Echo Tomography of Black Hole Accretion Flows in AGN

- 1: SDSS-RM: Composite Mean and RMS of 849 quasars
- The RMS spectrum fits $f_\nu \sim \nu^{1/3}$
- 2: STORM on NGC 5548: Continuum delay maps
- Disc inclination: $i = 36^\circ +/- 10^\circ$
- $\tau(\lambda)$ => Disc $T(R)$ is steeper than expected $T \sim R^{-1}$
- Disc surface brightness is lower than expected
- X-rays alone are not driving the UV/optical variations
- 3: STORM on NGC 5548: Emission-Line velocity-delay maps
- BLR is Keplerian from 2 to 20 light days
- $M_{\rm BH} = 7 \times 10^7\ {\rm M_{sun}}$. BLR inclination $i = 45^\circ$
- Sharp outer rim. Far side obscured. Barber-pole residuals.

SDSS-RM (Reverberation Mapping)

- PI: Yue Shen
- SDSS spectroscopic monitoring of 849 quasars (0.12<z<4.3) (plus ~100 comparison stars.)
- SDSS-III (2014, 32 epochs/6mo)
- SDSS-IV (2015-2019+..., 12 epochs /6mo)
- Bok+CFHT photometric (g,i) monitoring.

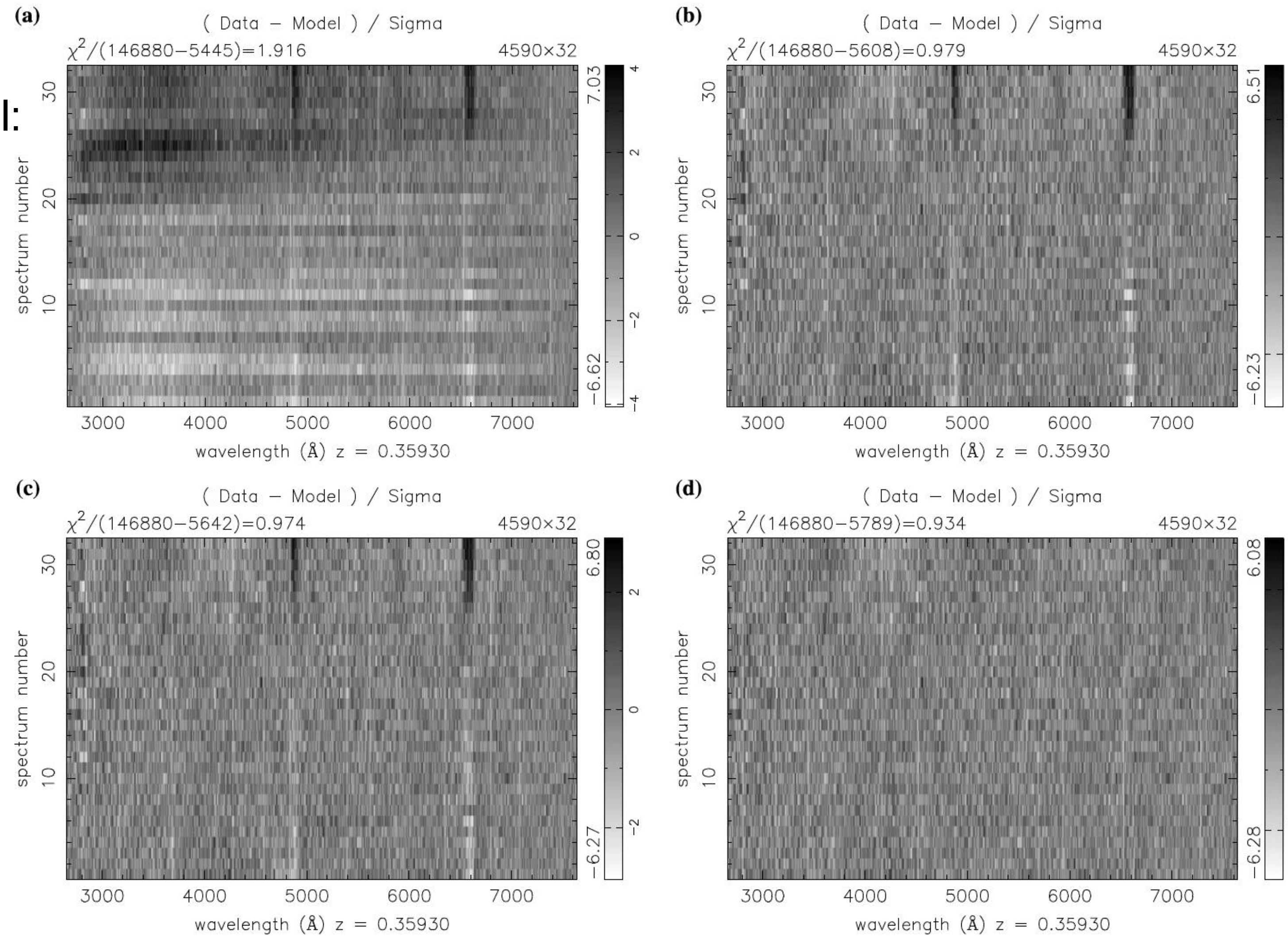
- Primary Goals: Measure light travel time delays.
- Emission-line lag vs continuum => black hole masses
- Continuum lag vs wavelength => accretion disk T(r) profiles.

- Pilot for SDSS-V => Black Hole Mapper

PrepSpec Analysis : Fit Residuals

Model:
A

AC



ACBF

ACF

Shen et al. 2016 ApJ 818, 30

PrepSpec : Mean and RMS spectra, Line and Continuum Lightcurves

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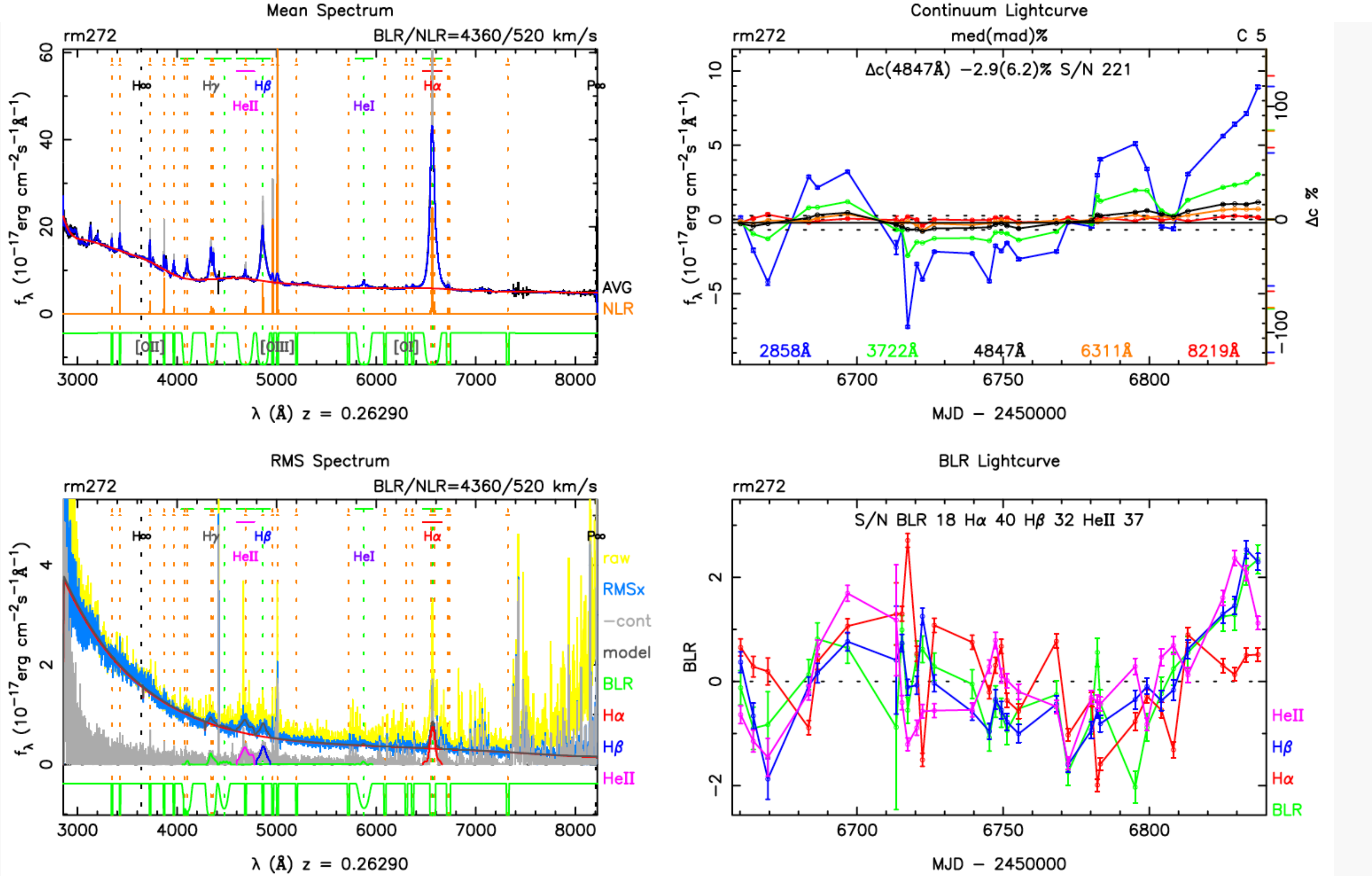
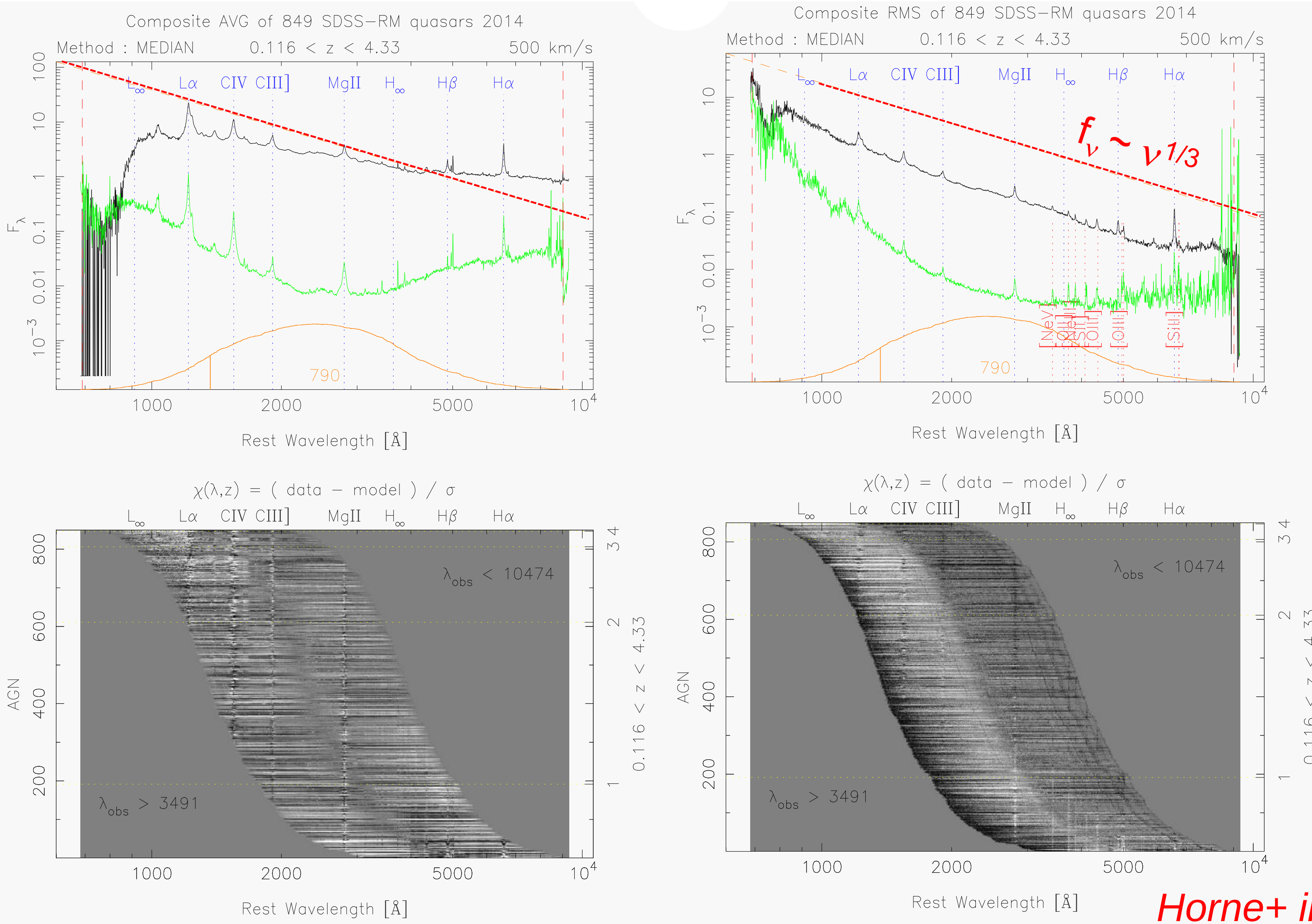


Composite Mean and RMS Spectra

- Composite Mean Spectrum

Composite RMS Spectrum

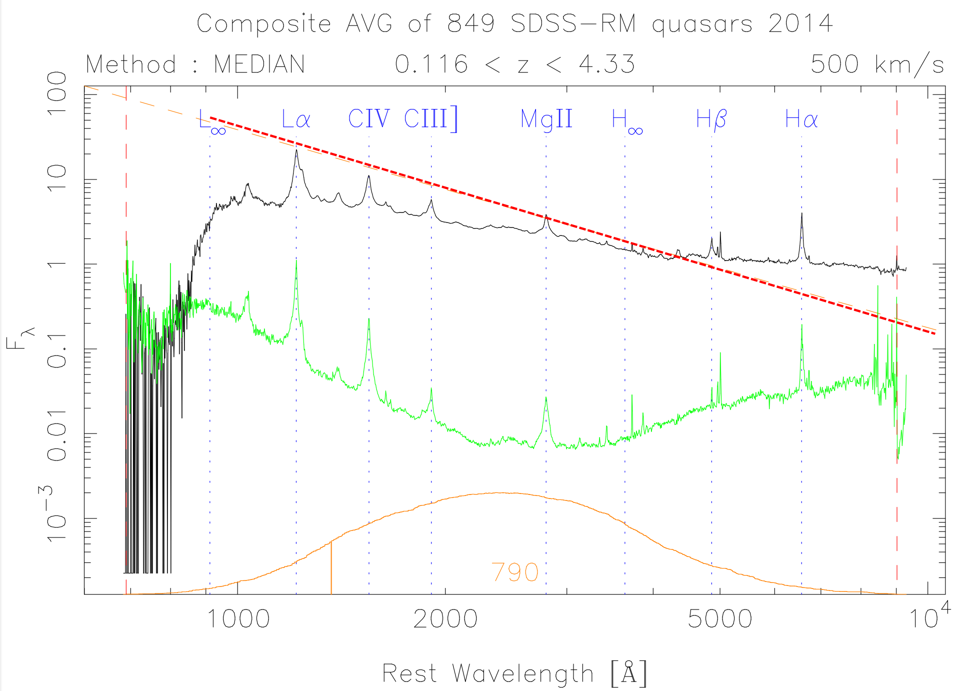


Horne+ in prep.

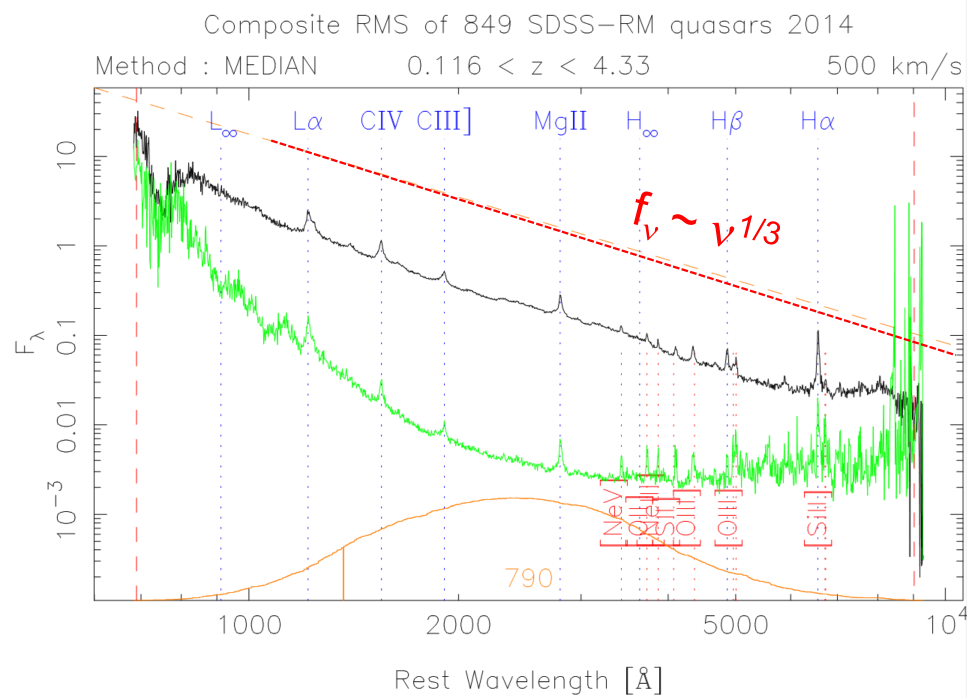
Composite Mean and RMS Spectra

Variations isolate the Disc Spectrum:

Composite Mean Spectrum



Composite RMS Spectrum



Horne+ in prep.

$$T \propto r^{-3/4} \Rightarrow f_\nu \propto \nu^{1/3}$$

2014 STORM Campaign : NGC 5548

STORM = Space Telescope and Optical Reverberation Mapping

PI: Brad Peterson HST+Swift+Chandra+ground 180d in 2014.

Published :

I : *HST*-COS observations. – De Rosa+ (2015) ApJ 806:128

II : *Swift-HST* continuum observations.– Edelson+ (2015) ApJ 806:129

III : Continuum interband lags, FUV+optical – Fausnaugh+ (2016) ApJ 821:56

IV : Anomalous behavior of UV emission lines – Goad+ (2016) ApJ 824:1

V : Optical emission line variations – Pei+ (2017) ApJ 837:131

VI : Accretion disk modeling – Starkey+ (2017) ApJ 835:65

VII : Chandra X-ray observations – Mathur+ (2017) ApJ 846:55

In the pipeline :

VIII : Absorption line variations – Kriss+ (2019) ApJ, in press.

IX : Velocity-delay maps – Horne+ (2019) ApJ, in prep.

X : Photoionization modeling – Dehghanian+(2019) ApJ, in press.

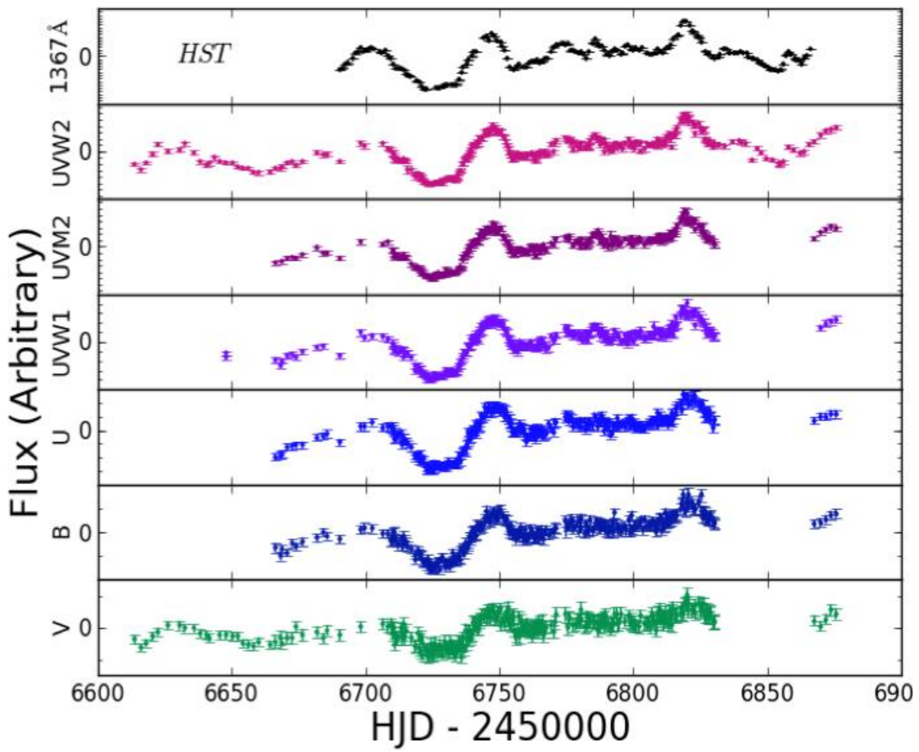
Dynamical modeling – Pancoast+

NIR and *Spitzer* observations – TBD

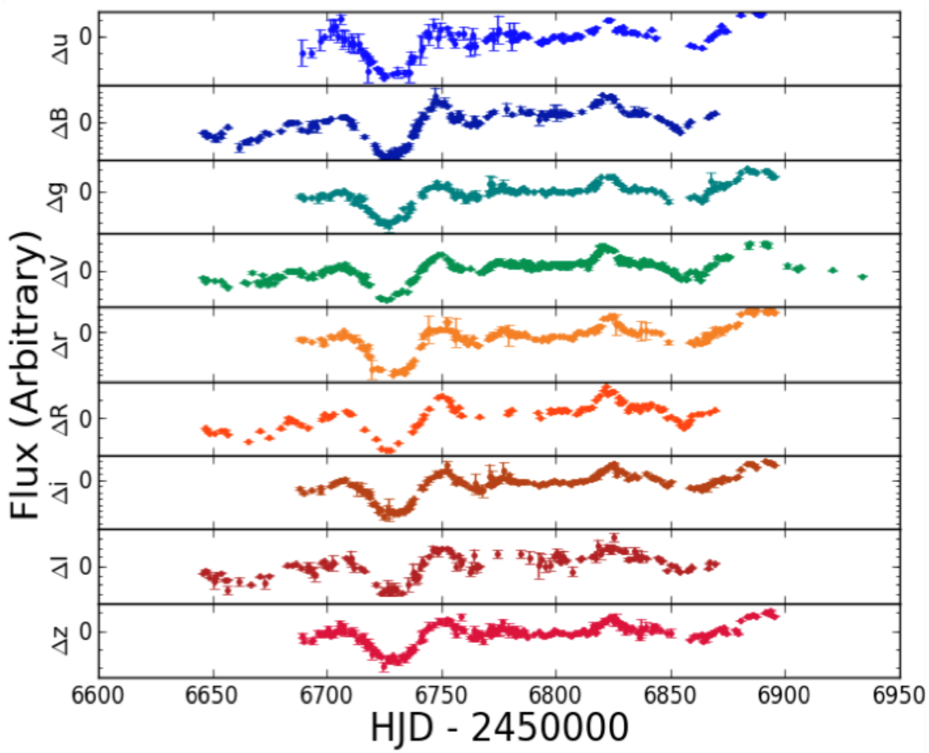
STORM: UV, optical lightcurves

HST: 1/day *SWIFT:* 2 /day

Ground-based > 600 epochs



Edelson, et al. 2015

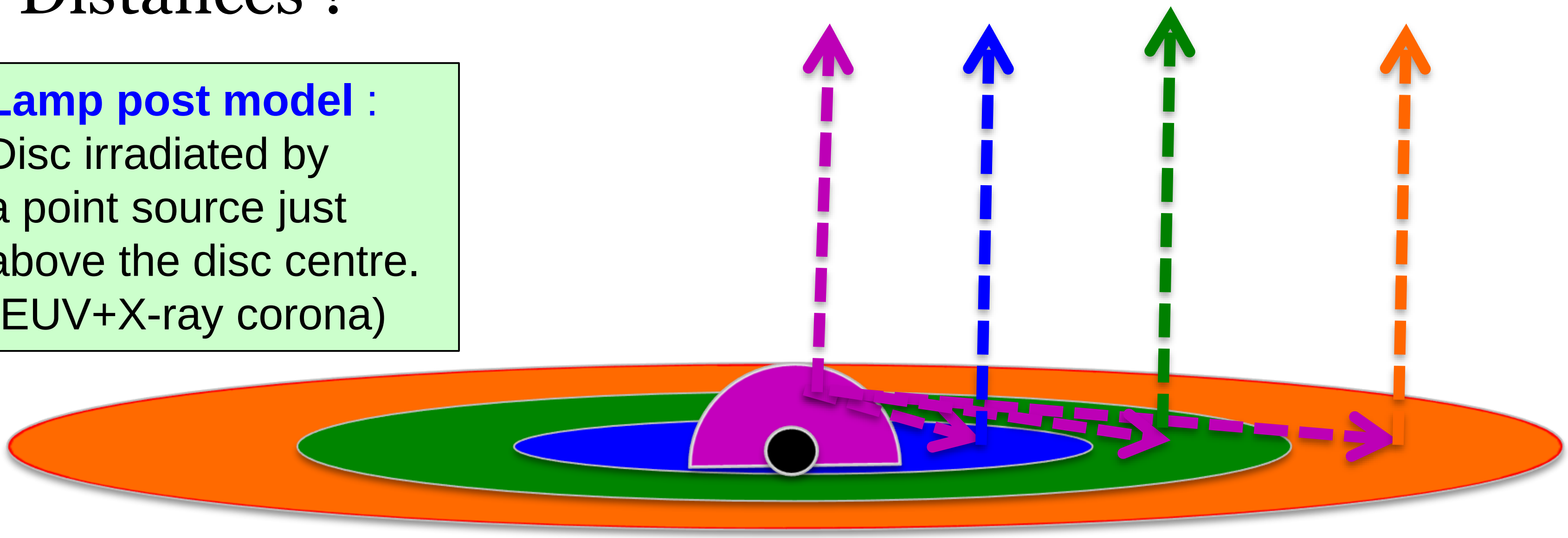


Fausnaugh, et al. 2016

Continuum Echo Mapping : T(R) profiles of Accretion Discs

- Measure the time delay spectrum $\tau(\lambda)$
- To find the disk temperature profile $T(R)$
- Test disc models: $T \sim (M\, dM/dt)^{1/4}\, R^{-3/4} \Rightarrow \tau \sim \lambda^{4/3}$
- Measure Mass x Accretion Rate ($M\, dM/dt$)
- Distances ?

Lamp post model :
Disc irradiated by
a point source just
above the disc centre.
(EUV+X-ray corona)



Accretion Disk Reverberations

Assumptions:

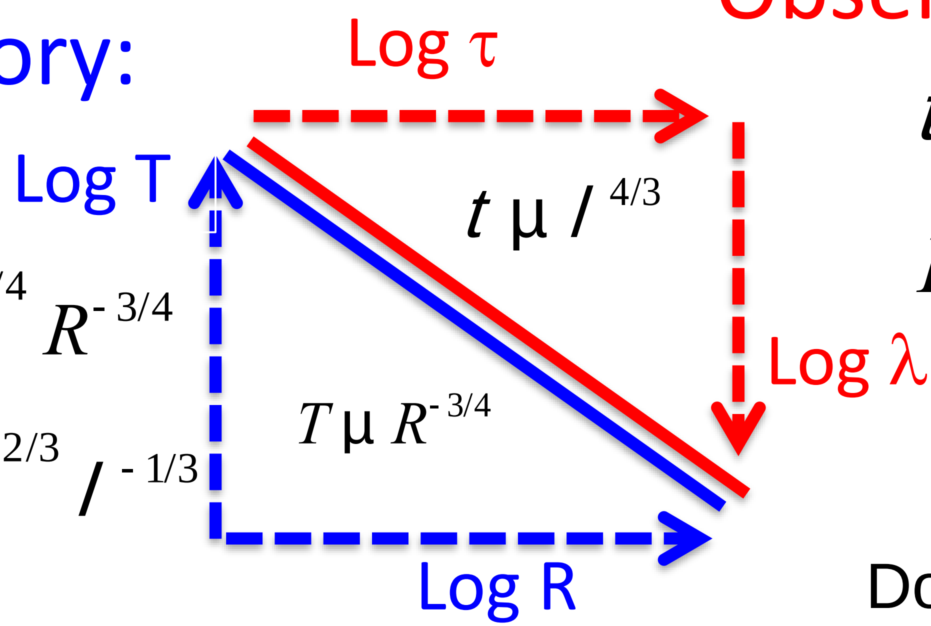
Light travel time: Thermal Emission: Flat geometry:

$$R \sim c\,t \qquad T \sim \frac{h\,c}{5k\,\lambda} \qquad d\Omega = \frac{2\pi\,R\,dR\cos i}{D^2}$$

Disc Theory:

$$T \propto \left(M\,\dot{M}\right)^{1/4} R^{-3/4}$$

$$L_\nu \propto \left(M\,\dot{M}\right)^{2/3} \lambda^{-1/3}$$



Observables:

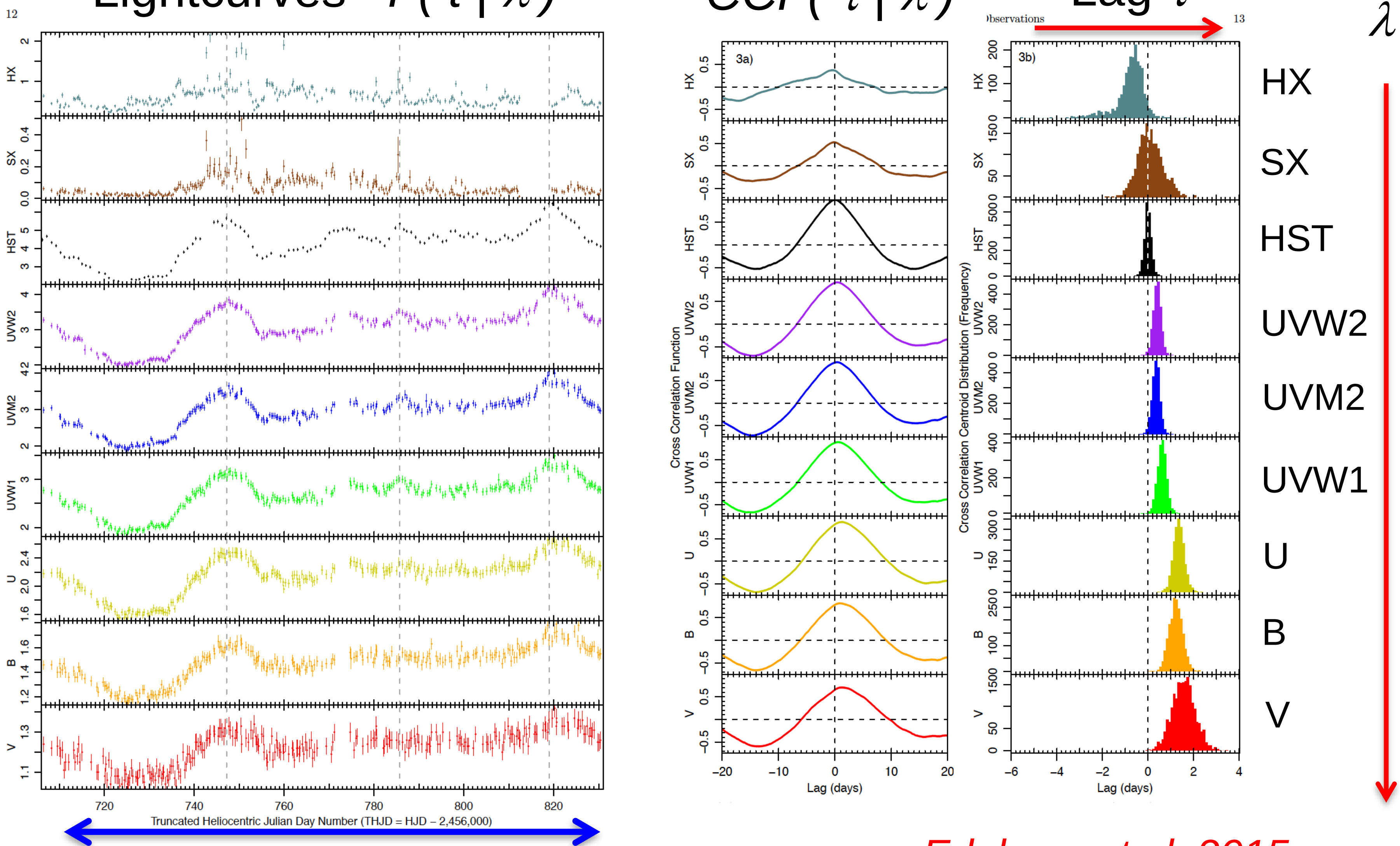
$$\tau \propto \left(M\,\dot{M}\right)^{1/3} \lambda^{4/3}$$

$$F_\nu \propto L_\nu \cos(i) / D^2$$

Do these agree?

NGC 5548 STORM : Swift Data

Lightcurves $F(t \mid \lambda)$ | $CCF(\tau \mid \lambda)$ | Lag τ

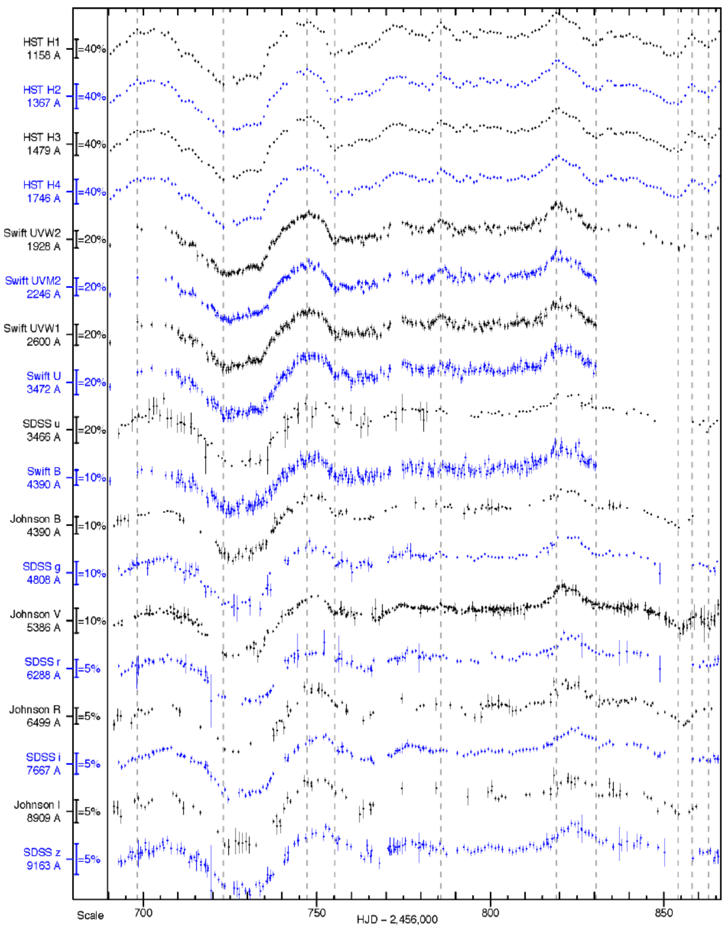


120 days

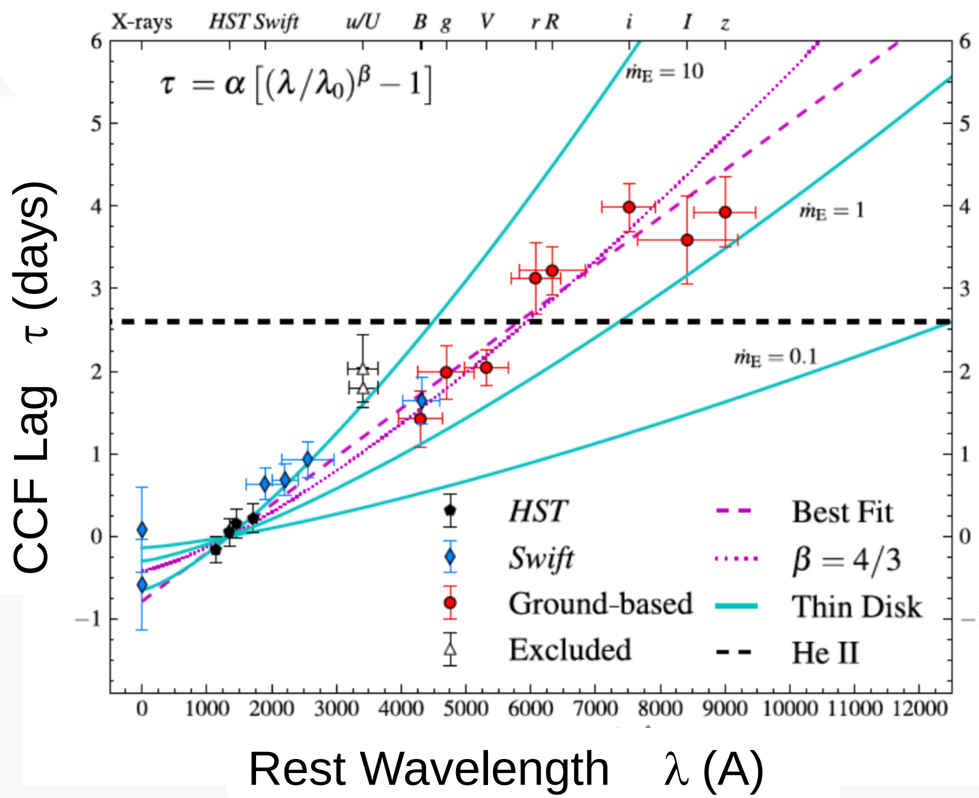
Edelson, et al. 2015

Lightcurves $f(\lambda,t)$ => CCF Lags $\tau(\lambda)$

UV (1150 A)



Optical (9000 A)

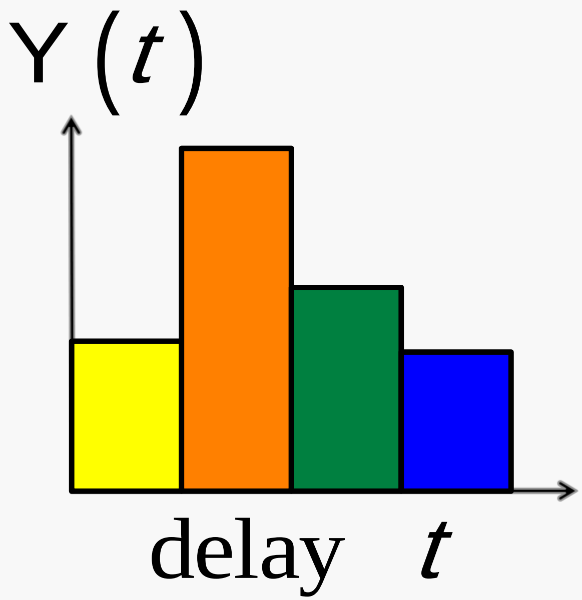


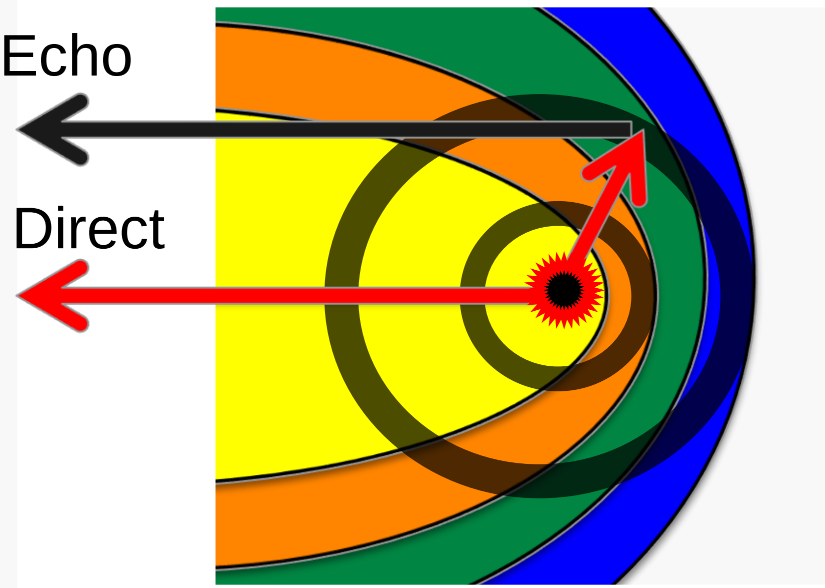
UV lightcurves (HST, Swift)
Optical lightcurves (LCO+LT+… many telescopes)
Cross-correlate to find time delay vs wavelength.

Fausnaugh, et al. 2016

Echo Tomography
Beyond CCF Time Lags

Light travel time delay τ "slices up" the region on iso-delay paraboloids. => micro-arcsec resolution.

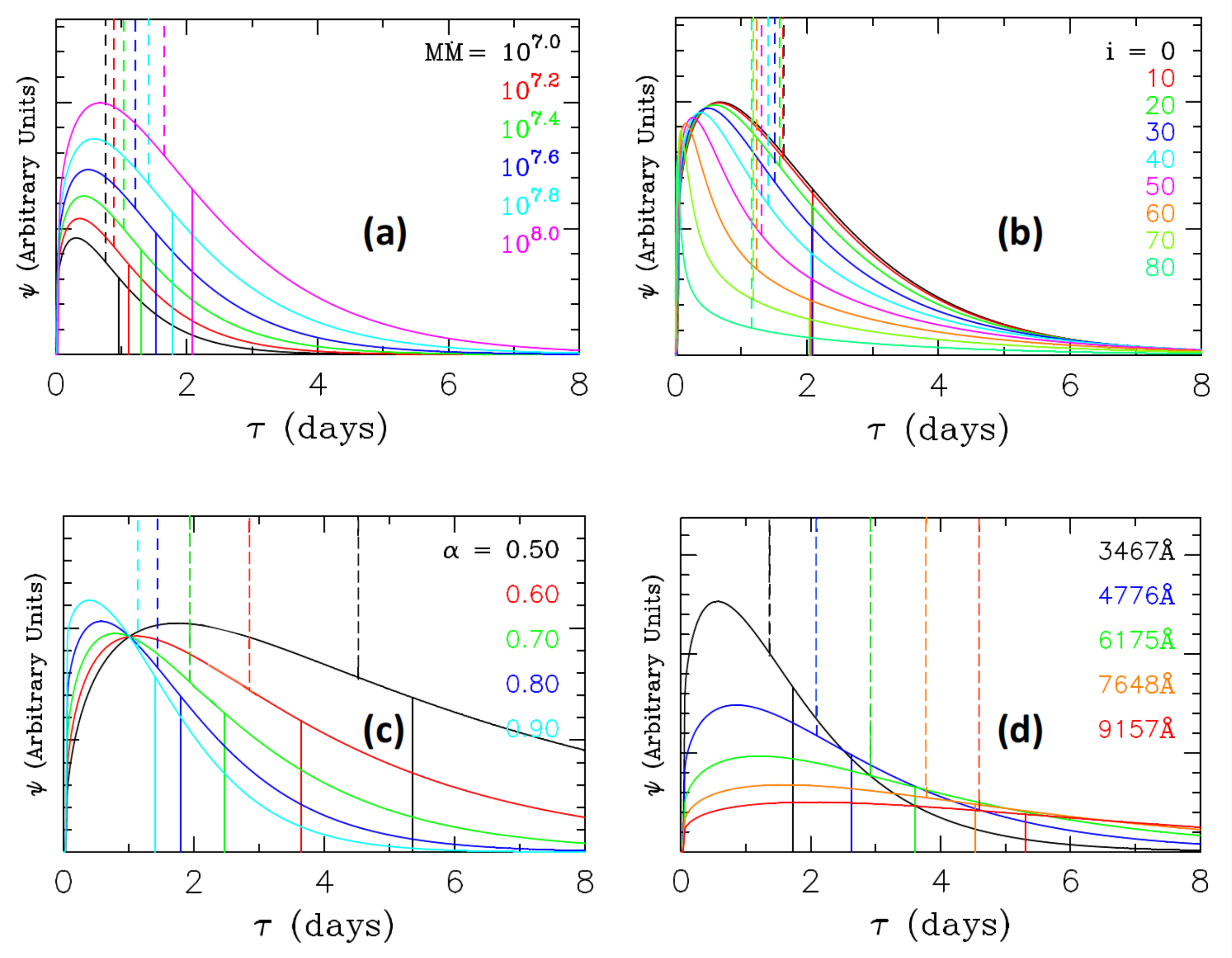




$$t = \frac{R}{c}\left(1 + \cos q\right)$$

Blackbody Disc Delay Maps

$T(R) = T_1 (R / R_1)^{-\alpha}$



Mean delay
$< \tau > \sim (M\ Mdot)^{1/3}\ \lambda^{4/3}$
Independent of
disk inclination.

Delay map shape
depends on
disk inclination

And slope α of
$T(r) \sim R^{-\alpha}$
temperature profile

Theory: $\alpha = 3/4$

Starkey, et al. 2016

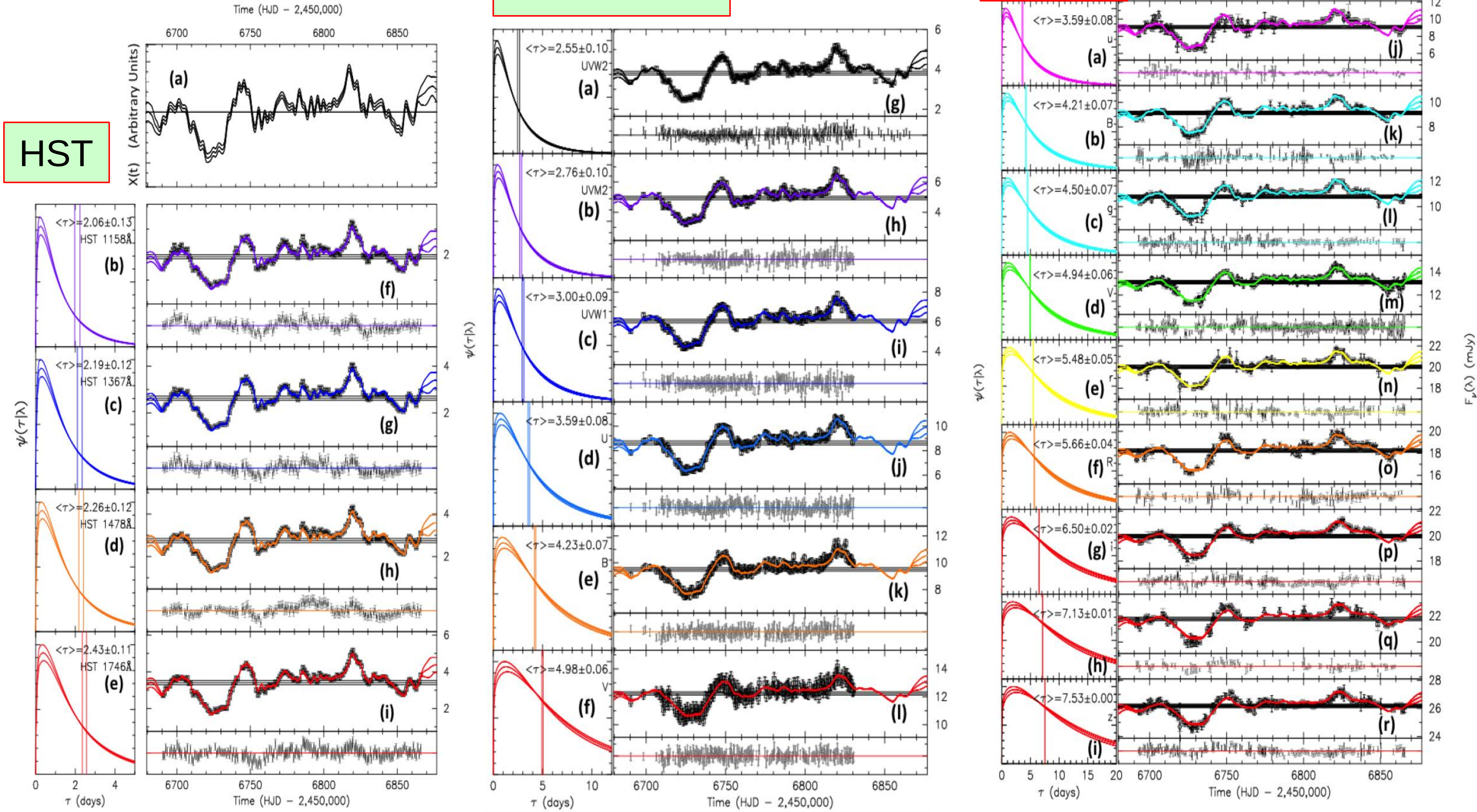
CREAM : MCMC Lightcurve Fits

Driving Lightcurve X(t)

Swift UV/OT

Optical

HST



Starkey, et al. 2017

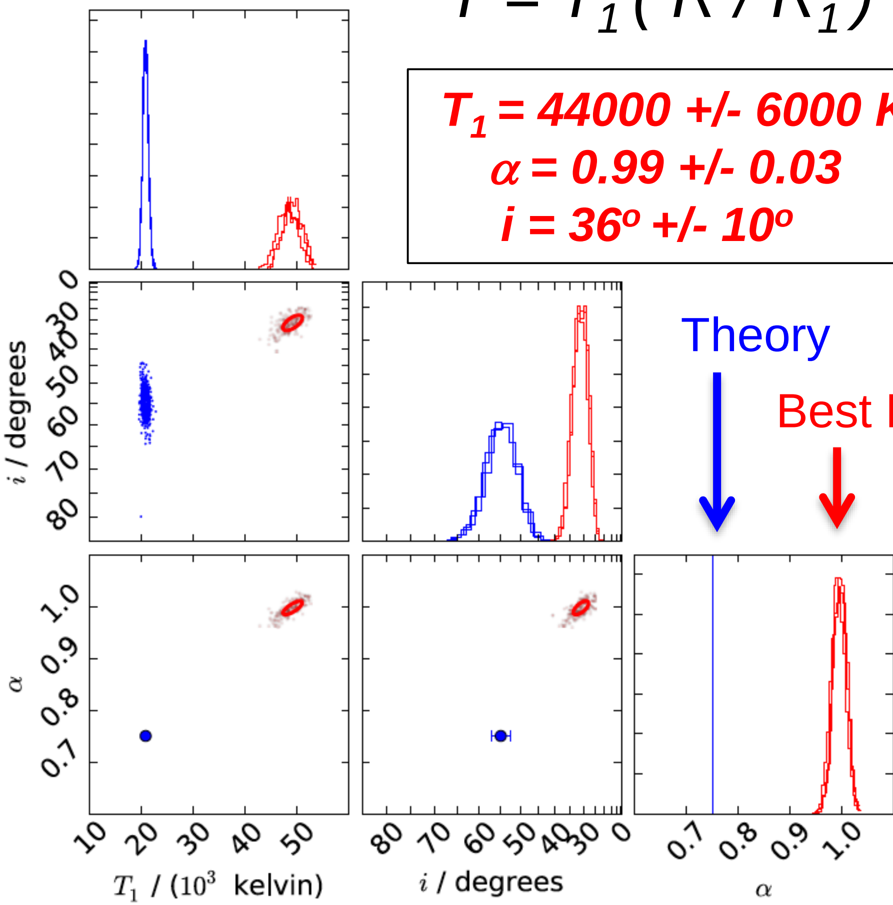
T(R) Profile

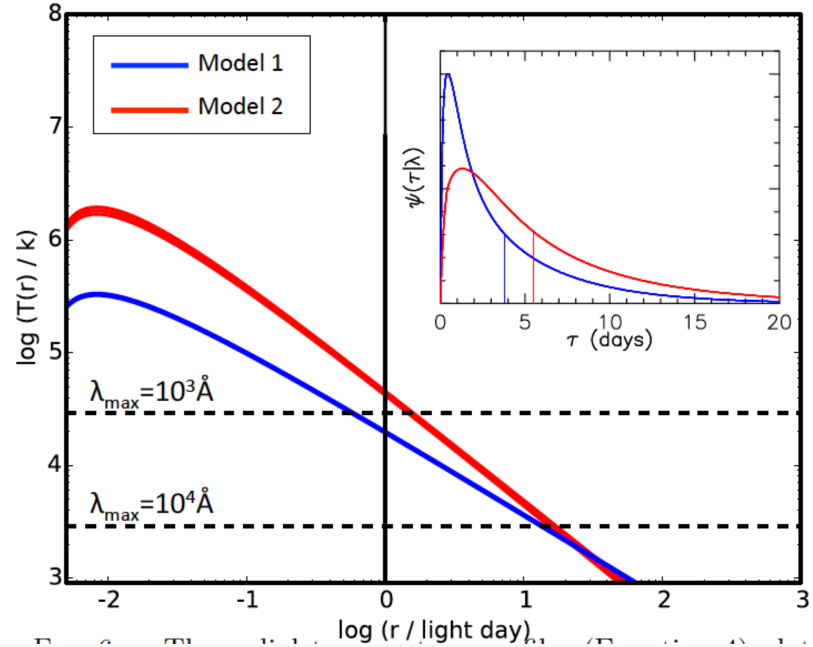
steeper than expected.

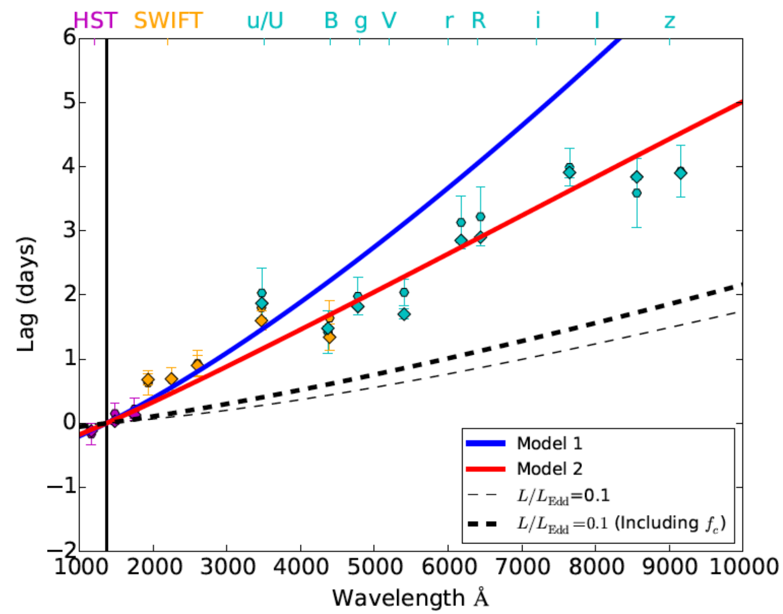
$T \sim R^{-1}$ rather than $R^{-3/4}$.

$$T = T_1 \, (R / R_1)^{-\alpha}$$

T_1 = 44000 +/- 6000 K
α = 0.99 +/- 0.03
i = 36^o +/- 10^o





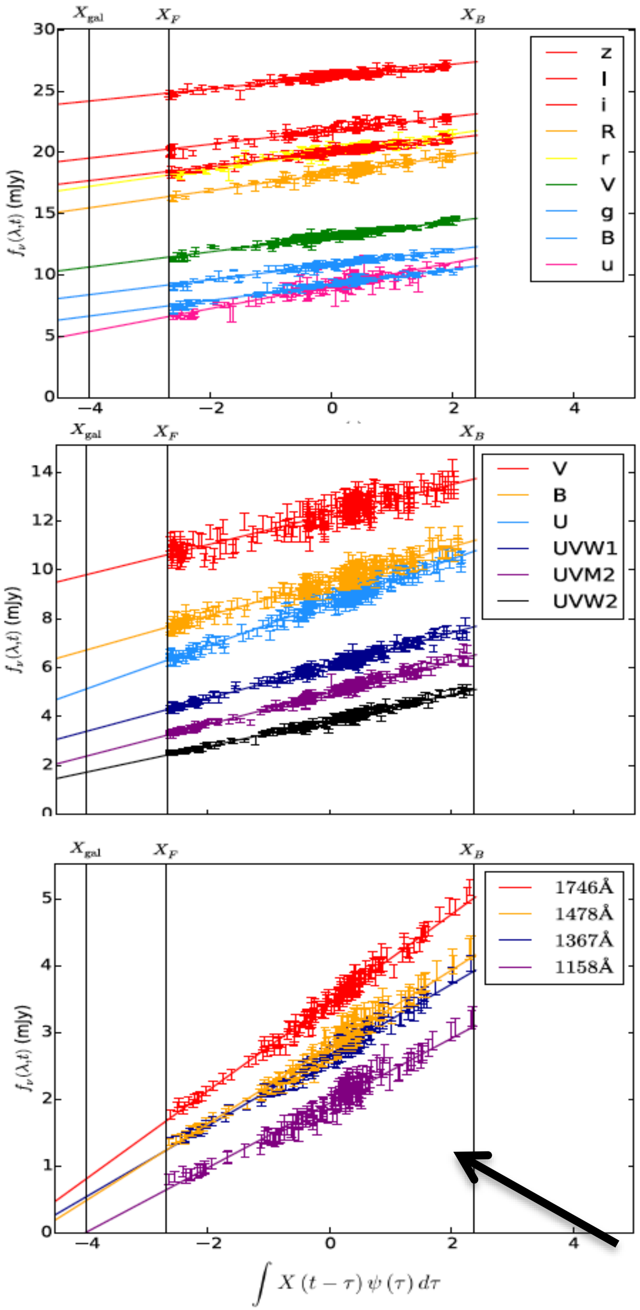


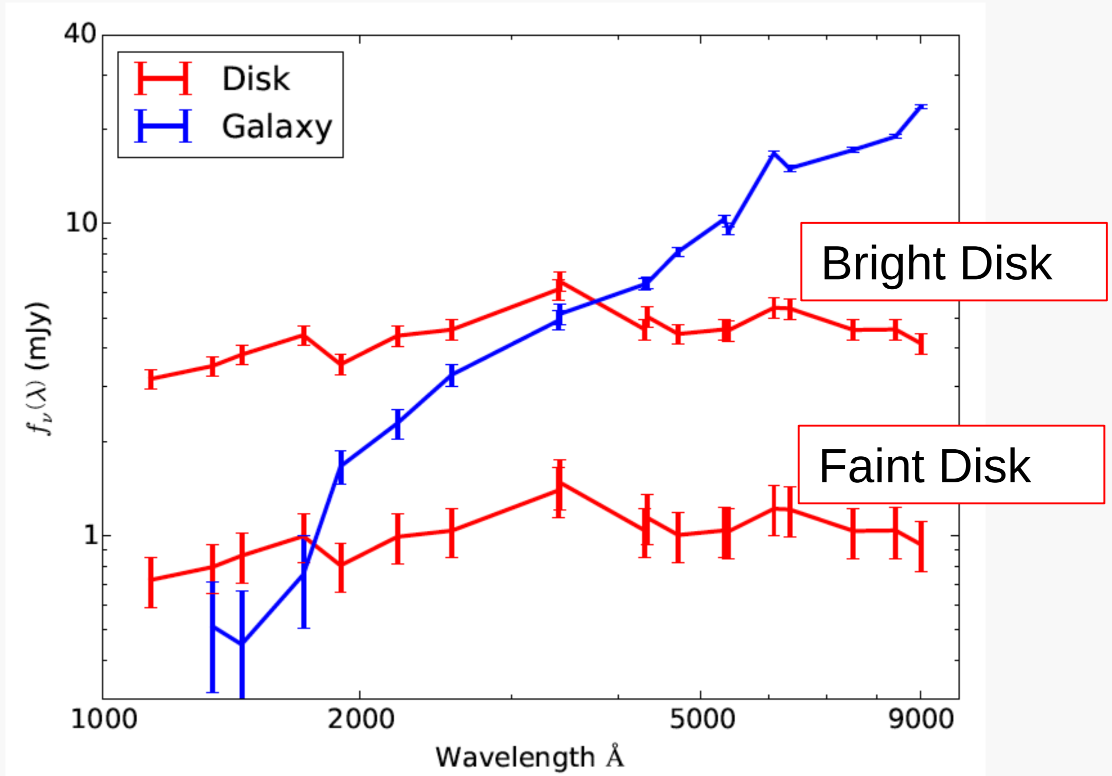
Starkey, et al. 2017

Disc Spectrum

Use ***variations*** to isolate the Disc Spectrum

$$F(\lambda, t) = A(\lambda) + S_{disk}(\lambda)\, X(t)$$
$$= G(\lambda) + S_{disk}(\lambda)\, (X(t) - X_G)$$
$$\langle X \rangle = 0 \qquad \langle X^2 \rangle = 1$$



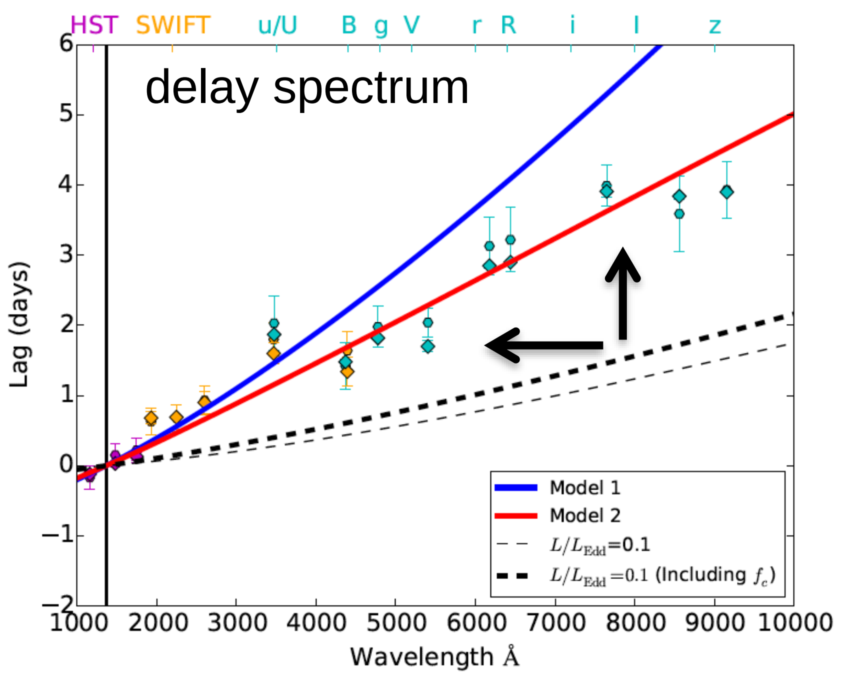


Note linear variations
over x5 in flux at 1158A

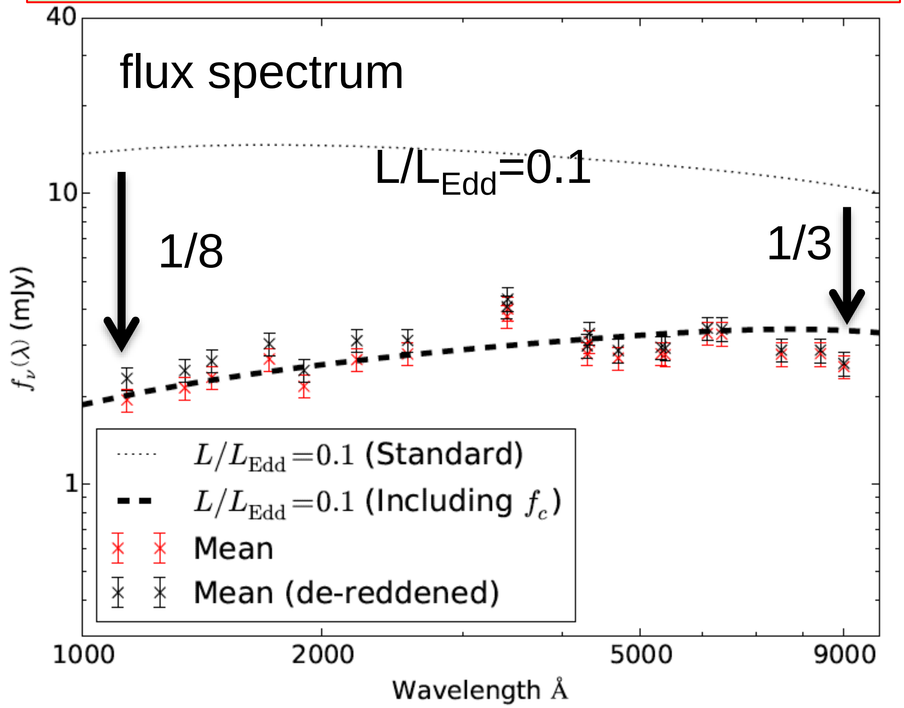
Starkey, et al. 2017

Standard Disc Model Fails ☹

Disc $\tau(\lambda)$ => $T(R)$ steeper than expected ($T \sim R^{-1}$ vs $R^{-3/4}$)



Disc $f_\nu(\lambda)$ is fainter than expected (for L/L_{Edd}=0.1)



How does the standard disc model fail?

Disk is too hot (or large).

T(R) is too steep.

Surface brightness is too dim.

Starkey, et al. 2017

Why does the disc model fail ?

Dust ? (affects flux but not delay)

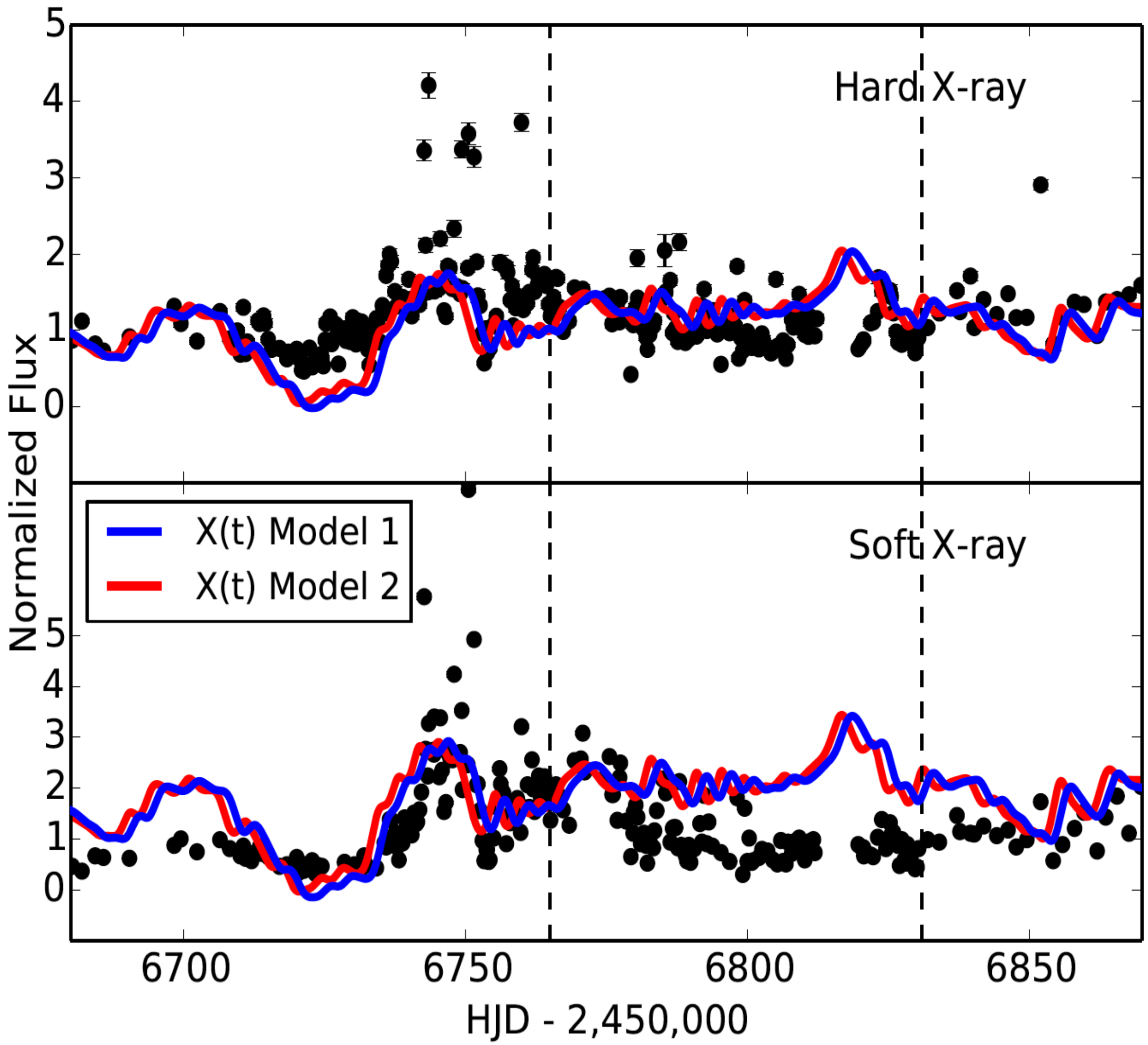
Wrong M_{BH}? (higher / lower L_{edd})

Diffuse continuum from BLR ?

Patchy irradiation (shadows) ?

Tilted inner disc ?

X-rays vs Driving Lightcurve

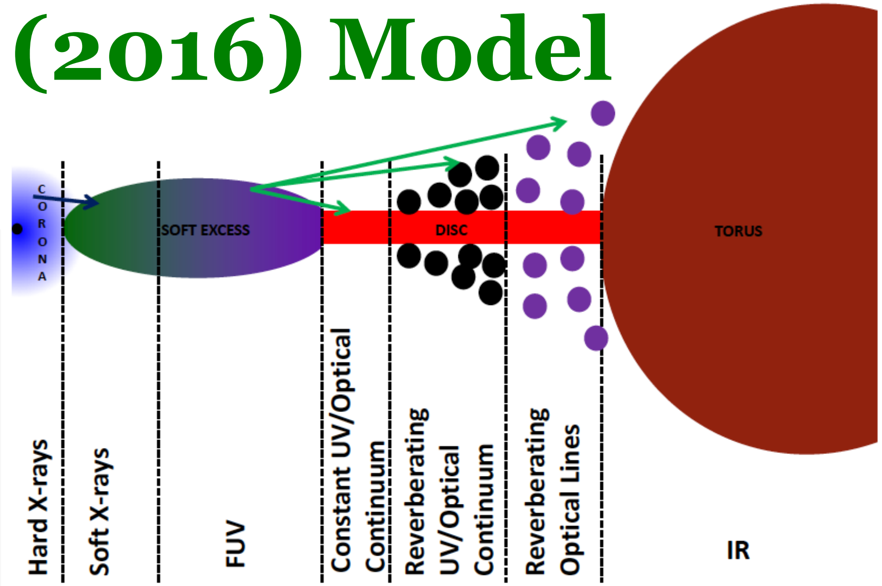


X-ray variations don't match the inferred driving lightcurve. ☹

UV variations do. ☺

Starkey, et al. 2017

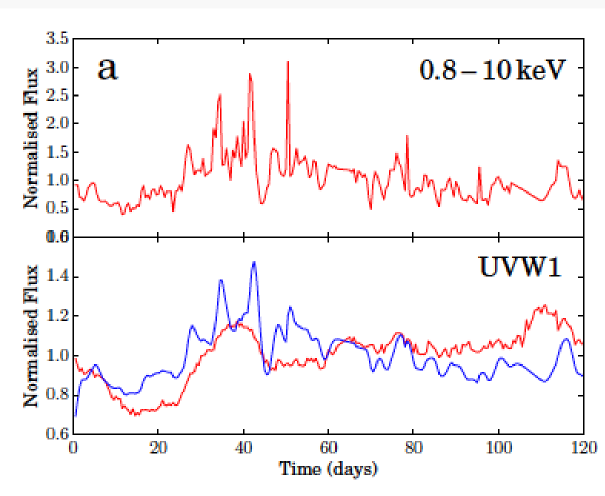
Gardner & Done (2016) Model



Two-stage reprocessing ?

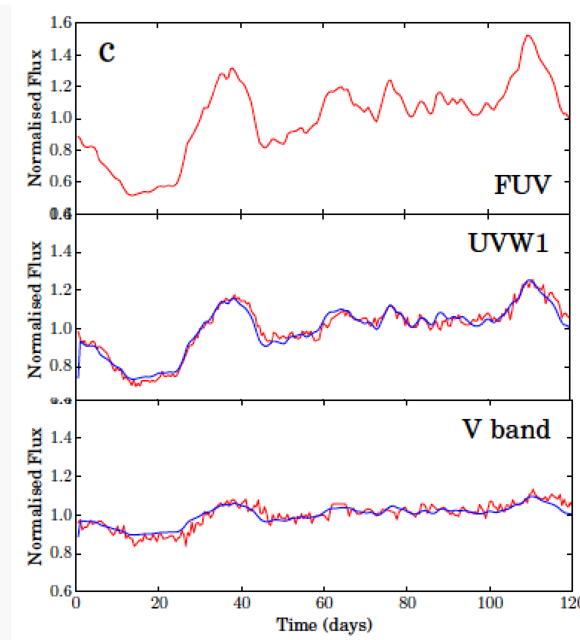
1. X-rays heat FUV torus.

2. FUV torus heats the accretion disk and BLR



☹

Need more delay smearing
to blur the rapid X-ray variations.



☺

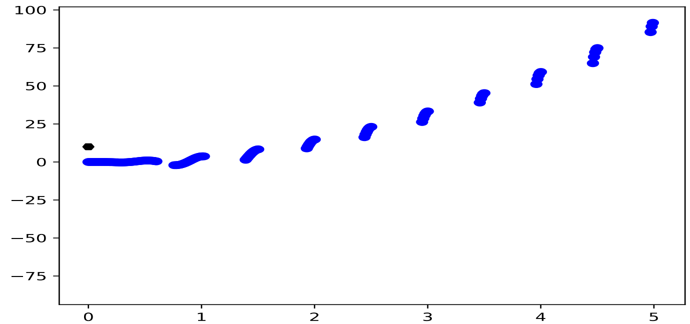
☺

Gardner & Done, 2016

Warps/Waves/Ripples on the Disc ?

- Wave crests see the lamp-post.
- Shadows fill the troughs.
- Steepens *T(R)* profile, lowers surface brightness.

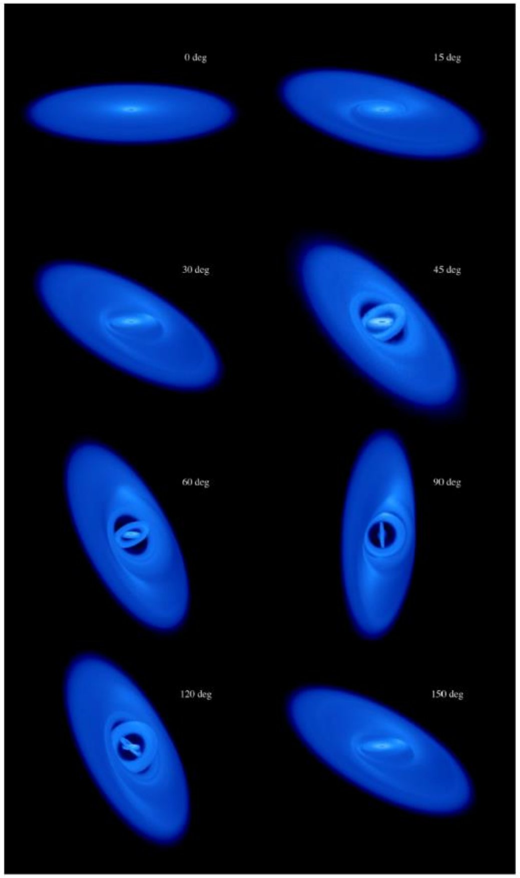
Starkey, Lin, Horne, in prep



- Tilted inner disc (aligning with BH spin).
- Anisotropic irradiation, self-irradiation.
- Precession (rotating structure) observable?

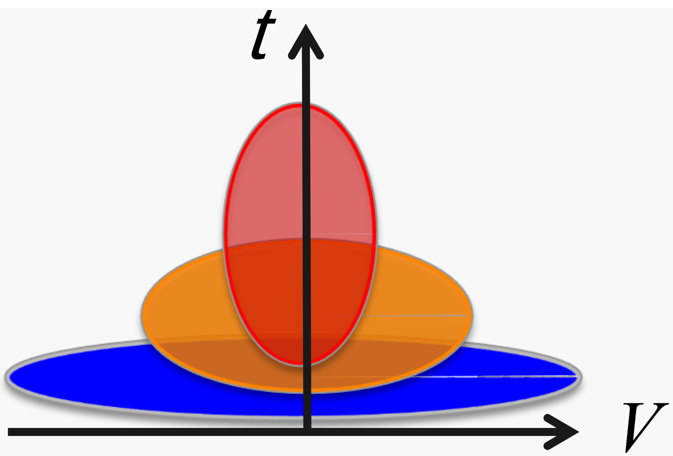
Nealon, Price, Nixon 2015 MNRAS

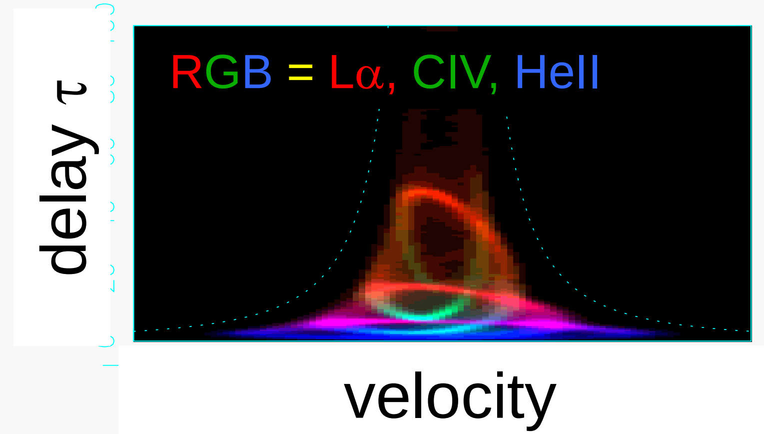
3d SPH simulations



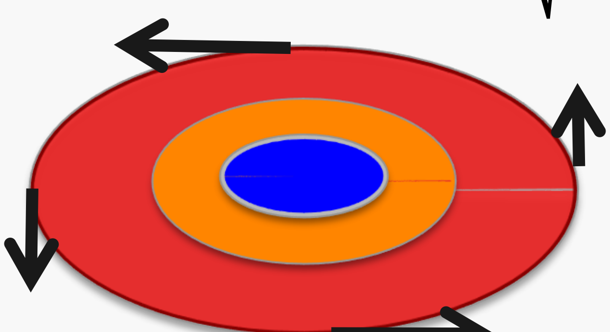
2D : Velocity-Delay Maps Ψ(v, τ)

Simulation: Photo-ionised Keplerian disc with spiral density waves

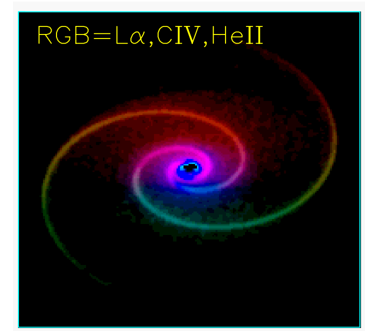




$$t = \frac{R}{c}\left(1 + \sin i \cos q\right) \qquad V = \sqrt{\frac{GM}{R}} \sin i \sin q$$

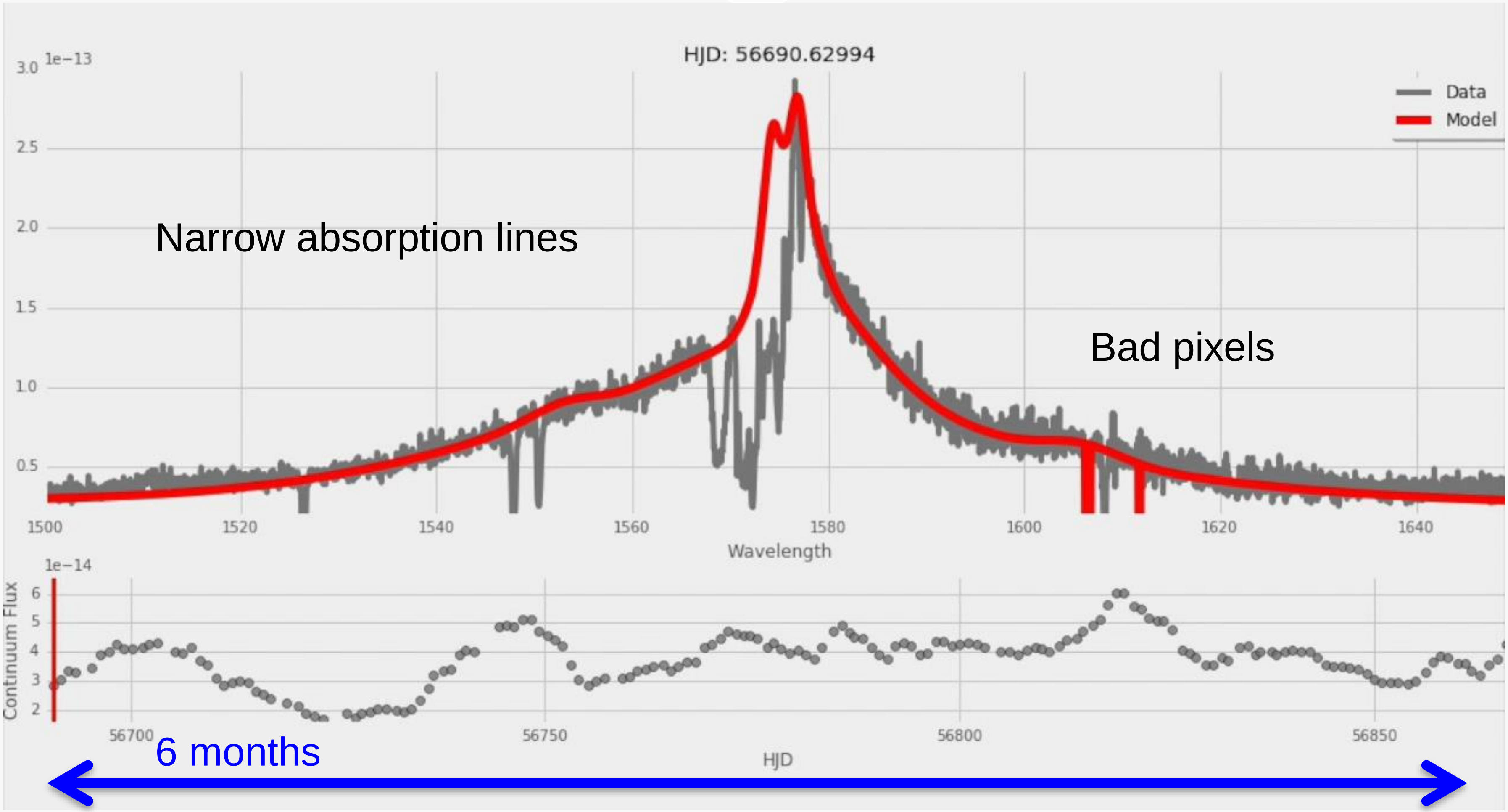


sky view:



Horne, et al. 2004

STORM : 172 Daily HST/COS Spectra
C IV Variations



De Rosa, et al. 2015

CCF Lags => BLR size R/c~6d

AGN STORM
***HST* PROGRAM**

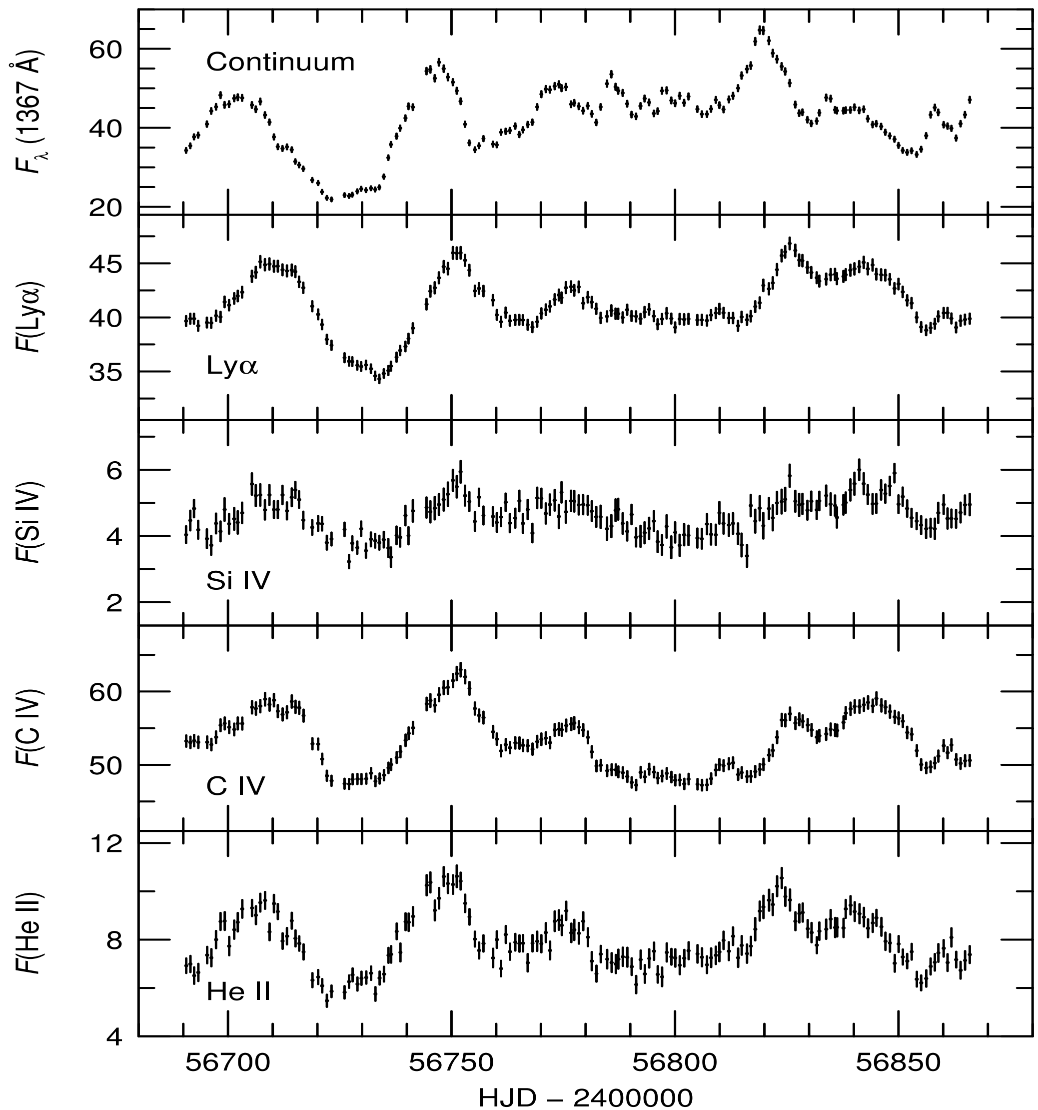
Mean lags relative to 1367 Å continuum

Ly α	6.19 ± 0.27 days
Si IV	5.44 ± 0.70 days
C IV	5.33 ± 0.46 days
He II	2.50 ± 0.33 days

Cross-correlation lags

$< \tau > \sim R / c$

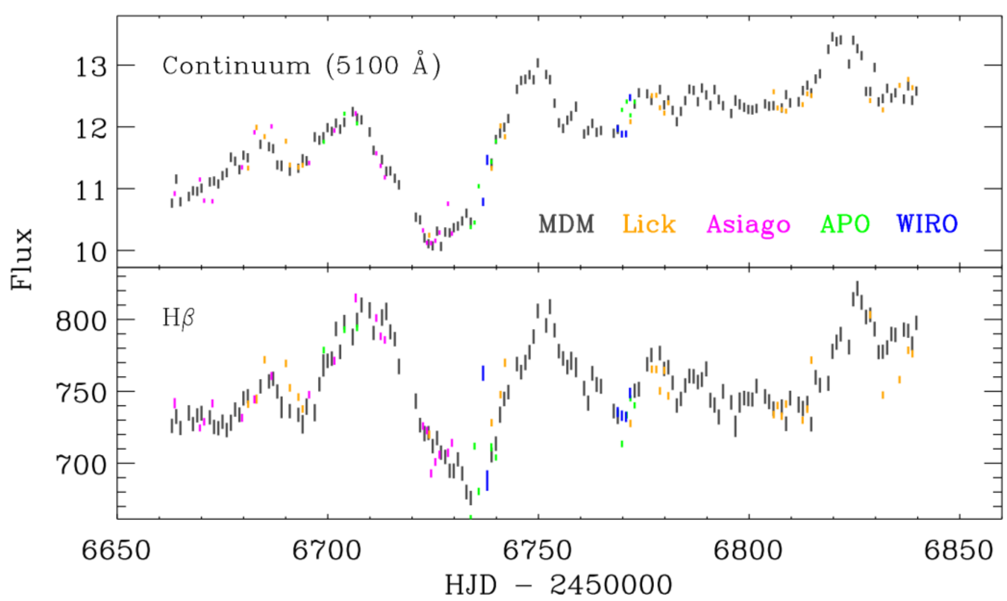
=> radius *R* of emission-line region



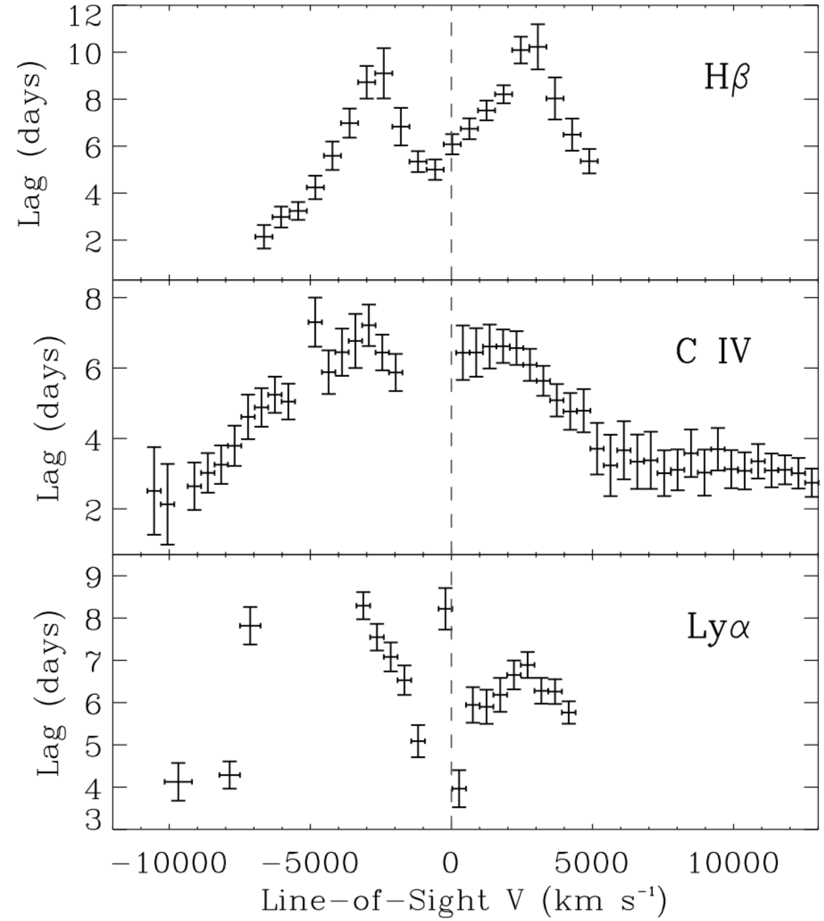
De Rosa, et al. 2015

M-shaped Velocity-Delay Structure

5100A + Hβ lightcurves



Velocity-resolved CCF delays



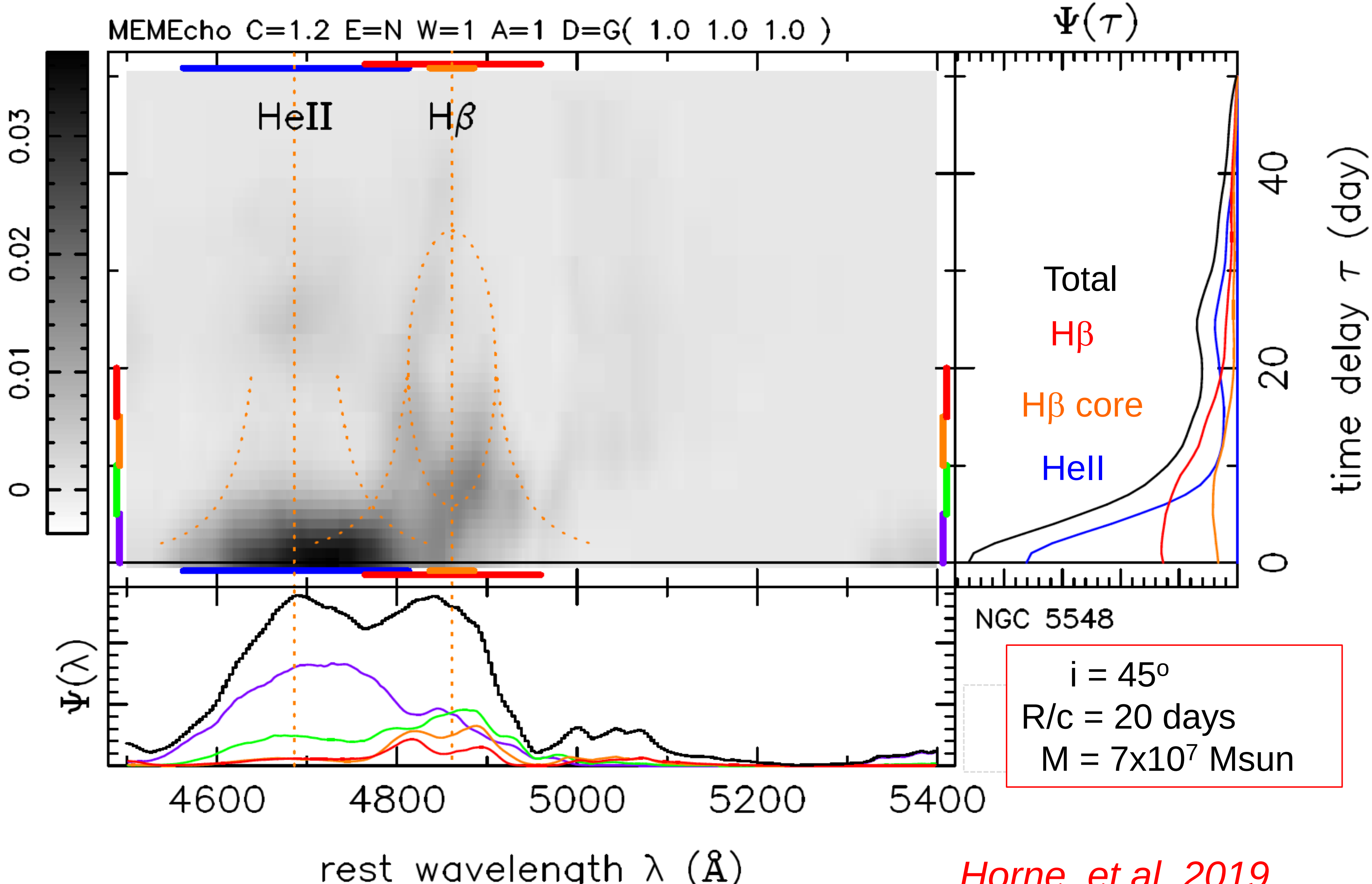
M-shaped τ(V) structure

6-day delay at V = 0

Similar for Lα, CIV, Hβ

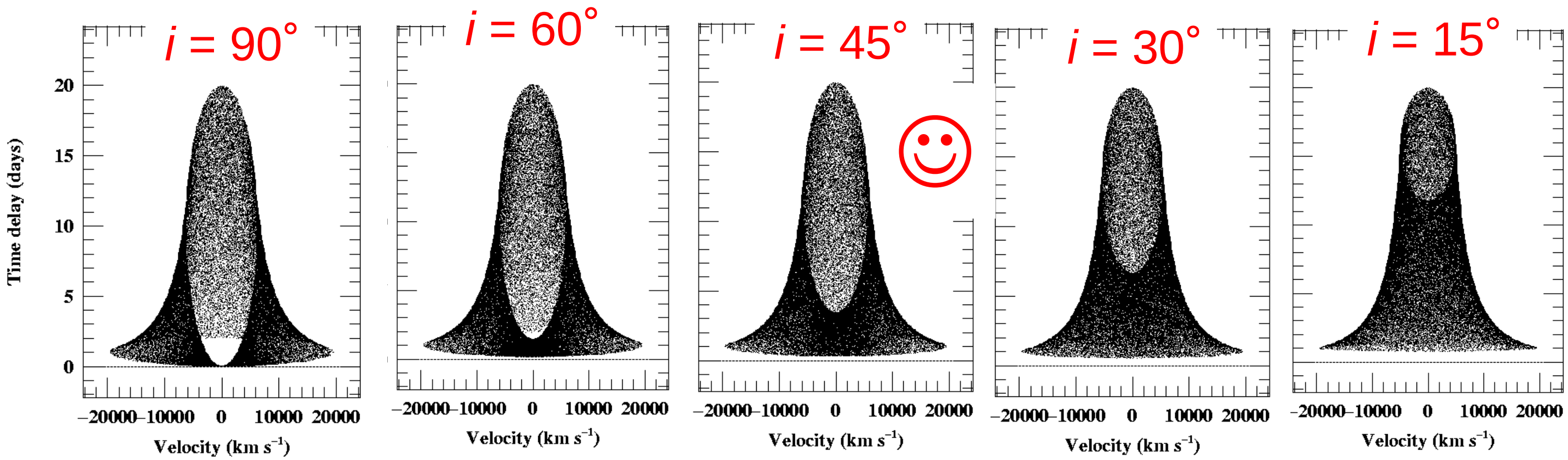
Pei, et al. 2017

Optical lines : Velocity-Delay Map



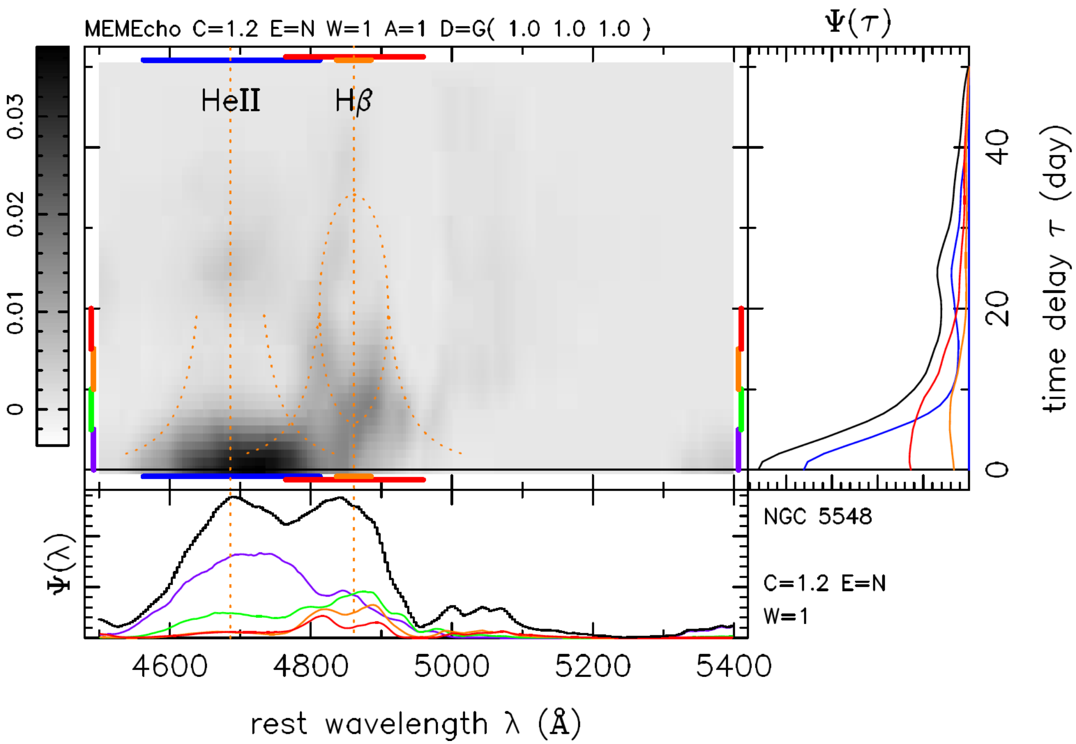
Horne, et al. 2019

Comparison with Toy Models

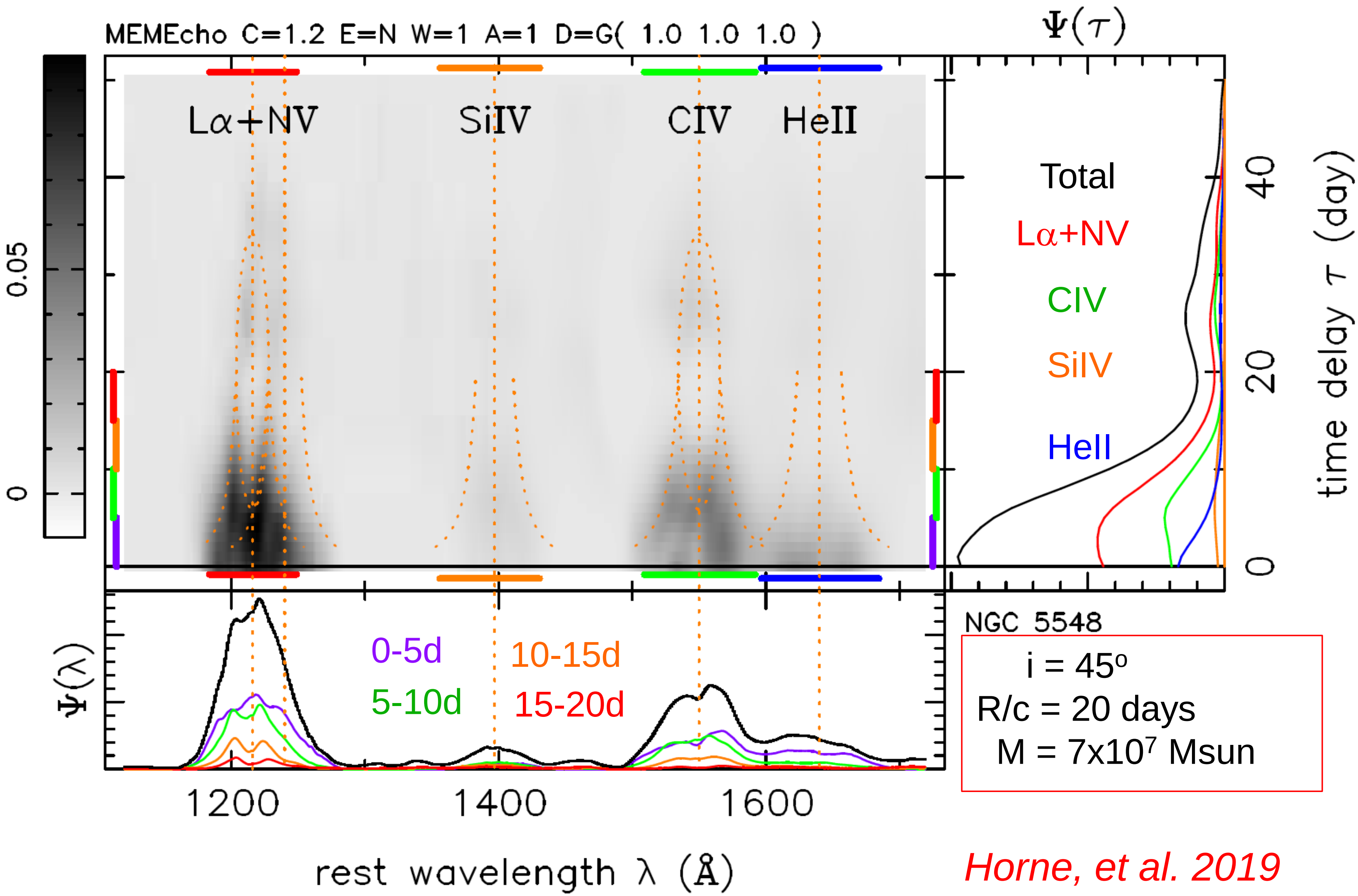


Keplerian Envelope
+ Elliptical Ring
➔
Disc-like Geometry
and Kinematics
2 to 20 light days

i = 45°
R/c = 20 days
M = 7x10^7 Msun



HST (UV lines) Velocity-Delay Map



Horne, et al. 2019

“Barber-Pole” Residuals

Model :

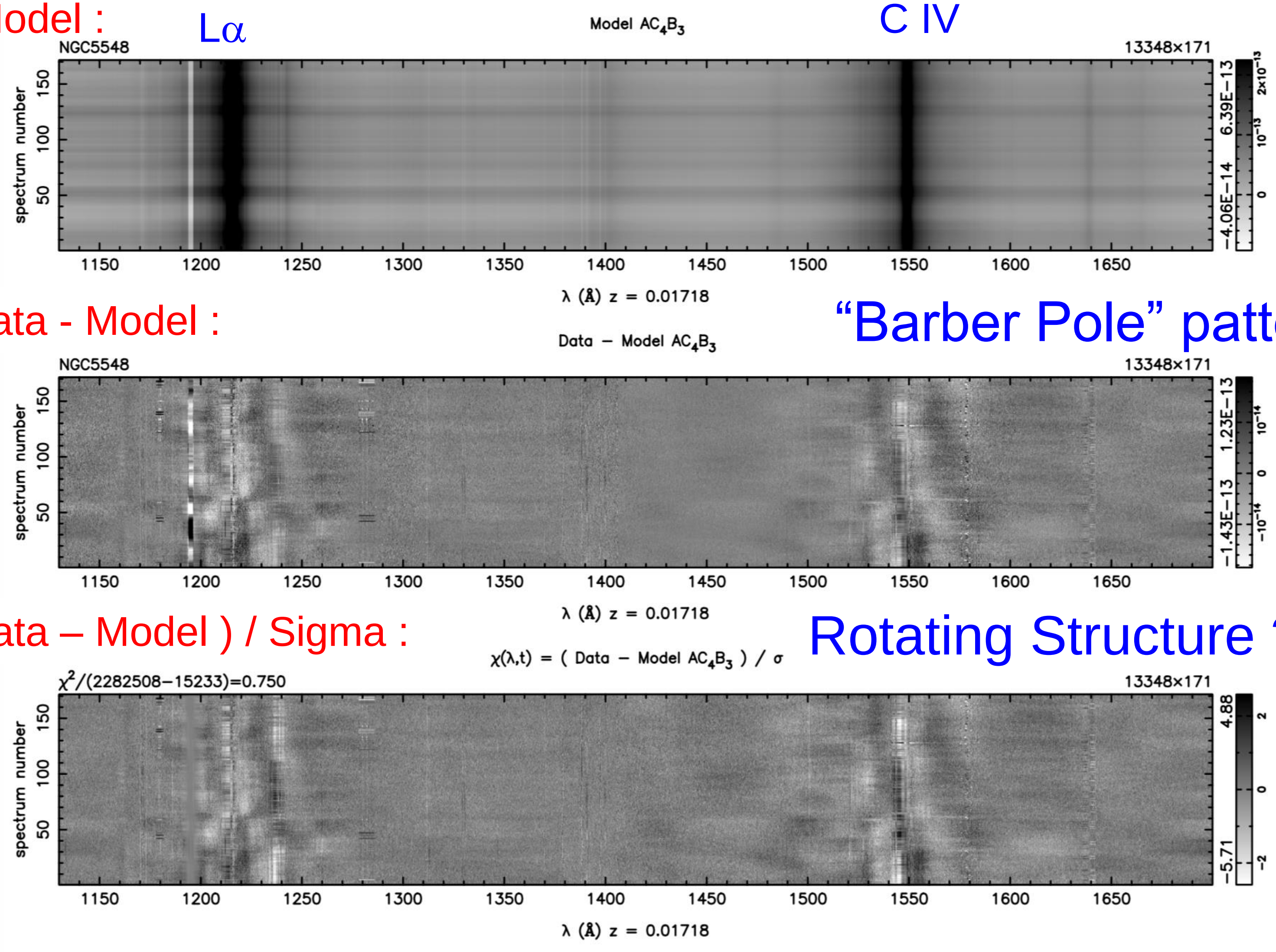
Lα

C IV

Data - Model :

(Data – Model) / Sigma :

Time =>



“Barber Pole” pattern.

Rotating Structure ?

Wavelength =>

Horne, et al. 2019

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- $M_{BH} = 7 \times 10^7\ M_{sun}$. BLR inclination $i = 45^o$
- Sharp outer rim. Far side obscured. Barber-pole residuals.

Thanks for Listening