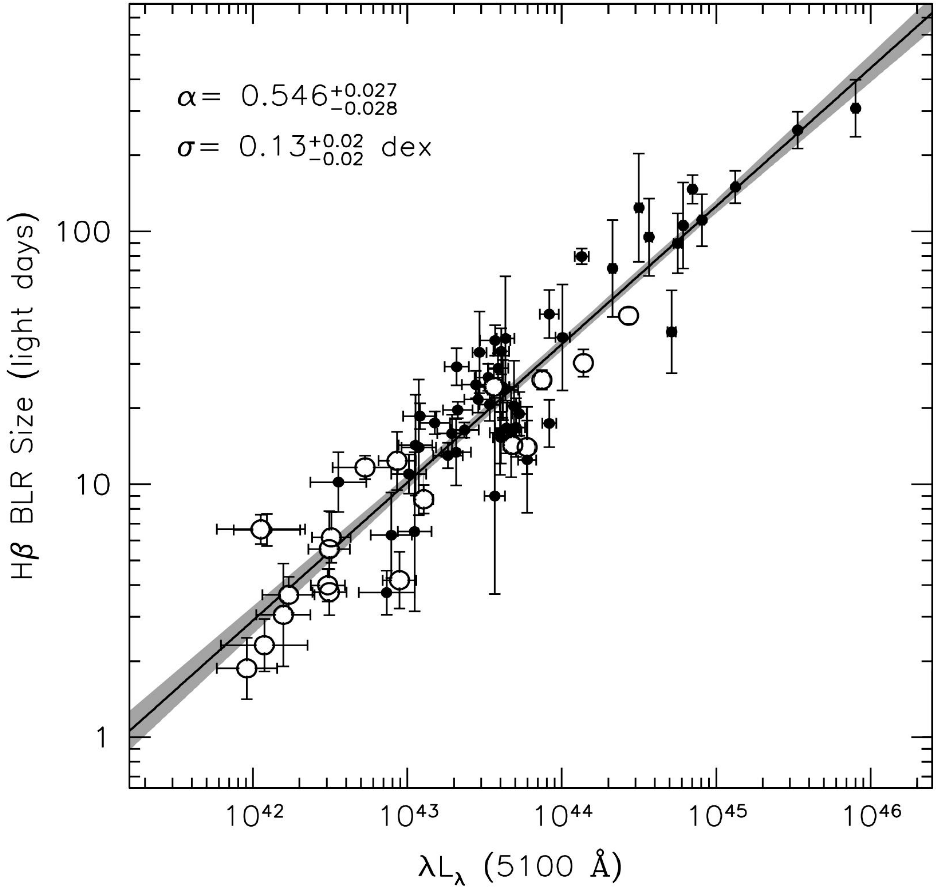


Questions:

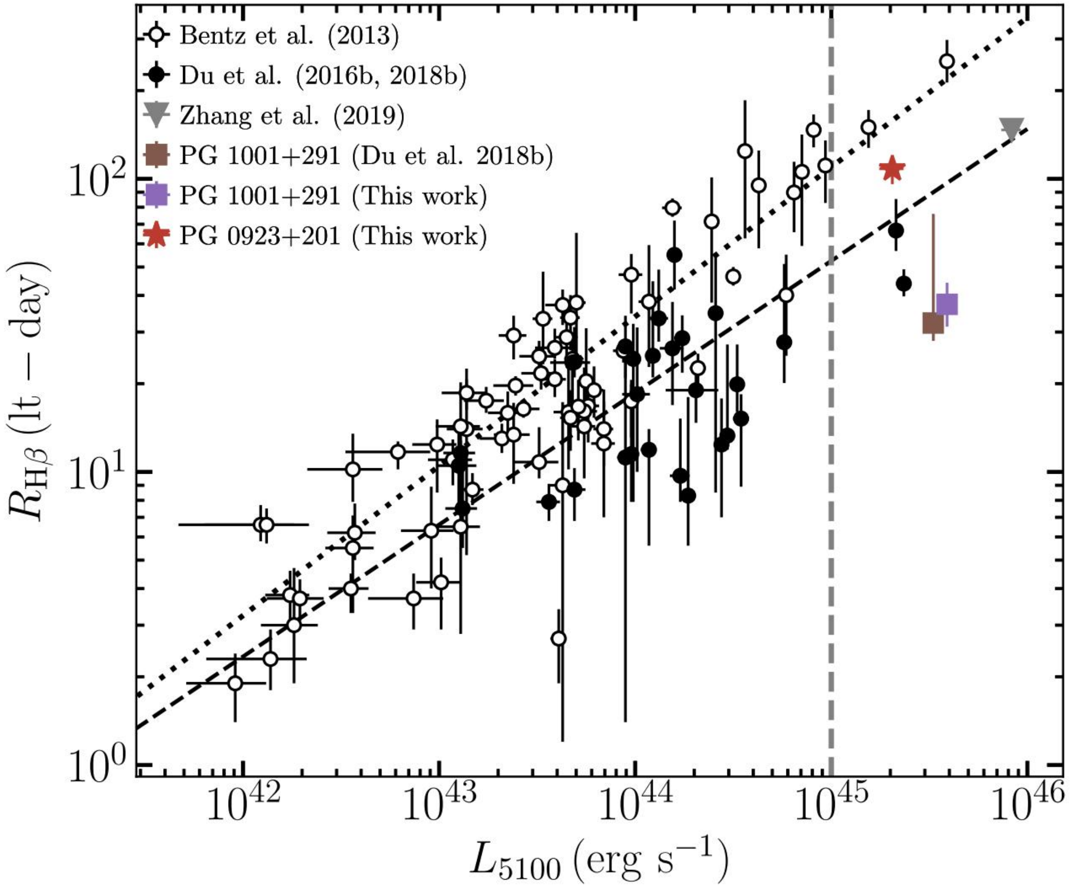
- Accretion rates?
- Luminous quasars?
- Intermediate-mass BH?

Super-Eddington AGNs & Shortened time lags

SEAMBH project:
Super-Eddington Accreting Massive Black Holes

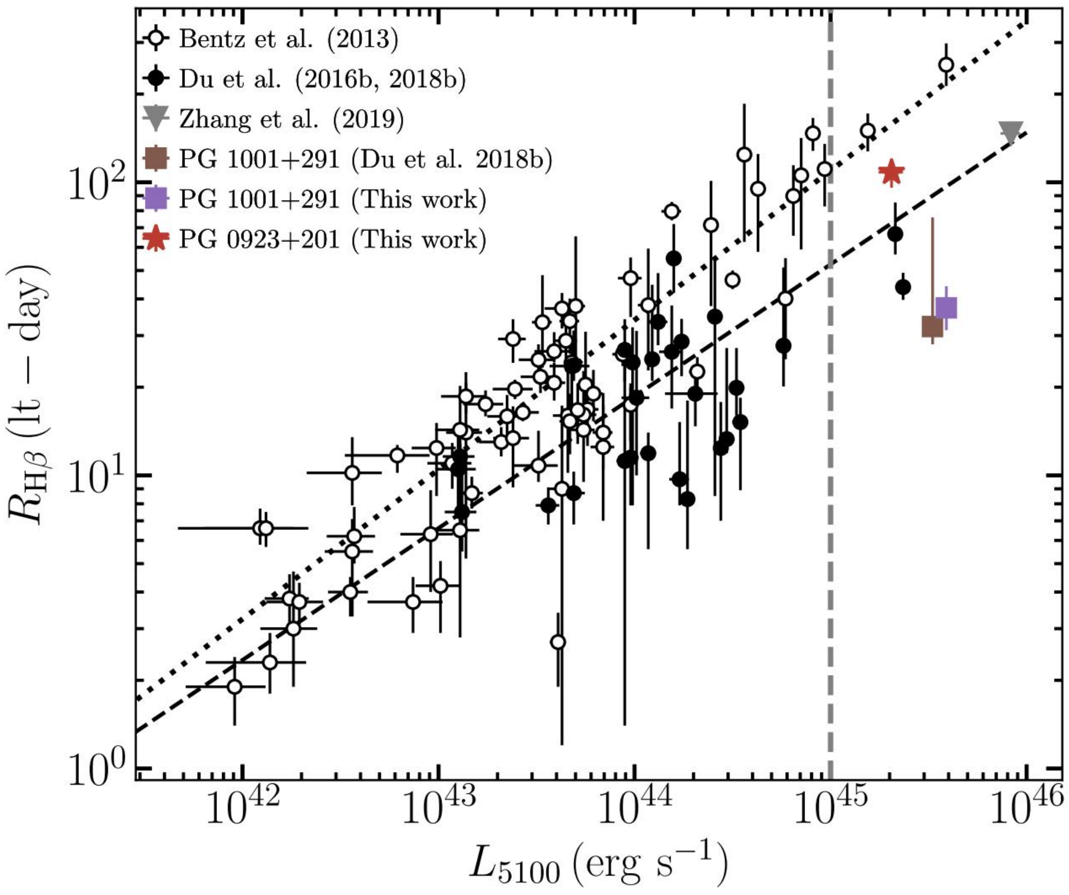


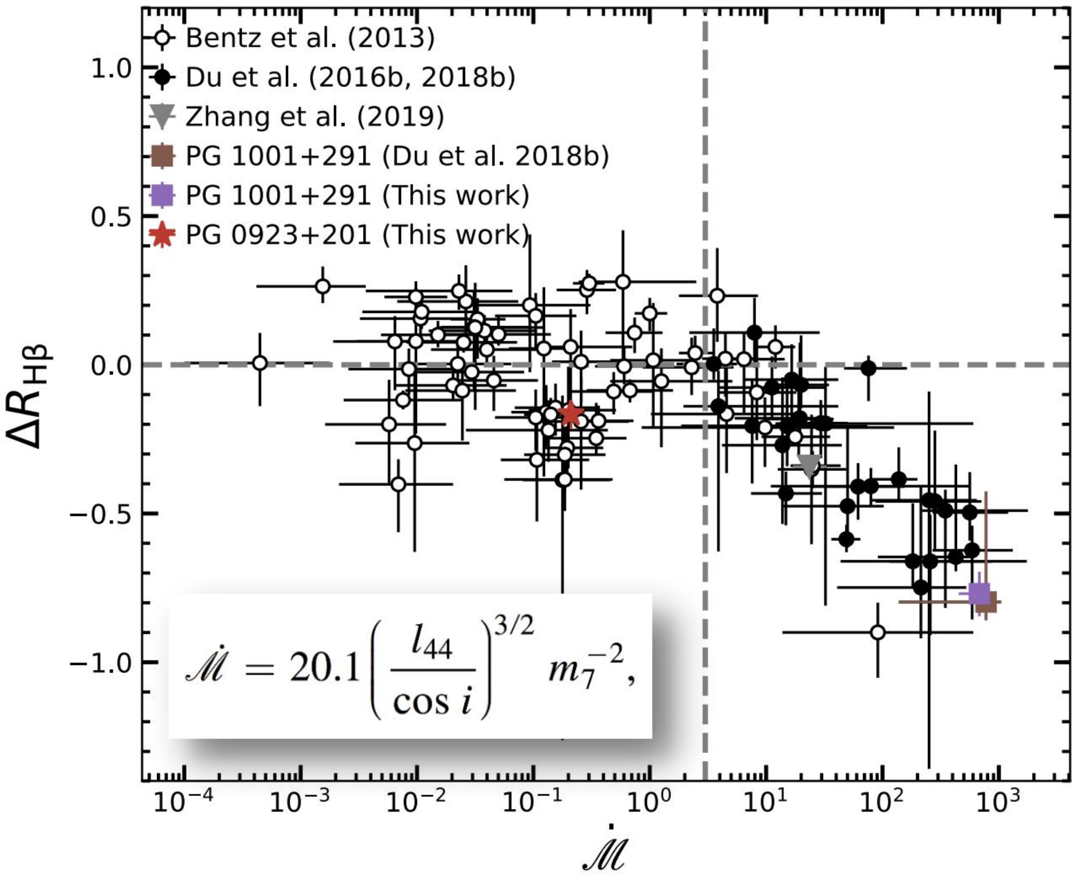
Bentz et al. 2013



Du et al. (2014; 2015; 2016a; 2018),
Wang et al. (2014), Hu et al. (2015), Li et al. (2021)

Super-Eddington AGNs & Shortened time lags



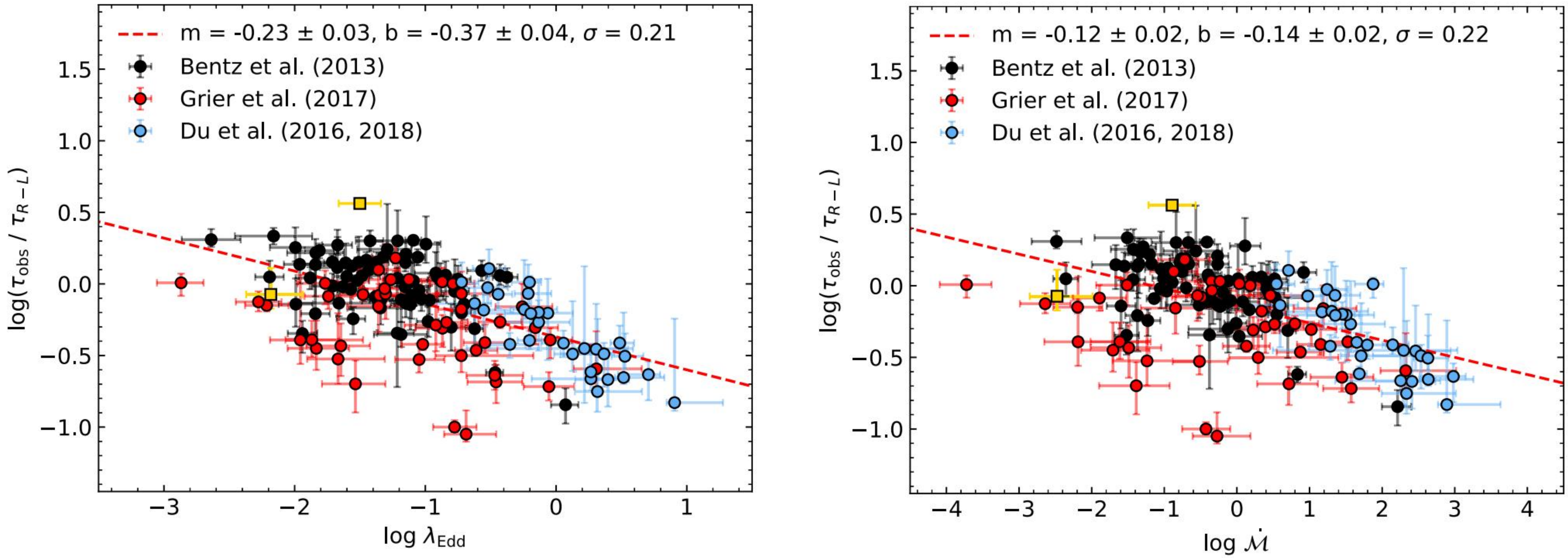


Du et al. (2014; 2015; 2016a; 2018),
Wang et al. (2014), Hu et al. (2015), Li et al. (2021)

Overestimate BH mass by factors 3-8

Super-Eddington AGNs & Shortened time lags

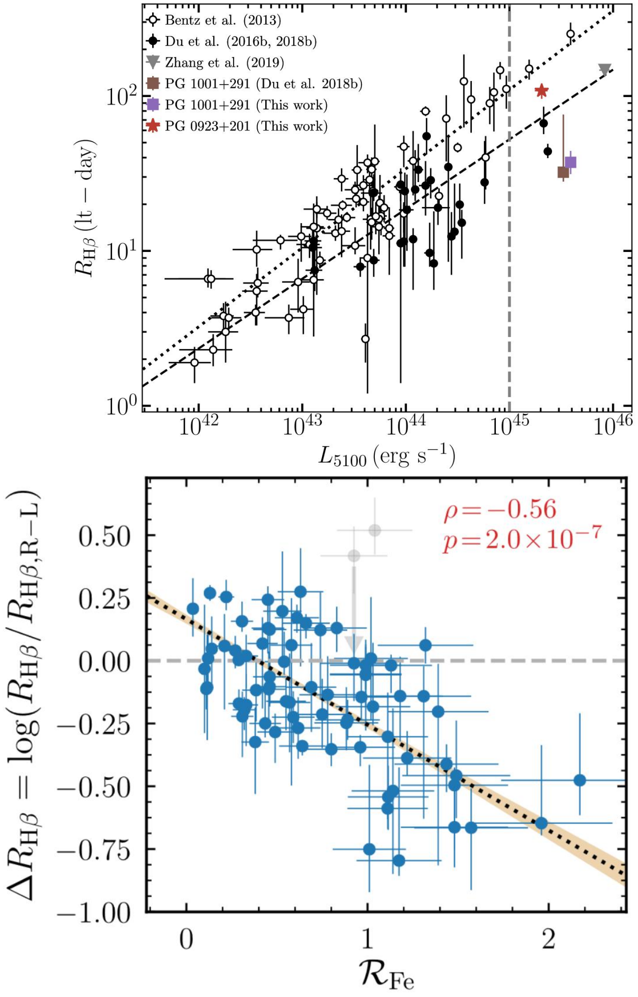
SDSS-RM in Hβ R-L relation

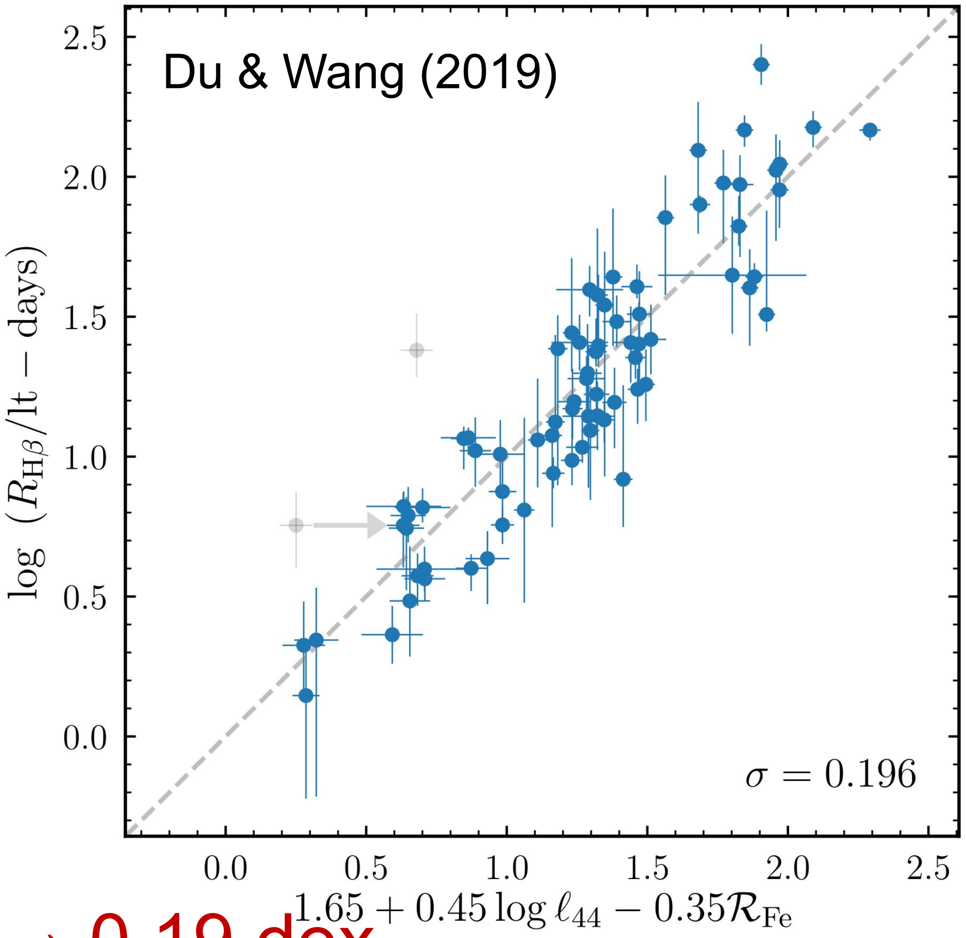


- Spearman's $\rho \sim -0.5$, $p \sim 10^{-11}$
- Monte Carlo simulations: R–L offsets are not due to observational bias

Fonseca Alvarez et al. (2020)

New scaling relation



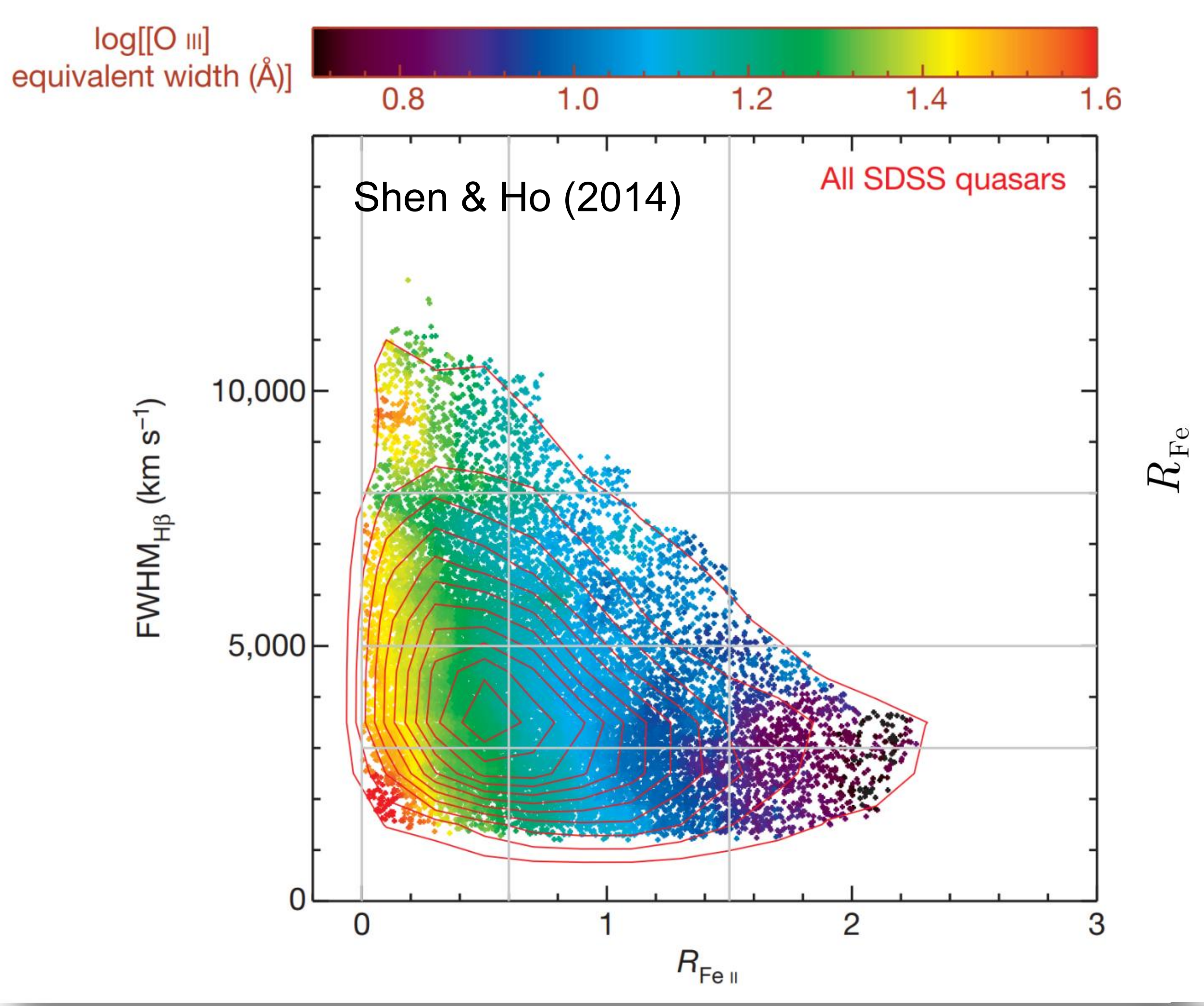


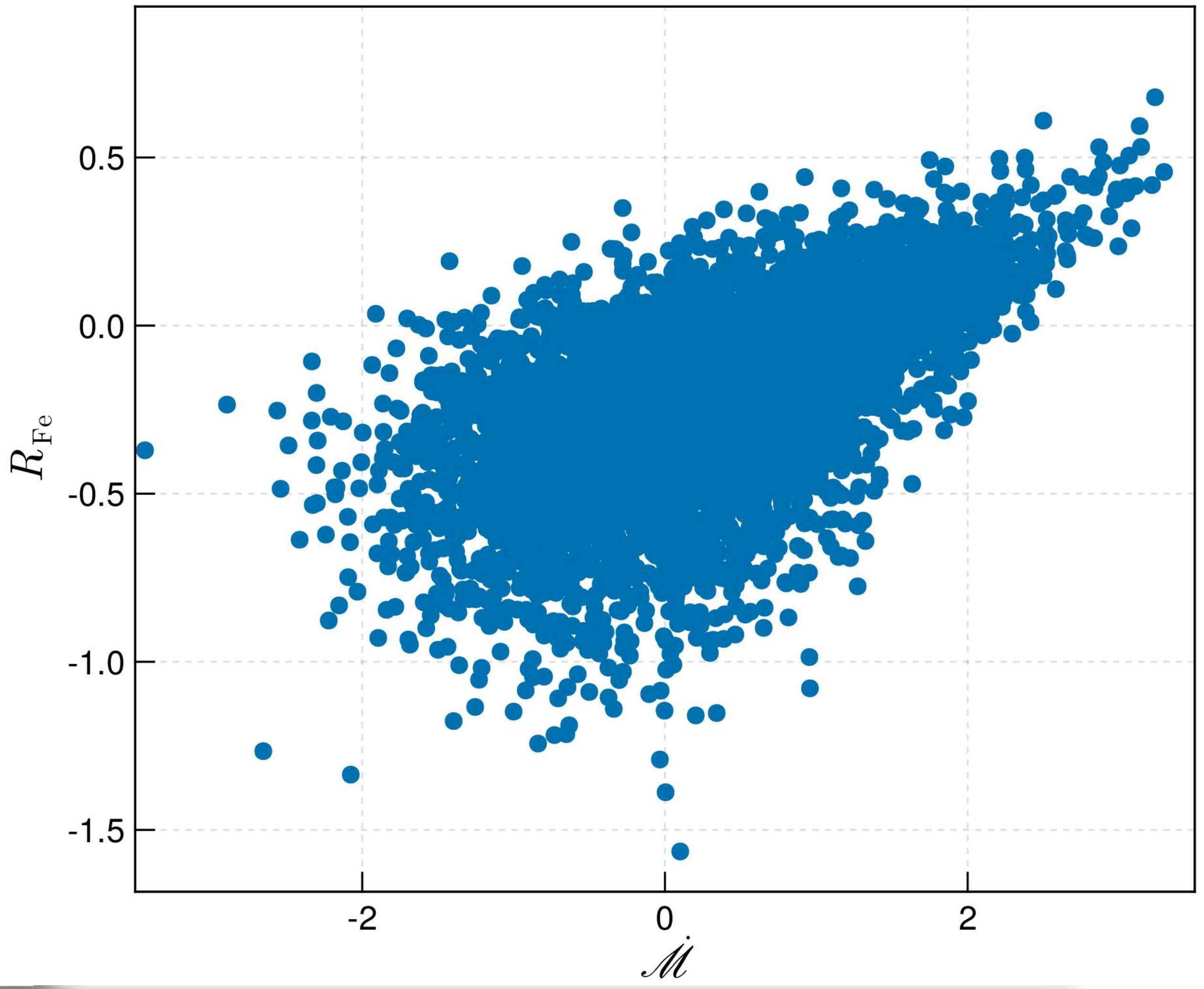
scatter: 0.3 dex → 0.19 dex

A new scaling relation

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

New scaling relation

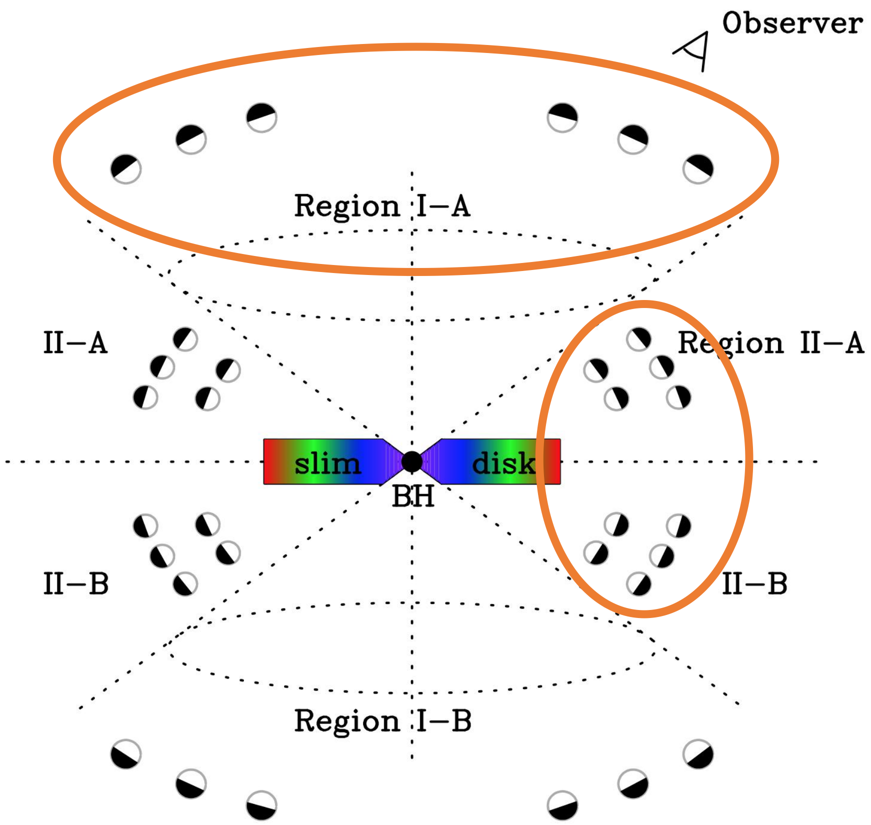




A new scaling relation

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

Possible explanations



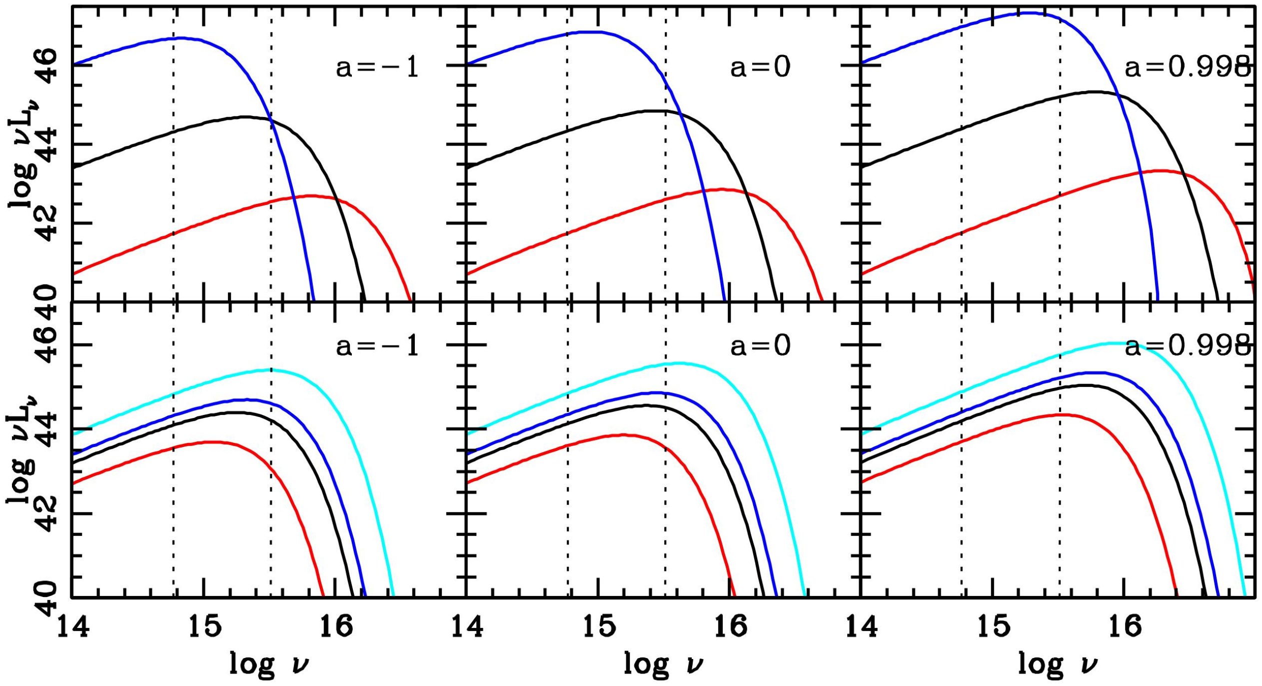
the self-shadowing effect (Wang et al. 2014):

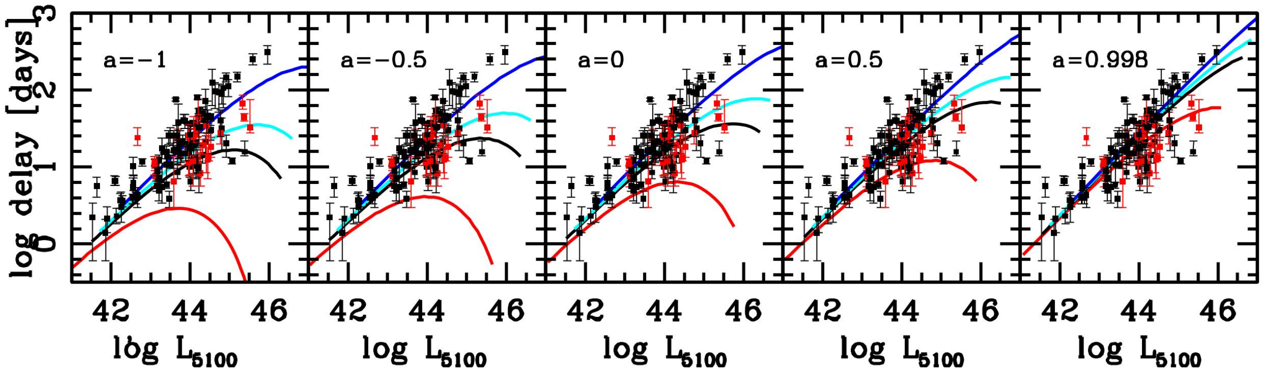
Clouds (Region II) are closer to BH

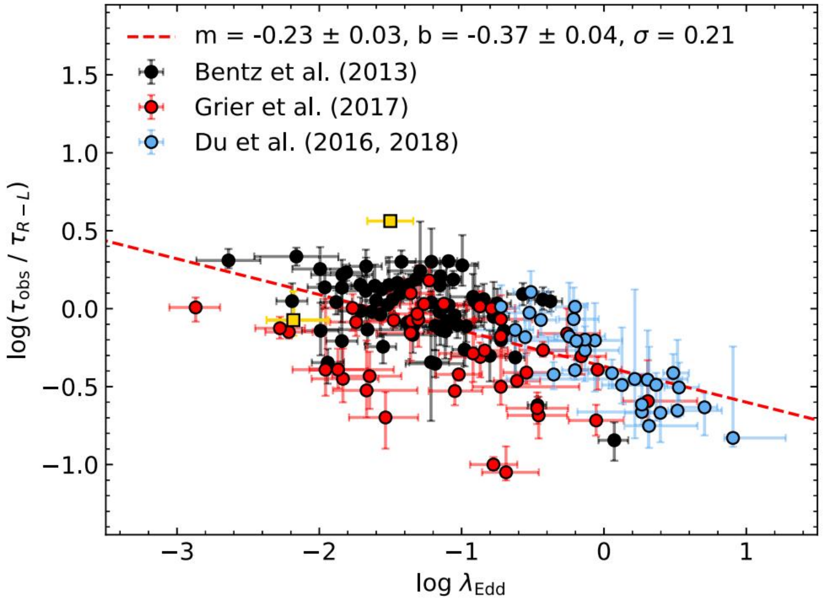
$$\frac{R_{\rm BLR,I}}{R_{\rm BLR,II}} = \left(\frac{L_{\rm ion,I}}{L_{\rm ion,II}}\right)^{1/2} = \left(\frac{F_{\rm ion,I}}{F_{\rm ion,II}}\right)^{1/2},$$

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

Possible explanations





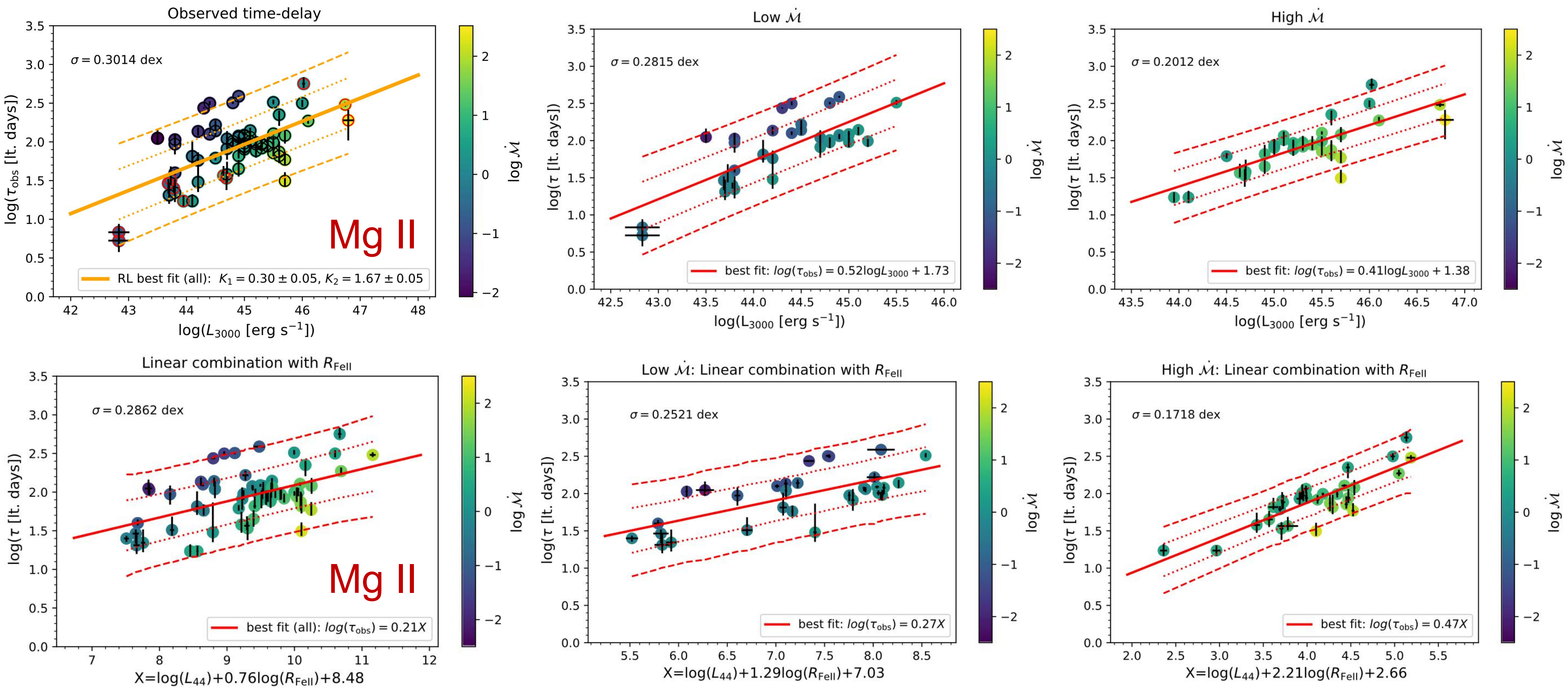


Retrograde accretion in low-accretion-rate AGNs (a = -1):

Shortened time lags

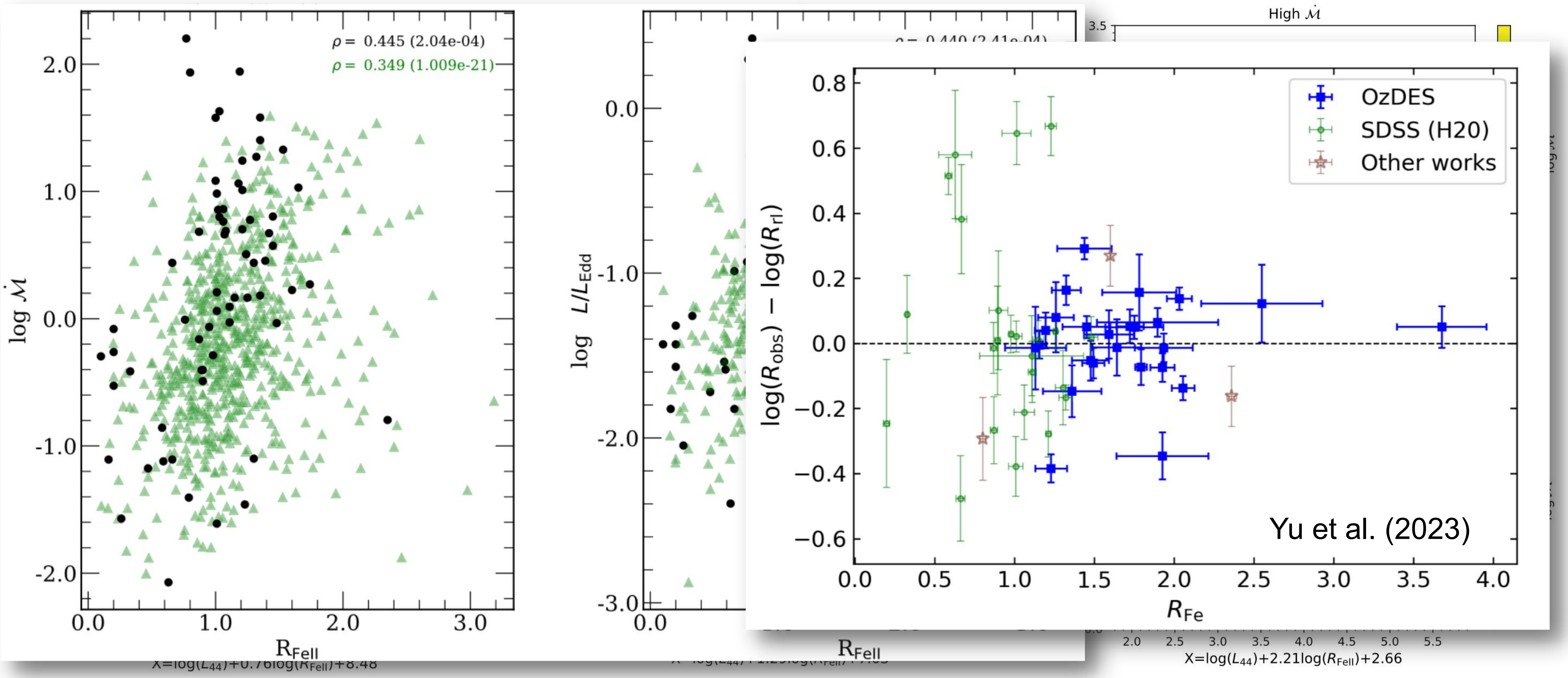
(Wang et al. 2014, Czerny et al. 2019)

Super-Eddington AGNs & Shortened time lags in MgII?



Martinez-Aldama et al. (2020)

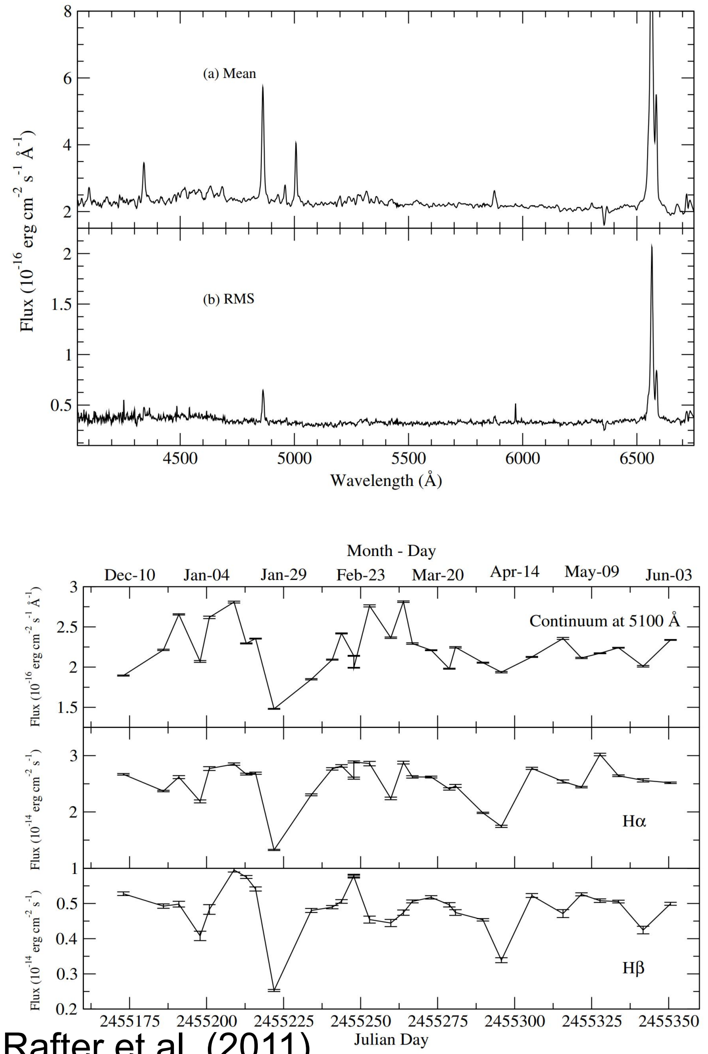
Super-Eddington AGNs & Shortened time lags in MgII?



Martinez-Aldama et al. (2020)

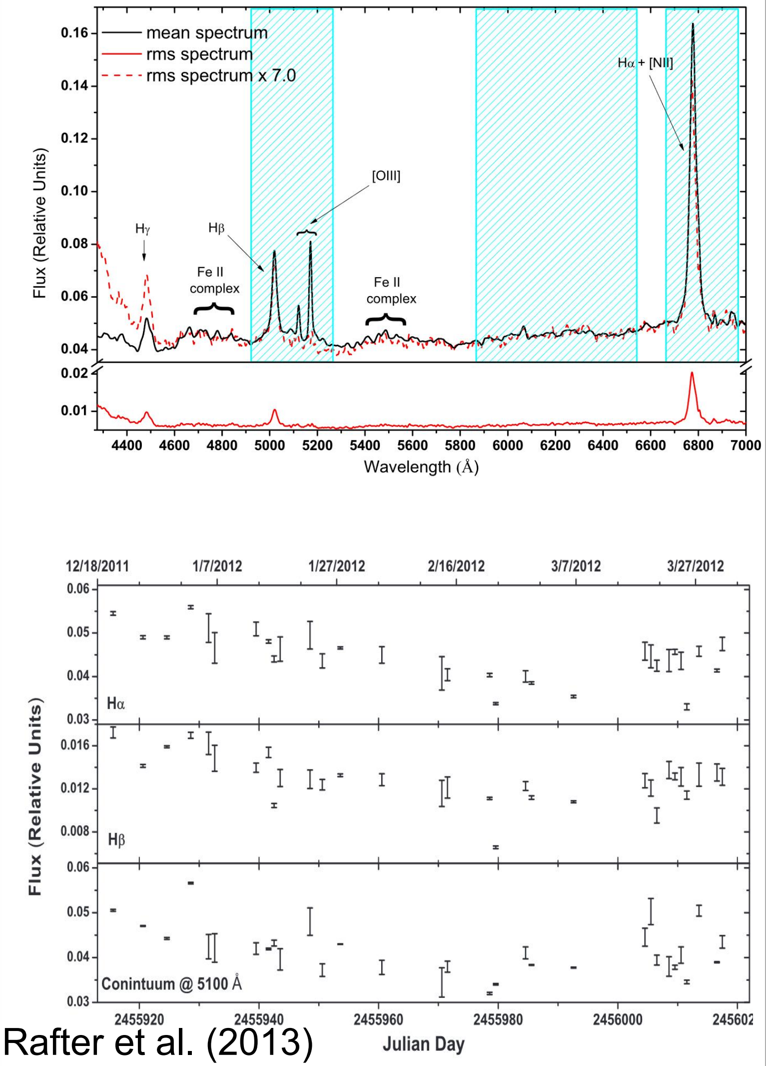
RM of intermediate-mass AGNs

SDSSJ114008 $M_{\rm BH} \leq 5.8 \times 10^5 M_\odot$



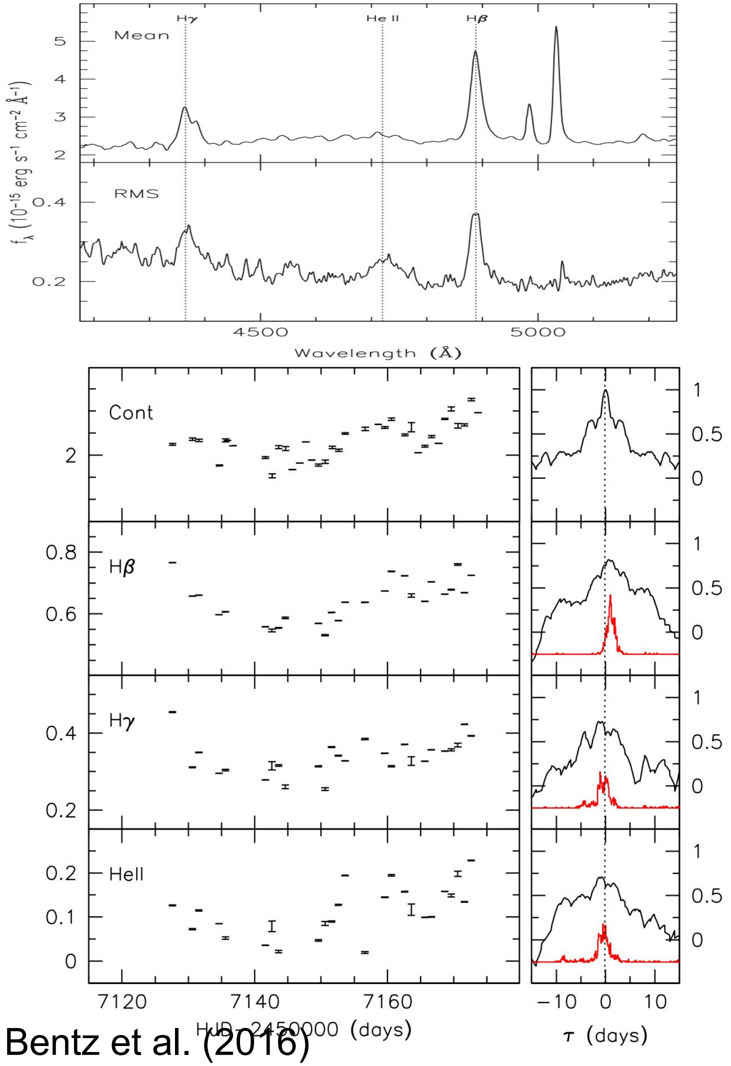
Rafter et al. (2011)

SDSSJ113913 $M_{\rm BH} \approx 3.8 \times 10^6 M_\odot$



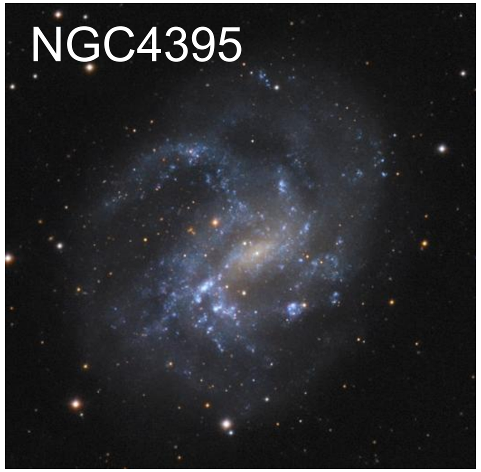
Rafter et al. (2013)

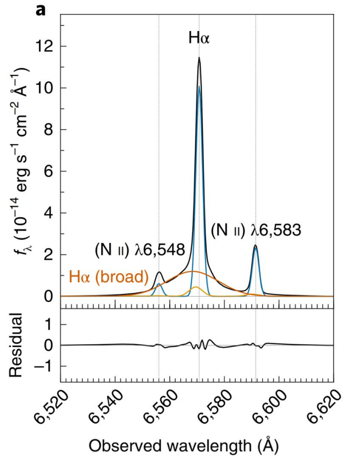
UGC06728 $M_{\rm BH} \approx 7.1 \times 10^5 M_\odot$

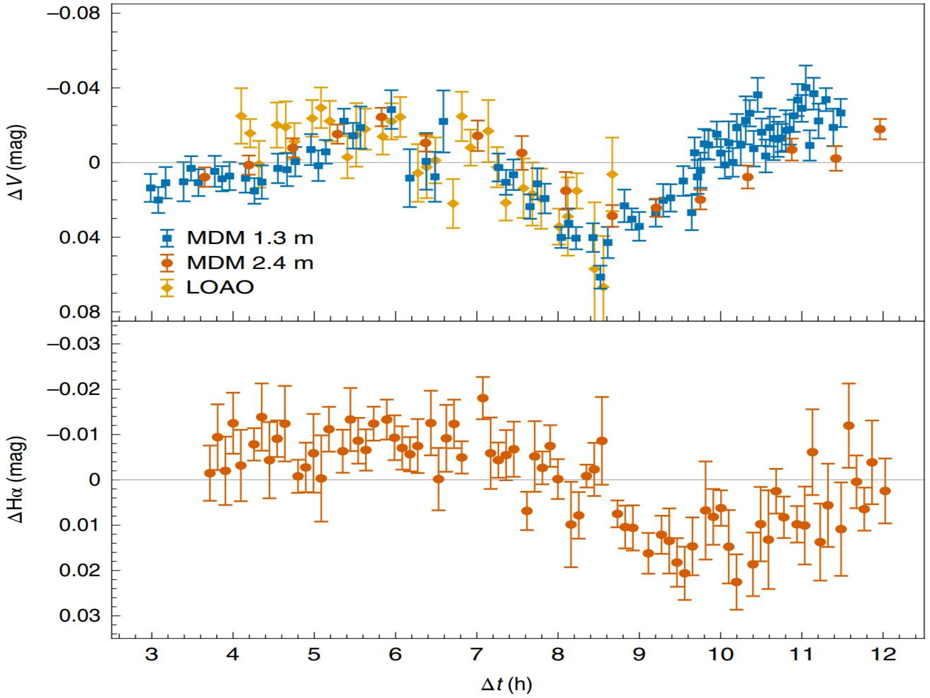


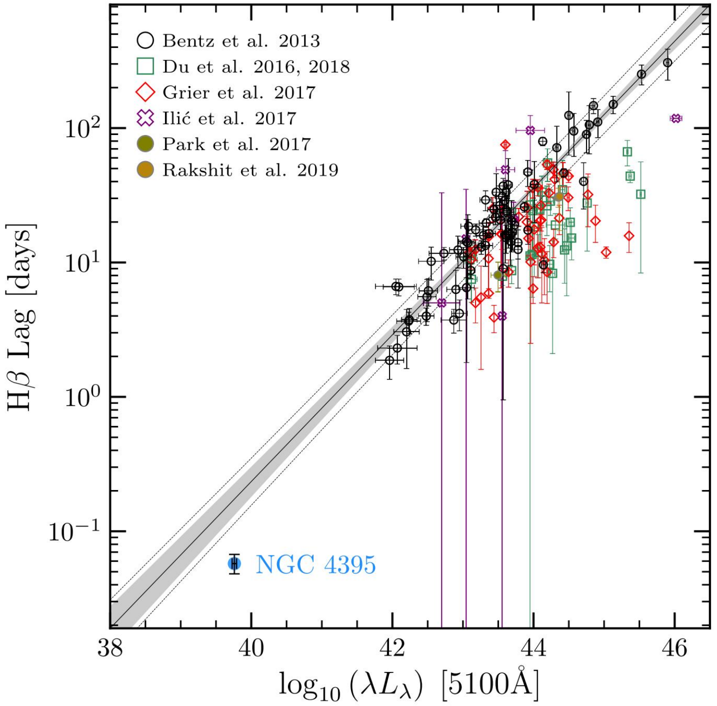
Bentz et al. (2016)

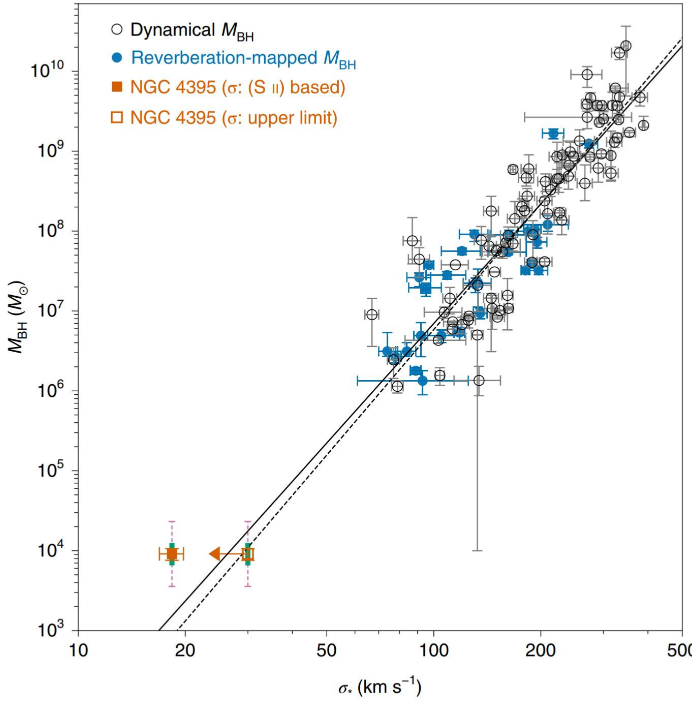
RM of intermediate-mass AGNs











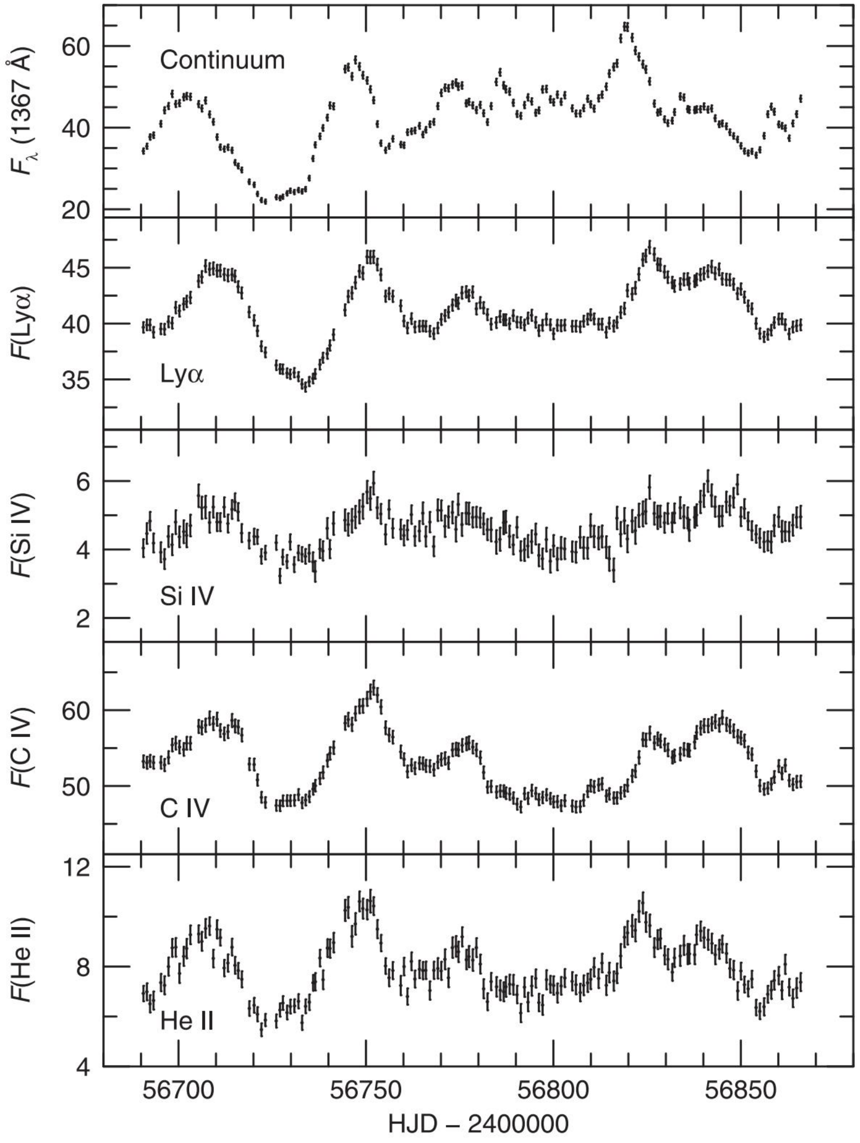
NGC 4395:

$$\tau_{H\alpha} = 83 \pm 14 \text{ min}$$
$$\sigma_{H\alpha} = 426 \pm 1 \text{ km s}^{-1}$$
$$M_{BH} = 9100 M_{\odot} \ (f_{\rm vir} = 4.5)$$
$$M_{BH} = 6500 M_{\odot} \ (f_{\rm vir} = 3.2)$$

Woo et al. (2019), Cho et al. (2020)

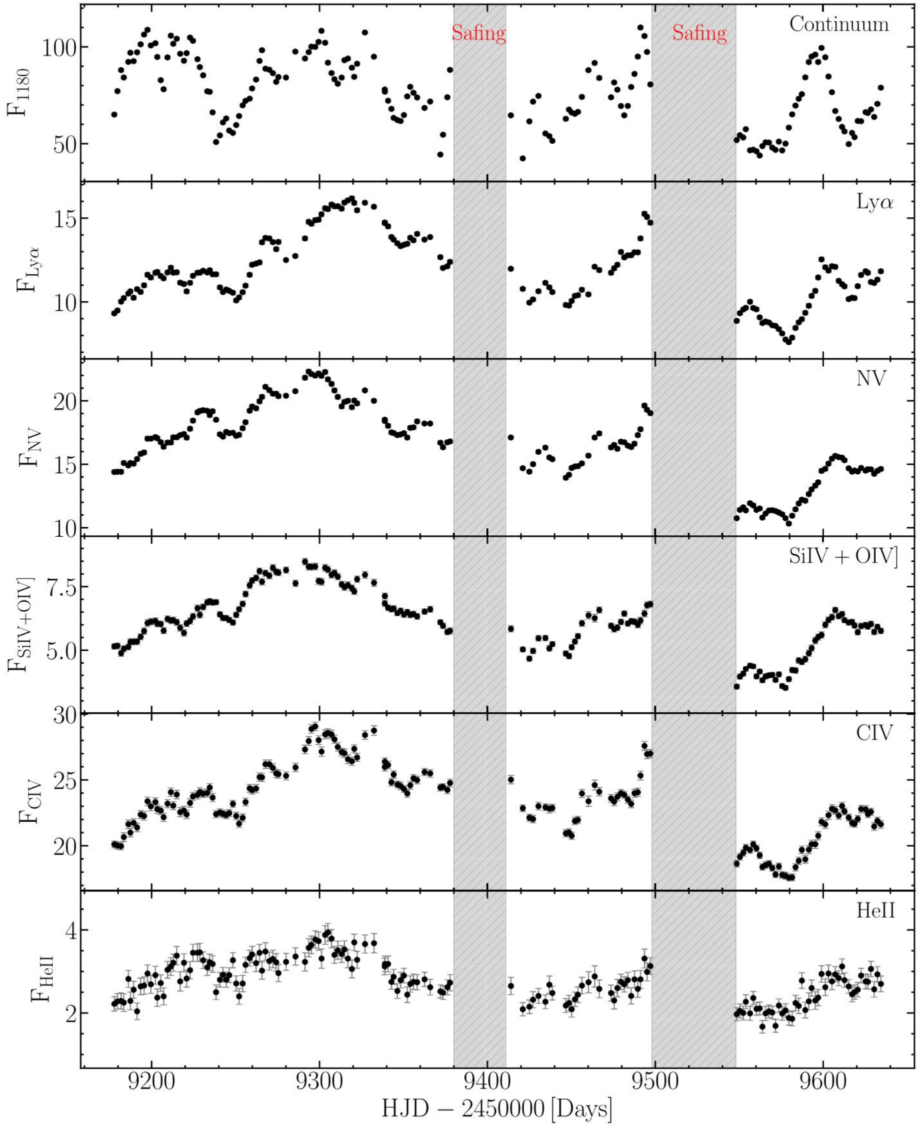
UV lines in high-redshift, high-luminosity quasars

NGC5548 in AGN STORM I



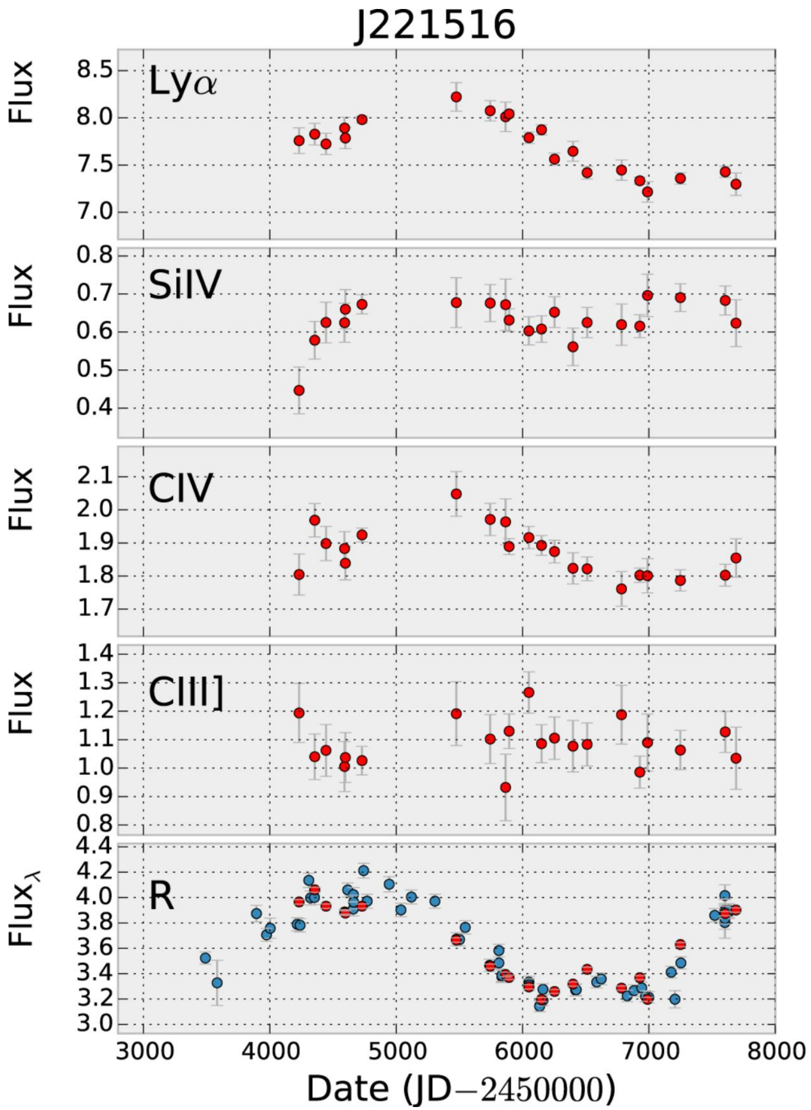
De Rosa et al. (2015)

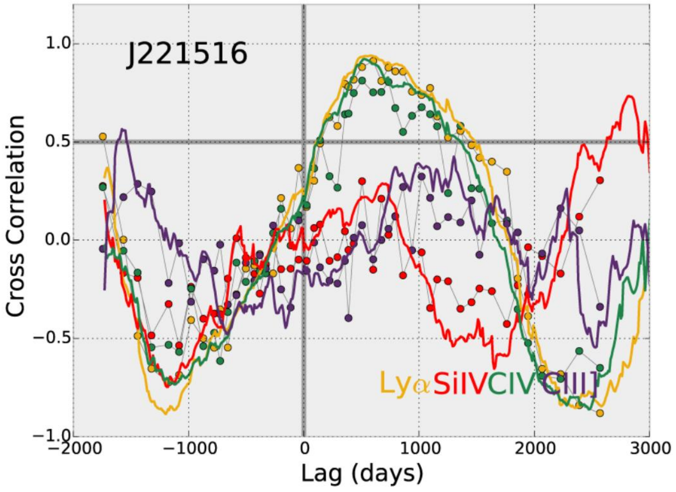
Mrk817 in AGN STORM II

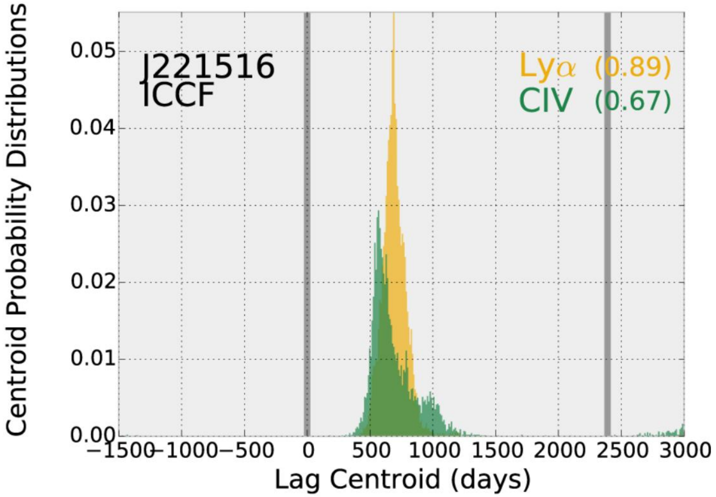


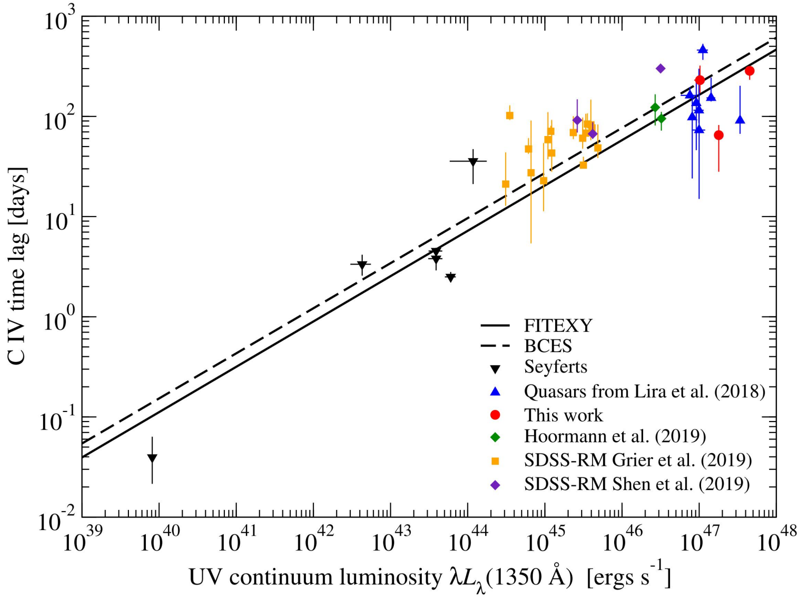
Homayouni et al. (2023)

UV lines in high-redshift, high-luminosity quasars









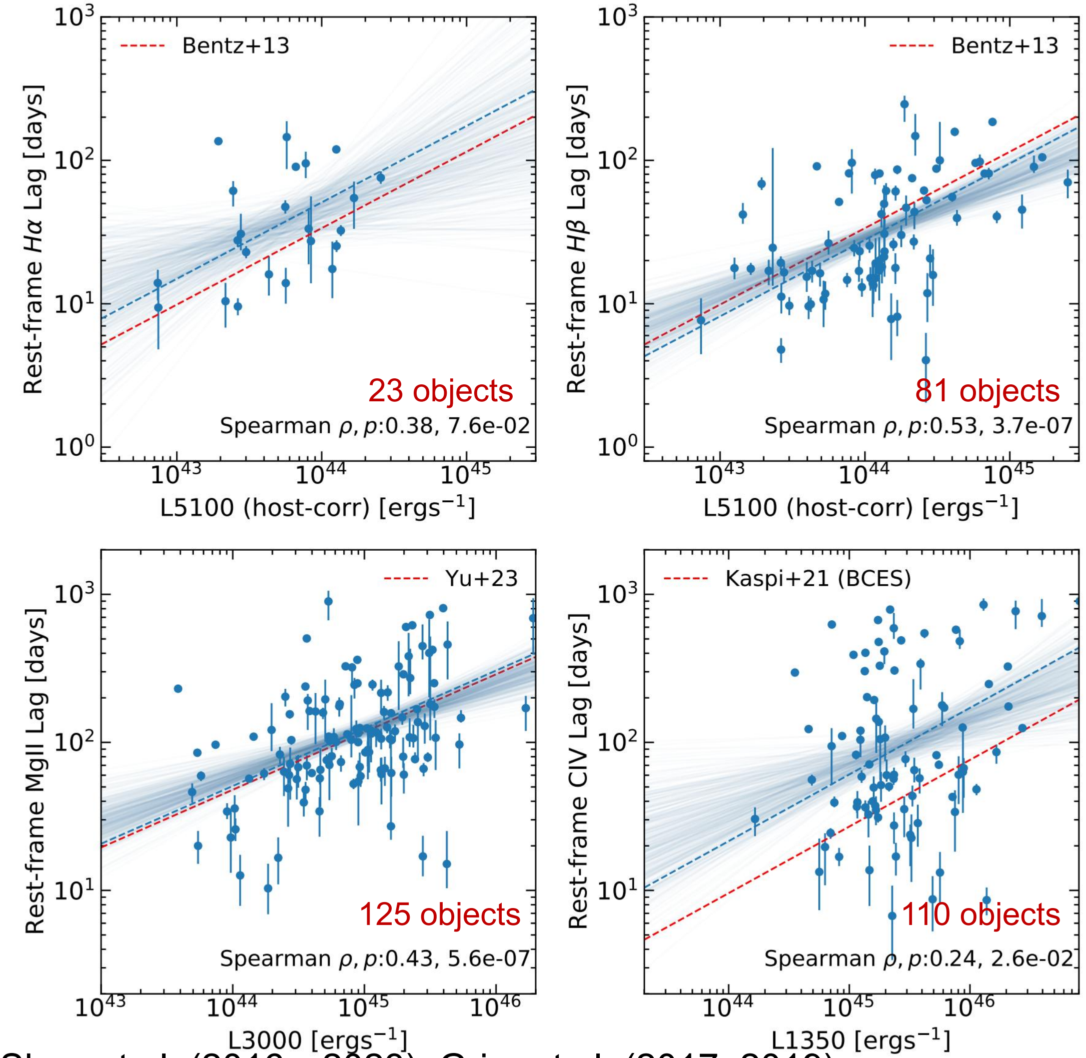
Quasars with $z \approx 2 \sim 3$

e.g., Lira et al. (2018), Hoormann et al. (2019), Grier et al. (2019), Kaspi et al. (2021)

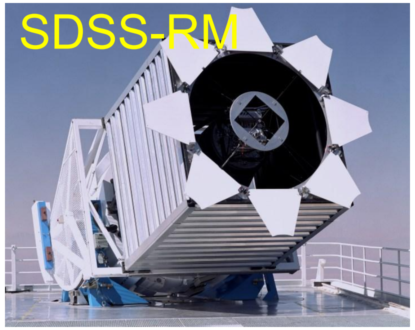
Larger samples

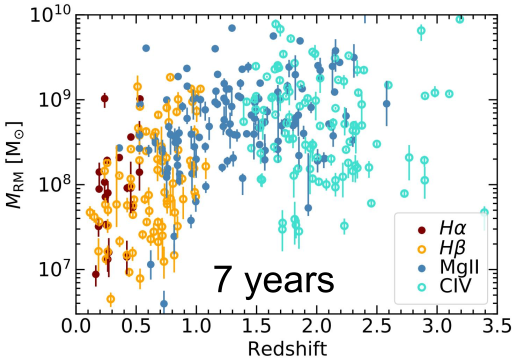
'Industrial'-scale RM based on multi-object & fiber-fed spectrographs

R-L relations from SDSS-RM

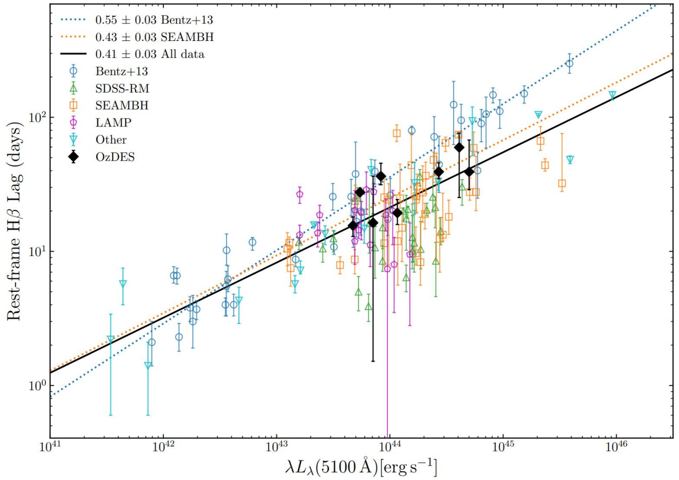


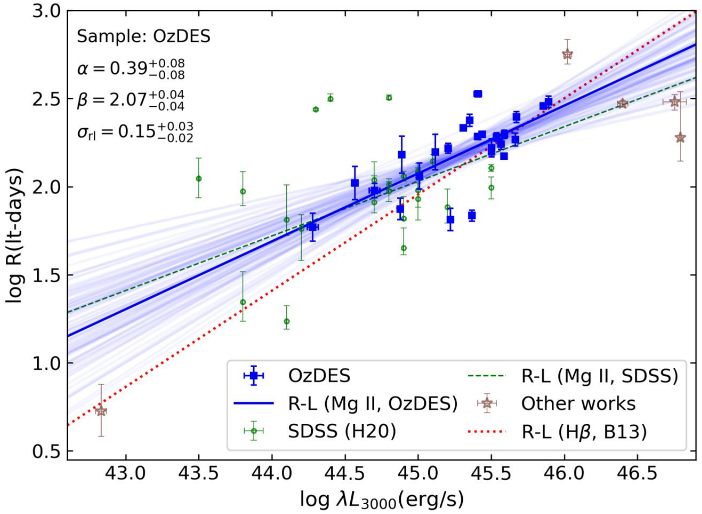
Shen et al. (2016, 2023), Grier et al. (2017, 2019), Homayouni et al. (2020)





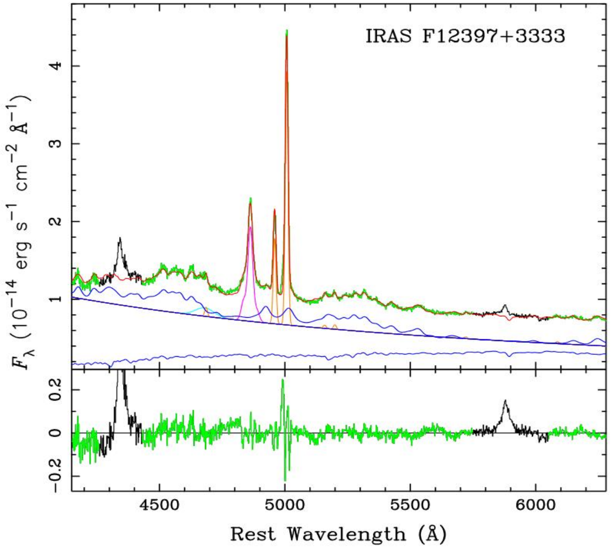
R-L relations from OzDES RM

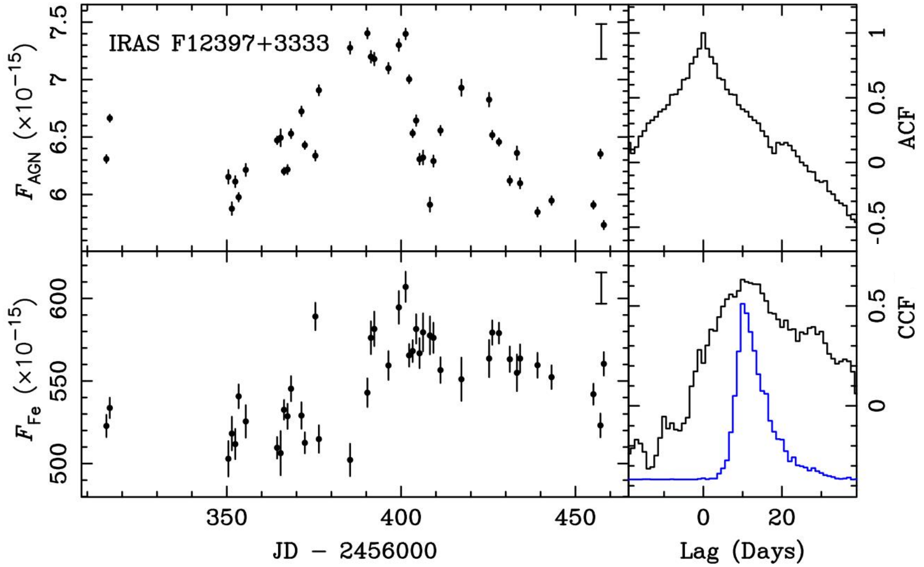


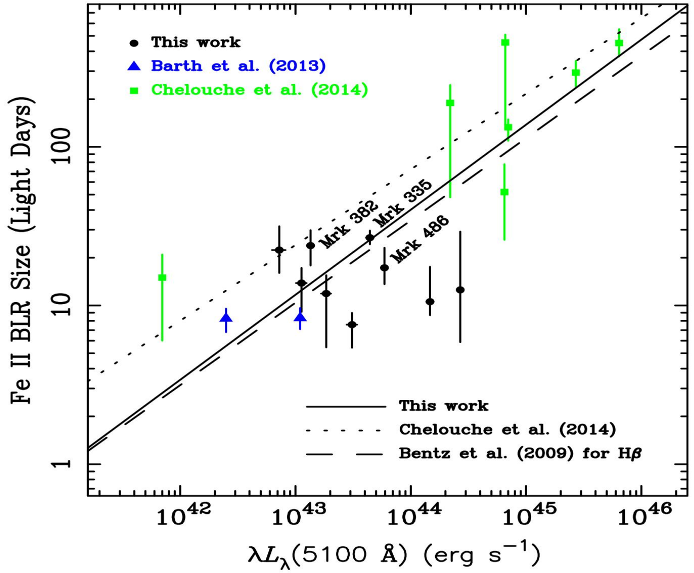


Malik et al. (2023), Yu et al. (2023)

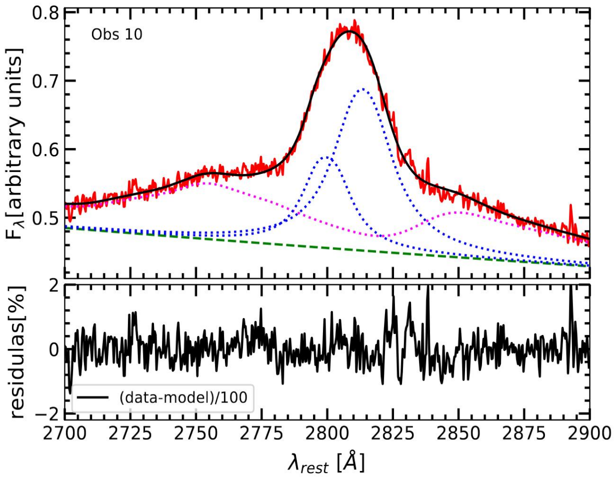
UV/optical Fe II emissions

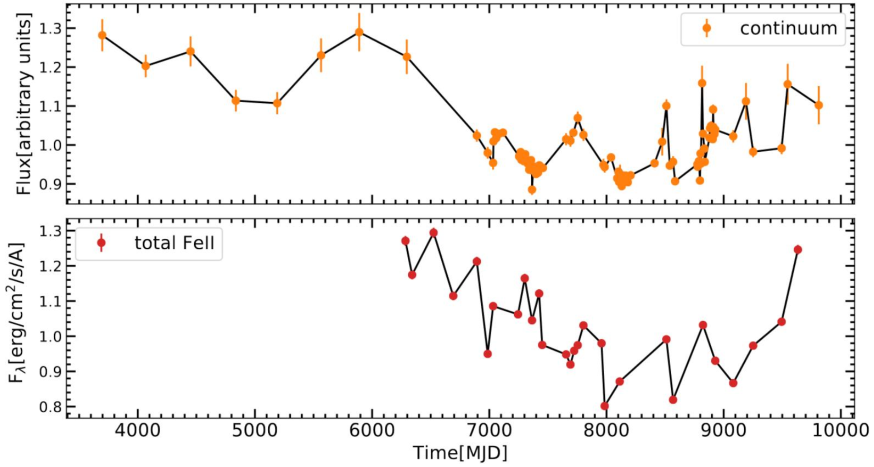


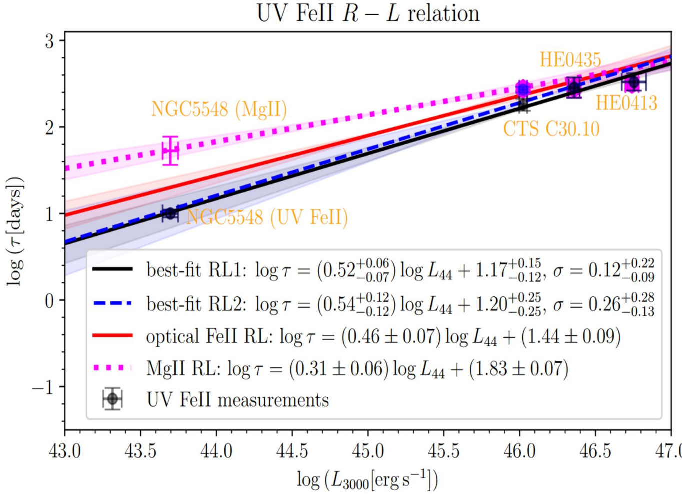




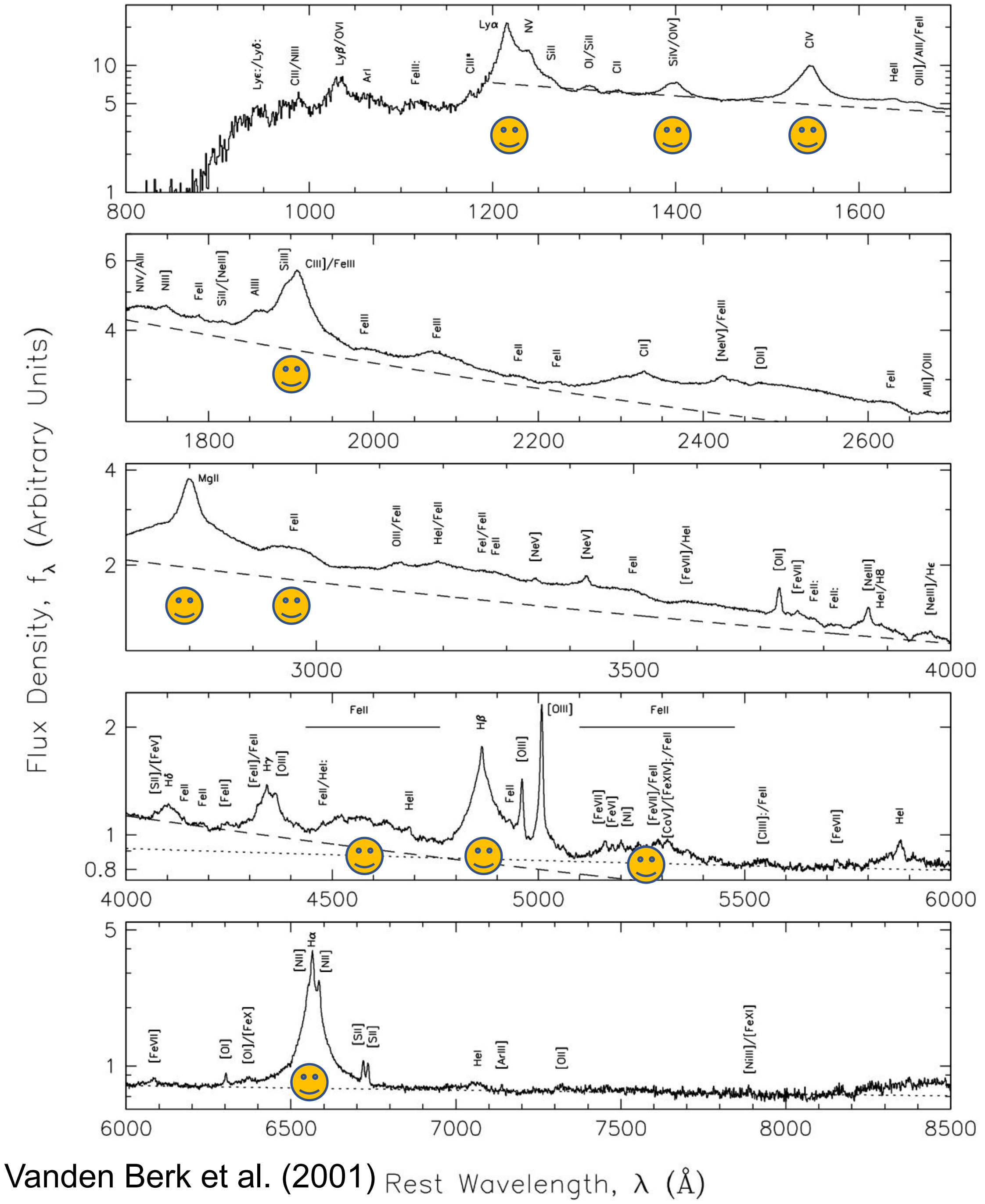
Barth et al. (2013), Chelouche et al. (2014), Hu et al. (2015)



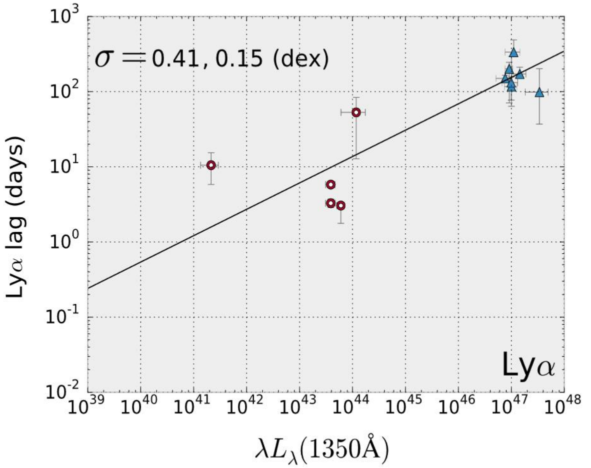


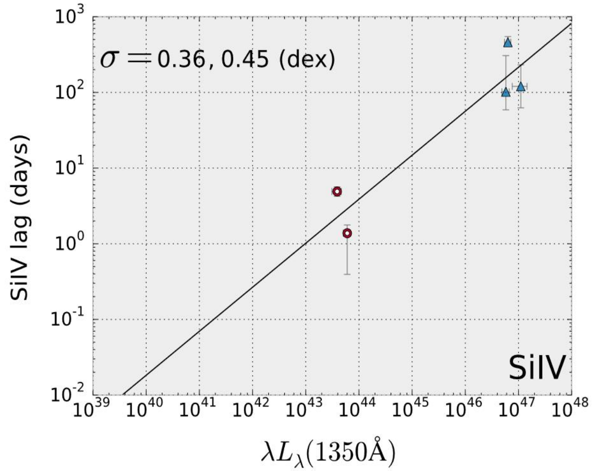


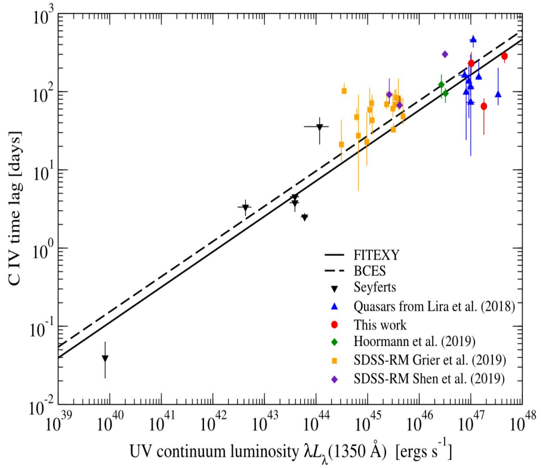
Prince et al. (2023)

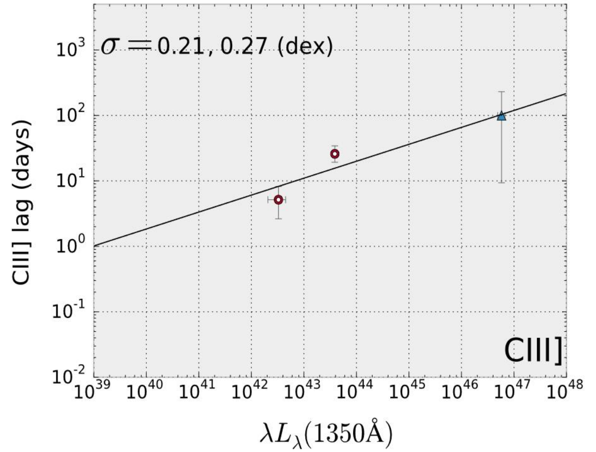


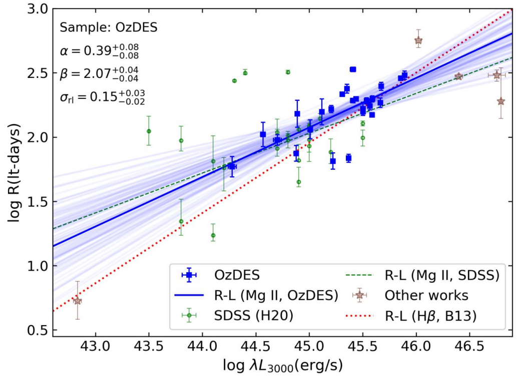
Vanden Berk et al. (2001)

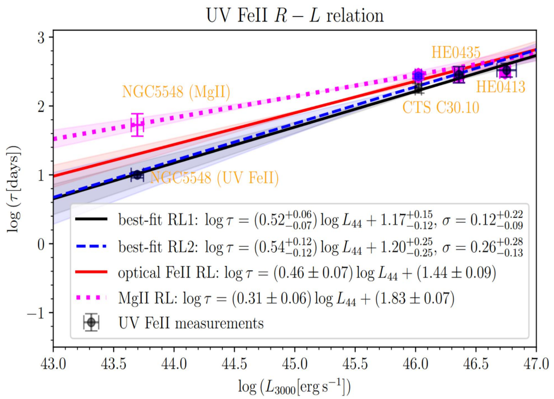


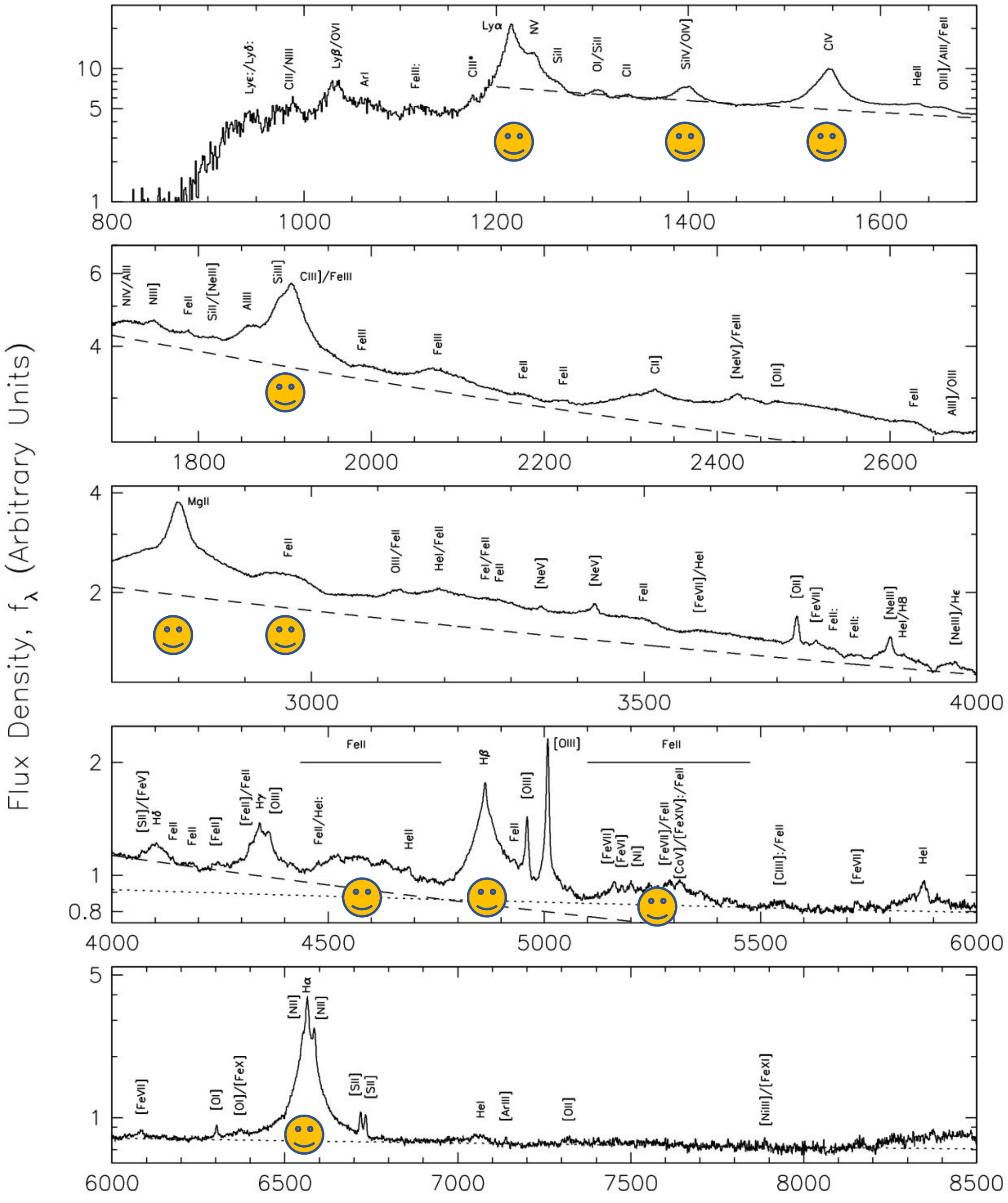




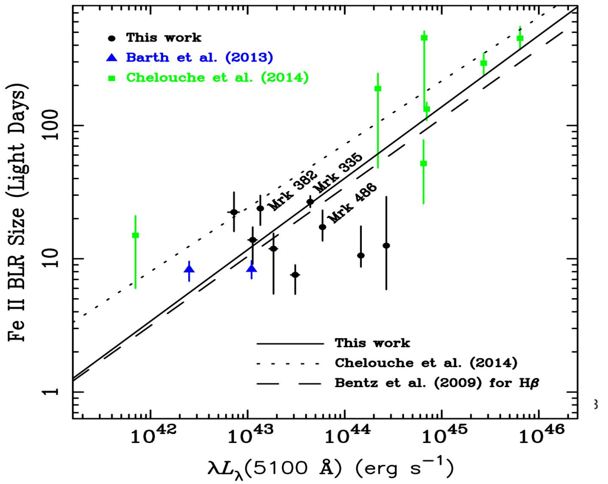


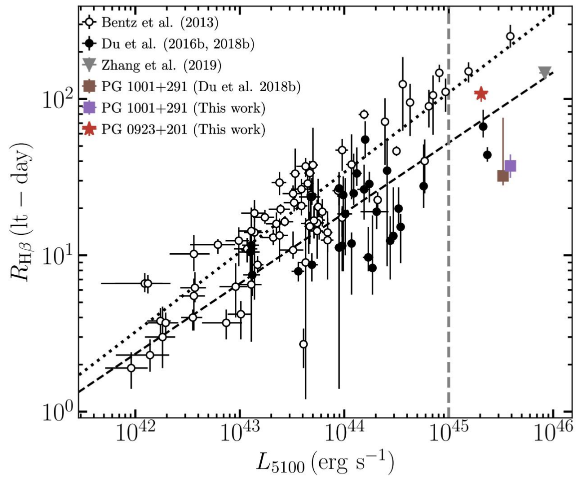


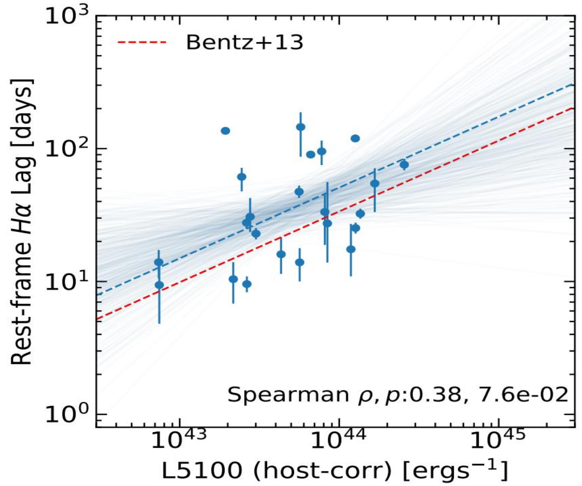


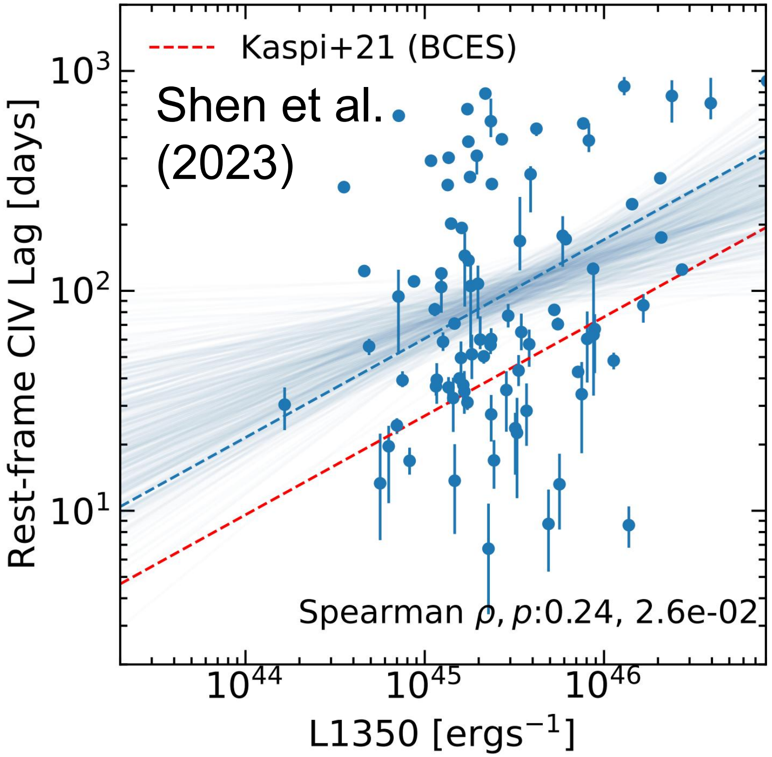


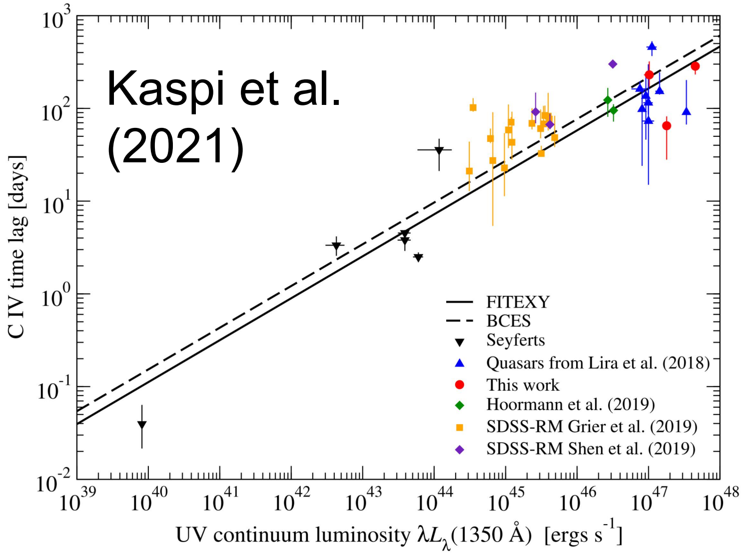
Vanden Berk et al. (2001)

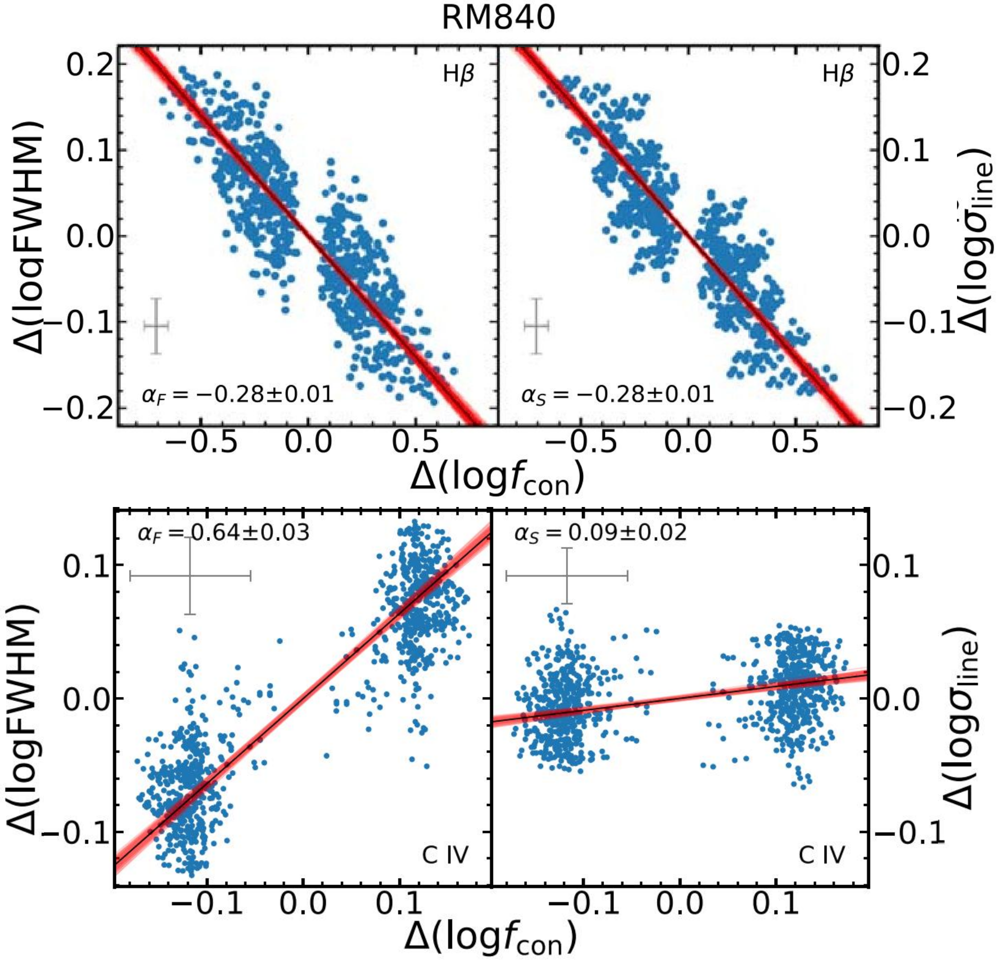






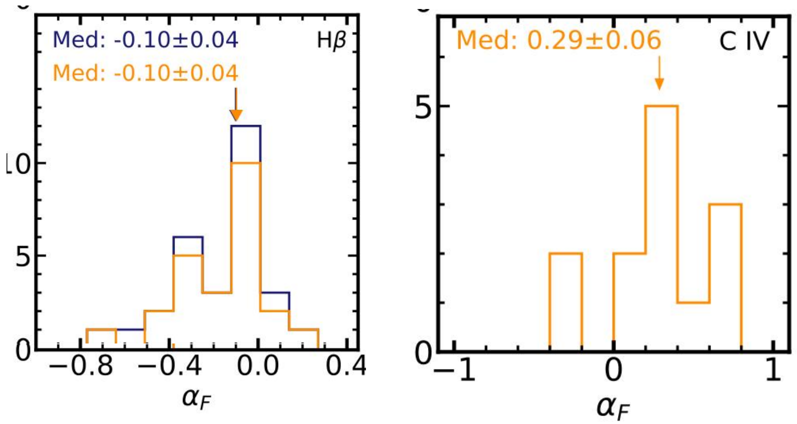




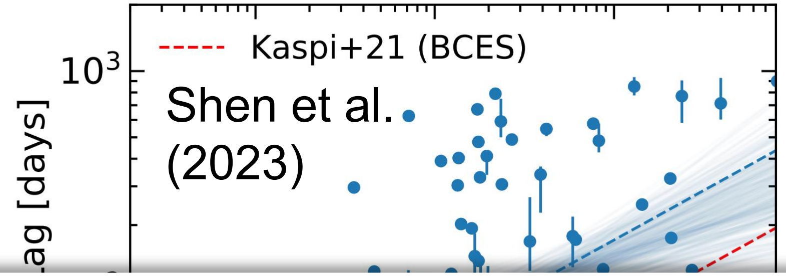


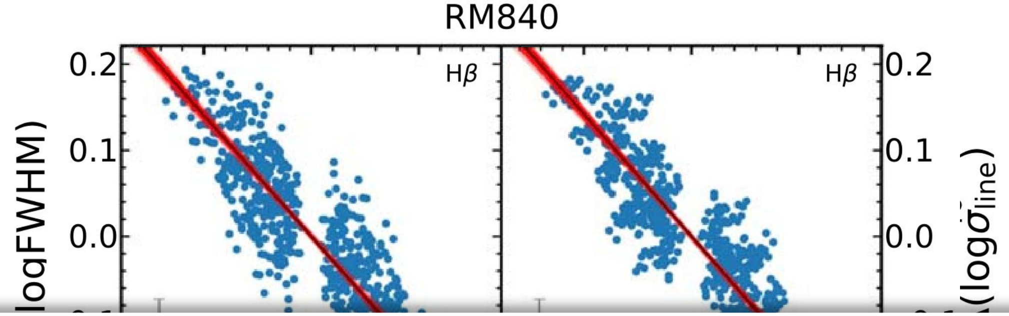
Normal breathing

Anti-breathing

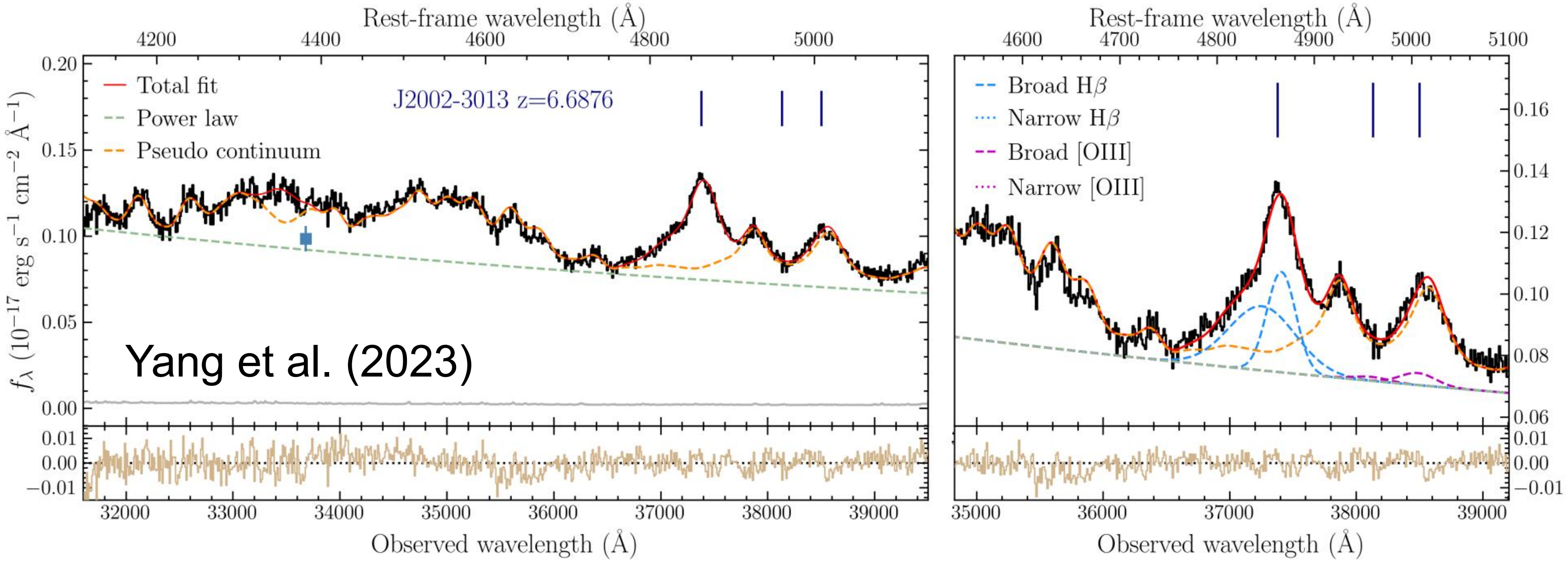


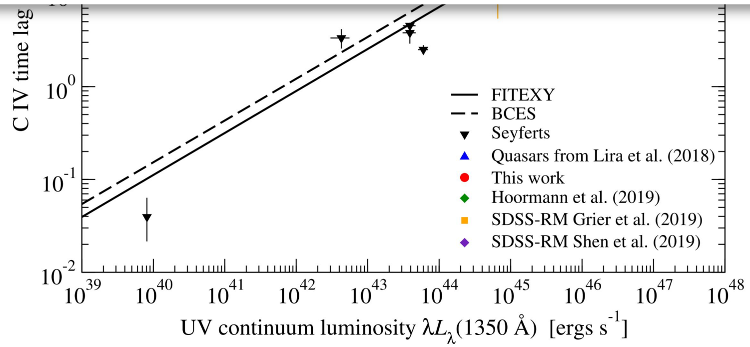
Wang et al. (2020)

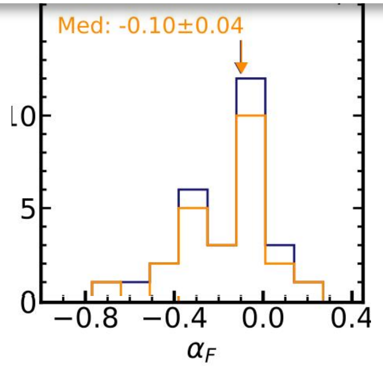


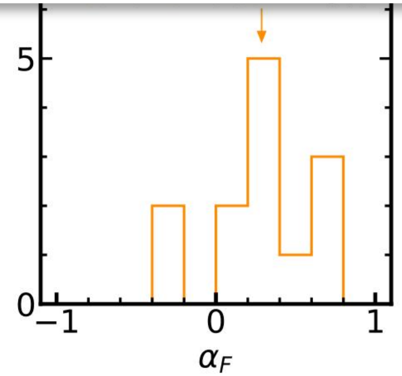


Normal breathing

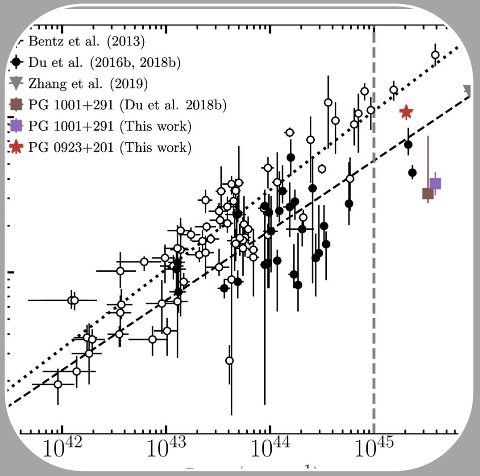




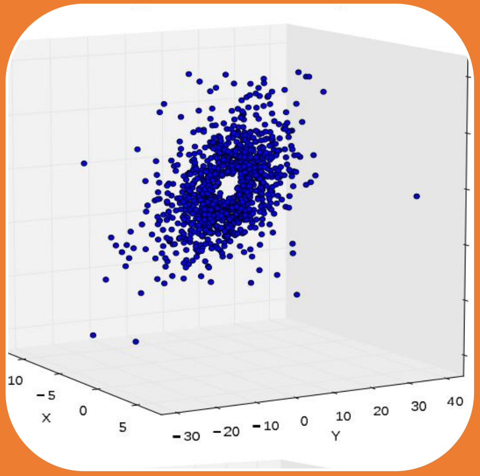




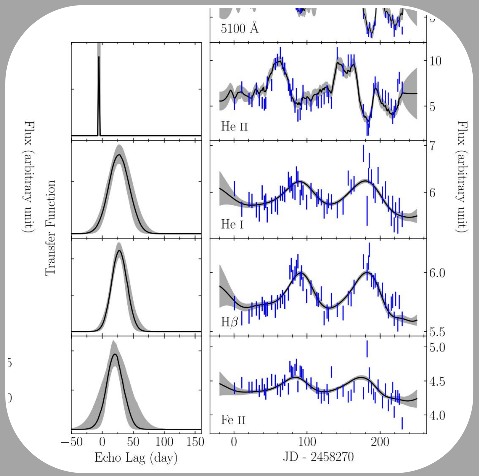
Wang et al.
(2020)



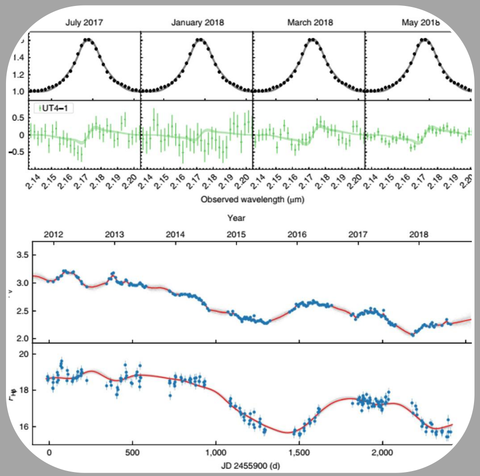
R-L relations



Velocity-resolved RM & BLR kinematics



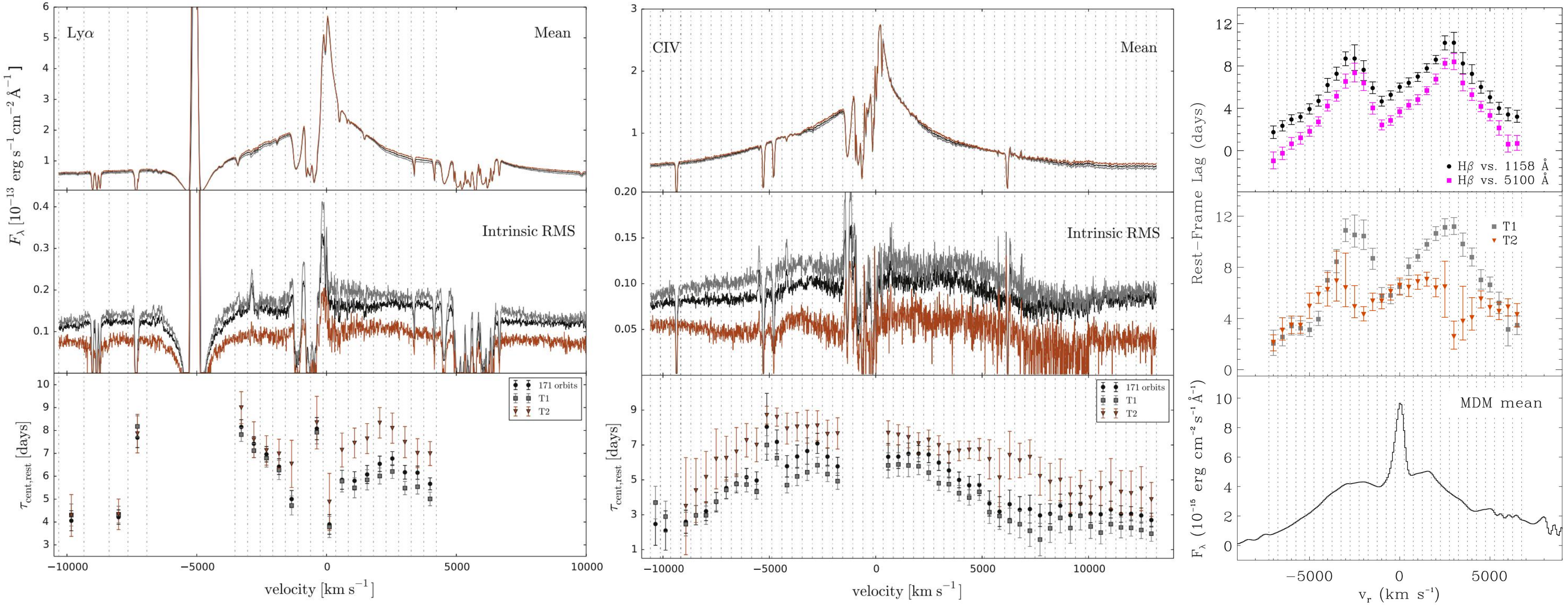
New phenomena



New applications

Velocity-resolved RM & BLR kinematics
NGC5548: A prototype

AGN STORM Project

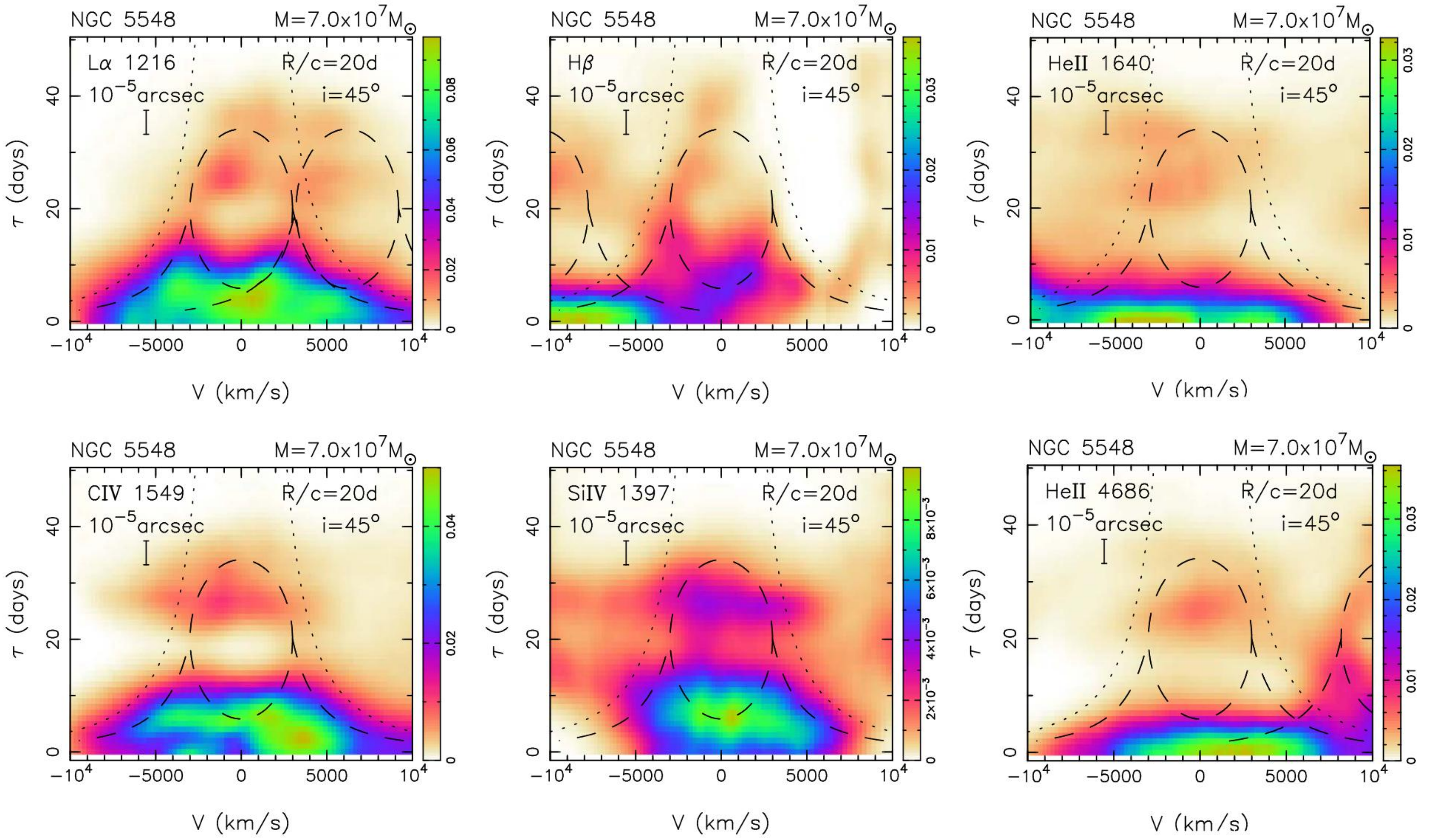


De Rosa et al. (2015)

Pei et al. (2017)

Velocity-resolved RM & BLR kinematics

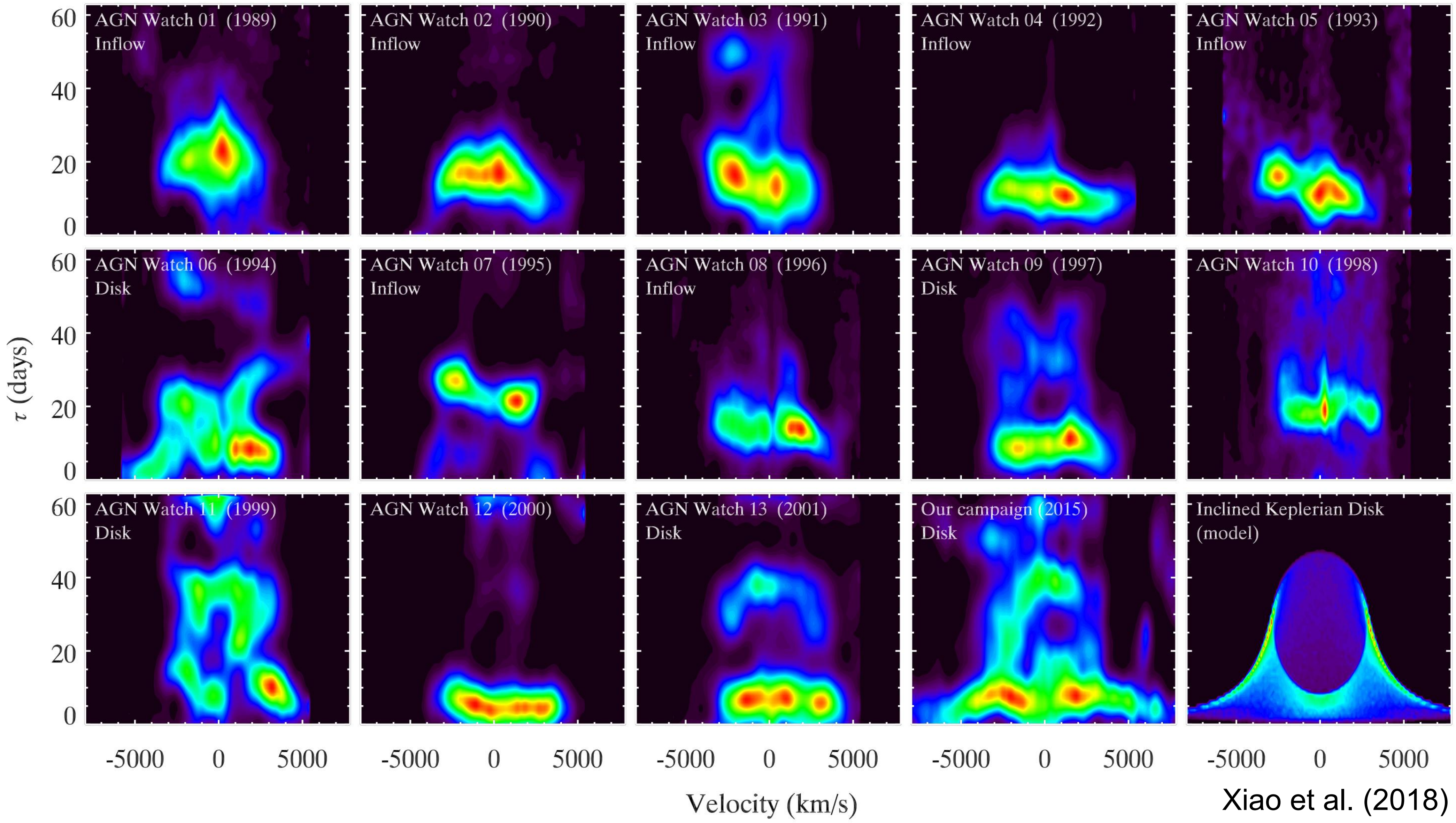
NGC5548: A prototype



Horne et al. (2021)

Velocity-resolved RM & BLR kinematics

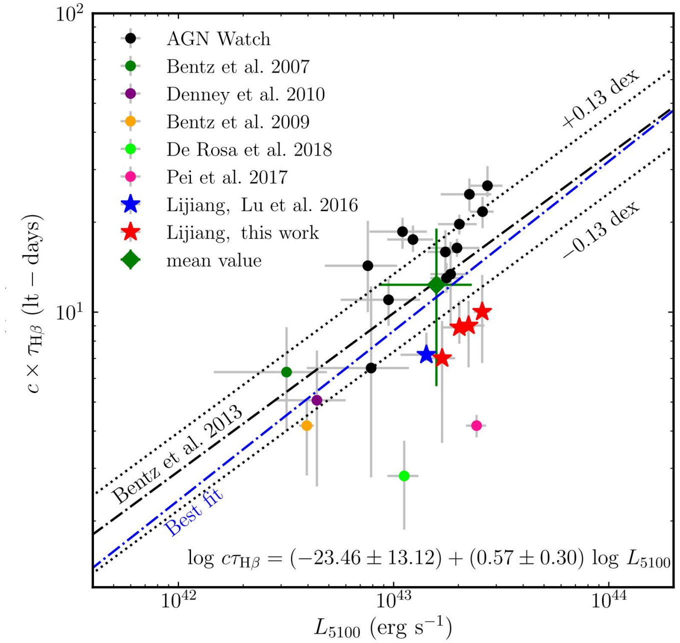
NGC5548: A prototype

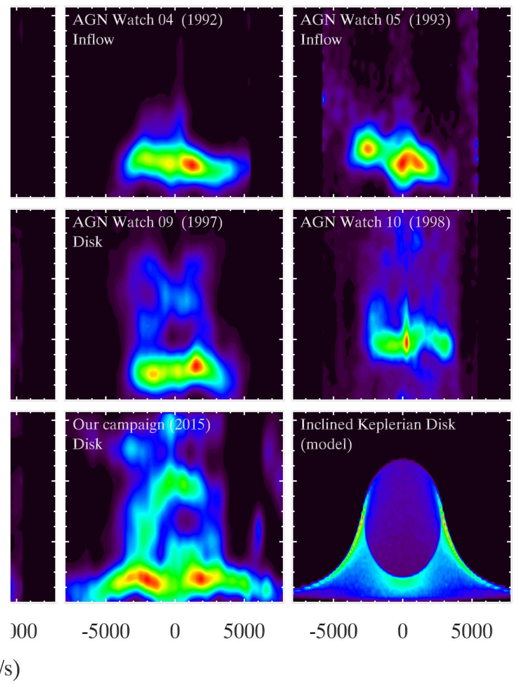


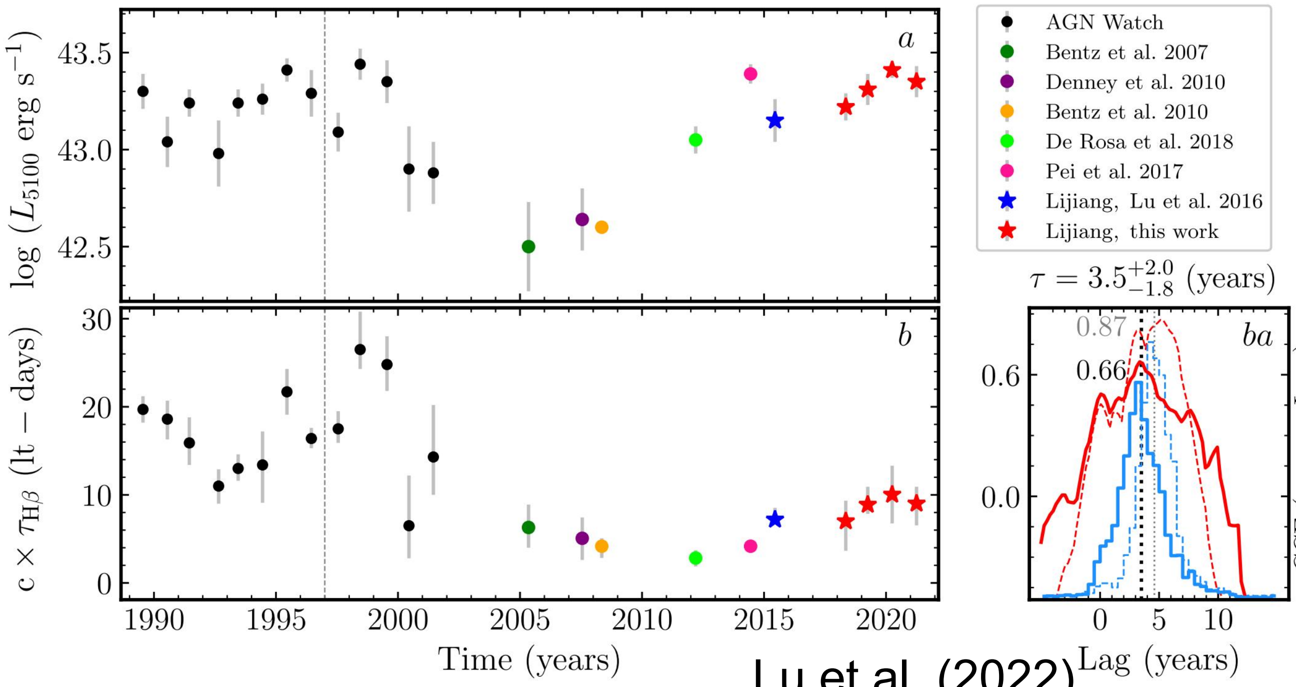
Xiao et al. (2018)

Velocity-resolved RM & BLR kinematics

NGC5548: A prototype







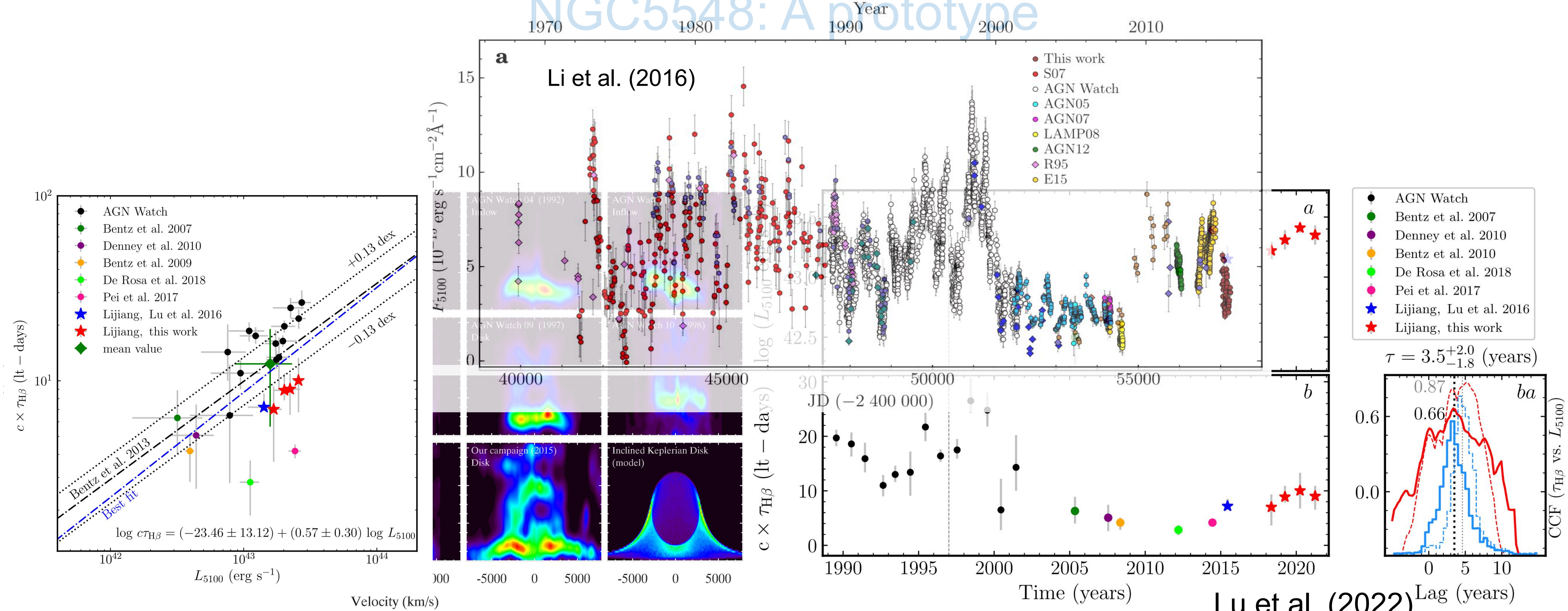
Lu et al. (2022)

Dynamical time scale

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

Velocity-resolved RM & BLR kinematics

NGC5548: A prototype



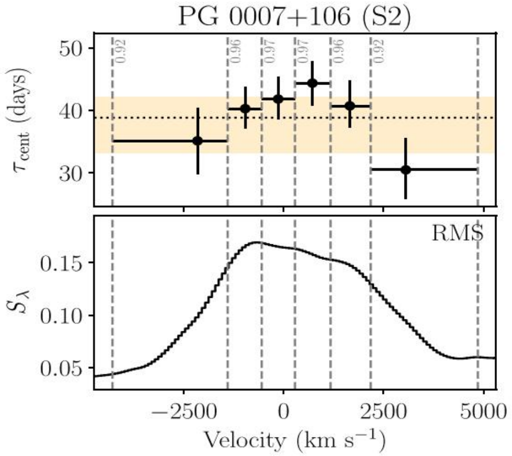
Lu et al. (2022)

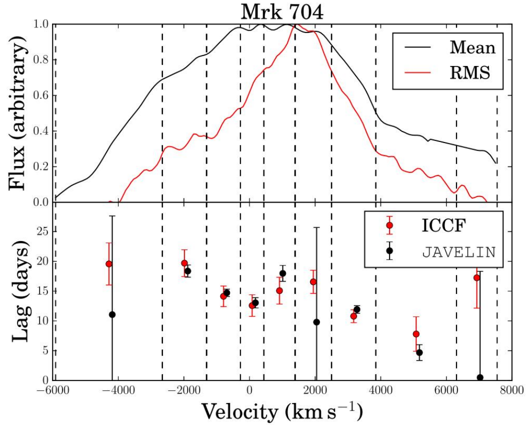
Dynamical time scale

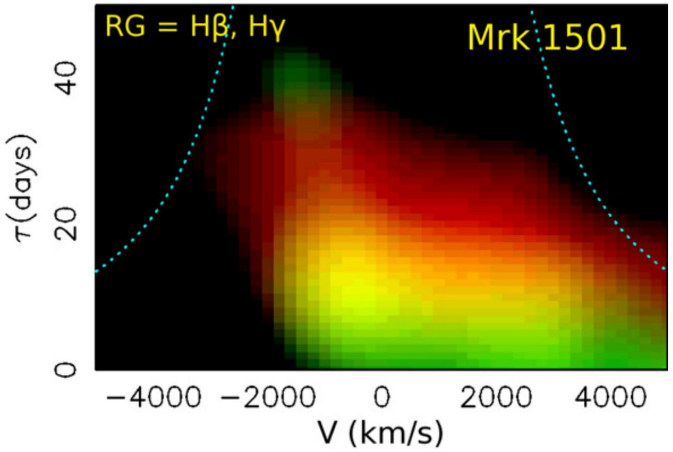
$$t_{\rm BLR} = \frac{c\tau_{\rm H\beta}}{V_{\rm FWHM}} = 3.36\,\tau_{20}\,V_{5000}^{-1}\ \text{years}$$

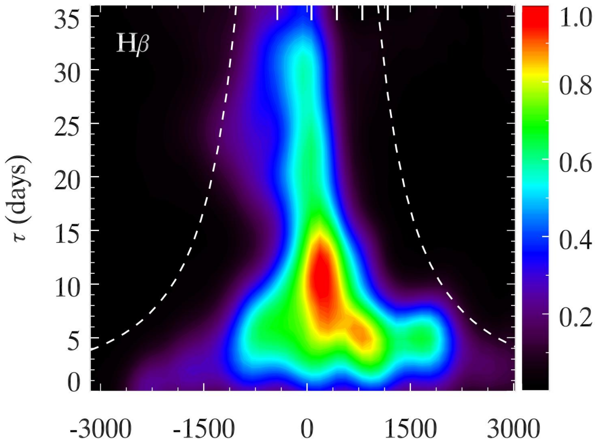
Velocity-resolved RM & BLR kinematics

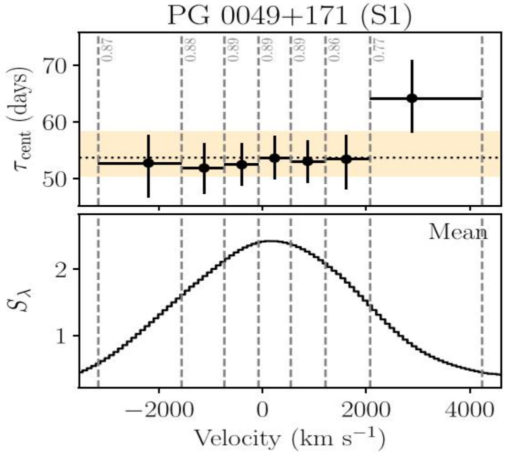
Velocity-resolved Lags & Velocity-delay Maps

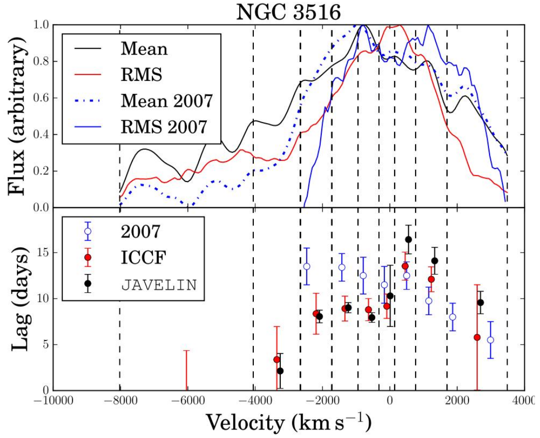


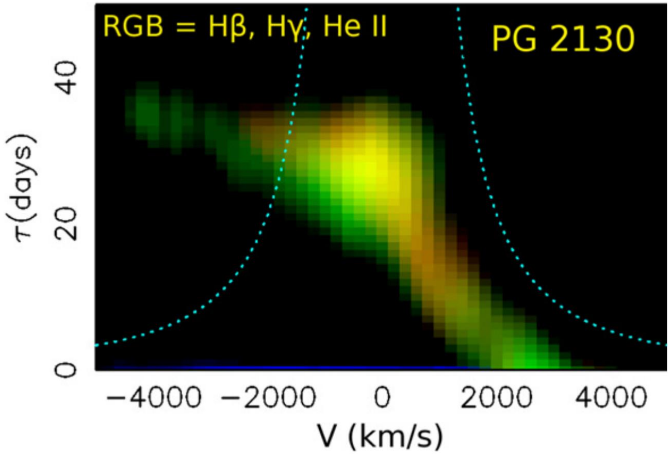


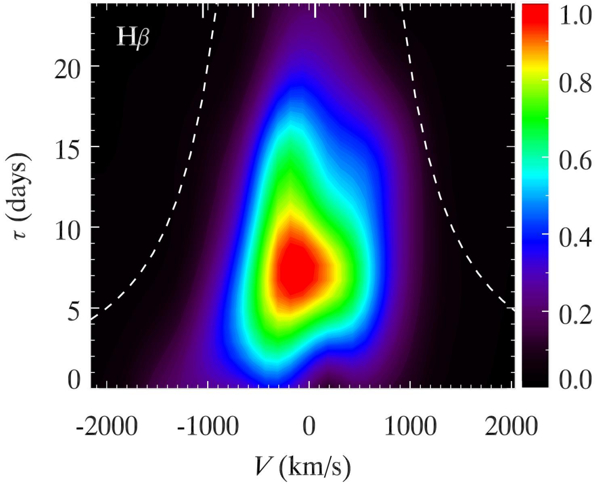












>50 objects:

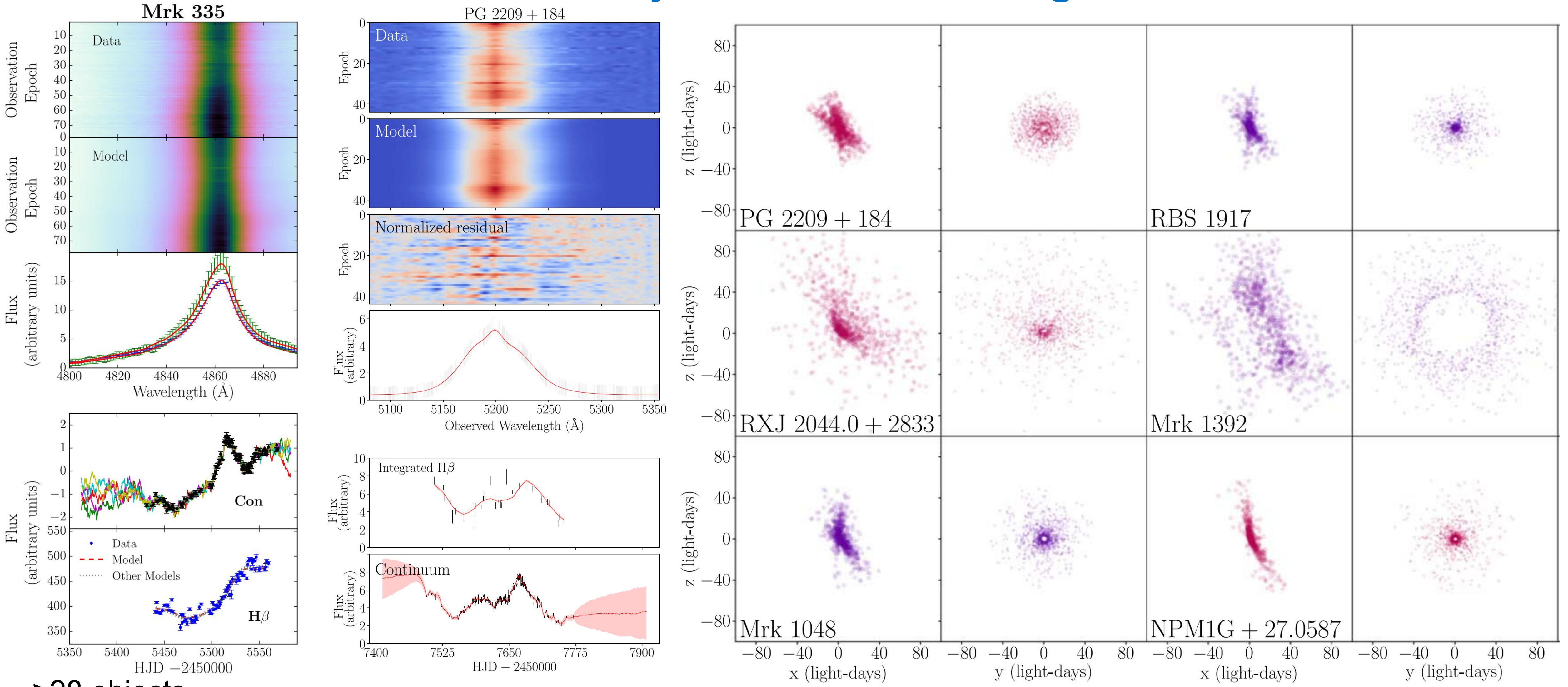
e.g., Grier et al. (2013), Du et al. (2016), De Rosa et al. (2018), Bao et al. (2022), U et al. (2022)…

>20 objects:

e.g., Grier et al. (2013), Skeilboe et al. (2015), Xiao et al. (2018), Horne et al. (2022)…

Velocity-resolved RM & BLR kinematics

BLR dynamical modeling



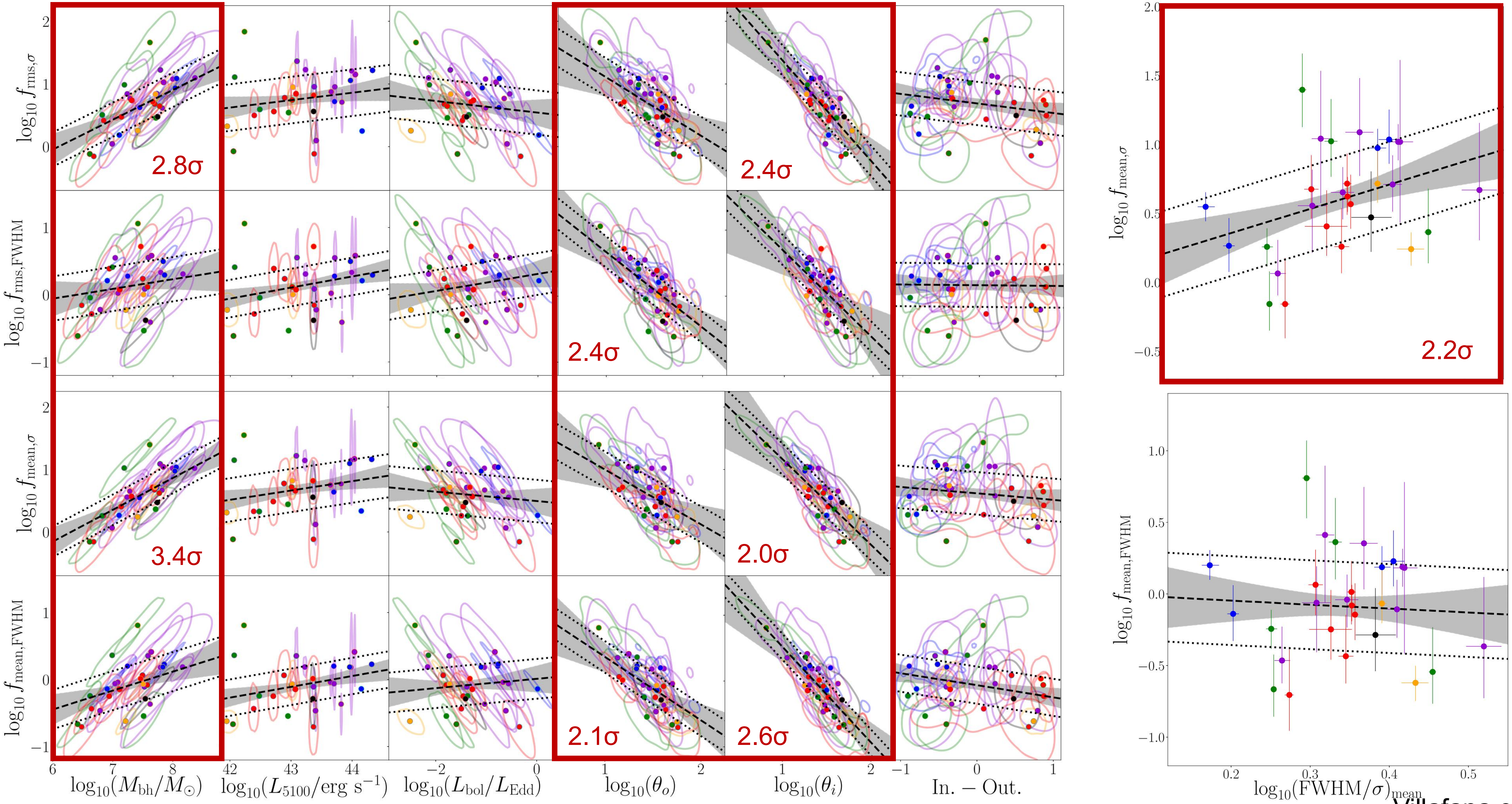
>28 objects

Pancoast et al. (2014), Grier et al. (2017), Williams et al. (2018), Bentz et al. (2021), Villafana et al. (2022)

Velocity-resolved RM & BLR kinematics

BLR dynamical modeling

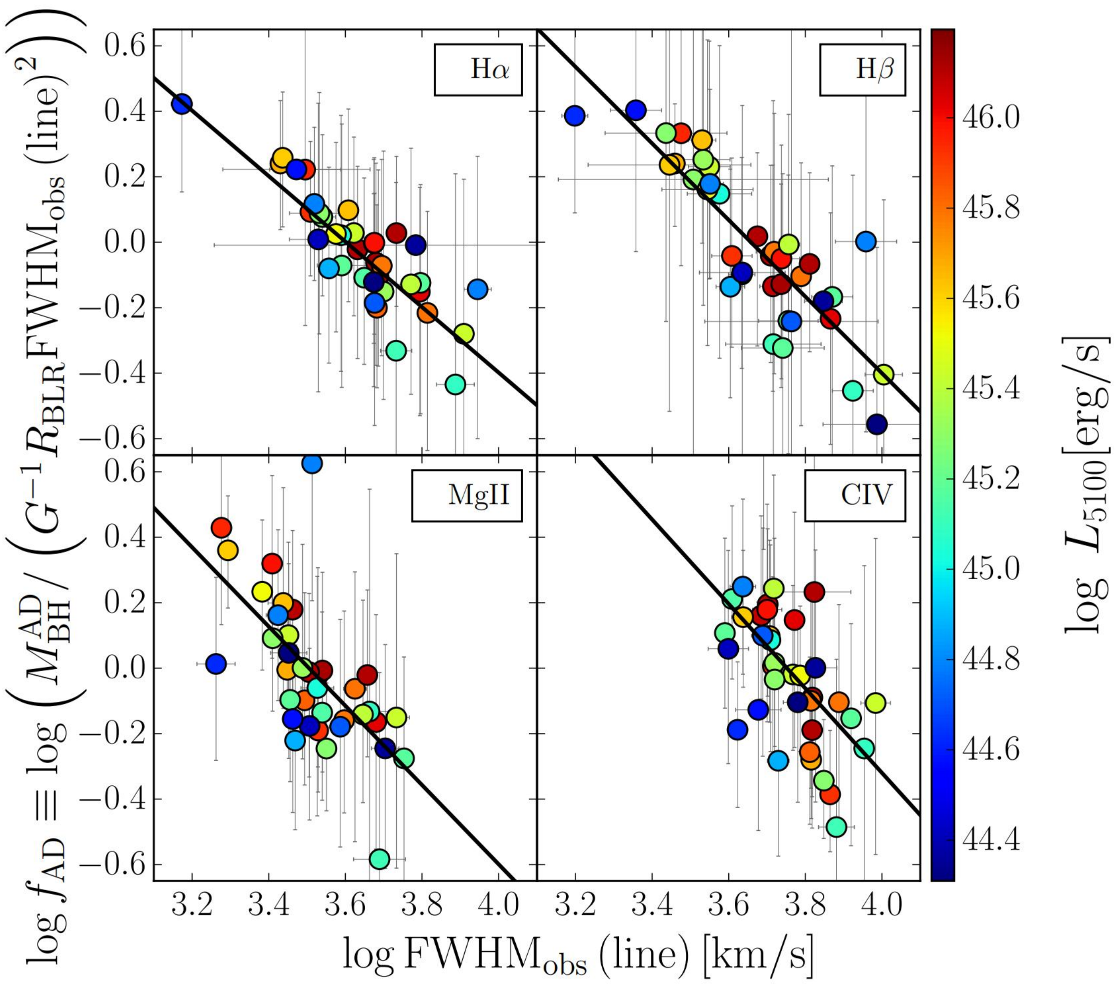
FWHM/sigma is smaller when BLR is smaller or thicker



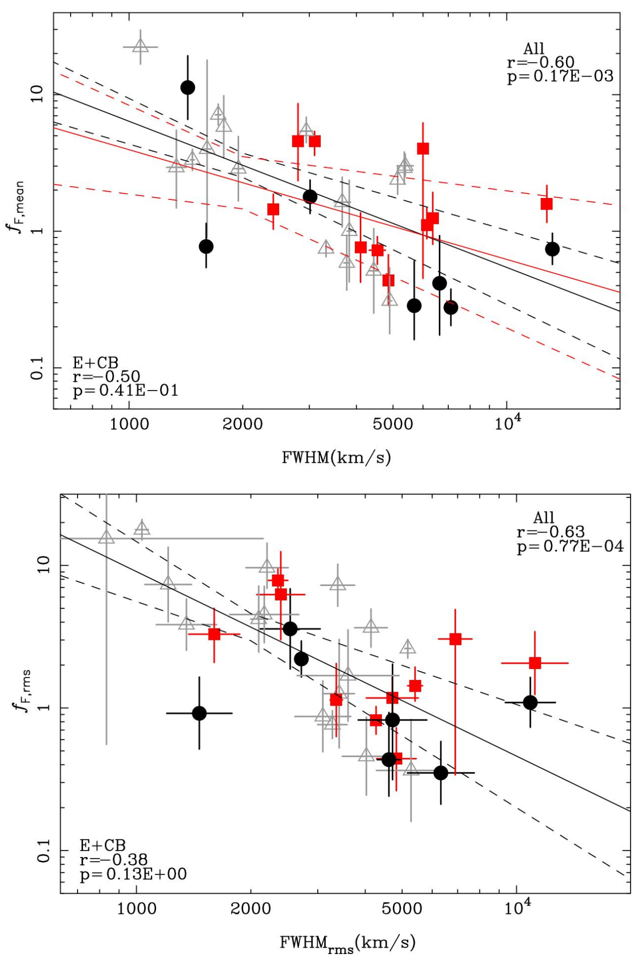
Villafana et al. (2023)

Velocity-resolved RM & BLR kinematics

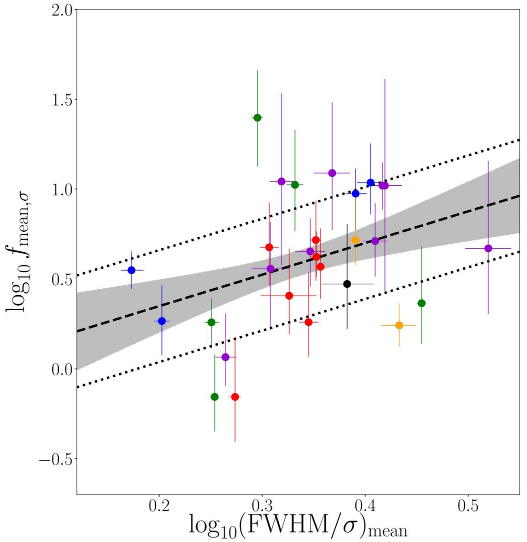
BLR dynamical modeling

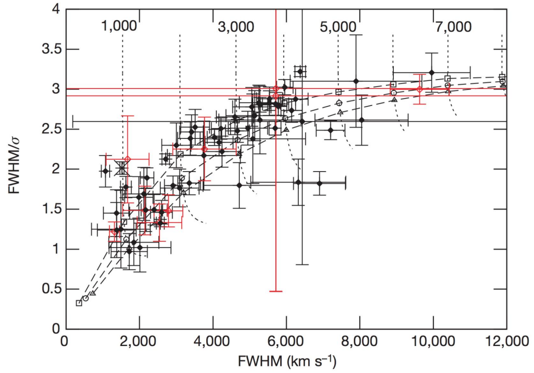


Accretion-disk based BH mass vs. single-epoch BH mass based R-L relation (Mejia-Restrepo et al. 2018)



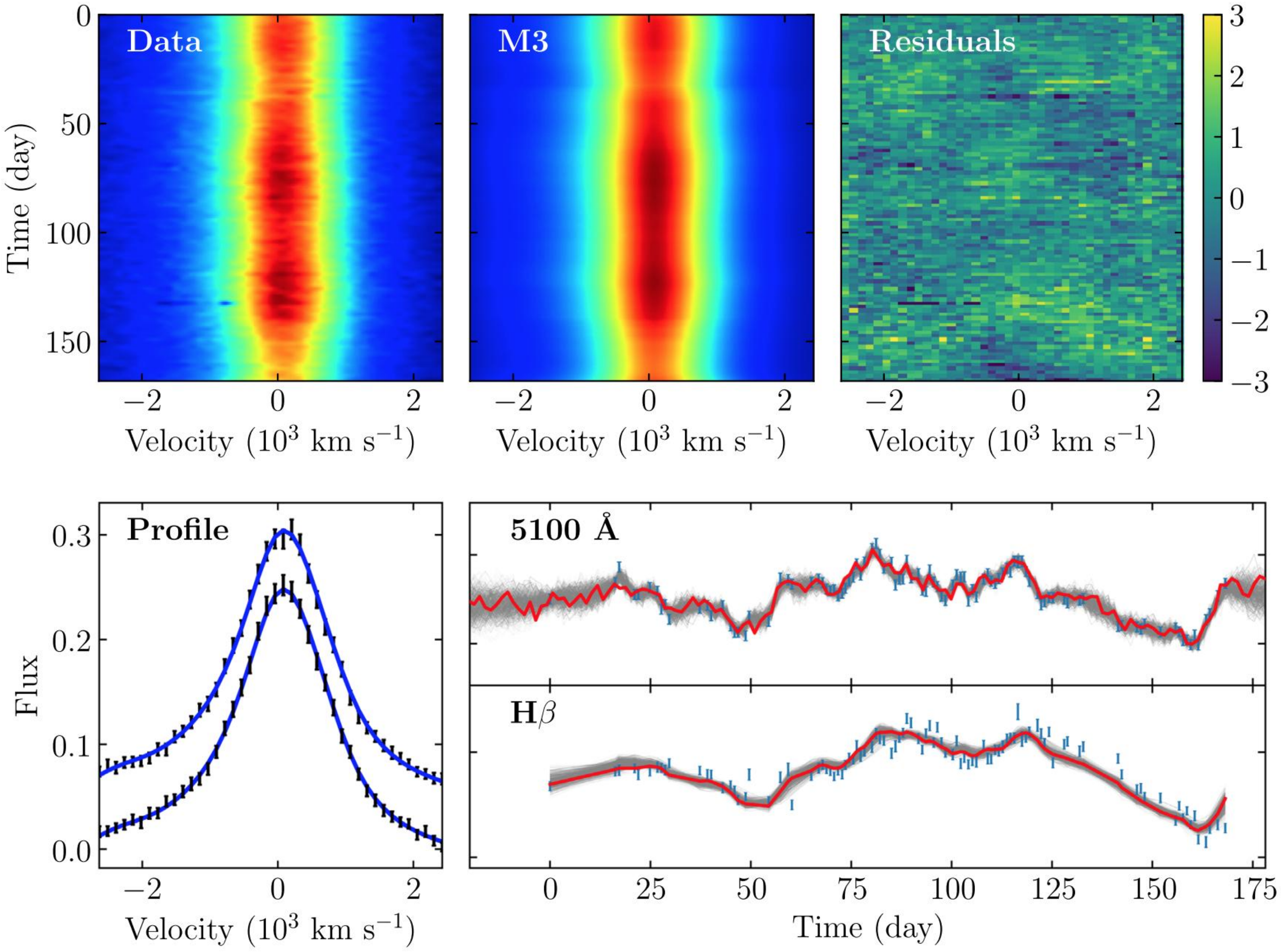
M-sigma based BH mass vs. RM BH mass (Yu et al. 2019)

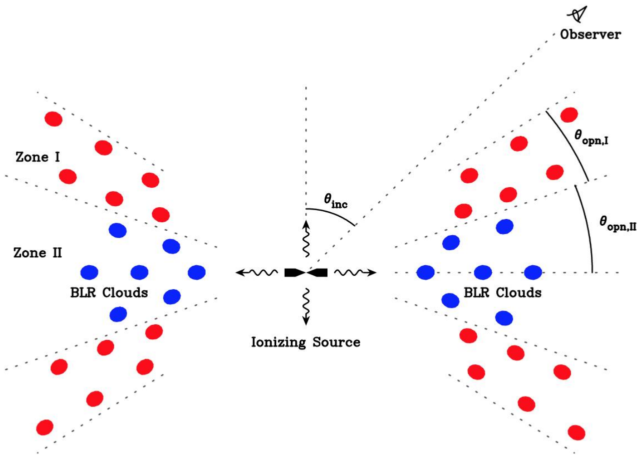


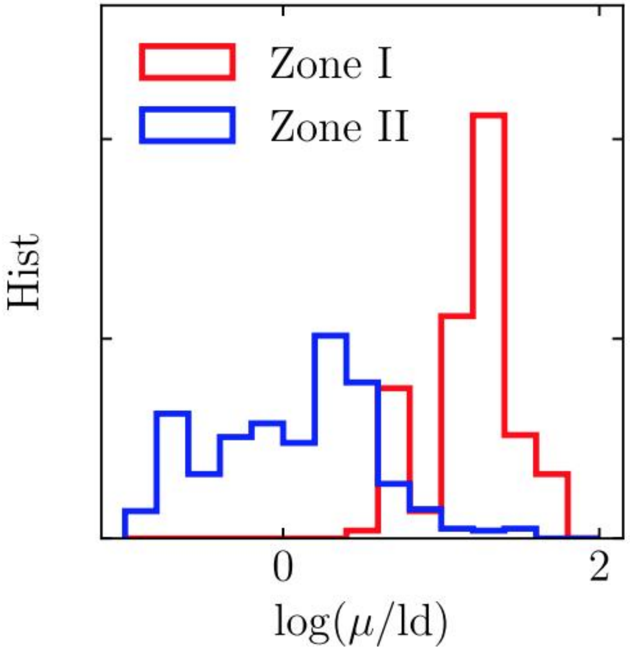


Correlation?
Anti-correlation?

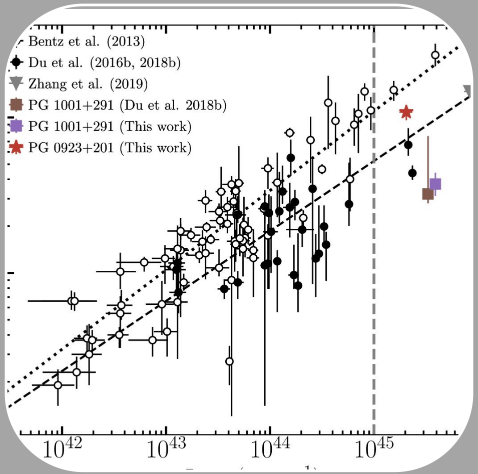
Velocity-resolved RM & BLR kinematics
BLRs in Super-Eddington AGNs



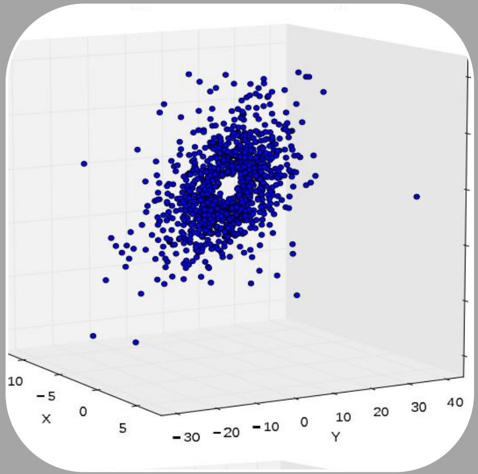




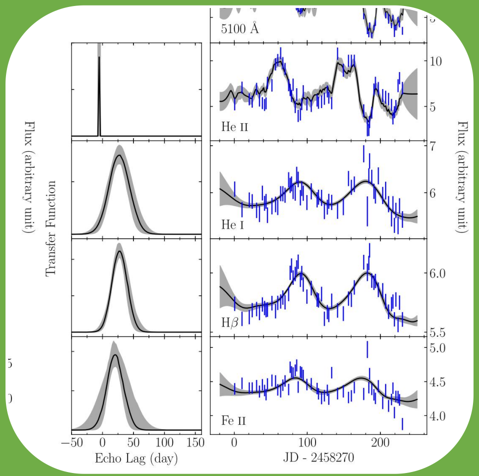
Li et al. (2018)



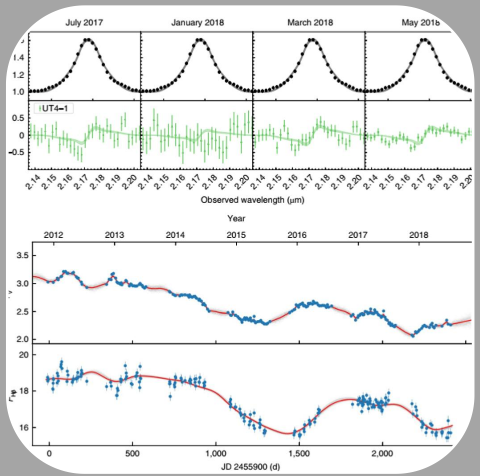
R-L relations



Velocity-resolved RM & BLR kinematics

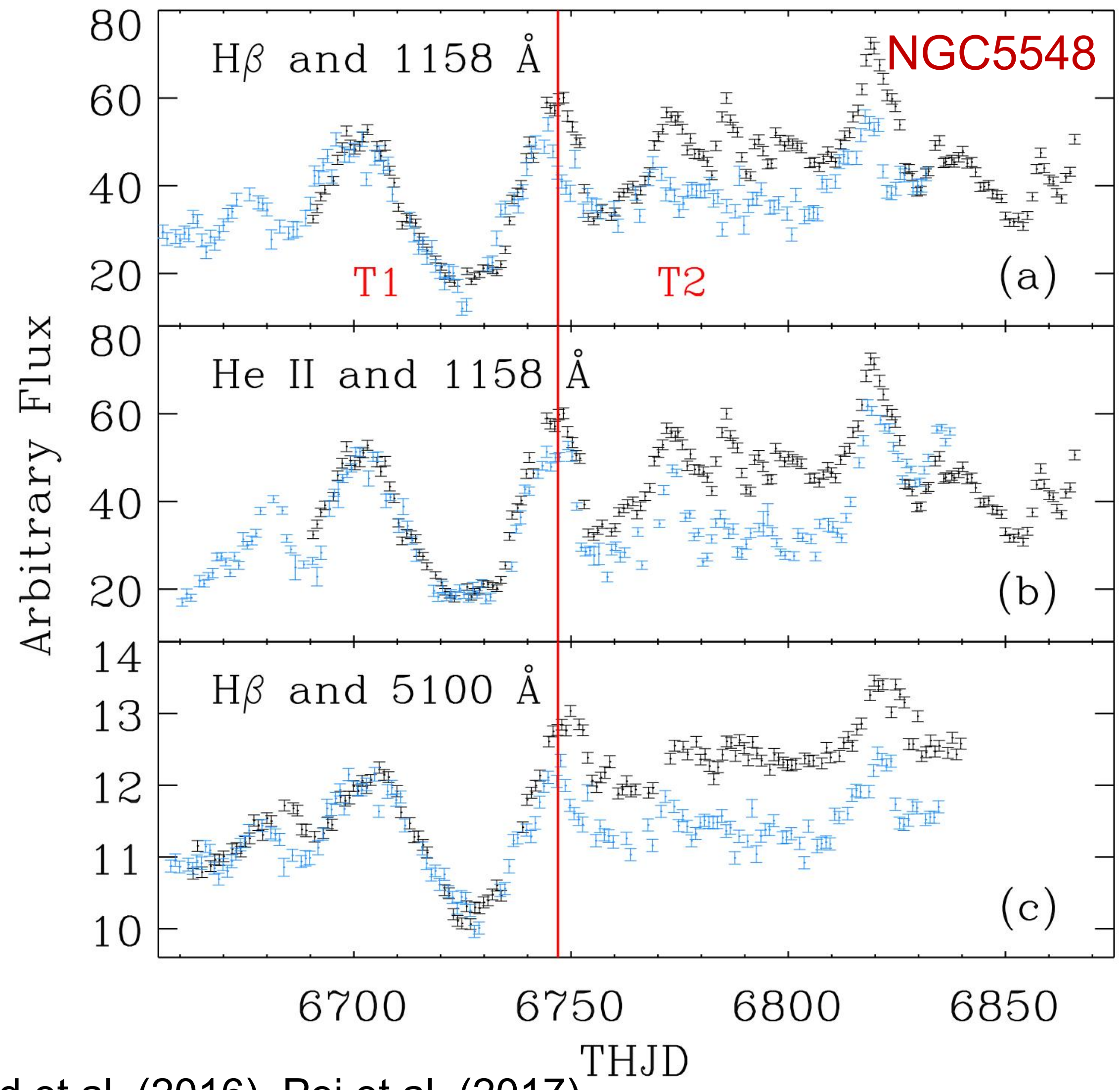


New phenomena

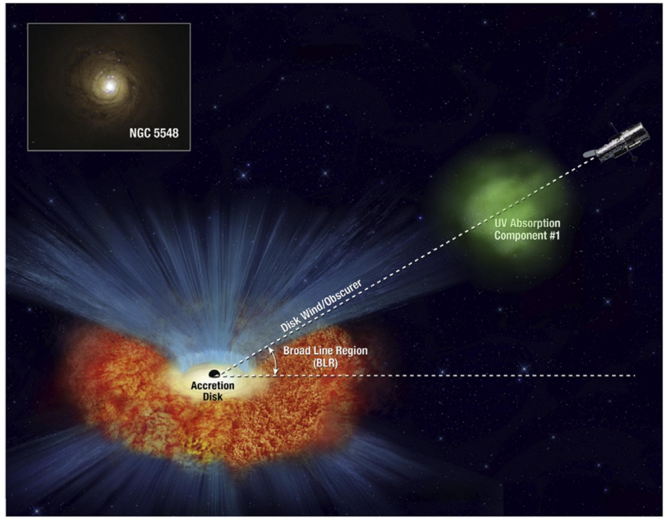


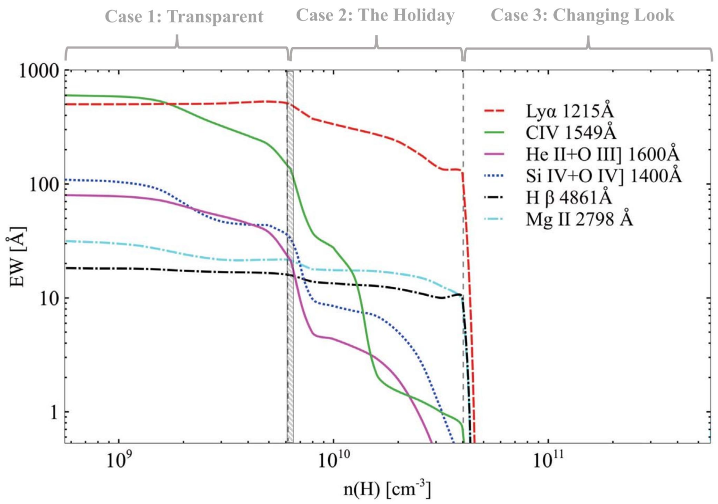
New applications

New phenomena
BLR "holiday"



Goad et al. (2016), Pei et al. (2017)

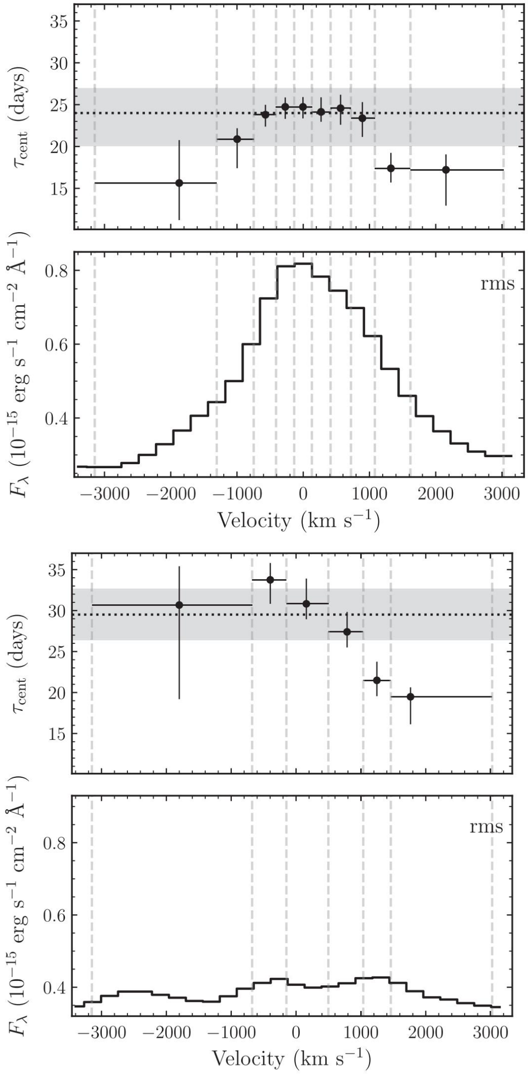


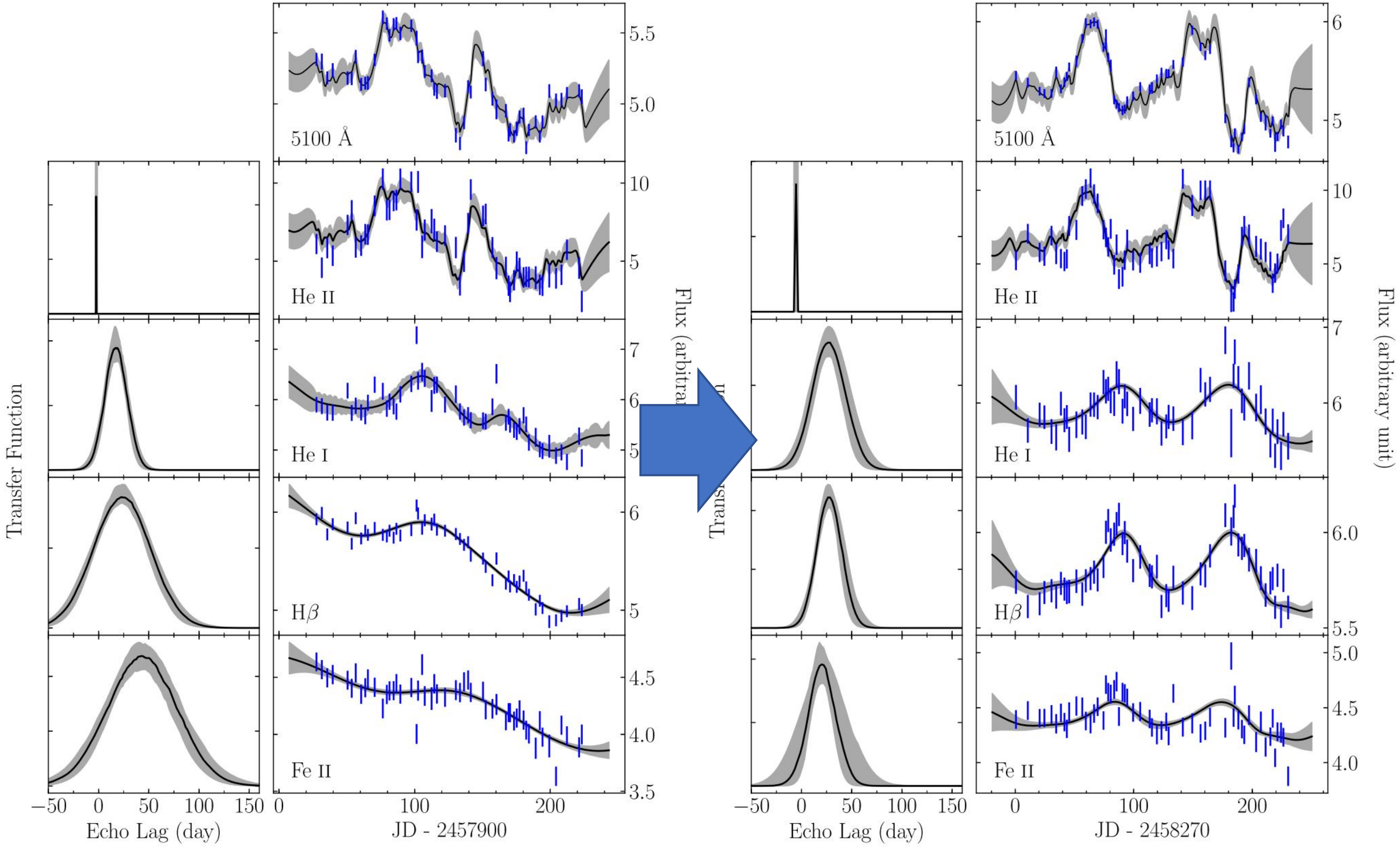


Dehghanian et al. (2019)

New phenomena

PG2130+099: BLR stratification structure reverses

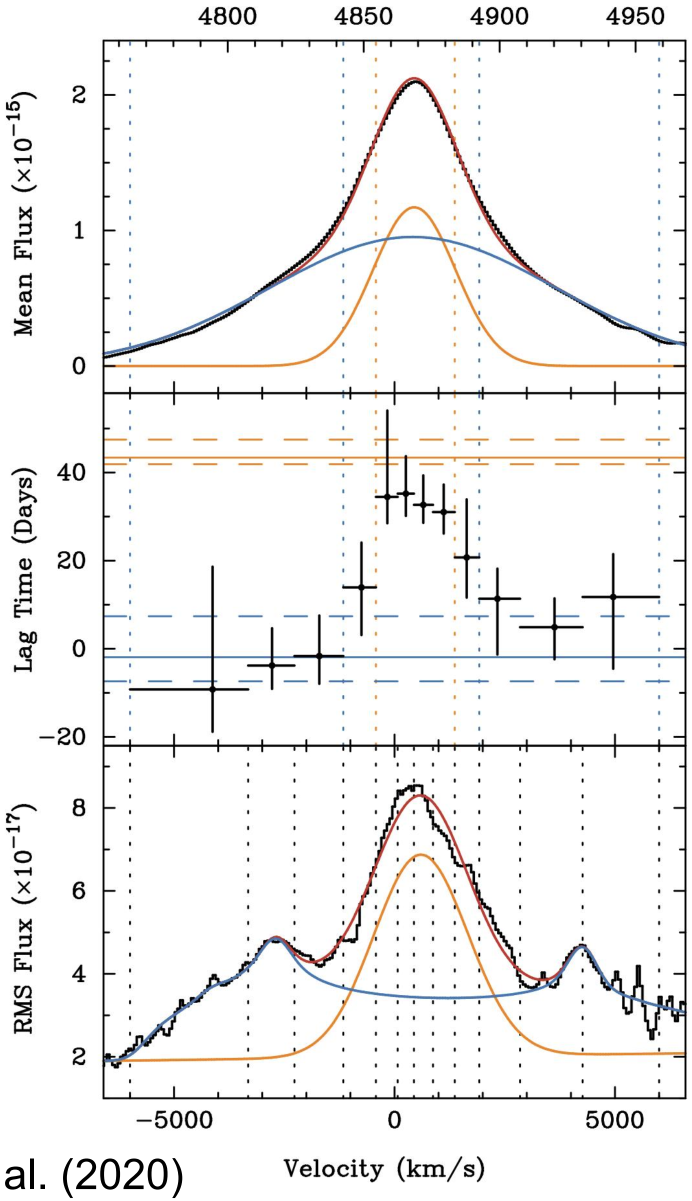




Hu et al. (2020)

New phenomena

PG0026+129: a small inner BLR



FWHM(IC): 1964km/s

FWHM(VBC): 7570km/s

KERRDISK

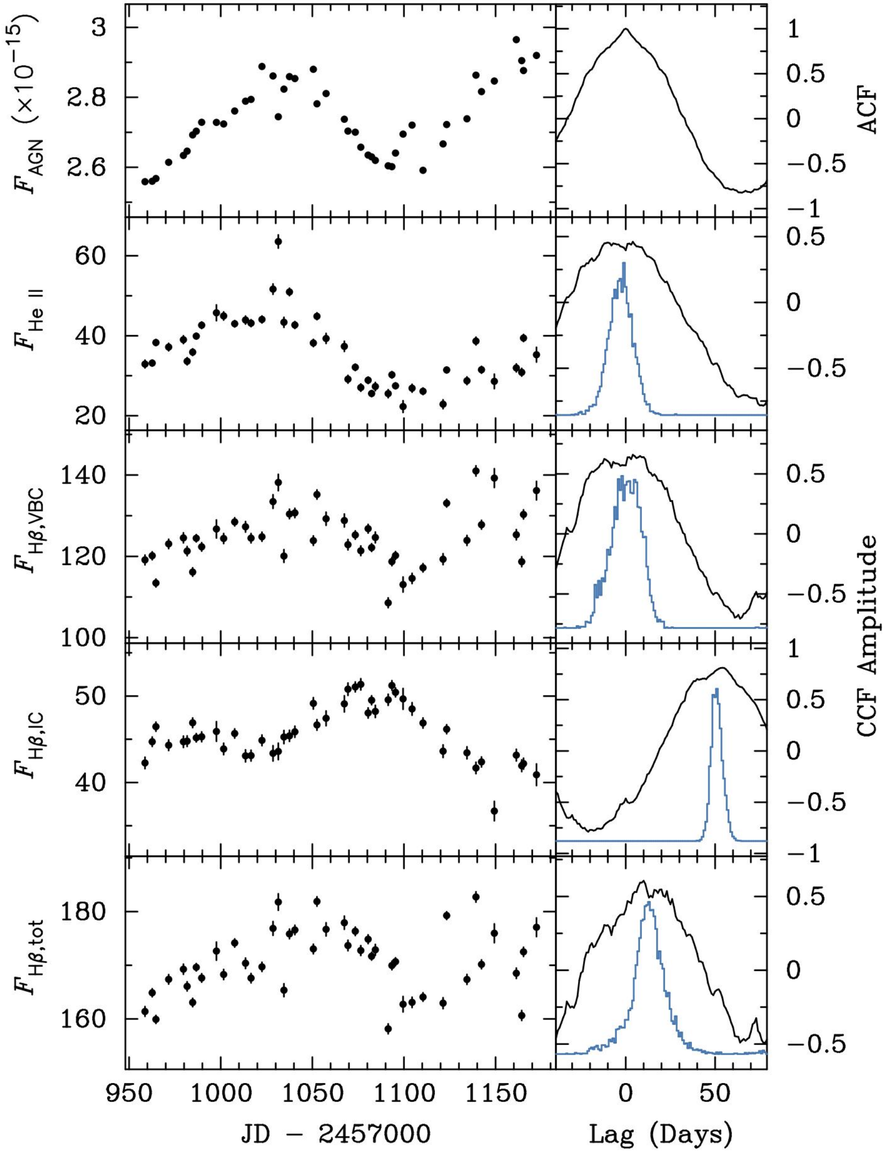
(Brenneman&Reynolds2006):

$R_{\rm in} = 152^{+15}_{-15} R_g$

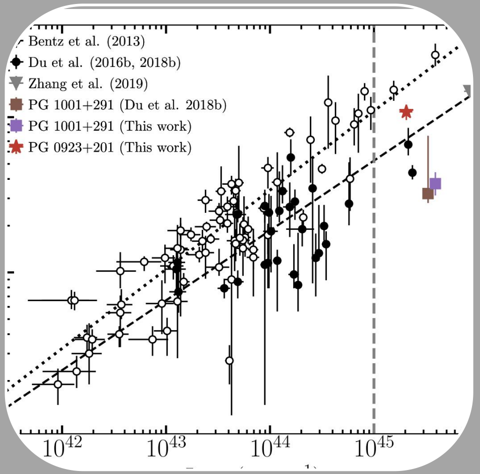
(0.25 lt-days)

$R_{\rm out} = 1389^{+924}_{-137} R_g$

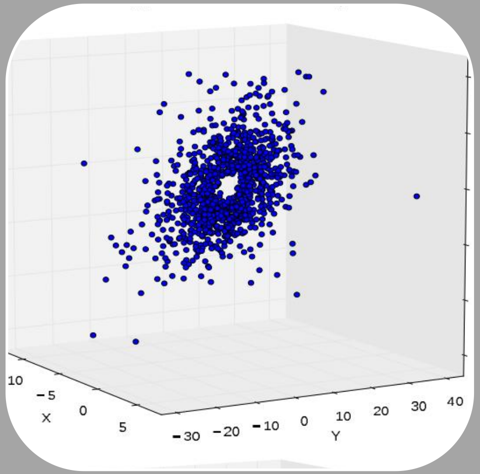
(2.29 lt-days)



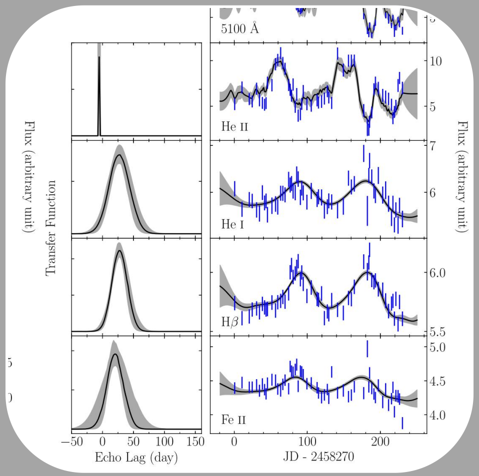
Hu et al. (2020)



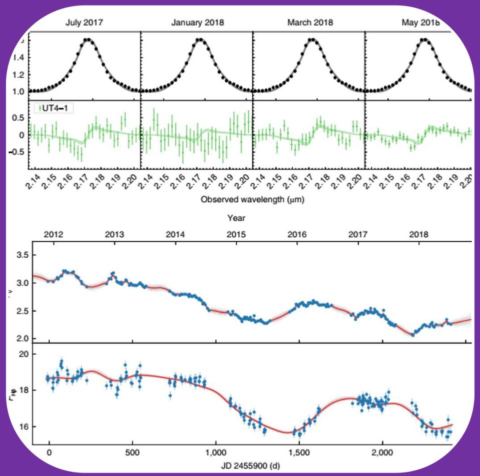
R-L relations



Velocity-resolved RM & BLR kinematics



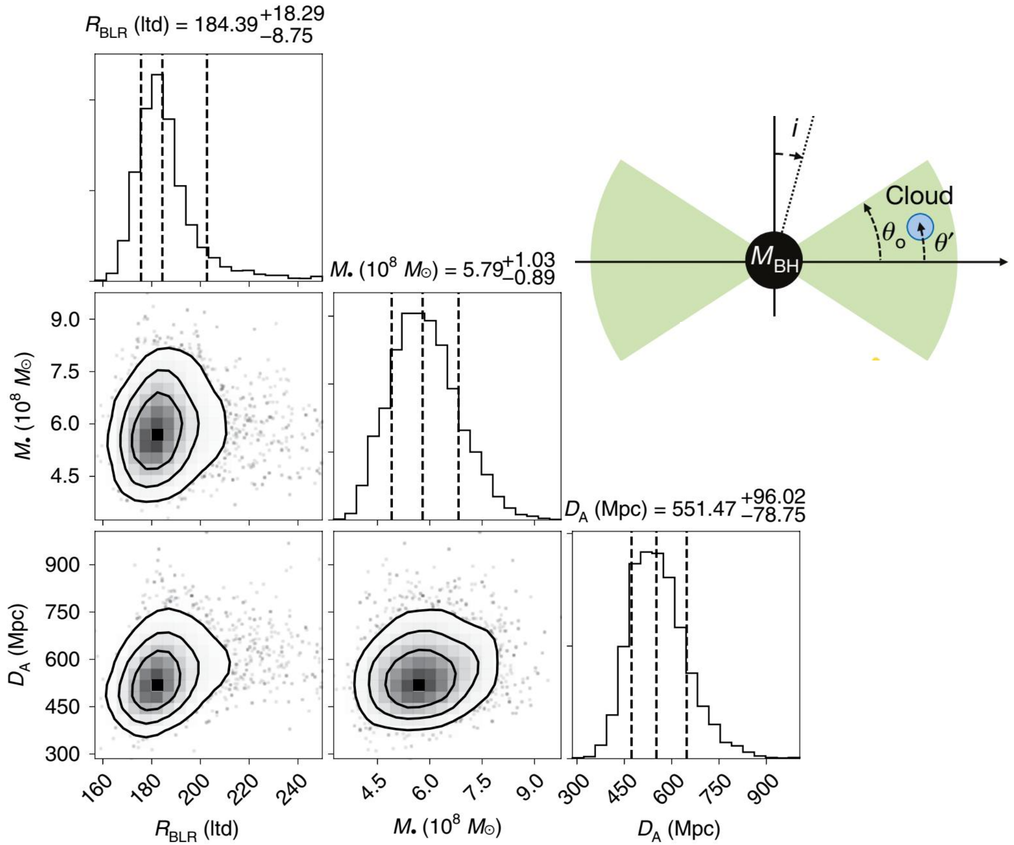
New phenomena

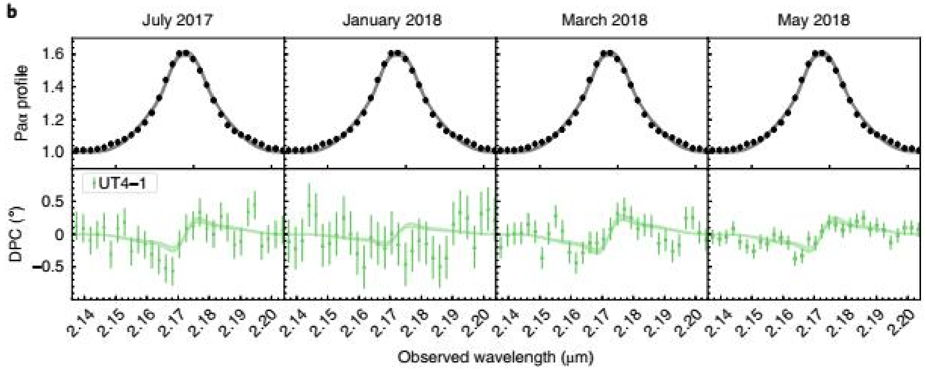


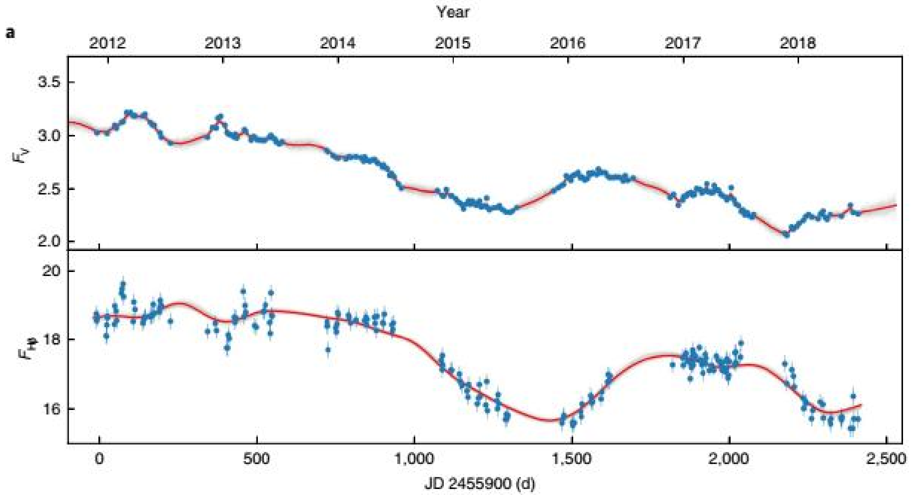
New applications

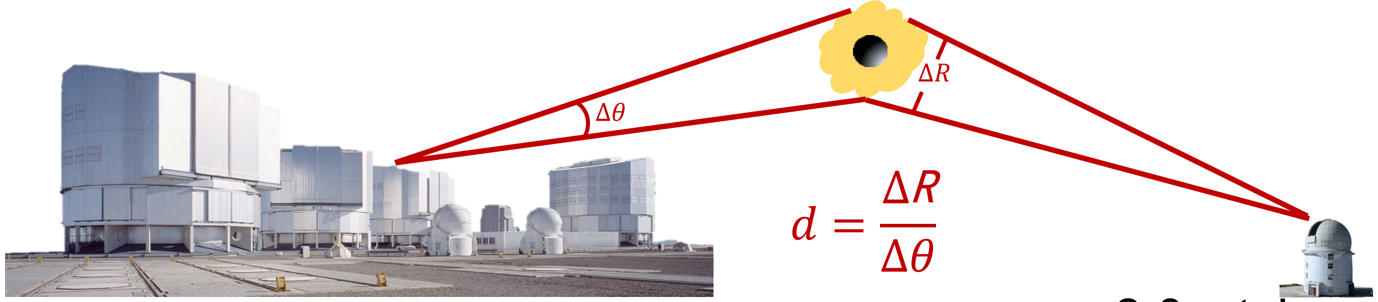
New applications of RM

Spectro-**A**strometry + **R**everberation **M**apping (SARM): Cosmological Distance and H_0









GRAVITY/VLTI

2-3m telescope

3C273 (Wang et al. 2020):

- ***M_{BH}* : precision of 15-20%**
- ***D_A* : precision of 16%**

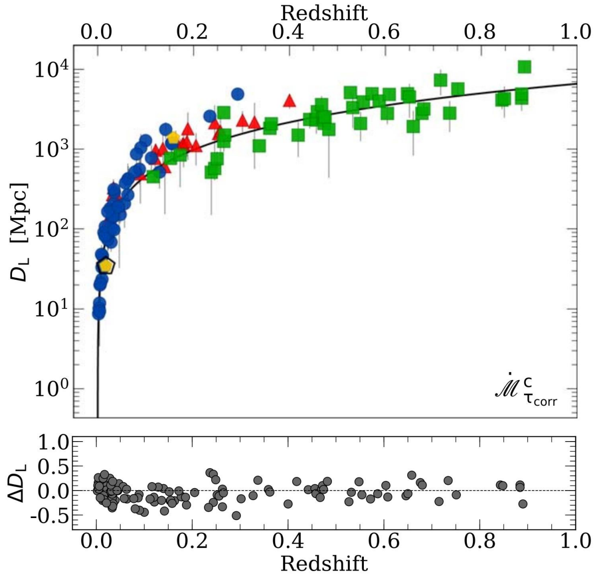
NGC 3783 (Gravity Collaboration et al. 2021) …

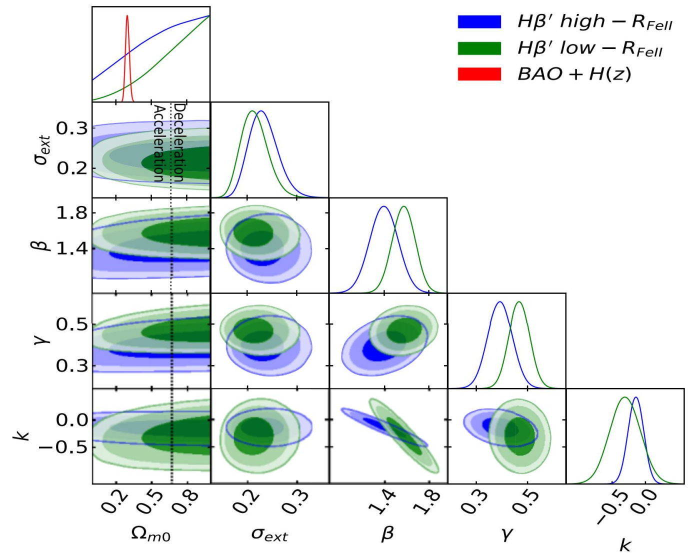
New applications of RM

Other cosmological distance tools based on RM

Based on R-L relation

(e.g., Watson et al. 2011, Martinez-Aldama et al. 2019, Khadka et al. 2022)

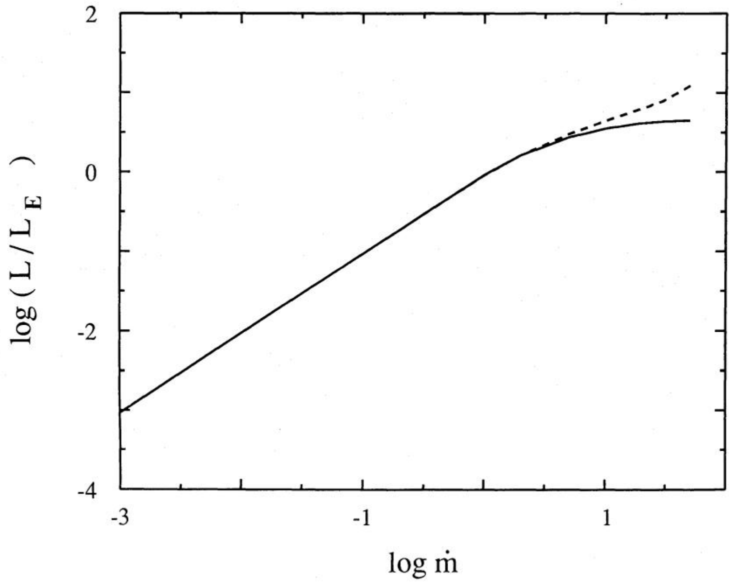


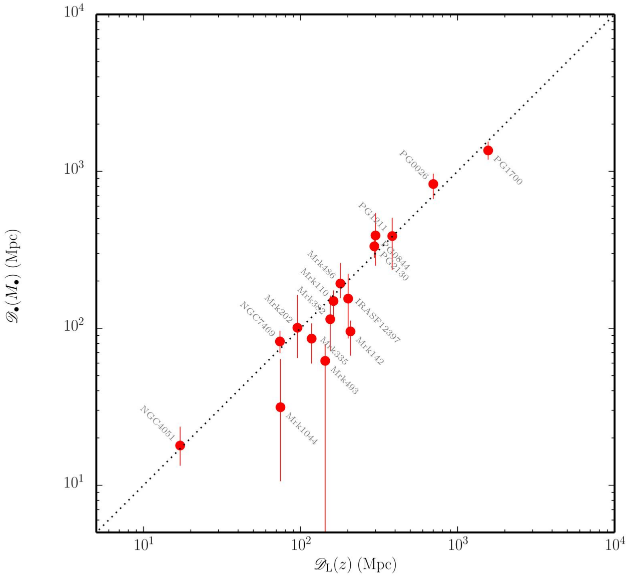


Based on the saturated luminosity of super-Eddington AGNs

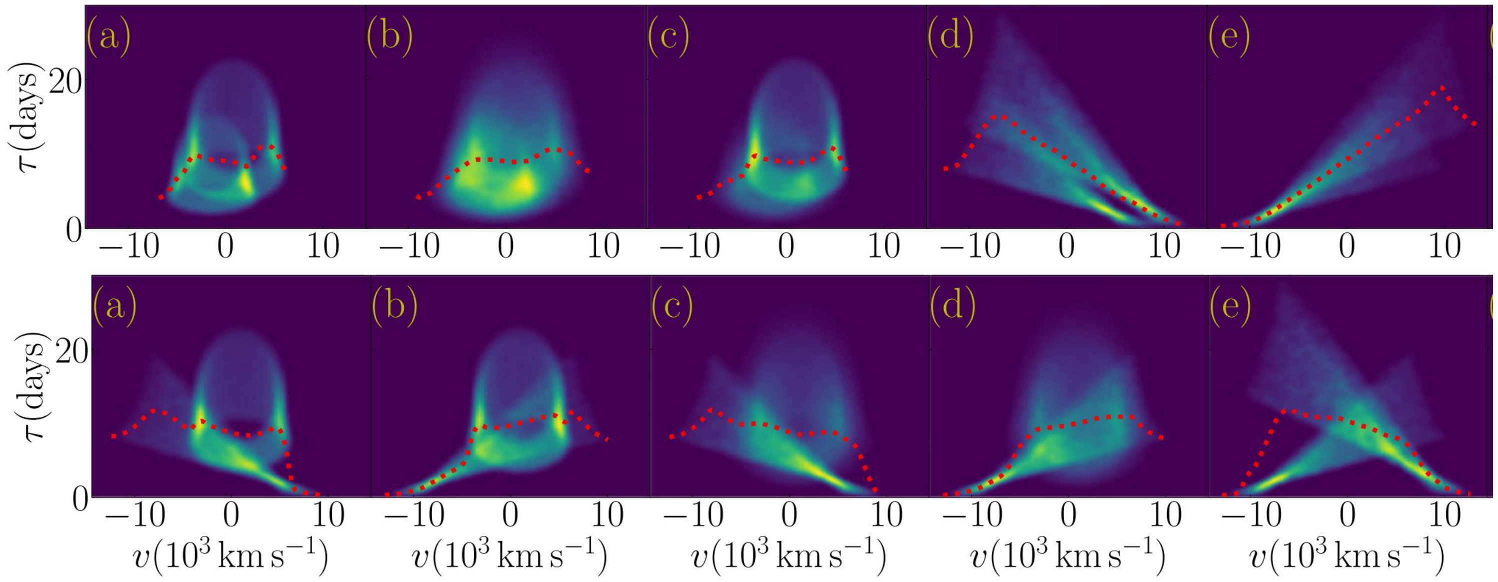
(Wang et al. 2013, 2014)

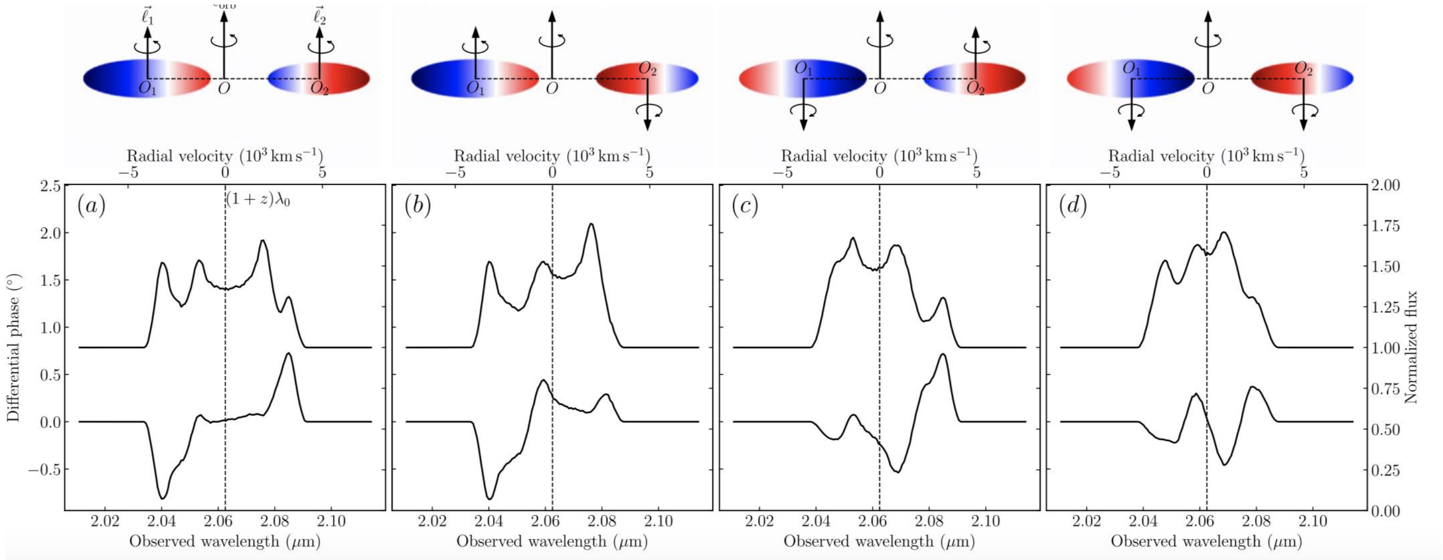
$$L_{\bullet} = l_0(1 + a\ln \dot{M}_{\bullet})M_{\bullet}$$

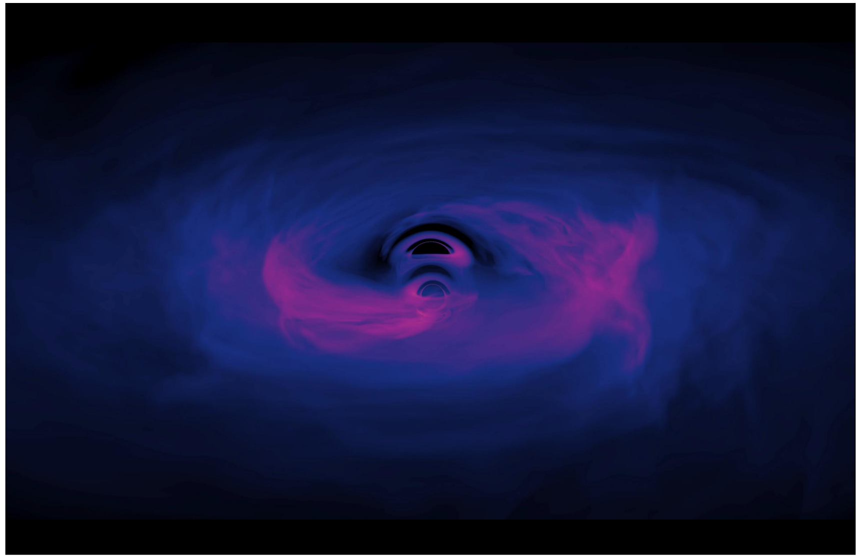




New applications of RM
Supermassive binary black holes





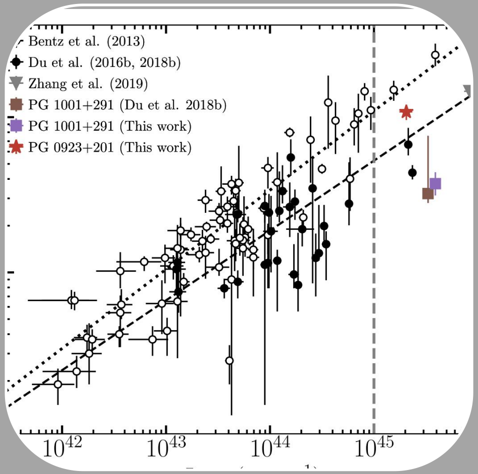


Offsets are due to orbital motion

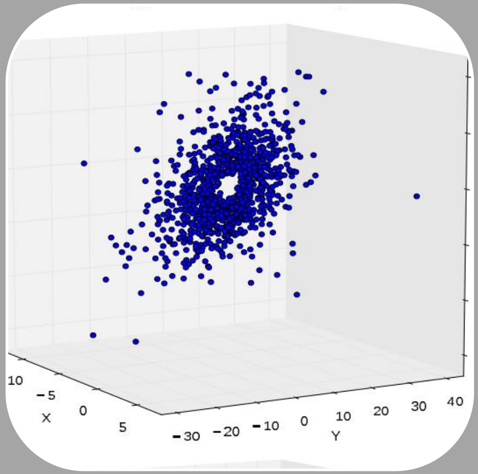
(Wang et al. 2018; Songsheng et al. 2020; Kovacevic et al. 2020)

MAHA project

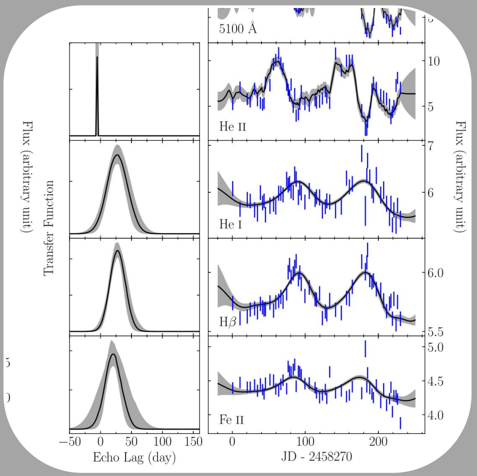
(Du et al. 2018; Brotherton et al. 2020; Bao et al. 2022)



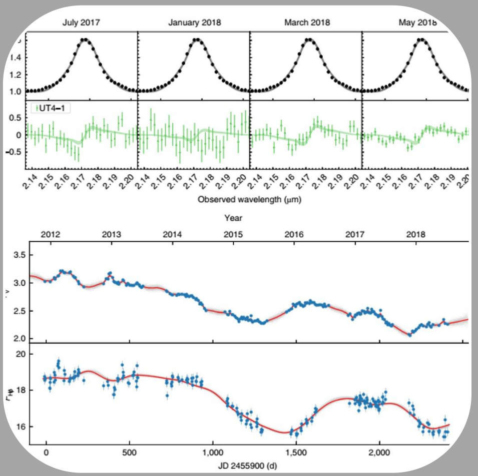
R-L relations



Velocity-resolved RM & BLR kinematics



New phenomena

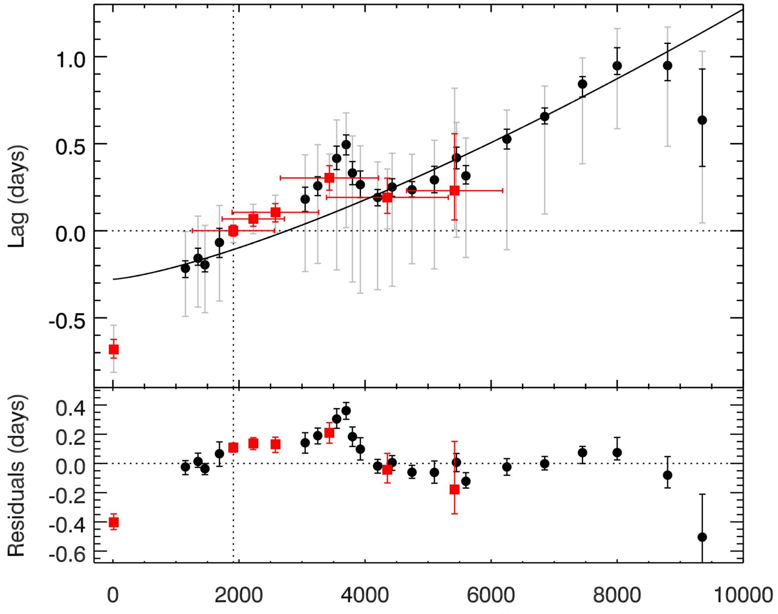


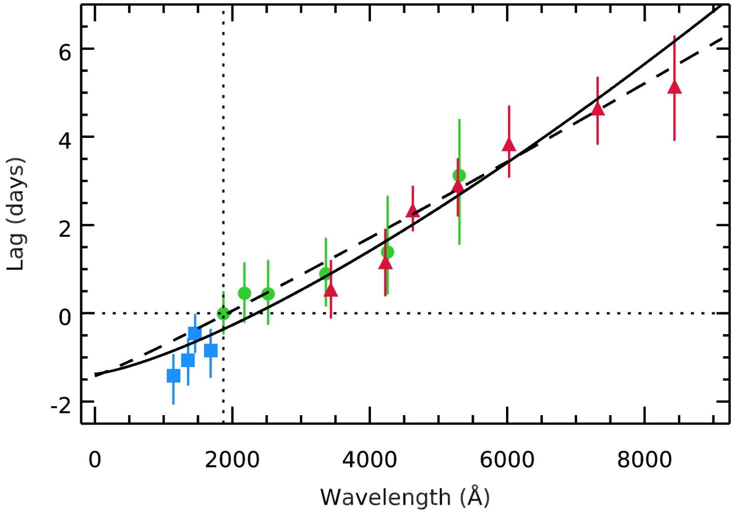
New applications

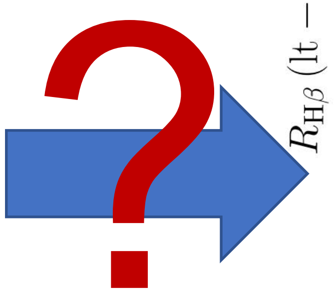
More questions to answer…

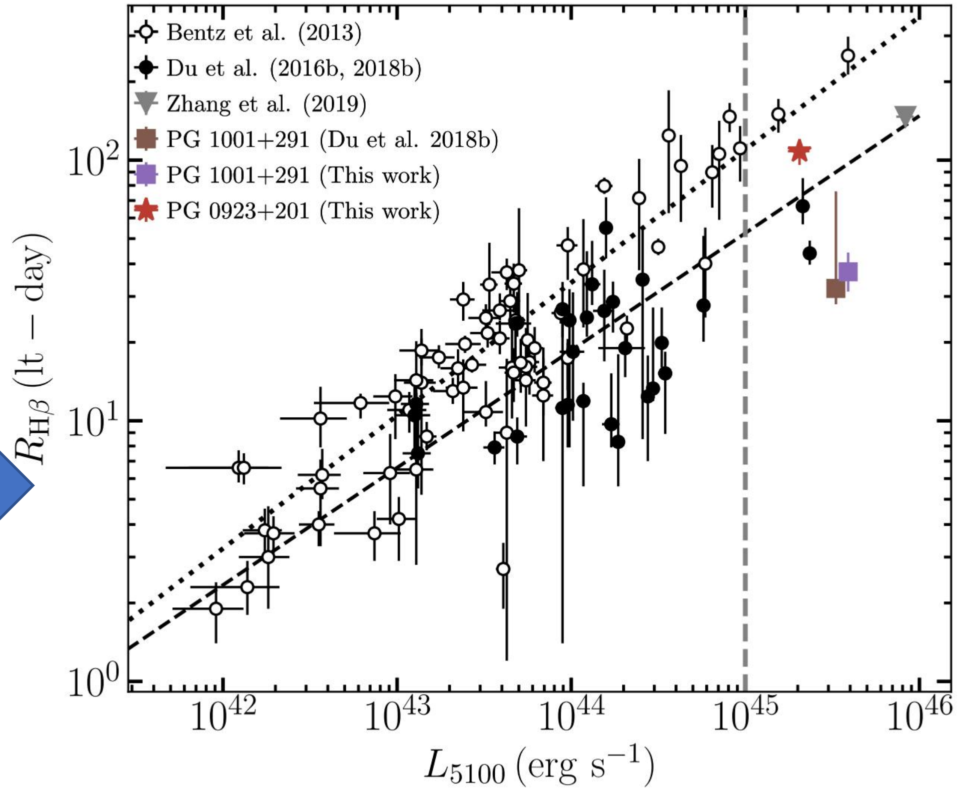
Next decade

Advancing the Understanding of Scatter in R-L Relations









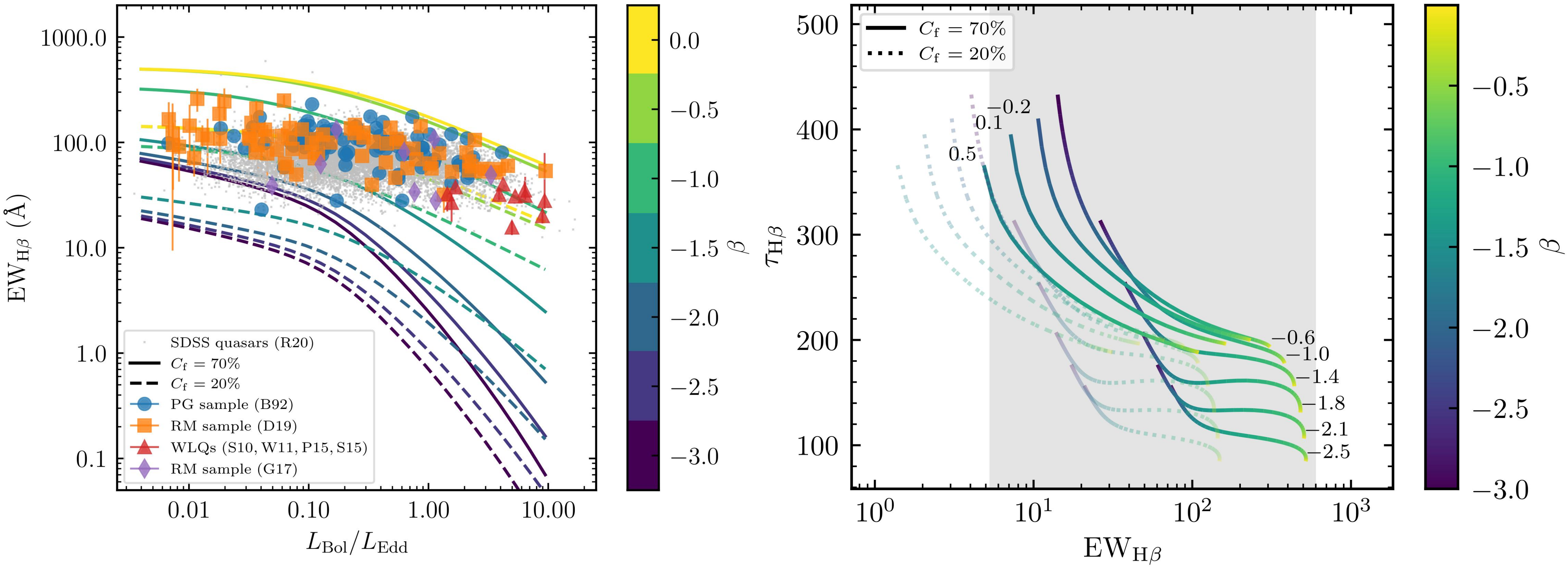
Lags in disc mapping are larger than expected (e.g., Edelson et al. 2015, 2019, Cackett et al. 2018, Kara et al. 2021):

- Contribution from diffuse continuum?
- Accretion disk is larger?

How dose it influence our understanding to R-L relation?

Next decade

Advancing the Understanding of Scatter in R-L Relations

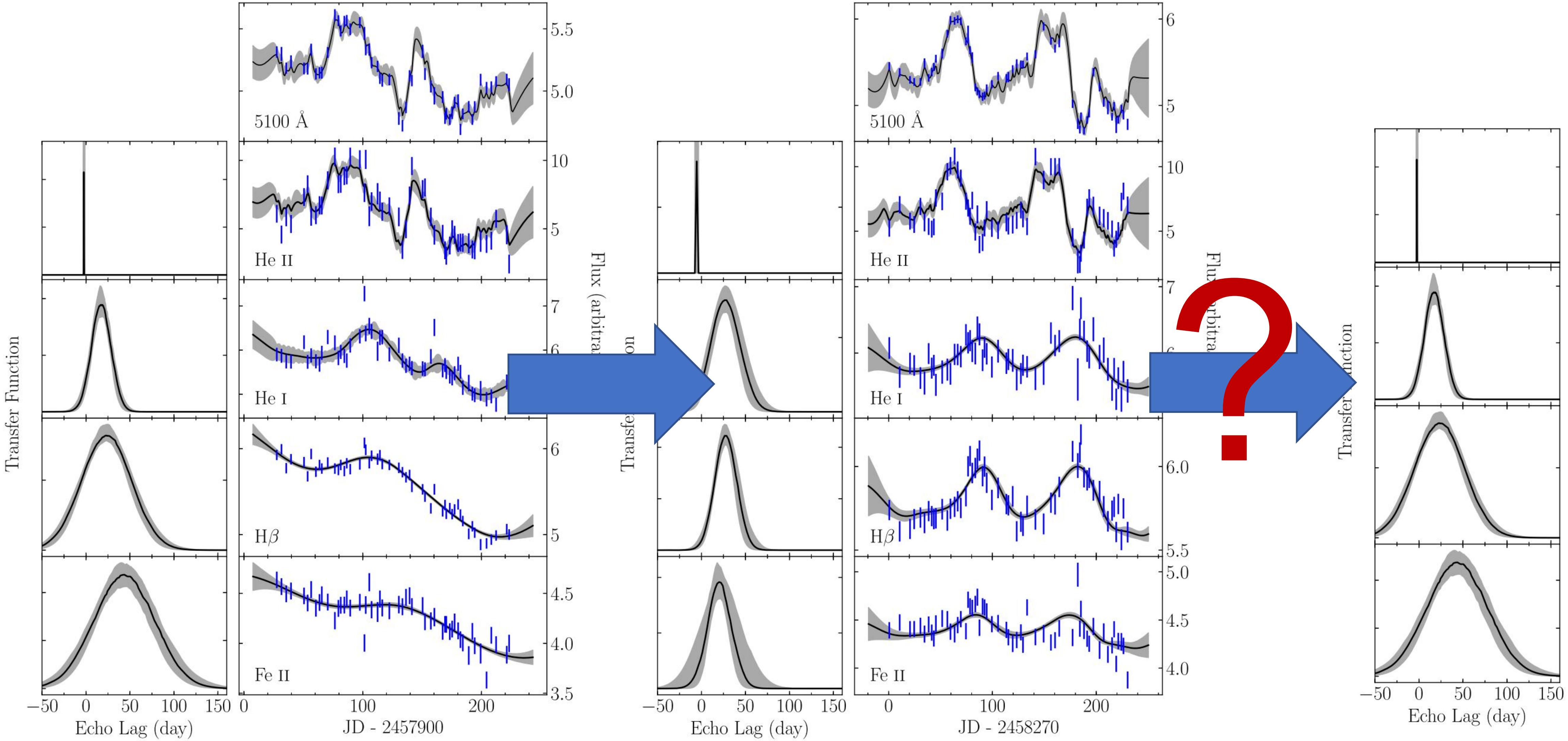


AGNs with low equivalent widths of Hβ: longer time lags?

Du et al. (2023)

Next decade

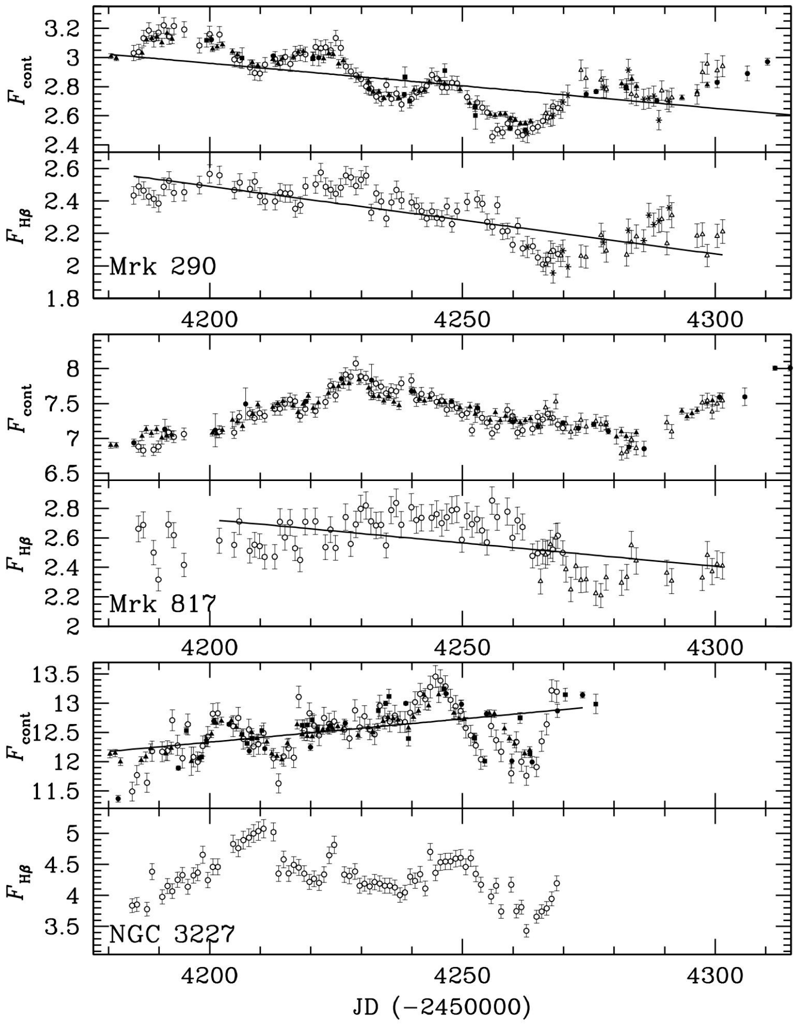
BLR stratification structure reverses, and fluctuation?

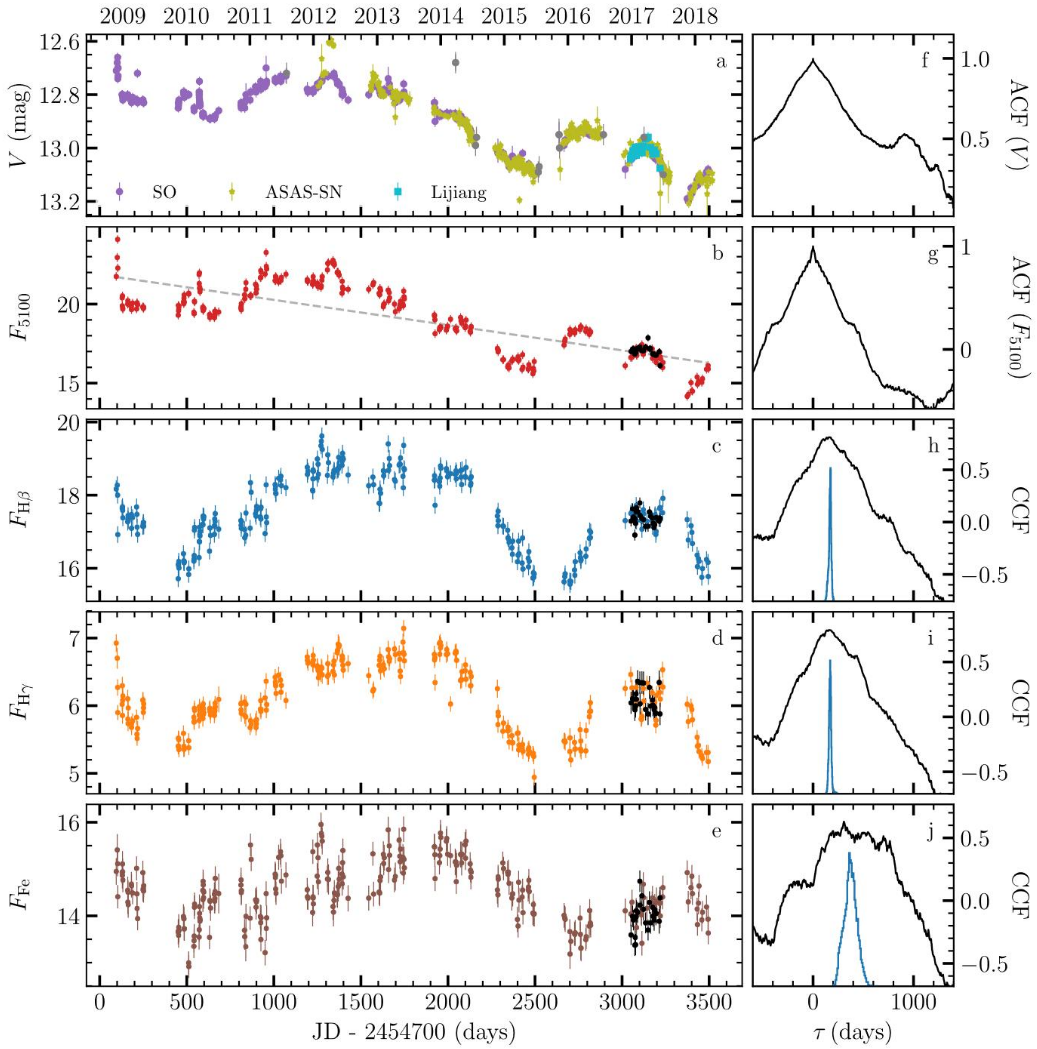


Hu et al. (2020)

Next decade

What is the physical reason for “long-term trend”?

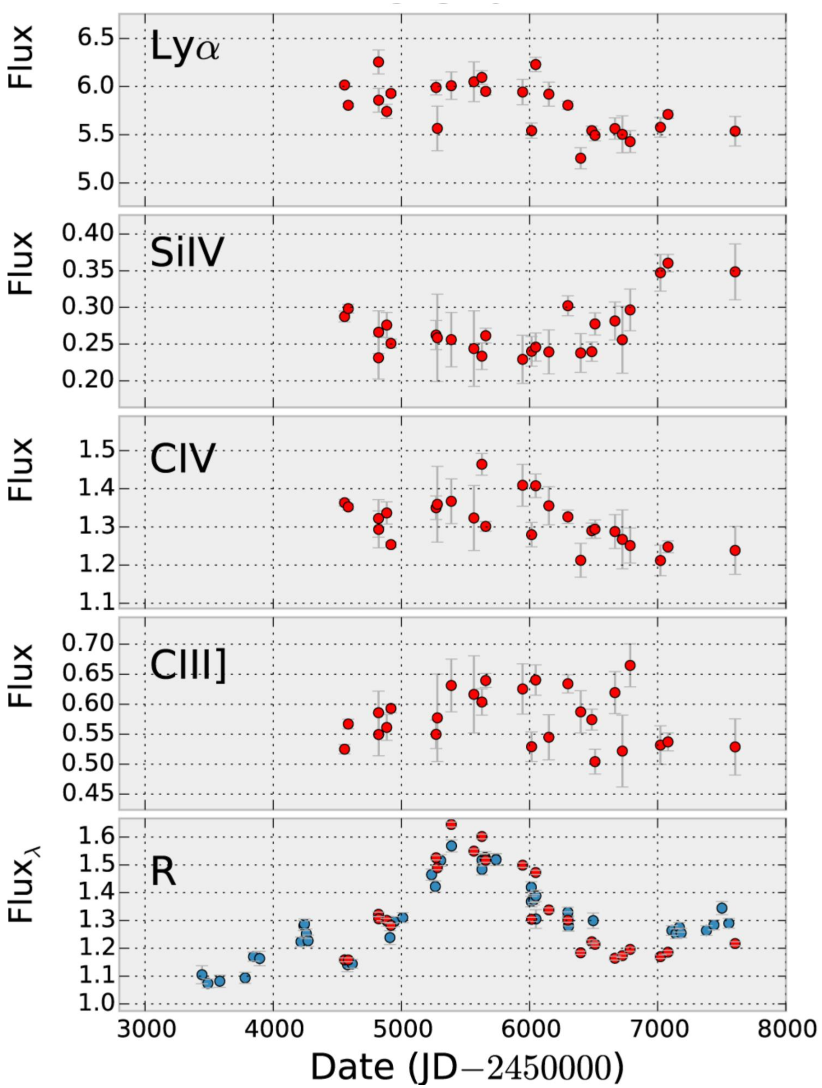




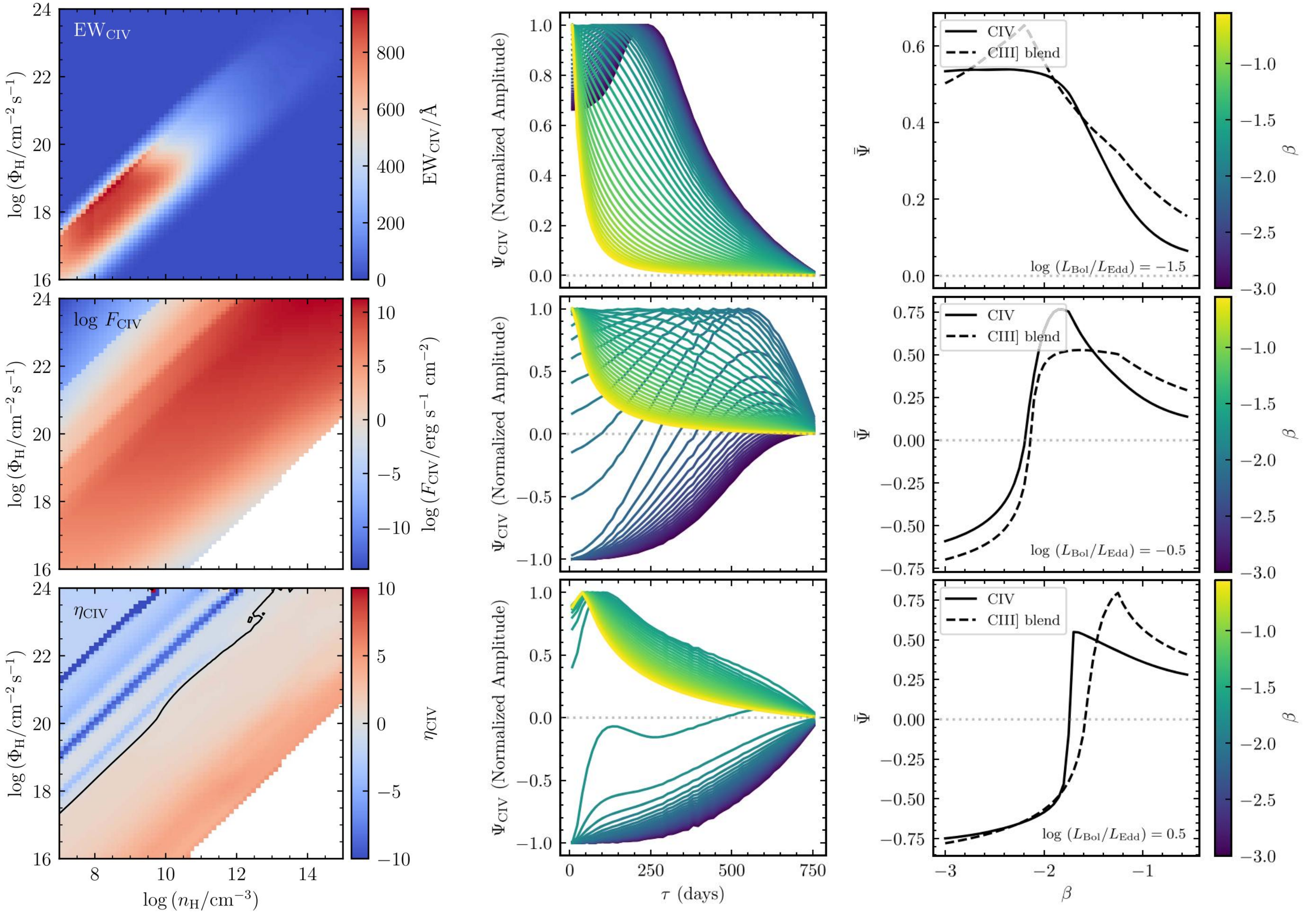
e.g., Denney et al. (2010), Zhang et al. (2019)…

Next decade

More abnormal behavior?



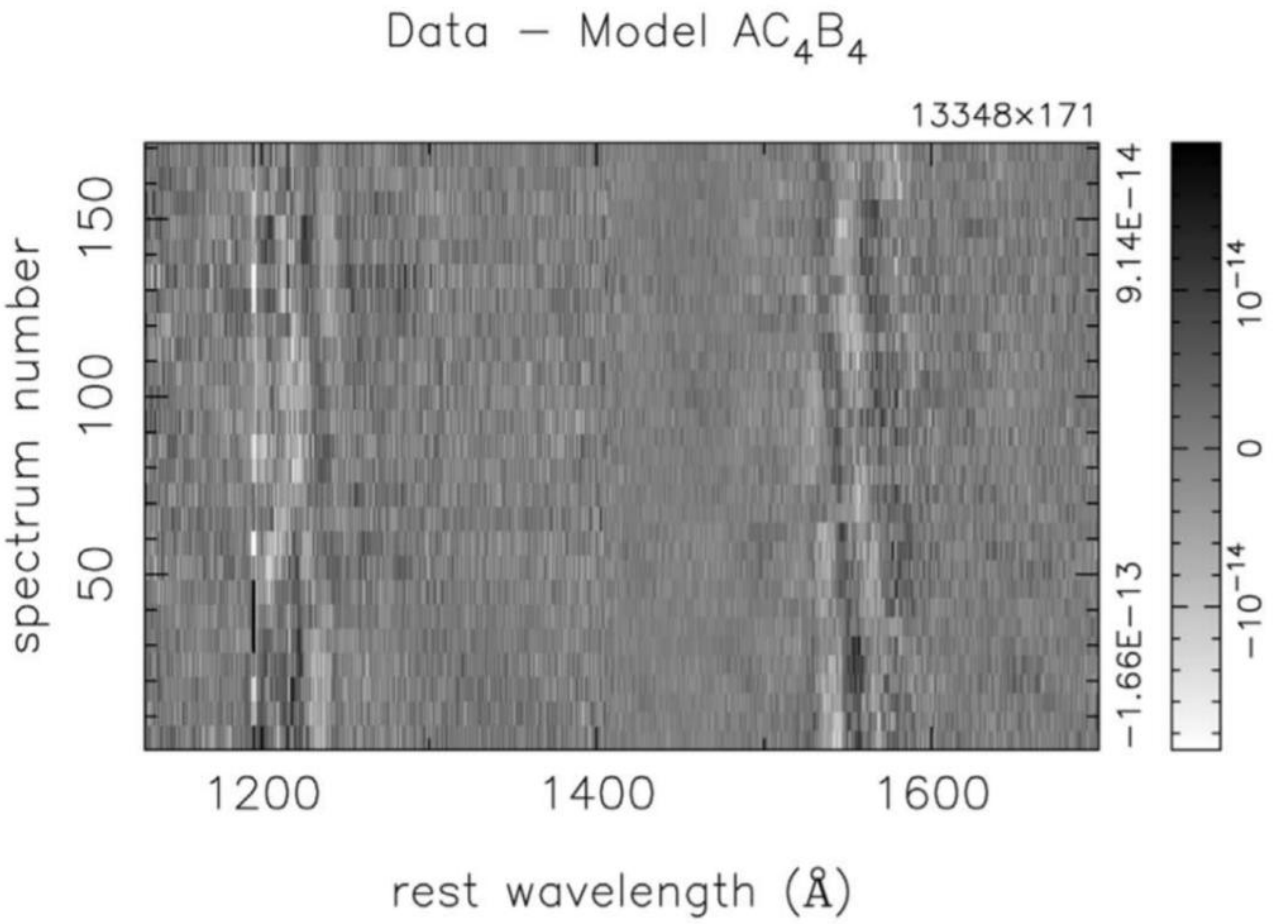
CT320, CT803, J224743 in Lira et al. (2018)



Du et al. (2023)

Barber-Pole pattern in NGC 5548

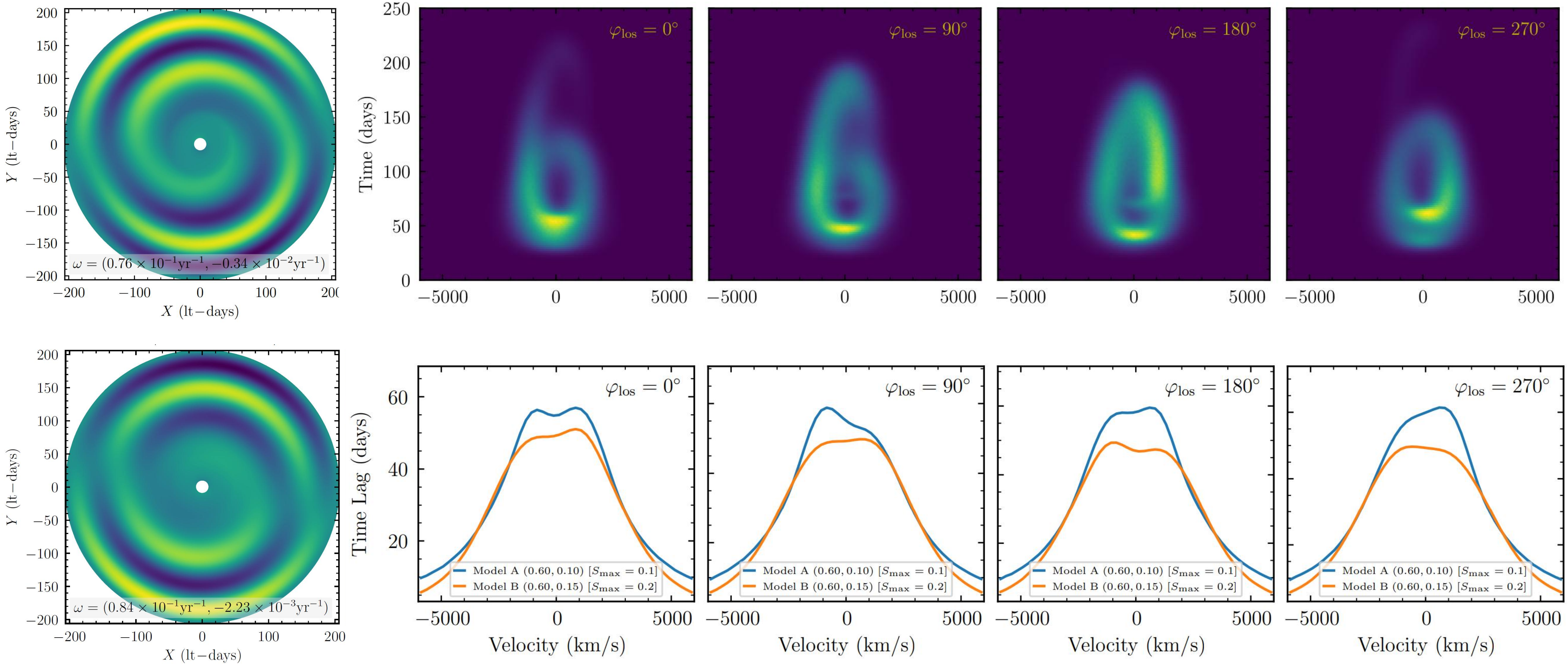
- residuals of the PREPSPEC
- a helical "Barber-Pole" pattern
- stripes moving from red to blue across the C IV and Lyα
- suggests azimuthal structures



Horne et al. (2021)

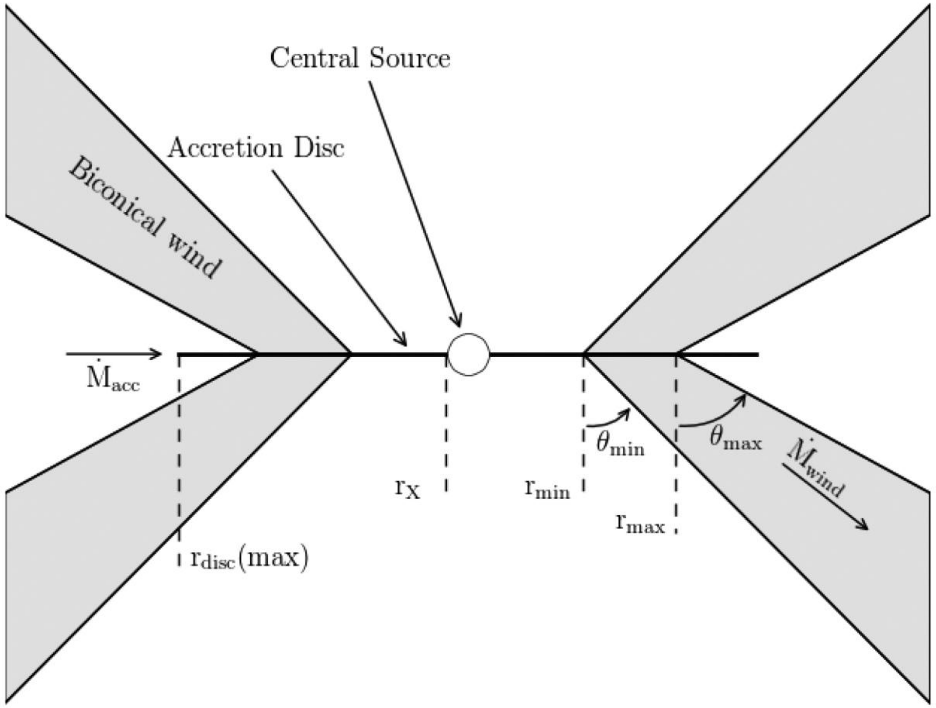
Next decade

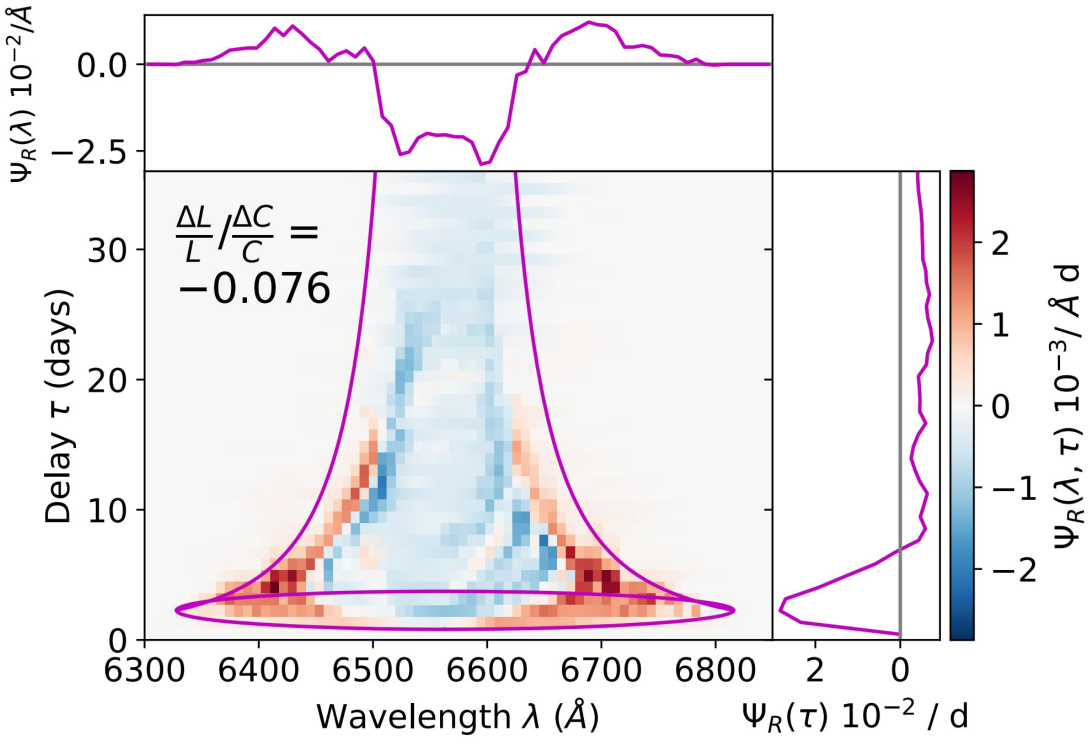
Substructures in BLRs & high-fidelity RM



e.g., Horne et al. (2004), Du et al. (2023), Wang et al. (2022)

Next decade
Substructures in BLRs & high-fidelity RM





Mangham et al. (2017)

Summary

- R-L relations
  - Shortened lags in super-Eddington AGNs
  - Lag measurements in luminous AGNs & intermediate-mass AGNs
  - R-L relations of multiple emission lines
- Velocity-resolved RM & BLR kinematics
  - Detailed study of NGC5548 from AGN STORM
  - Evolution of BLR kinematics driven by radiation variability
  - Sample size has been significantly expanded
  - What controls f factor?
  - Two BLR zones in super-Eddington AGN
- New phenomena
  - BLR "holiday"
  - Reverse of BLR stratification structure
  - A small inner BLR
- New applications
  - Spectro-Astrometry (Interferometry) + RM
  - Cosmological distance tools
  - Search of supermassive binary black holes
- More questions to answer…

Thanks!