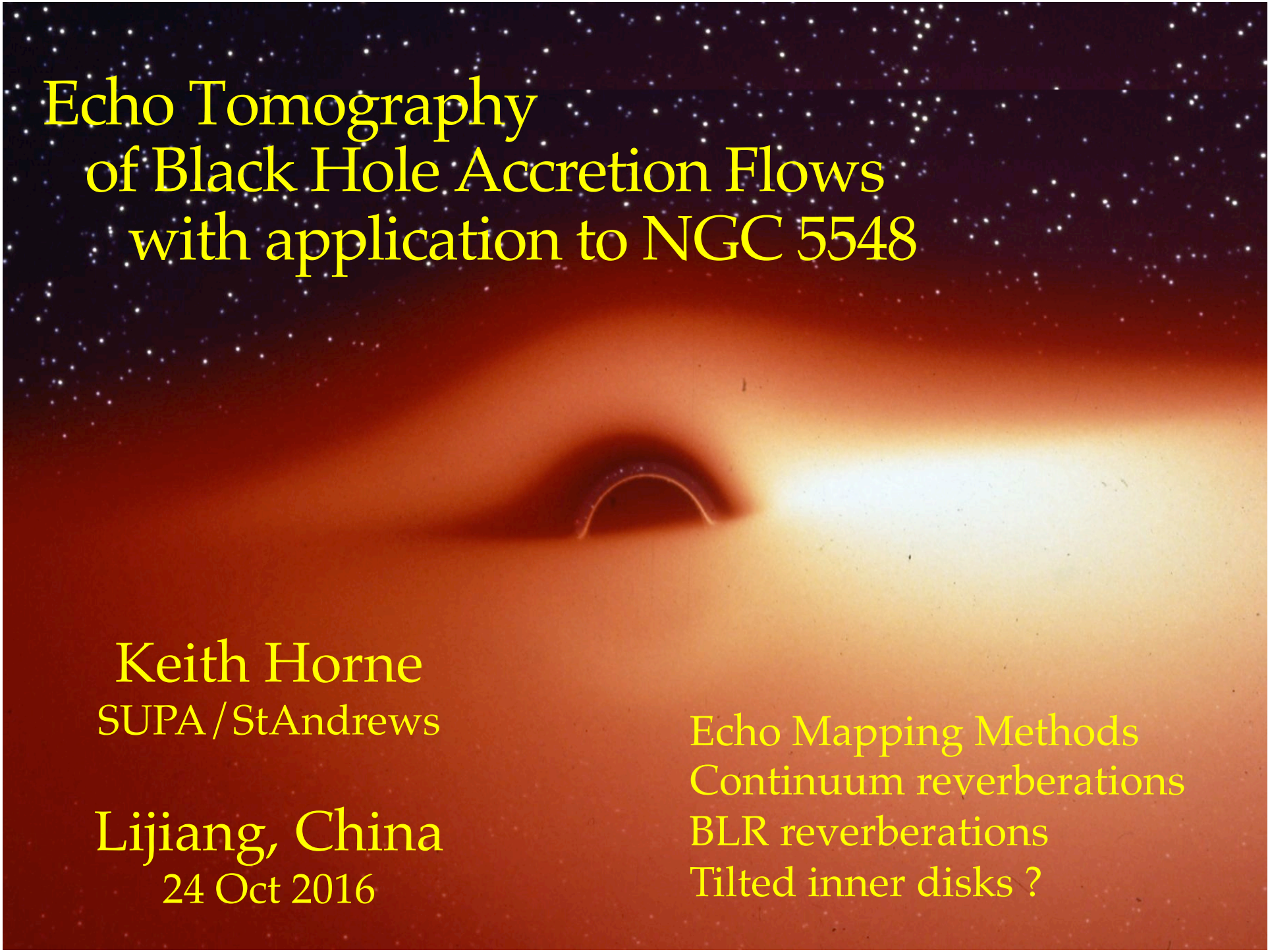
Echo Tomography of Black Hole Accretion Flows with application to NGC 5548



Keith Horne
SUPA/StAndrews

Lijiang, China
24 Oct 2016

Echo Mapping Methods
Continuum reverberations
BLR reverberations
Tilted inner disks ?

CCF Lags => BLR sizes

AGN STORM *HST* PROGRAM

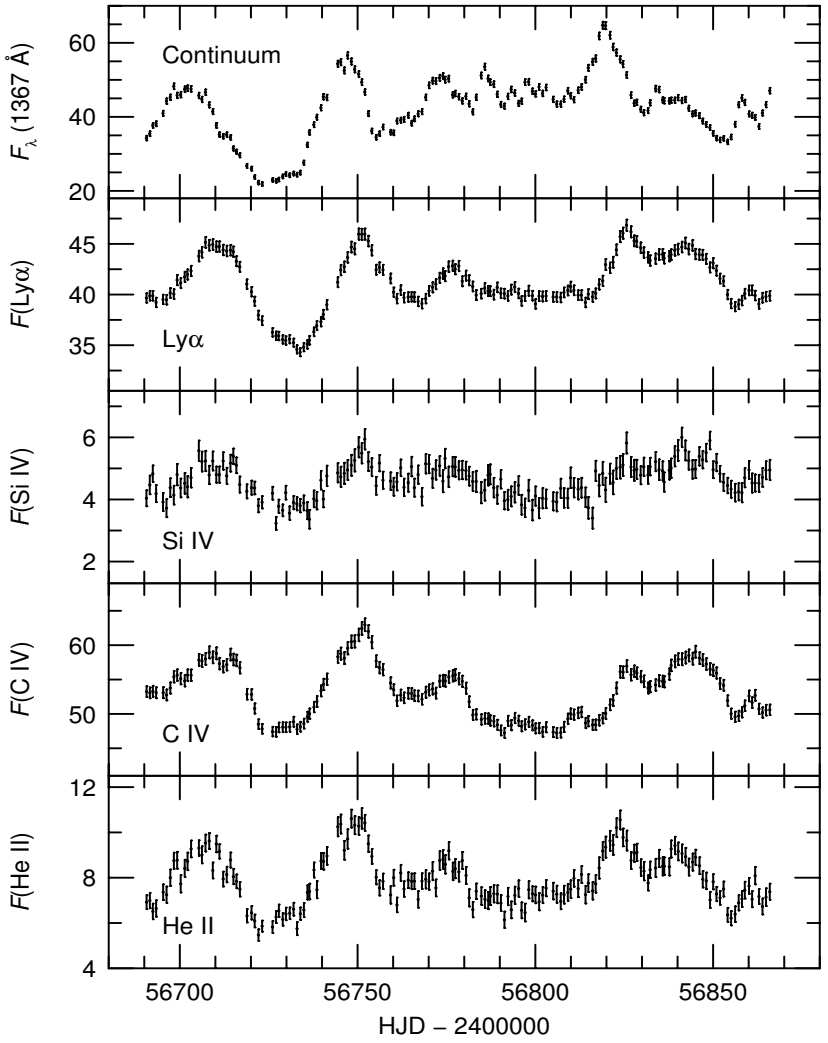
Mean lags relative to 1367 Å continuum

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

$\langle \tau \rangle \sim R / c$

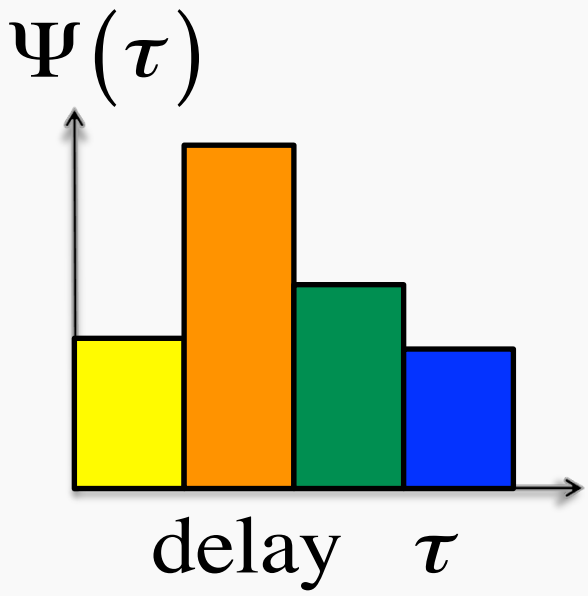
=> radius *R* of emission-line region

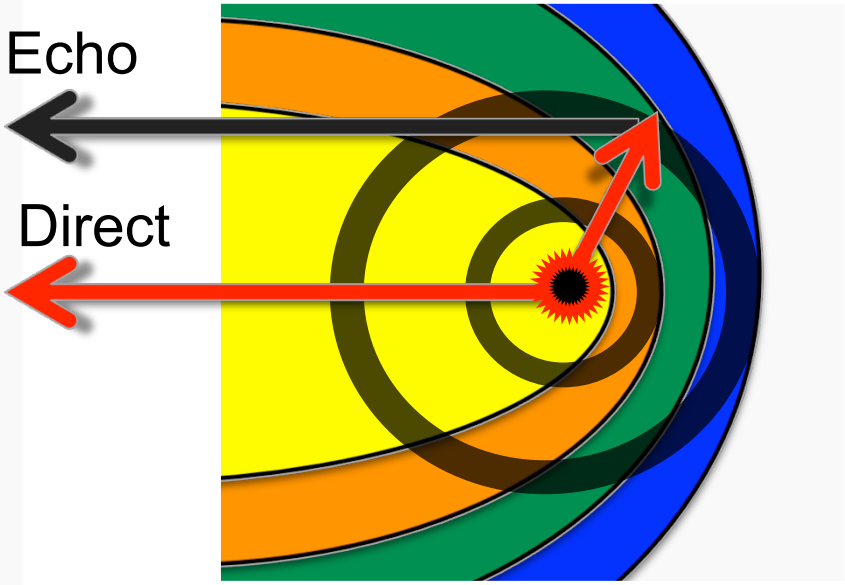


De Rosa et al, 2015

Beyond CCF lags: Echo Tomography

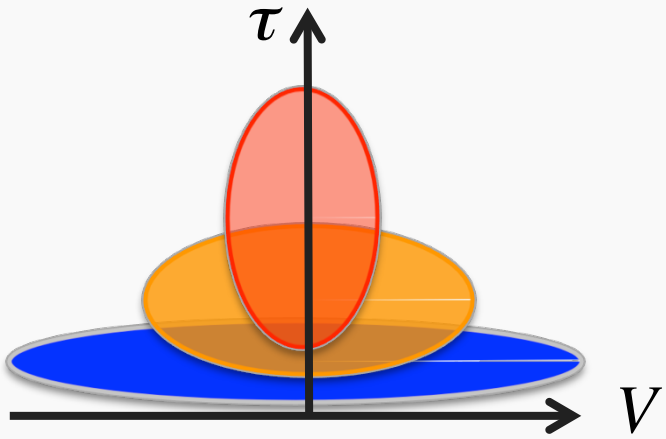
Light travel time delay τ "slices up" the region on iso-delay paraboloids. => micro-arcsec resolution.



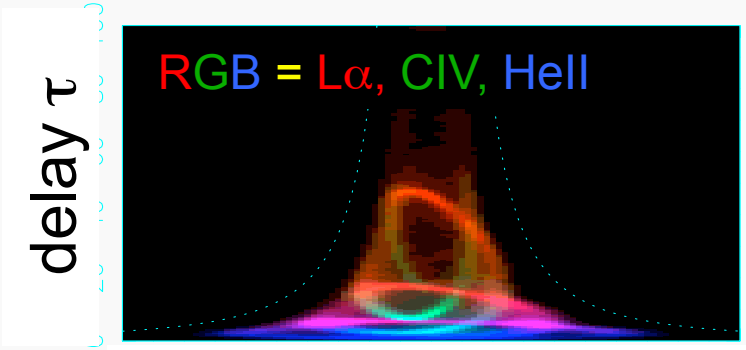


$$\tau = \frac{R}{c}\left(1+\cos\theta\right)$$

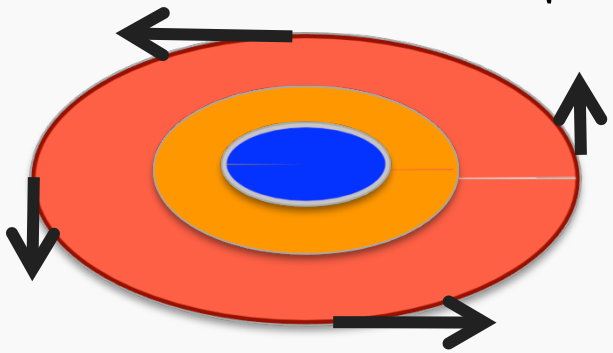
2D: Velocity-Delay Maps $\Psi(v, \tau)$



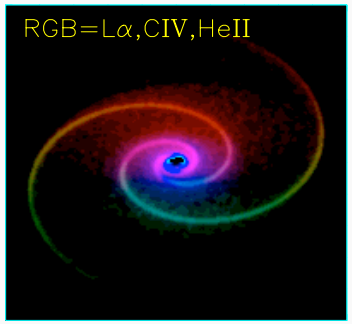
Simulation: Photo-ionised Keplerian disk with spiral density waves



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



sky view:



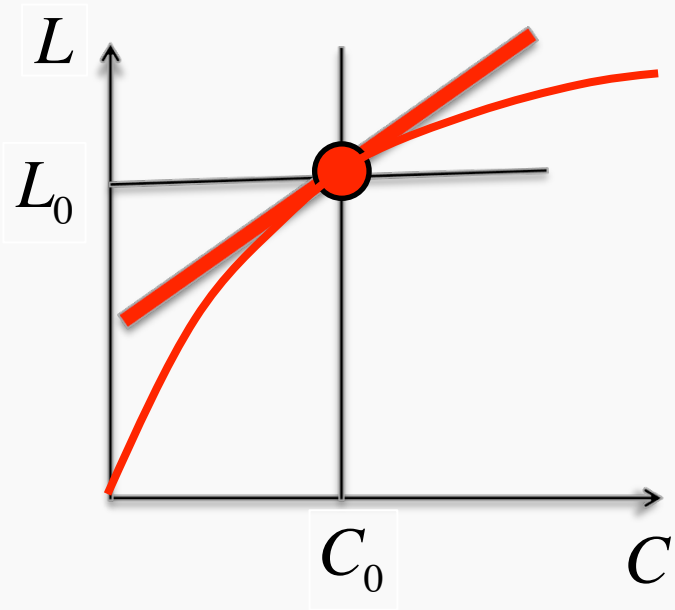
Linearised Echo Model

Lightcurve model:

Continuum: $C(t) = C_0 + \Delta C(t)$

Line: $L(t) = L_0 + \int_0^{\tau_{\max}} \Psi(\tau)\, \Delta C(t-\tau)\, d\tau$

model parameters : $C(t),\ L_0,\ \Psi(\tau)$.



Tangent-curve approximation
to **non-linear** line responses

Neglects **curvature** of *L(C)*

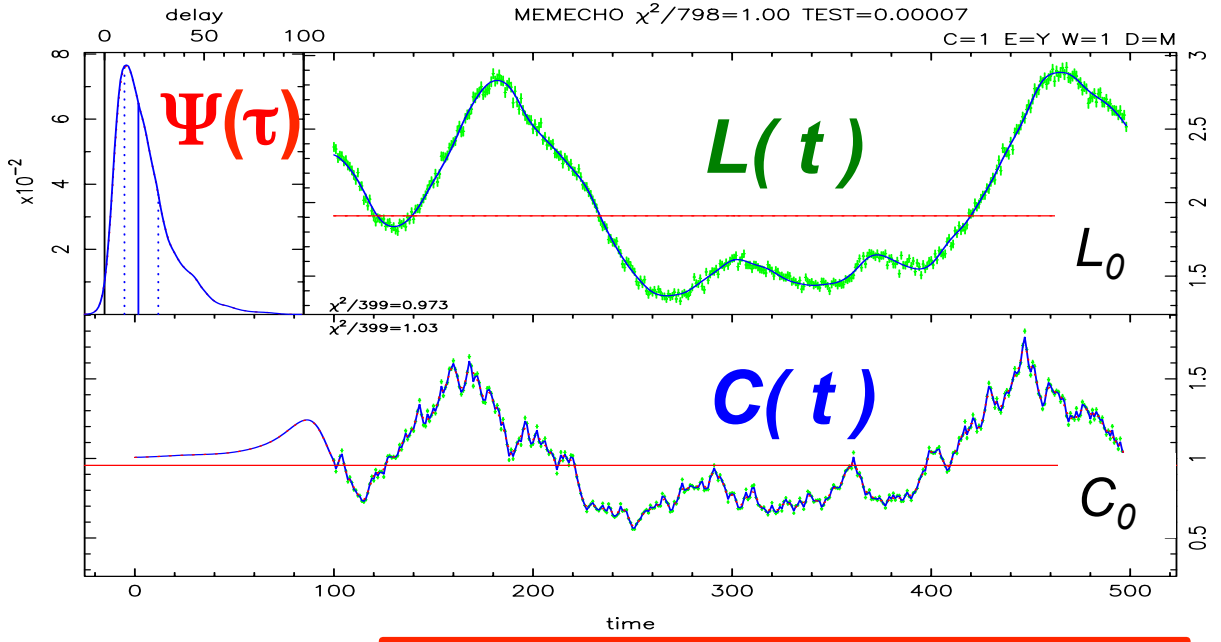
MEMEcho fits
Lightcurves => Delay Maps : Ψ(τ)

Emission-Line Lightcurve
L(t)
+
Continuum Lightcurve
C(t)
+
Maximum Entropy Fit
=
Delay Map
Ψ(τ)

Linearised echo model:

Continuum: $C(t) = C_0 + \Delta C(t)$

Line: $L(t) = L_0 + \int_0^{\tau_{\max}} \Psi(\tau)\, \Delta C(t-\tau)\, d\tau$



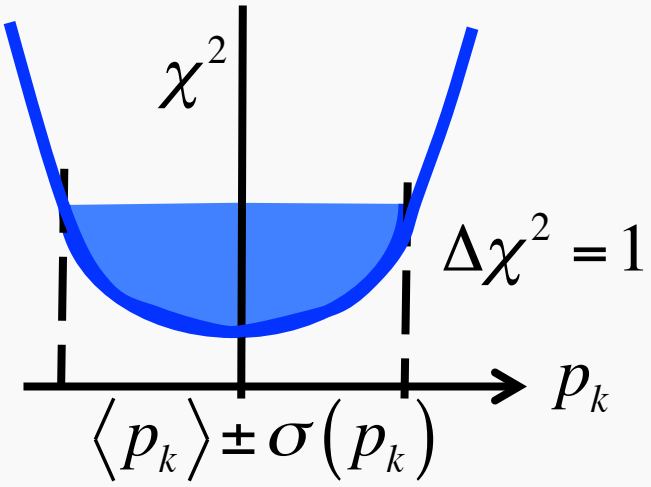
model parameters : $C(t)$, L_0, $\Psi(\tau)$.

MEMEcho : Maximum Entropy Fits

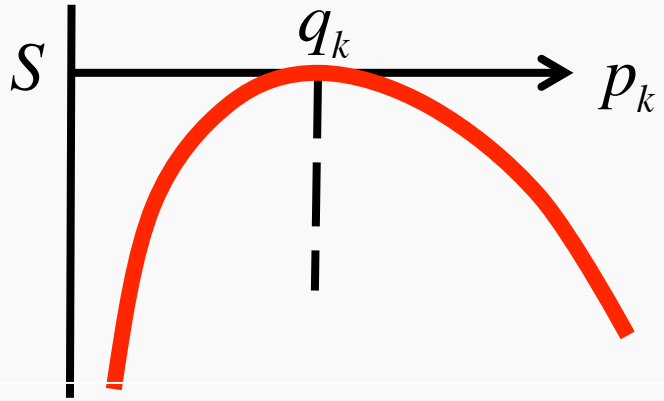
$$\Pr(\text{Model}\,|\,\text{Data}) \;\propto\; \exp\{-\chi^2/2\}\;\exp\{\alpha S/2\}$$

$$\chi^2 = \sum_{i}^{Ndat}\left(\frac{D_i-\mu_i}{\sigma_i}\right)^2 \qquad S = \sum_{k}^{Npix} p_k - q_k - p_k \ln(p_k/q_k)$$

1. Fit the data. $\alpha \Rightarrow 0$



2. Keep it "simple". $\alpha \Rightarrow \infty$



$p_k > 0$. $S_{\max} = 0$, when $p_k = q_k$.

default values: e.g. $q_k = \left(p_{k-1}p_{k+1}\right)^{1/2}$

Maximum Entropy Trajectory

Trajectory in parameter space, where $\nabla\chi^2 \propto \nabla S$, parameterised by α.

Simplest Model

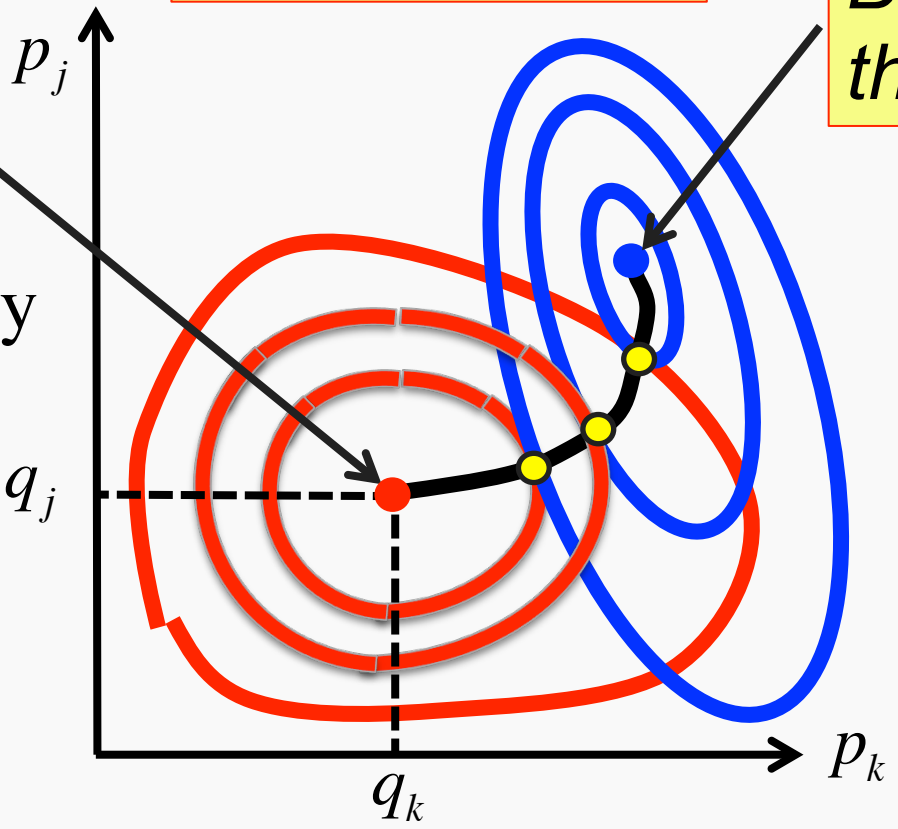
$\alpha \Rightarrow \infty$

maximum entropy

$p_k \Rightarrow q_k$

$S \Rightarrow S_{\max} = 0$

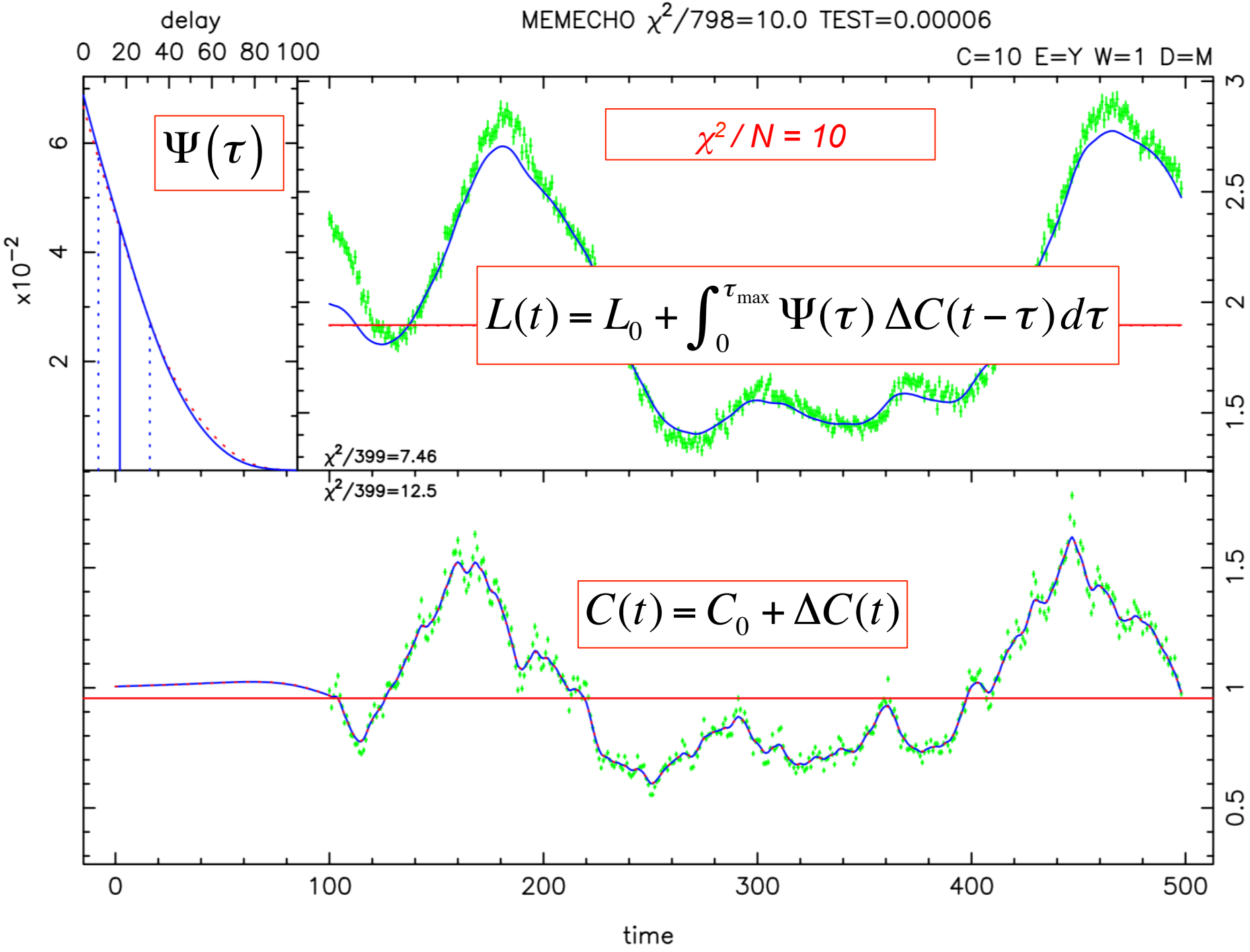
minimise $\chi^2 - \alpha S$

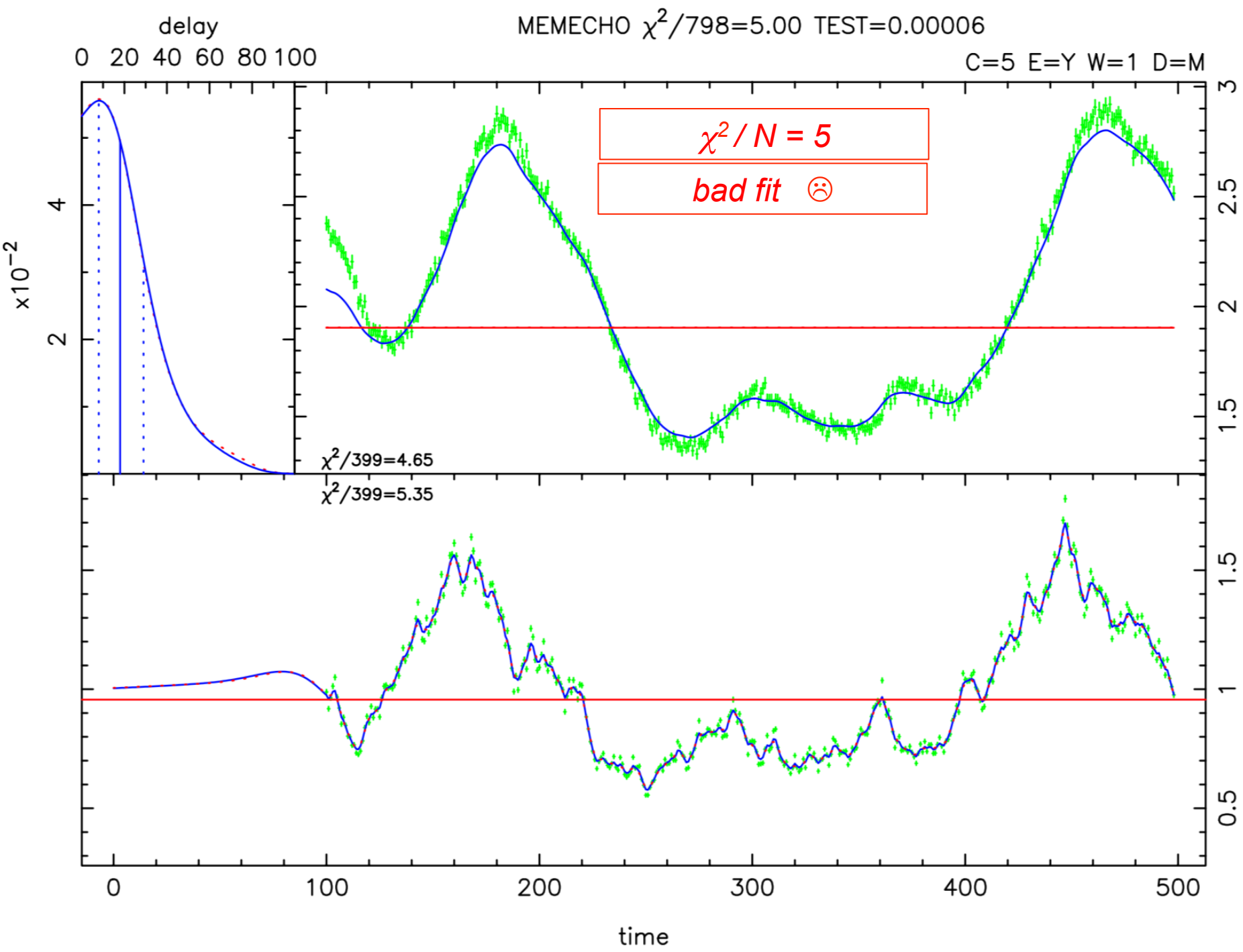


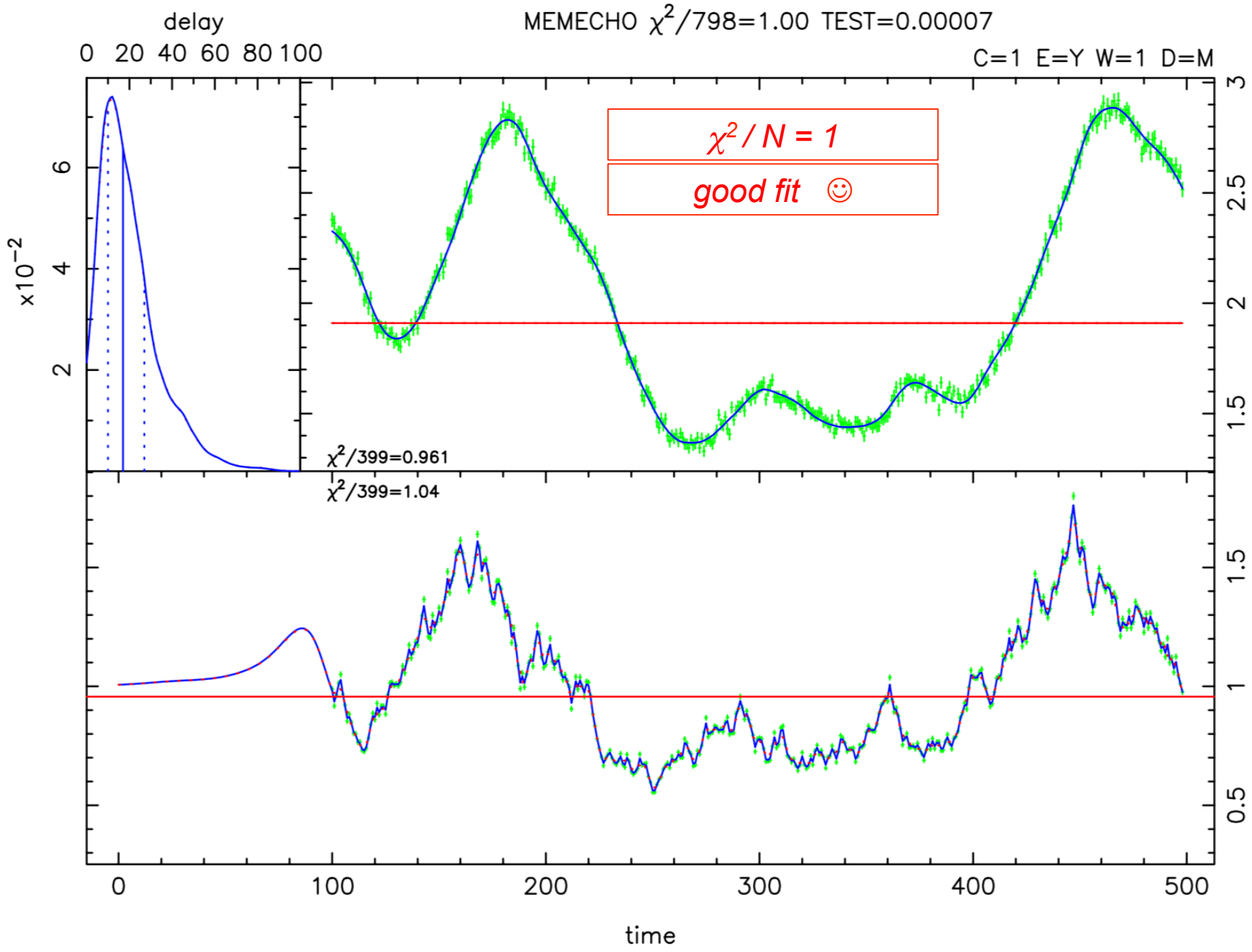
Best fit to the data

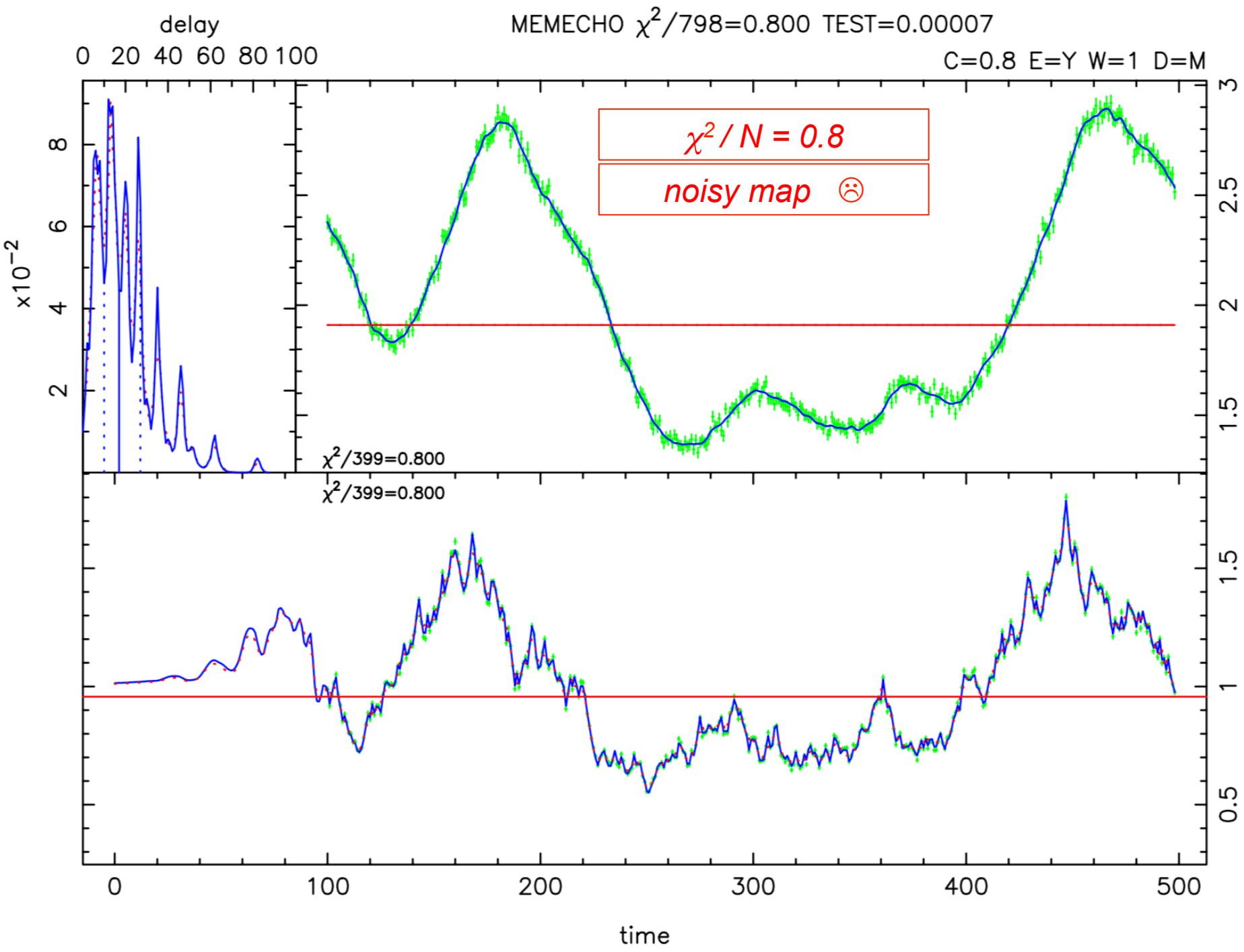
$\alpha \Rightarrow 0$

$\chi^2 \Rightarrow \chi^2_{\min}$


delay
0 20 40 60 80 100
MEMECHO χ^2/798=10.0 TEST=0.00006
C=10 E=Y W=1 D=M
$\Psi(\tau)$
$\chi^2 / N = 10$
$L(t) = L_0 + \int_0^{\tau_{max}} \Psi(\tau)\, \Delta C(t-\tau)\, d\tau$
χ^2/399=7.46
χ^2/399=12.5
$C(t) = C_0 + \Delta C(t)$
x10^{-2}
2
4
6
1.5
2
2.5
3
0.5
1
1.5
0
100
200
300
400
500
time


delay
0 20 40 60 80 100
MEMECHO χ^2/798=5.00 TEST=0.00006
C=5 E=Y W=1 D=M
χ^2 / N = 5
bad fit ☹
x10^{-2}
2
4
1.5
2
2.5
3
χ^2/399=4.65
χ^2/399=5.35
0.5
1
1.5
0
100
200
300
400
500
time


delay
0 20 40 60 80 100
MEMECHO χ^2/798=1.00 TEST=0.00007
C=1 E=Y W=1 D=M
x10^{-2}
2
4
6
χ^2 / N = 1
good fit ☺
χ^2/399=0.961
χ^2/399=1.04
1.5
2
2.5
3
0.5
1
1.5
0
100
200
300
400
500
time


delay
0 20 40 60 80 100
MEMECHO χ^2/798=0.800 TEST=0.00007
C=0.8 E=Y W=1 D=M
χ^2 / N = 0.8
noisy map ☹
x10^{-2}
χ^2/399=0.800
χ^2/399=0.800
time

2014 STORM Campaign NGC 5548

STORM = Space Telescope and Optical Reverberation Mapping
PI: Brad Peterson

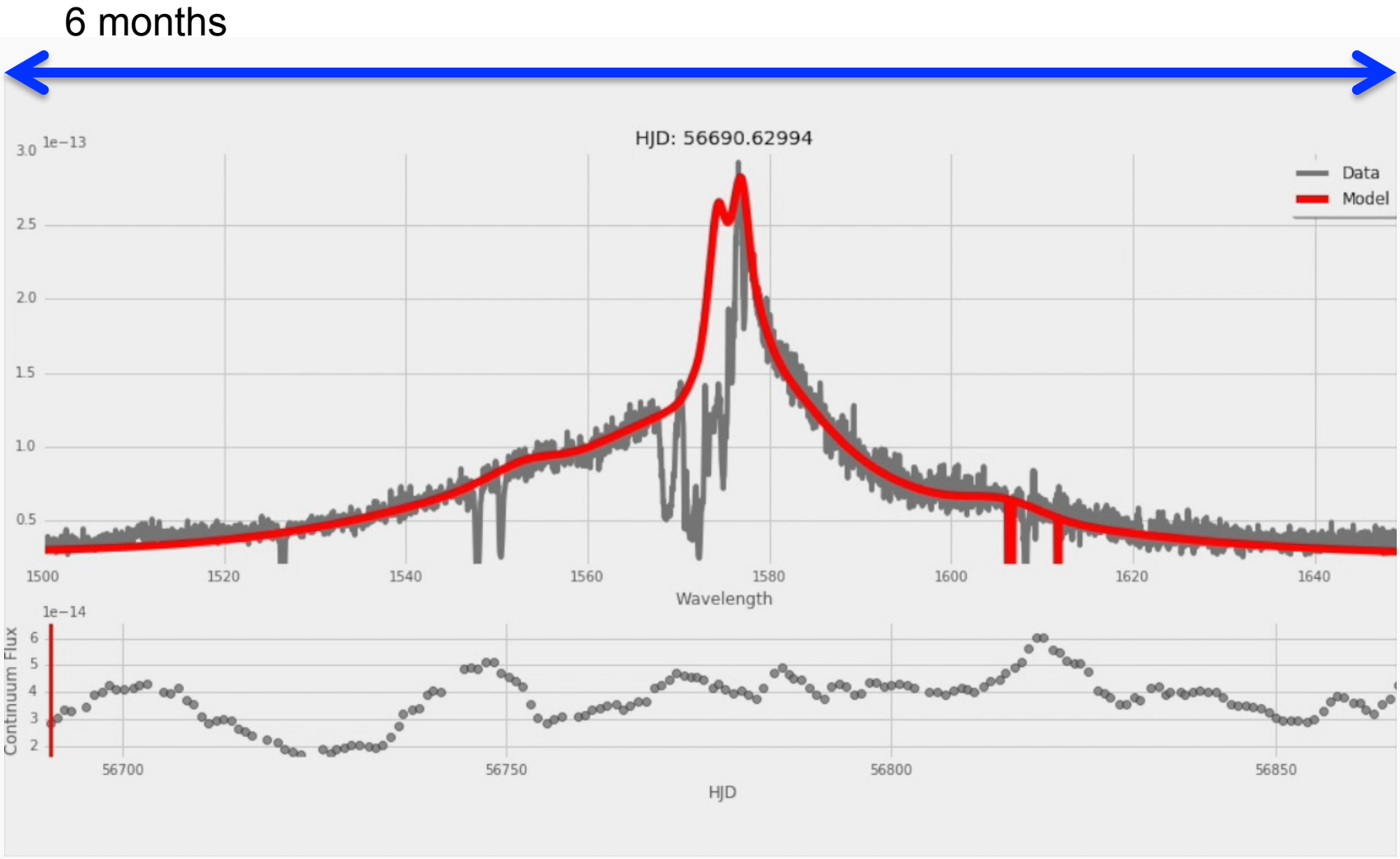
Published or submitted :

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 through *z* – Fausnaugh+ 2016 ApJ 821:56
IV : Anomalous behavior of UV emission lines – Goad+ 2016 ApJ 824:1
V : Optical emission line variations – submitted, Pei+
VI : Accretion disk modeling – submitted, Starkey+

In progress or planned :

Heuristic models of the UV emission lines – Kriss+
Chandra X-ray observations – Mathur+
Velocity-delay maps – Horne+
Dynamical modeling – Pancoast+
Absorption line variations – Kriss+
Photoionization modeling – TBD
NIR and *Spitzer* observations – TBD

STORM Campaign NGC 5548
C IV Variations

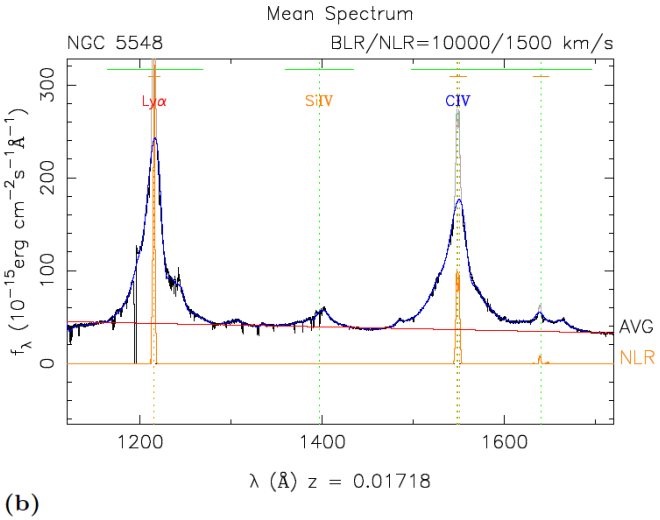


HST : Mean and RMS Spectra Line and Contuum Lightcurves

PrepSpec Analysis of HST data from *De Rosa et al,2015*.

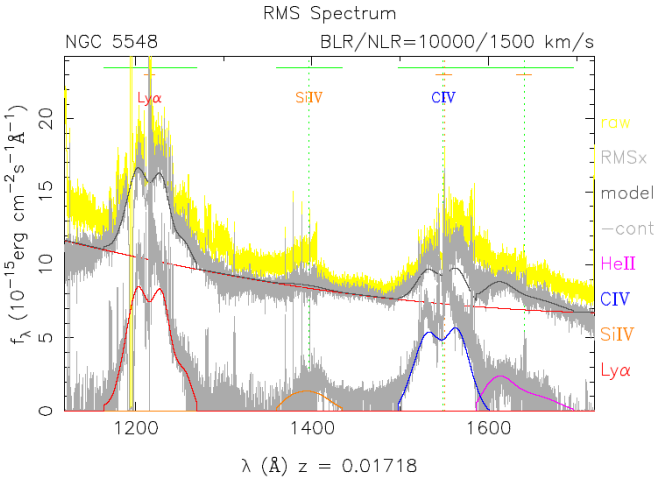
A(λ)

Mean spectrum



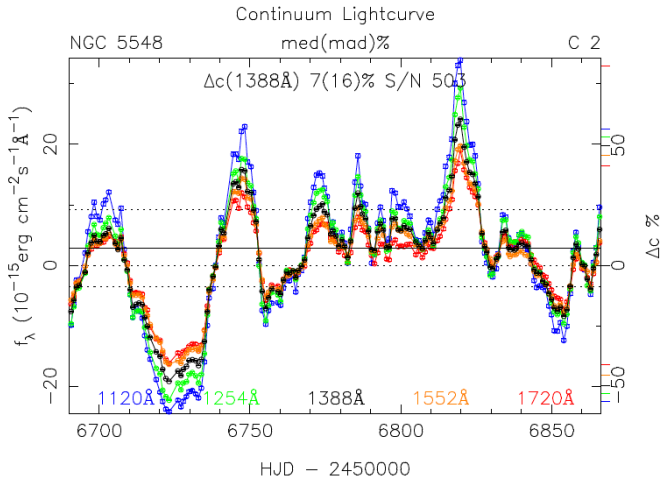
B(λ)

RMS spectrum



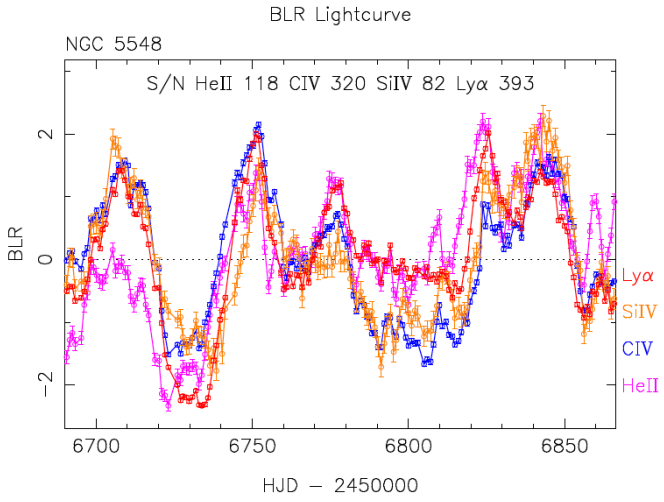
C(t | λ)

Continuum lightcurves



L(t)

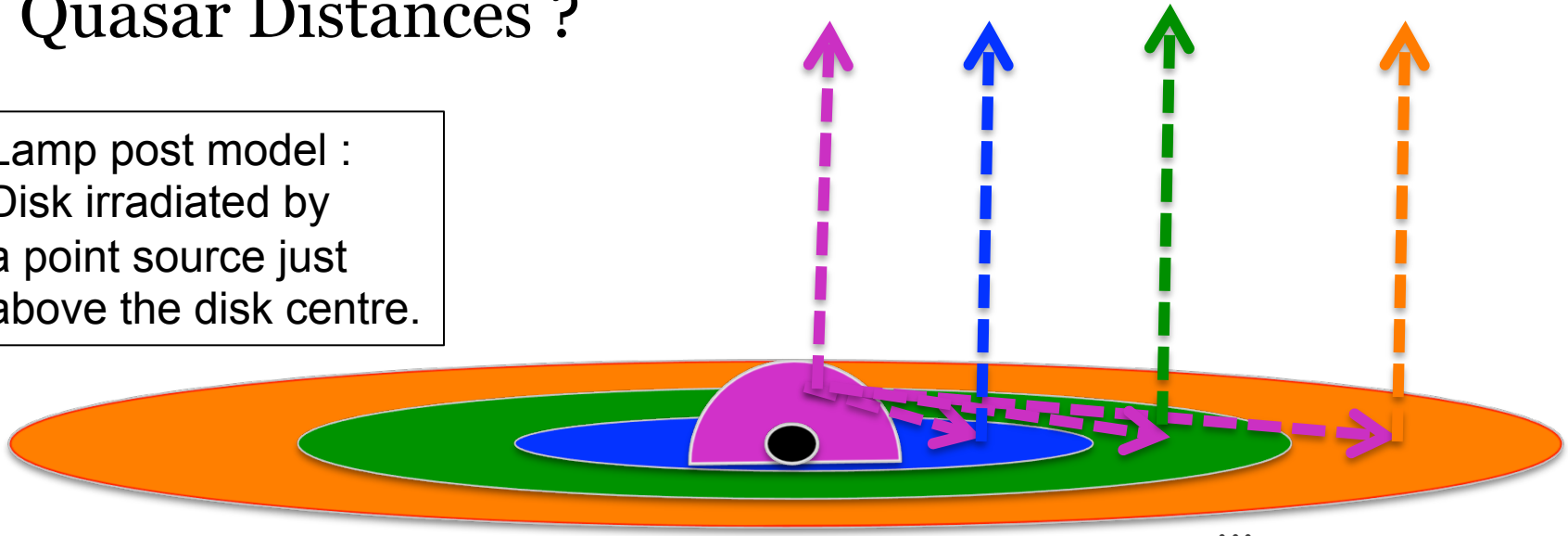
BLR lightcurves



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

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

Lamp post model : Disk irradiated by a point source just above the disk centre.



Accretion Disk Reverberations

Disk Theory:

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

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

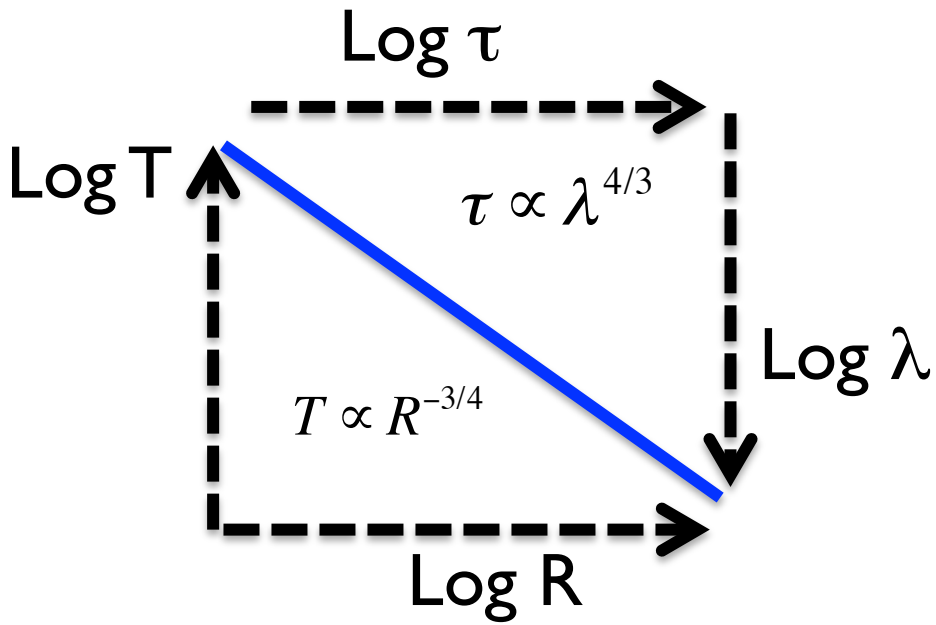
$$R \sim c\tau$$

$$T \sim \frac{hc}{k\lambda}$$

Observables:

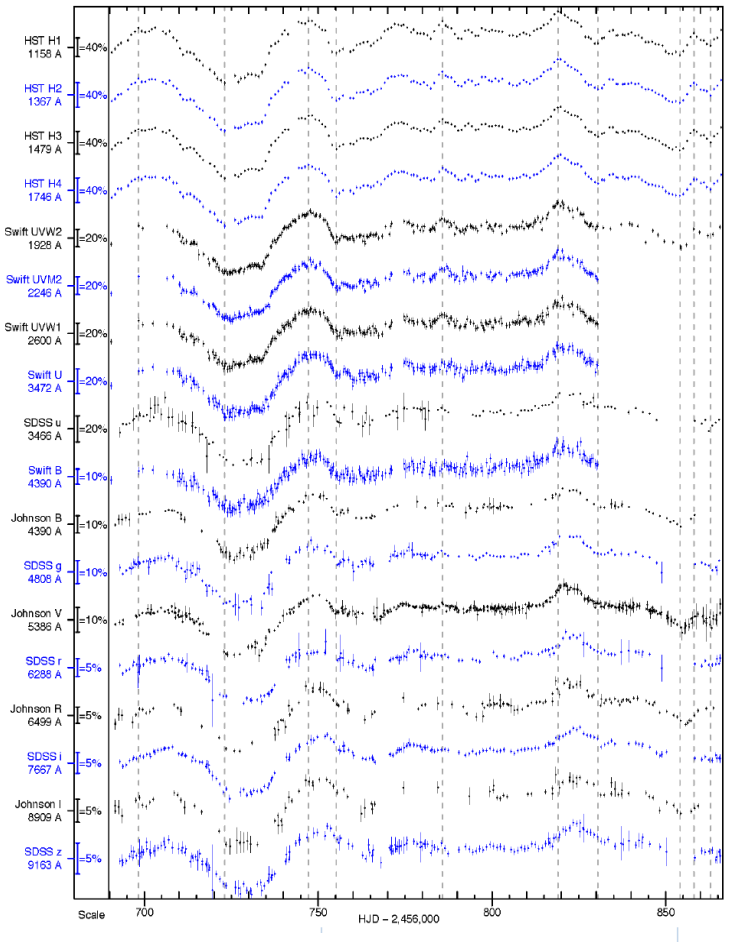
$$\tau \propto \left(M \dot{M}\right)^{1/3} \lambda^{4/3}$$

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

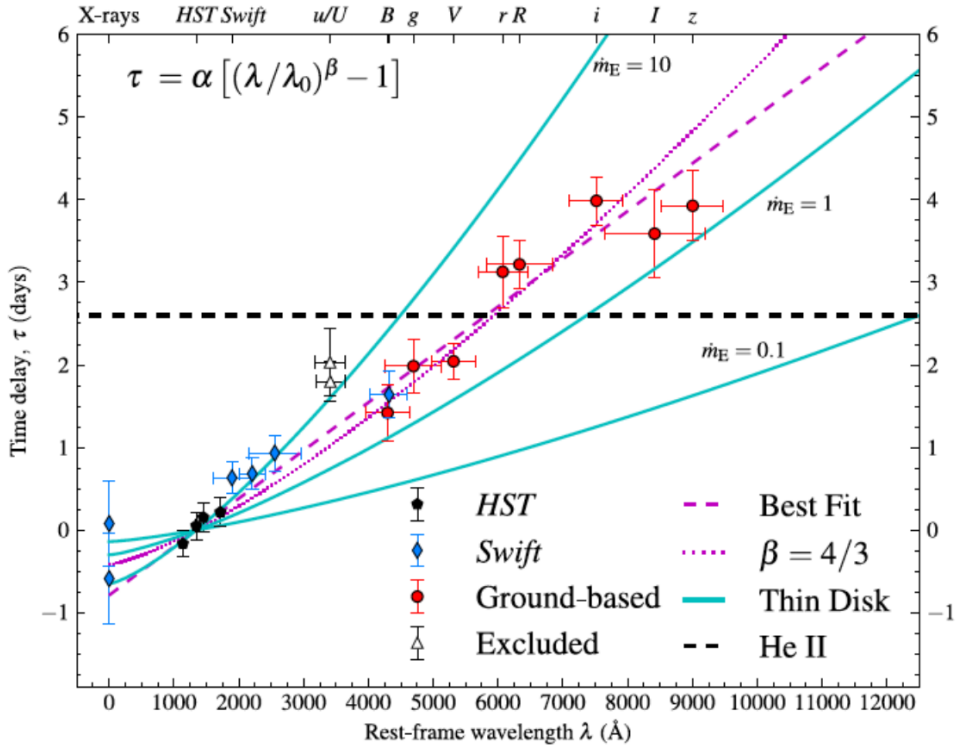


Lightcurves => Delay Spectrum

UV (1150 A)



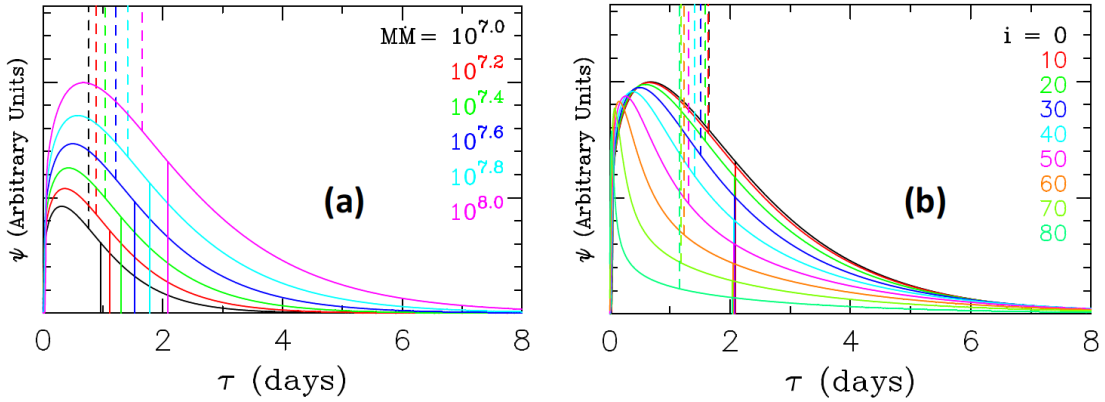
Optical (9000 A)



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

Fausnaugh et al. 2016

Blackbody Disk Delay Maps



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

Delay map shape depends on disk inclination

$$\tau(r,\theta) \approx \frac{r}{c}\left(1+\sin i\cos\theta\right)$$

$$T^4(r,t) = \frac{3GM\dot{M}}{8\pi\sigma r^3} + \frac{L_x\left(t-\tau(r,\theta)\right)(1-a)h_x}{4\pi\sigma r^3}$$

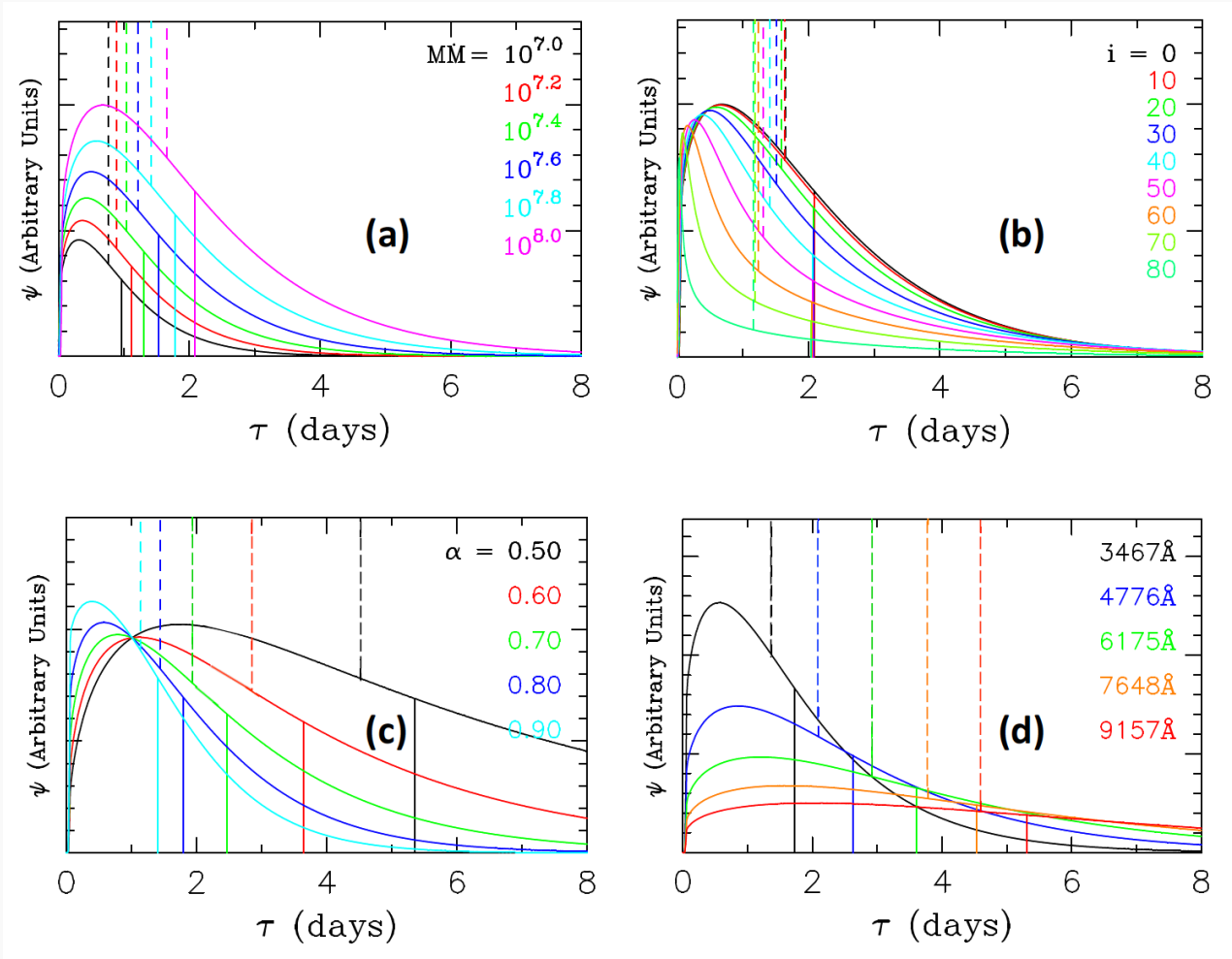
$$F_\nu(t,\lambda) \equiv \iint B_\nu\left(T(r,t),\lambda\right)\frac{r\,dr\,d\theta\cos i}{D^2}$$

$$\Psi(\tau,\lambda) \equiv \frac{dF_\nu(t,\lambda)}{dL_x(t-\tau)} = \iint \frac{B_\upsilon}{dT}\frac{dT}{dL_x}\frac{r\,dr\,d\theta\cos i}{D^2}\delta\left(\tau-\tau(r,\theta)\right)$$

Blackbody Disk Delay Maps

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

Starkey et al., 2016



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

Delay map shape depends on disk inclination

And slope α of $T(r)$ temperature profile

Theory: $\alpha = 3/4$

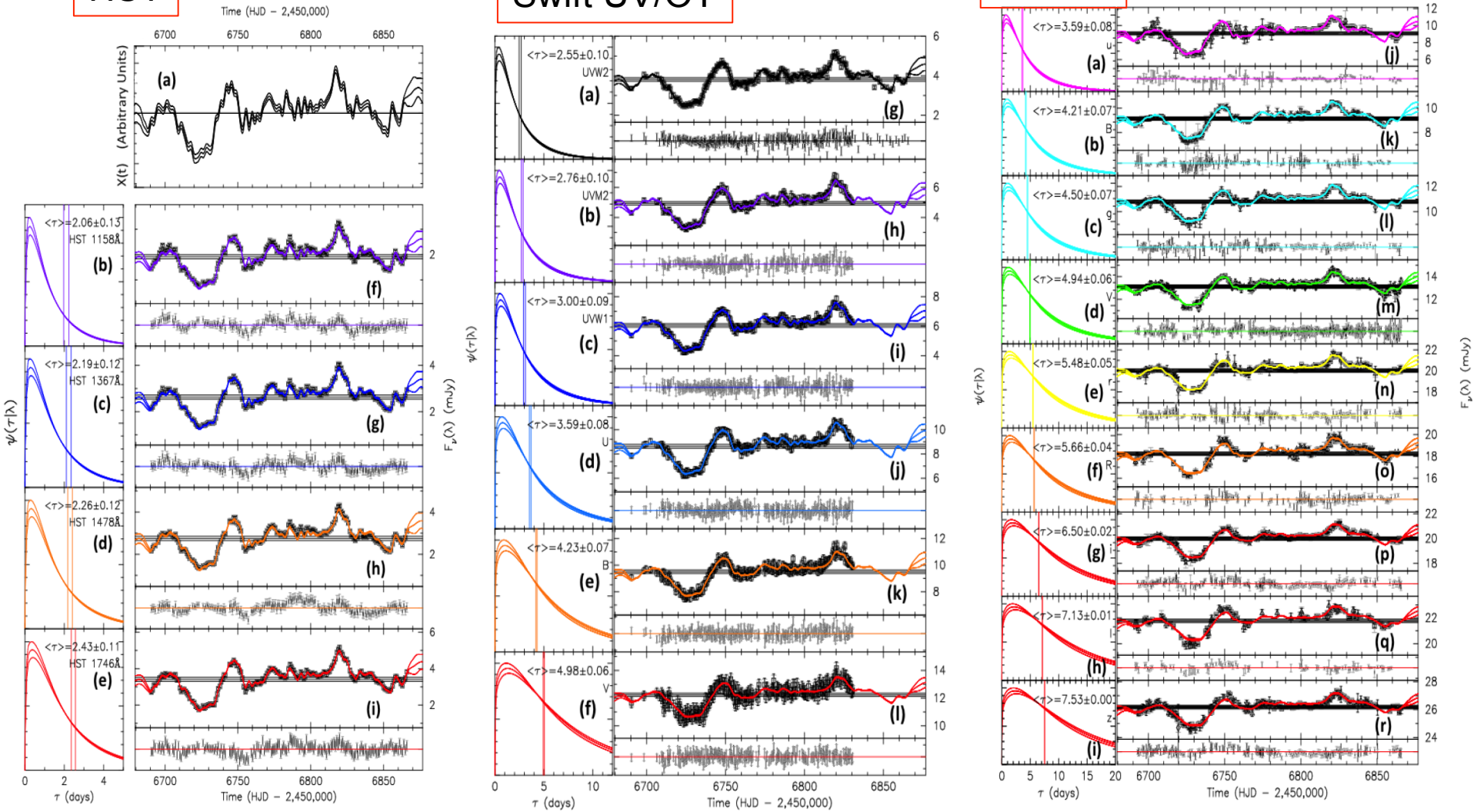
CREAM : MCMC Lightcurve Fits

HST

Swift UV/OT

Optical

Starkey et al.



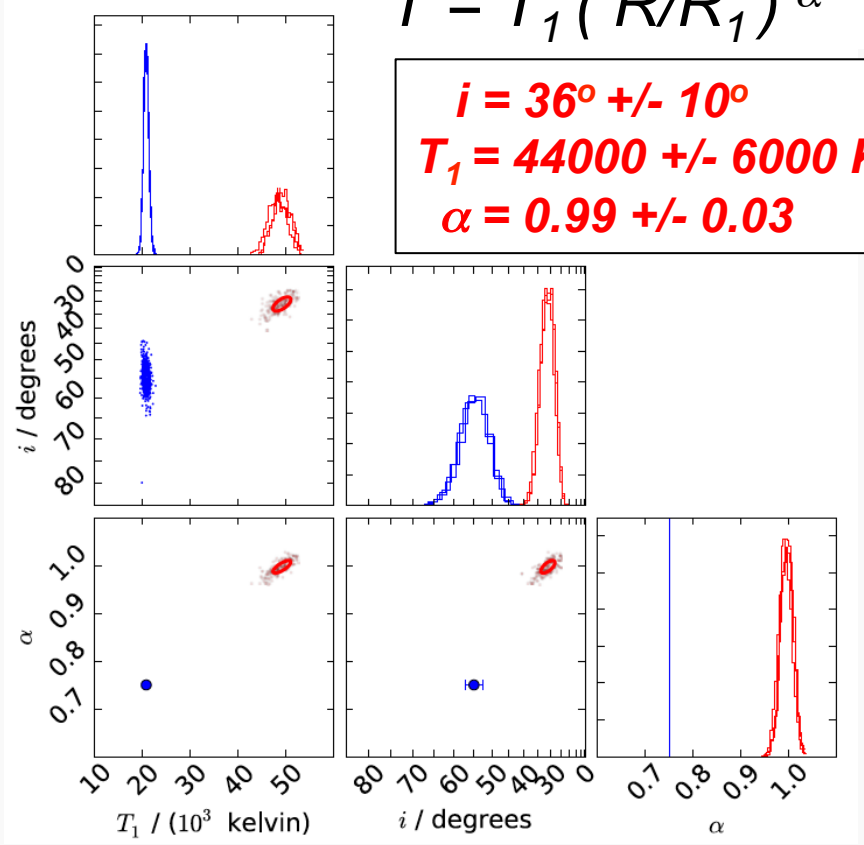
T(R) Profile

T(R) profile steeper than expected.

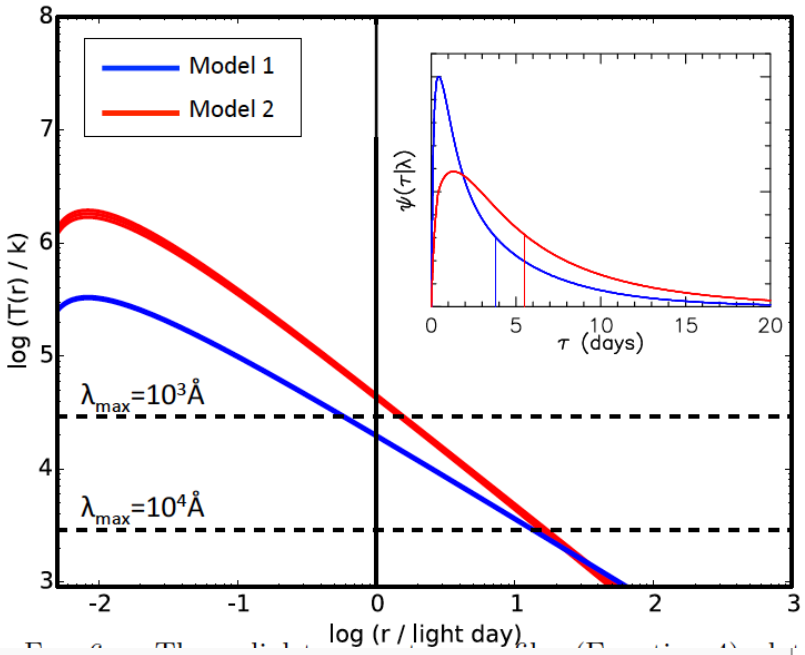
$T \sim R^{-1}$ rather than $R^{-3/4}$.

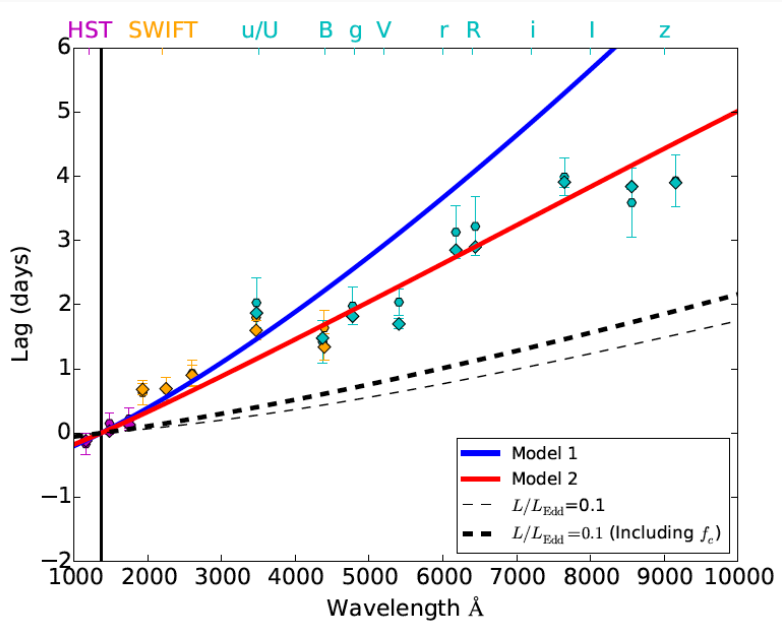
$$T = T_1 (R/R_1)^{-\alpha}$$

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

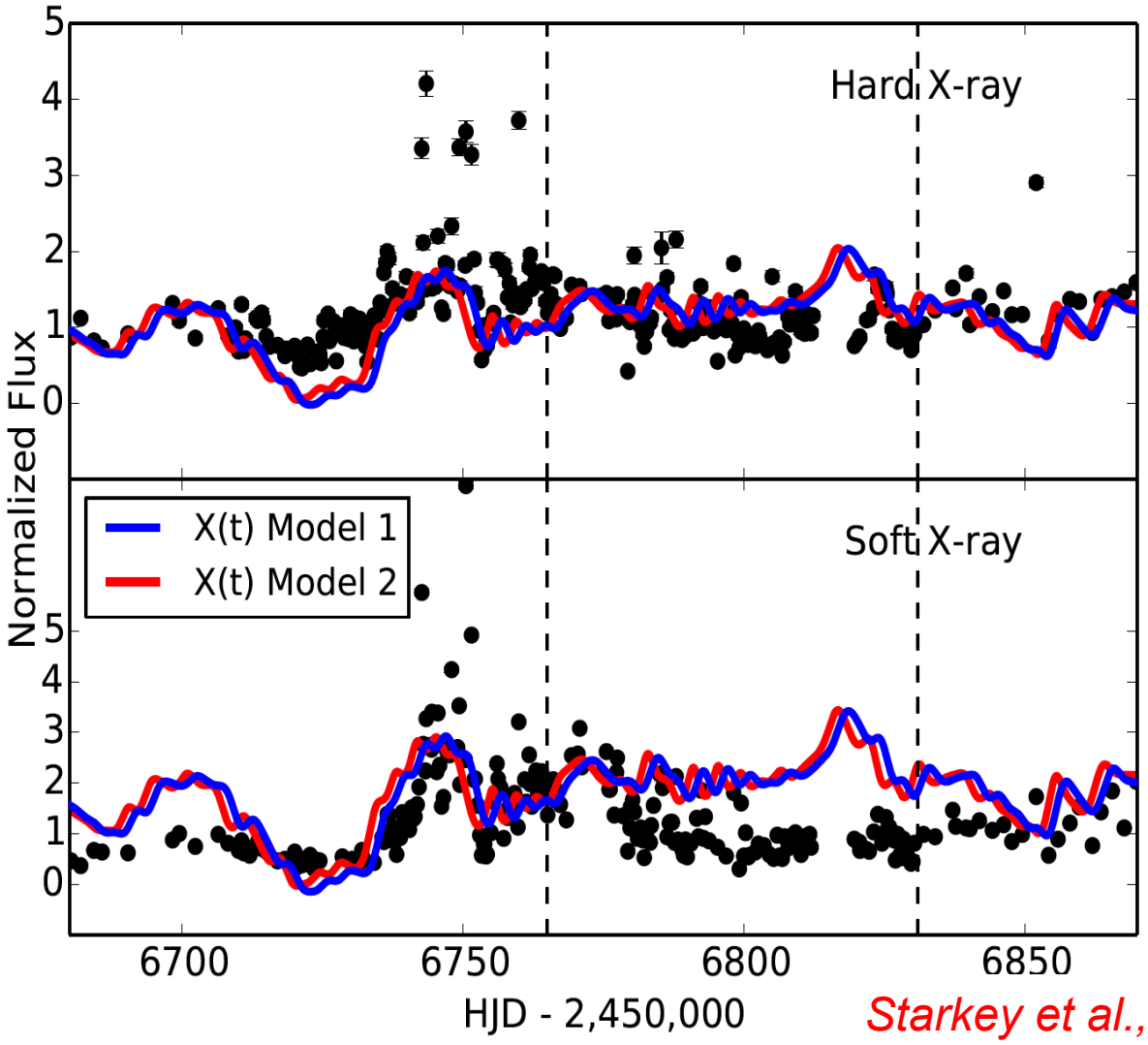


Starkey et al., submitted





X-rays vs Driving Lightcurve



X-ray variations don't match the required driving lightcurve

Starkey et al., submitted

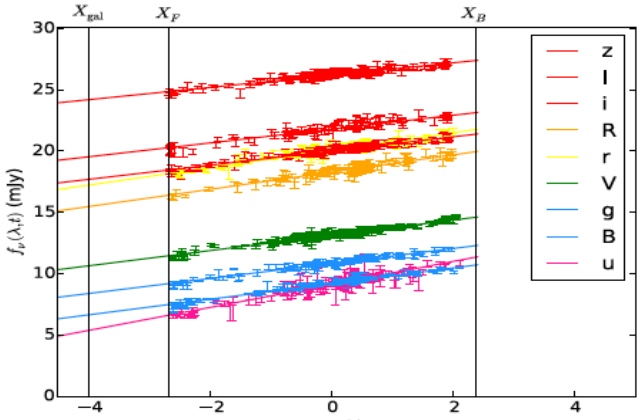
Disk Spectrum

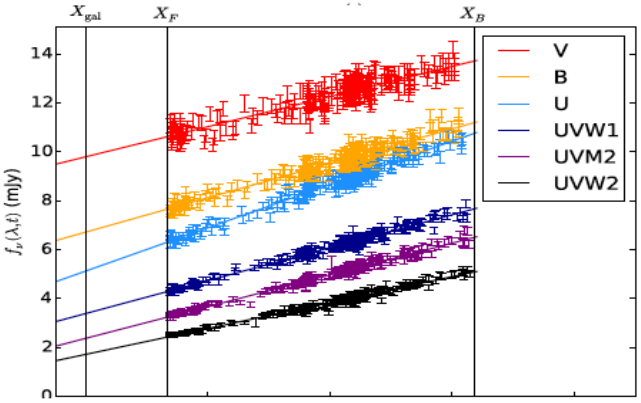
Variations isolate the Disk spectrum

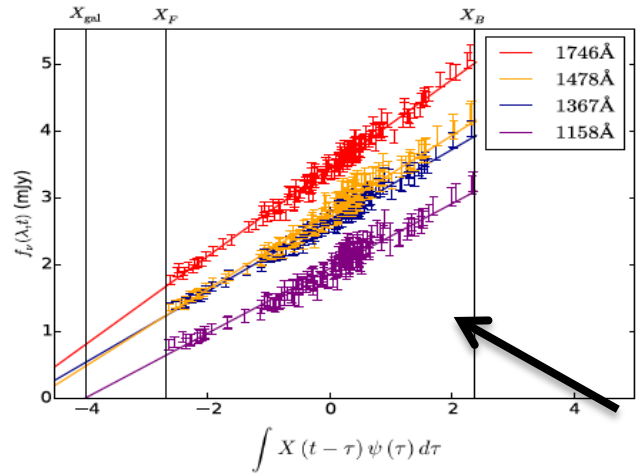
$F(\lambda,t) = A(\lambda) + S(\lambda)\,X(t)$

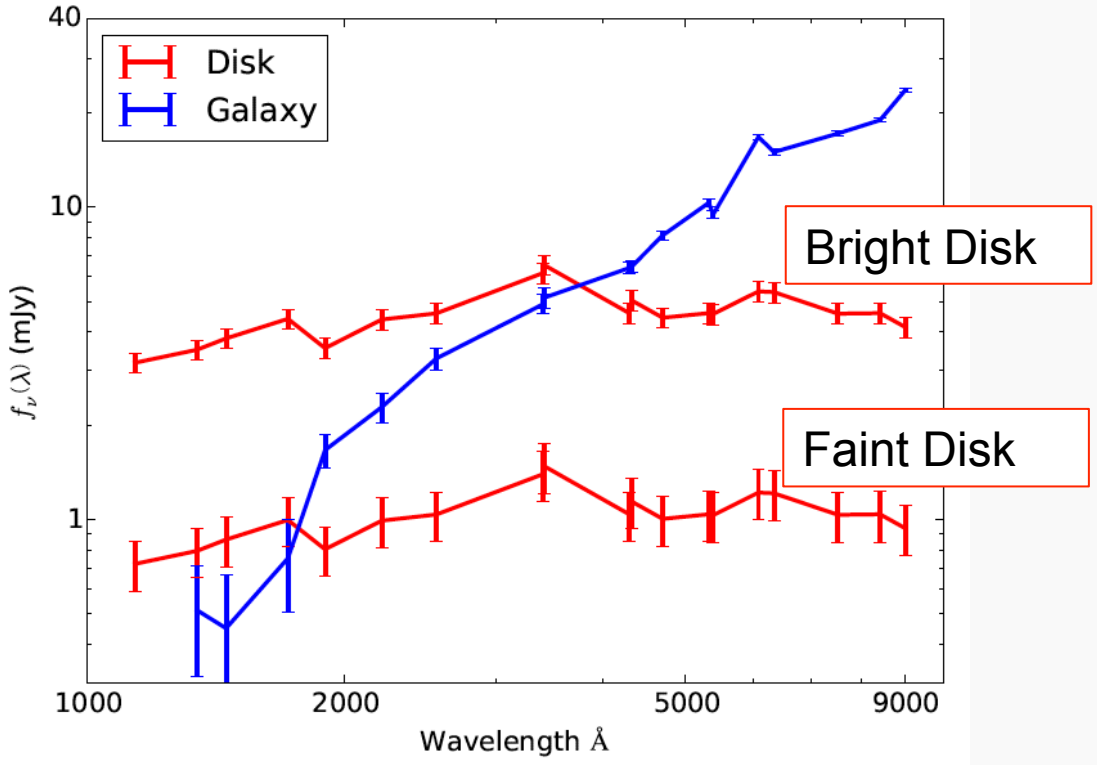
$= G(\lambda) + S(\lambda)\,(X(t) - X_G)$

$\langle X \rangle = 0 \quad \langle X^2 \rangle = 1$







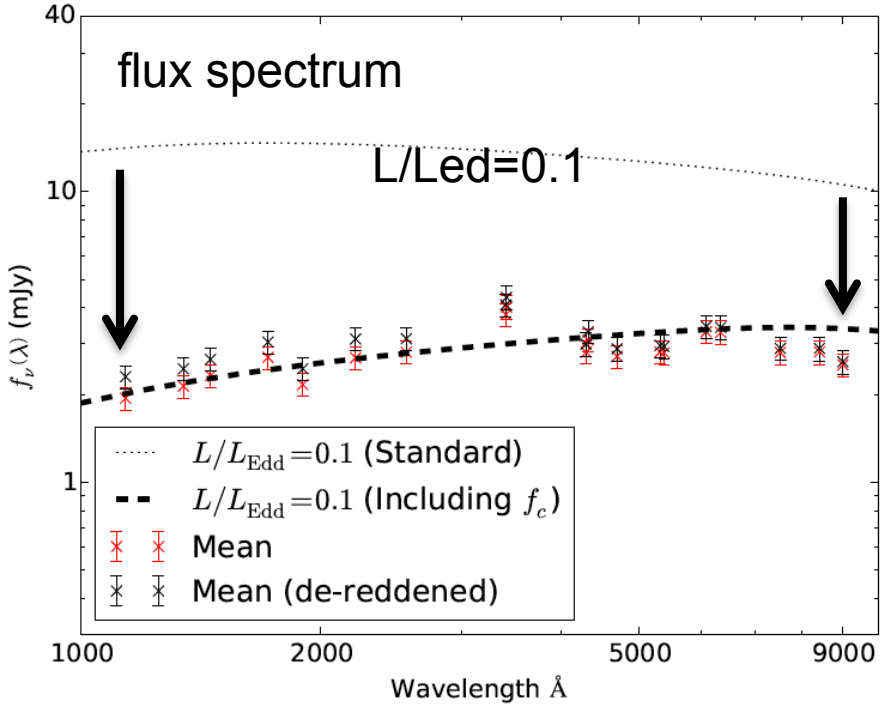


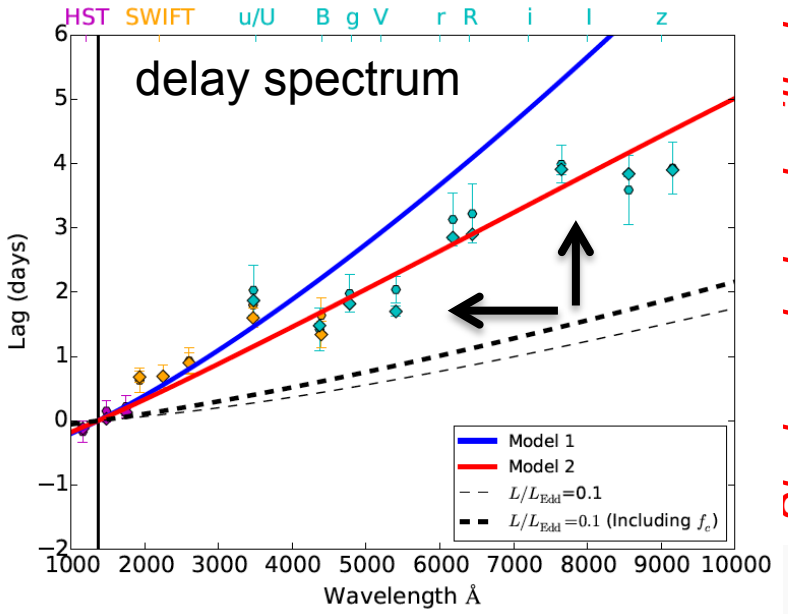
Note linear variations

Starkey et al. submitted

Standard Disk Model Fails

Disk flux spectrum is redder and fainter than expected (L/Led=0.1)
Disk delay spectrum is hotter and steeper than expected





Starkey et al. submitted

Questions:

Why does the standard disk model fail ?

Disk spectrum is too faint and red.

T(r) is too hot and steep.

Answers: (=New Questions)

Dust ? (affects flux but not delay)

Higher black hole mass ? (raises Led)

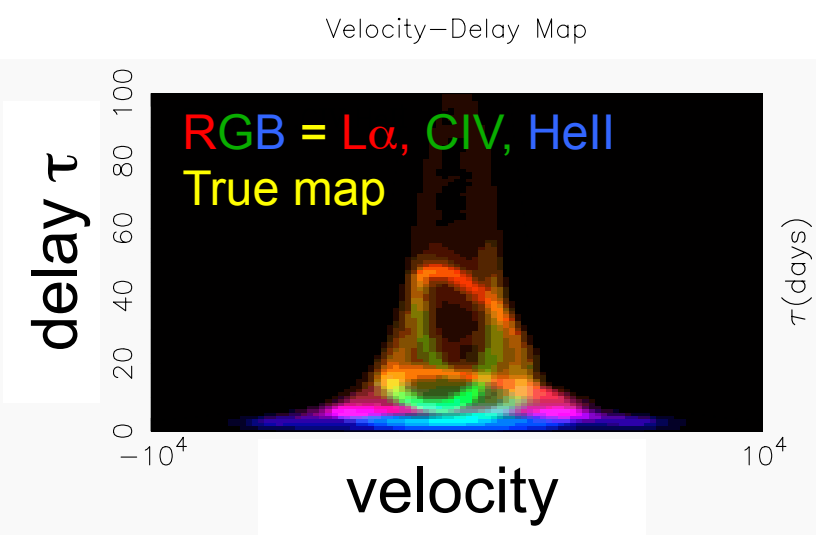
Diffuse continuum from BLR ?

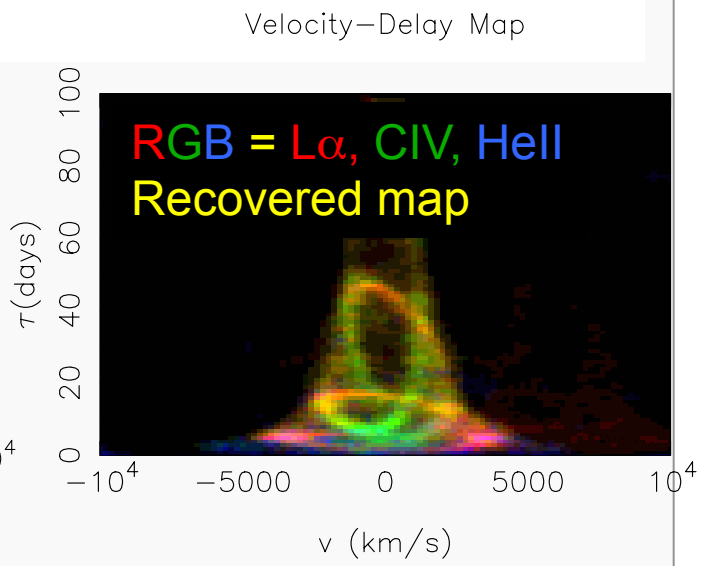
Partial irradiation (shadows) ?

Tilted inner disk ?

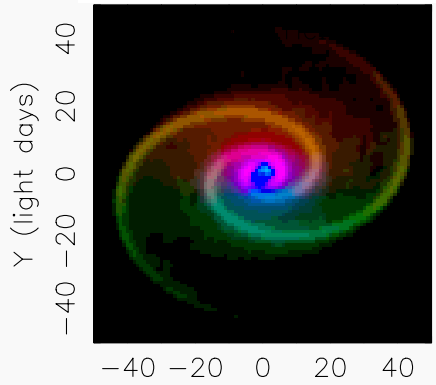
Velocity-Delay Maps : Ψ(v,τ) from Simulated HST data

MEMEcho recovers **Ψ(v,τ)** from simulated HST data





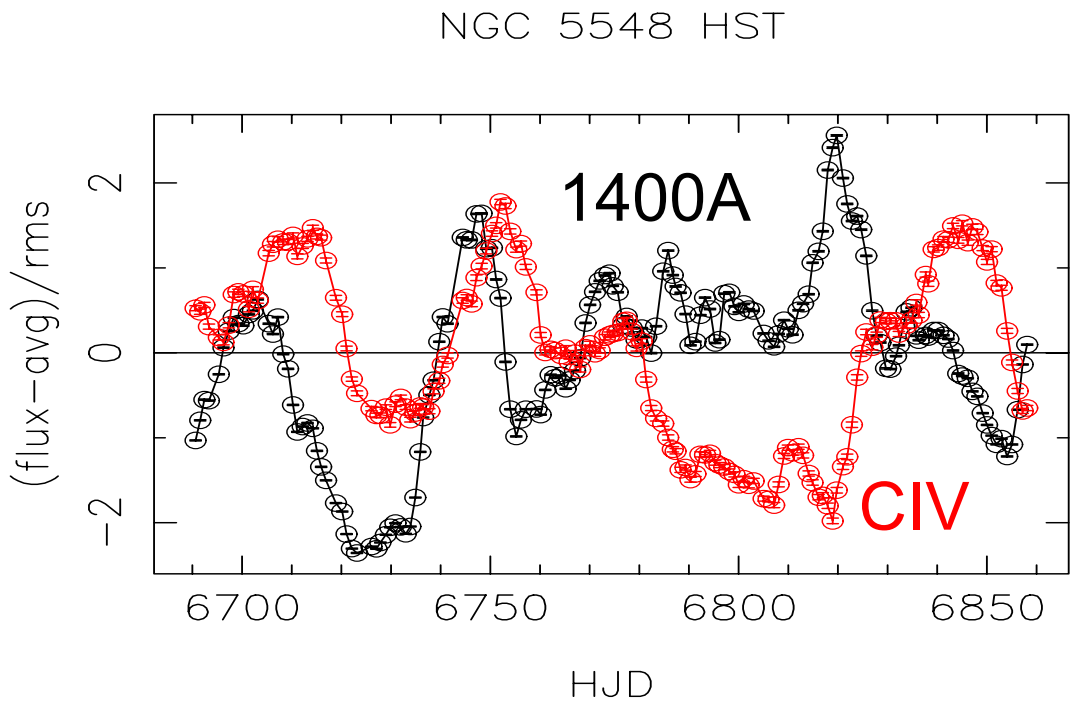
sky view:



Evident features:

- Virial envelope
- Spiral structure
- Radial ionisation
- Azimuthal anisotropy

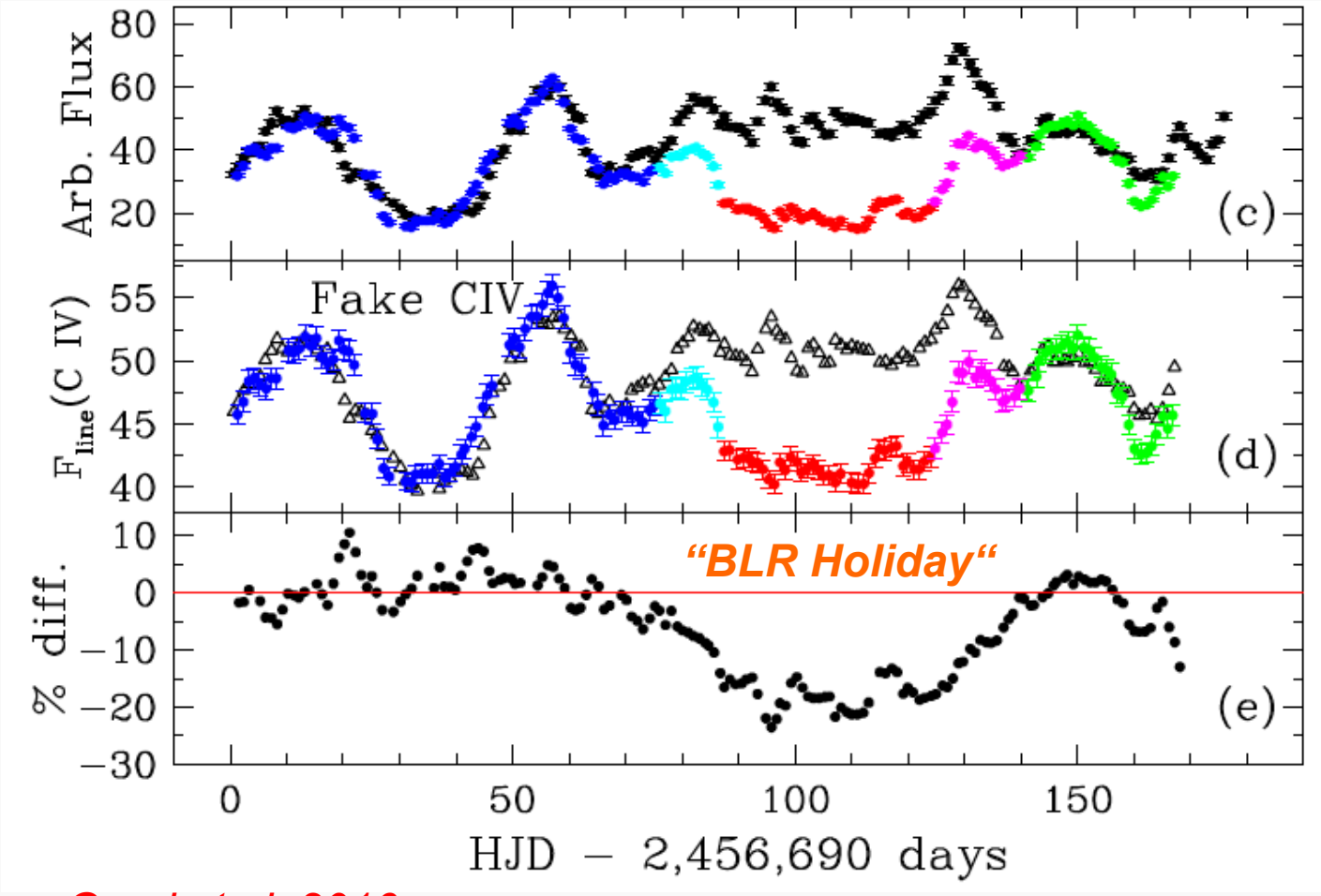
But : HST line variations are NOT simple continuum echos ☹



- Fast (5-20d) variations correlate, with clear (5-10d) lags.
- Slow (100d) variations may anti-correlate.
- **Linerarised echo model fails to fit the line variations ☹.**

Line Responses "De-cohere" 60 Days into STORM Campaign

Temporary Obscuration ? Change in the SED ?

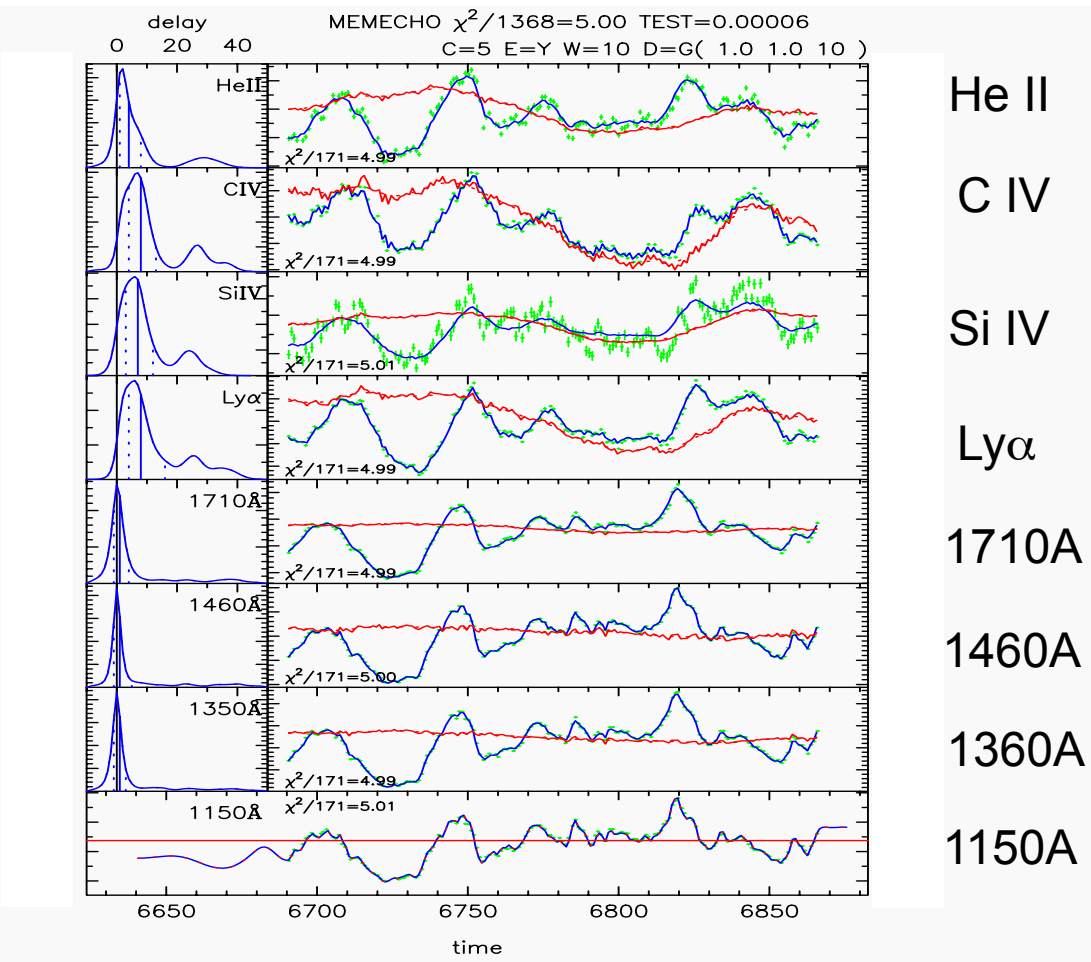


Goad et al. 2016

HST Lightcurves -> Delay Maps : Ψ(τ)

Linearised Echo Model Fails !

Model lines as **continuum echos** + **slow variations**



He II

C IV

Si IV

Lyα

1710A

1460A

1360A

1150A

Velocity-Delay Maps : f(λ,t) -> Ψ(v,τ)

HST spectra

f(λ, t)

=>

500 lightcurves

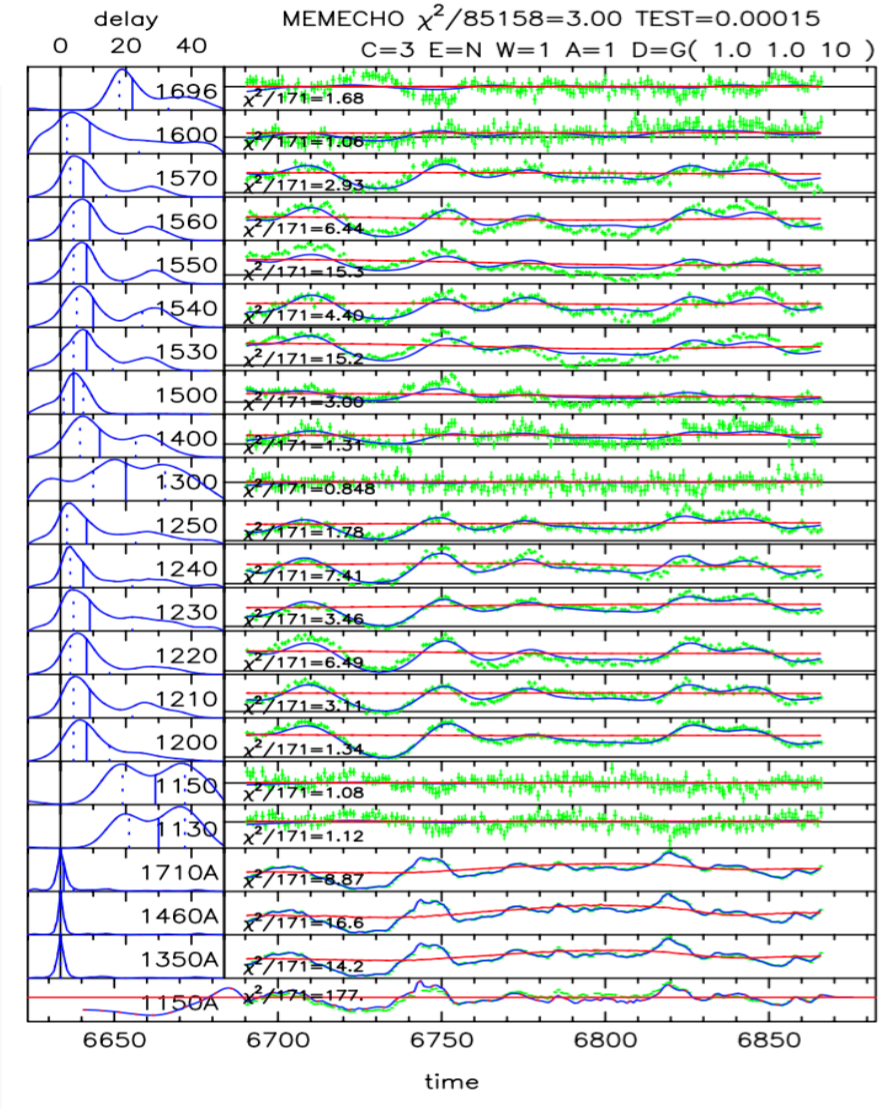
+

MEMEcho fit

=>

500 delay maps

Ψ(v, τ)



C IV

Lyα

1150-1710 continuum

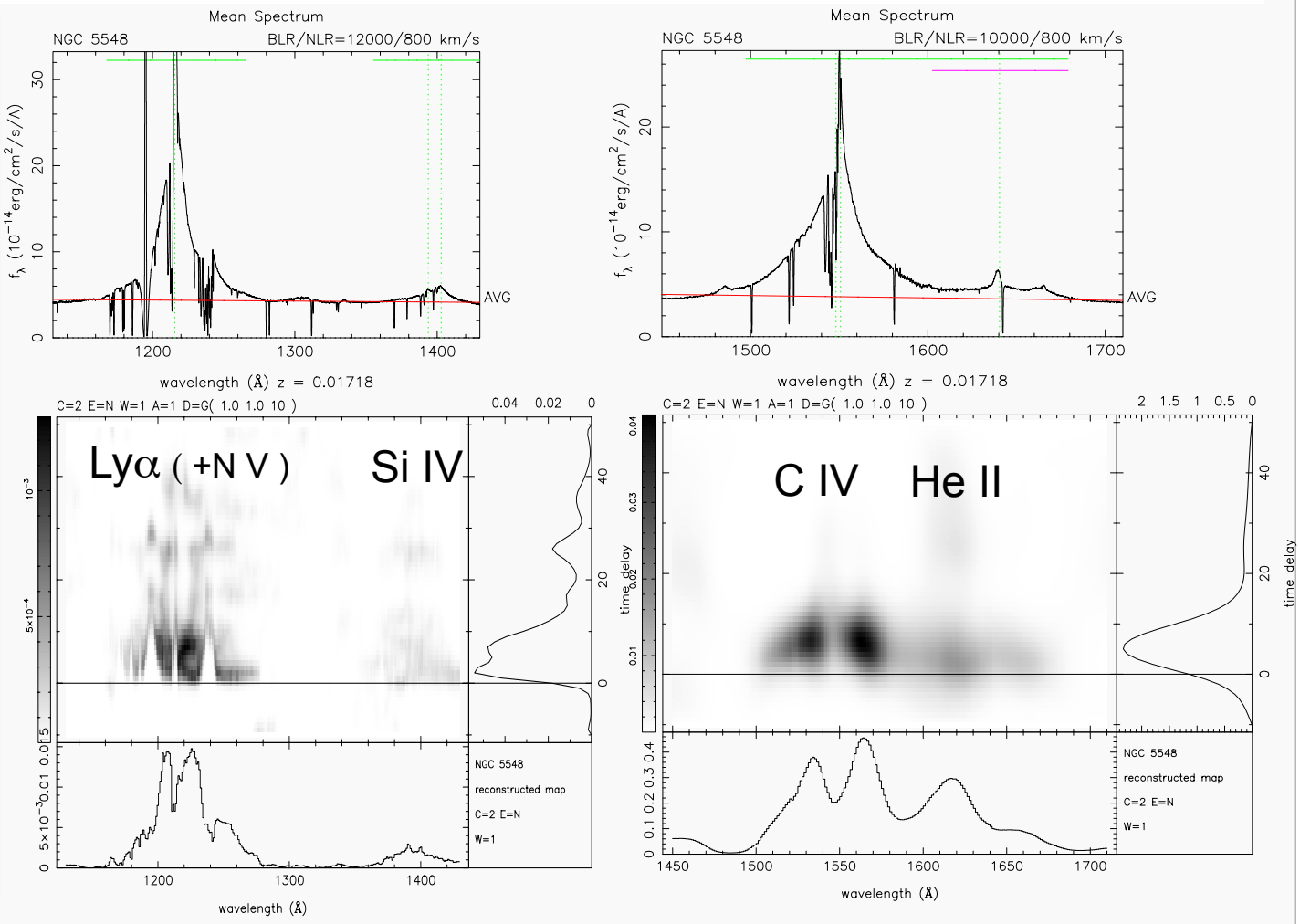
First MEMEcho fits (2015 Jan)
Ψ(v,τ) distorted by absorption lines ☹

Velocity-delay maps

Ψ(v, τ)

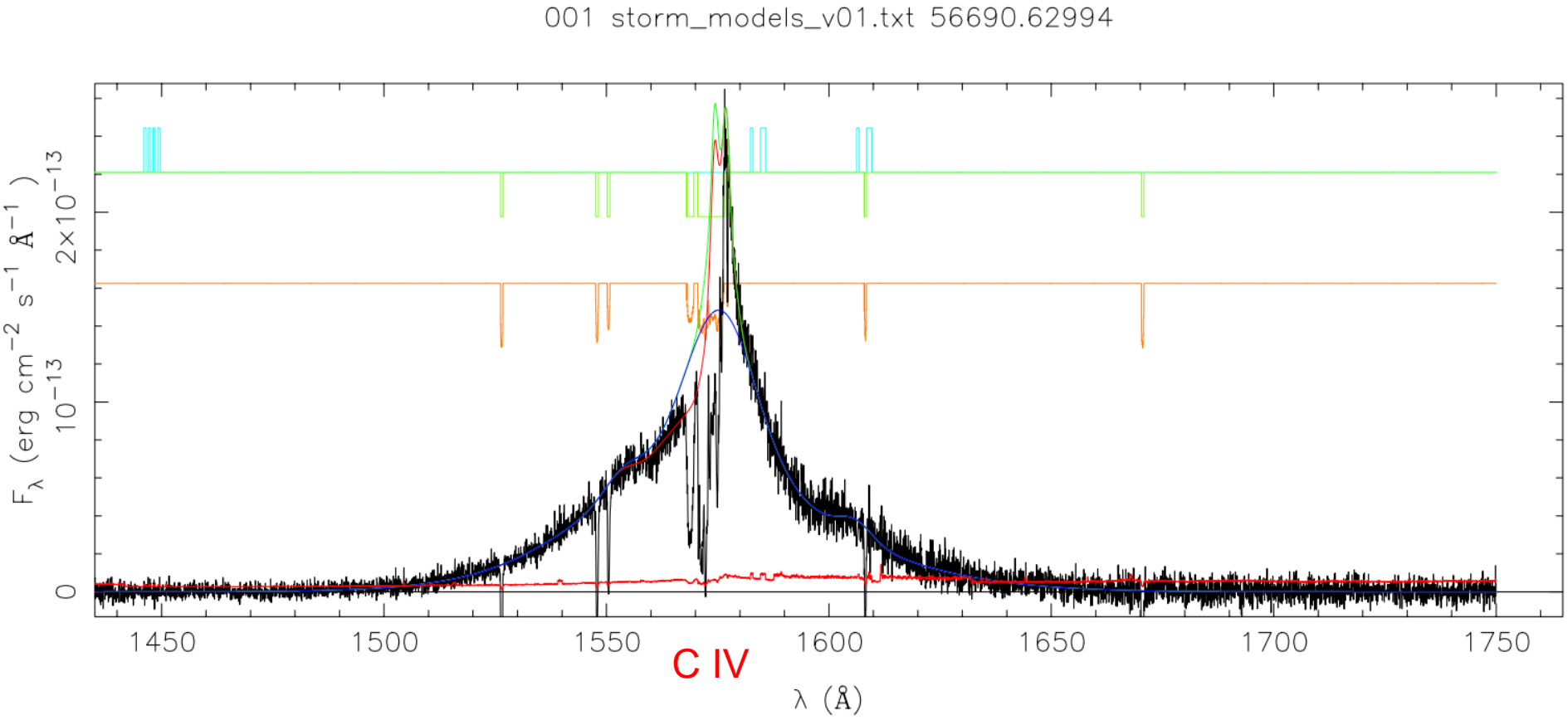
Distorted by absorption lines. ☹

To be improved...



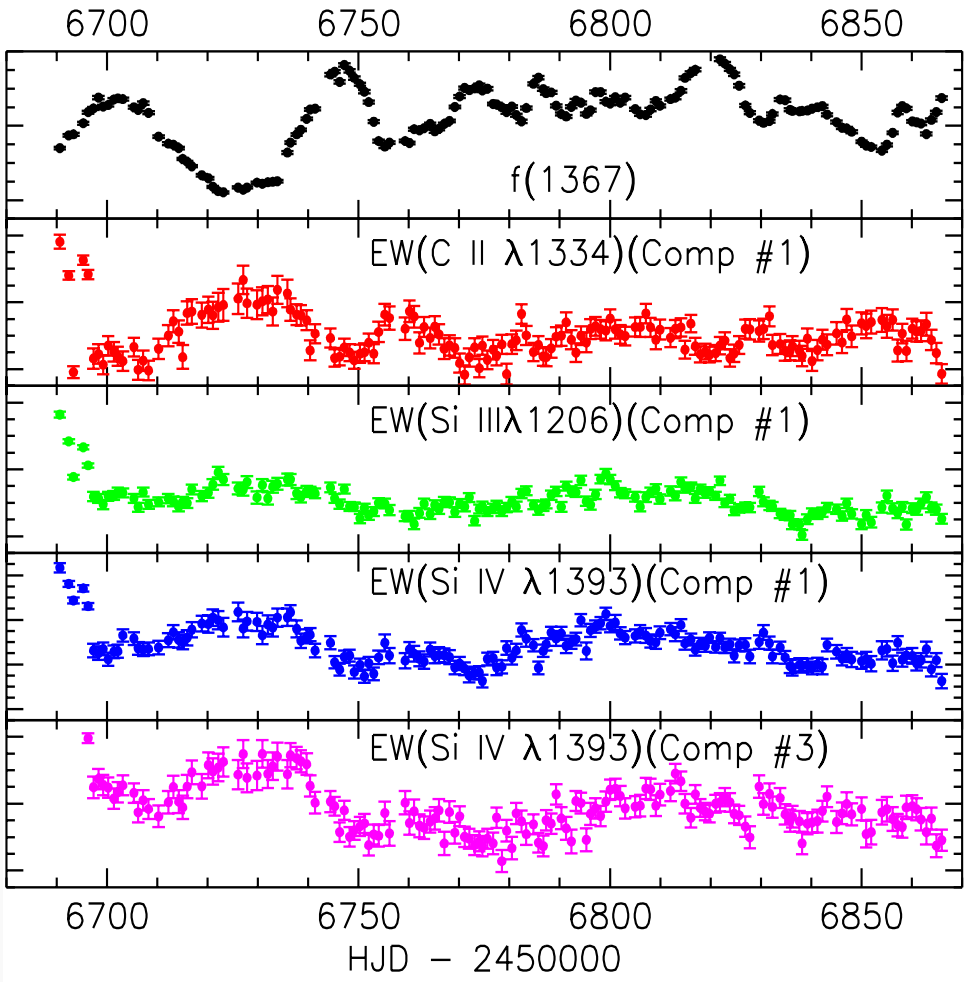
Spectral Modeling analysis (2016 Jul)

(de Rosa, Ely, Kriss) Use to remove absorption lines.



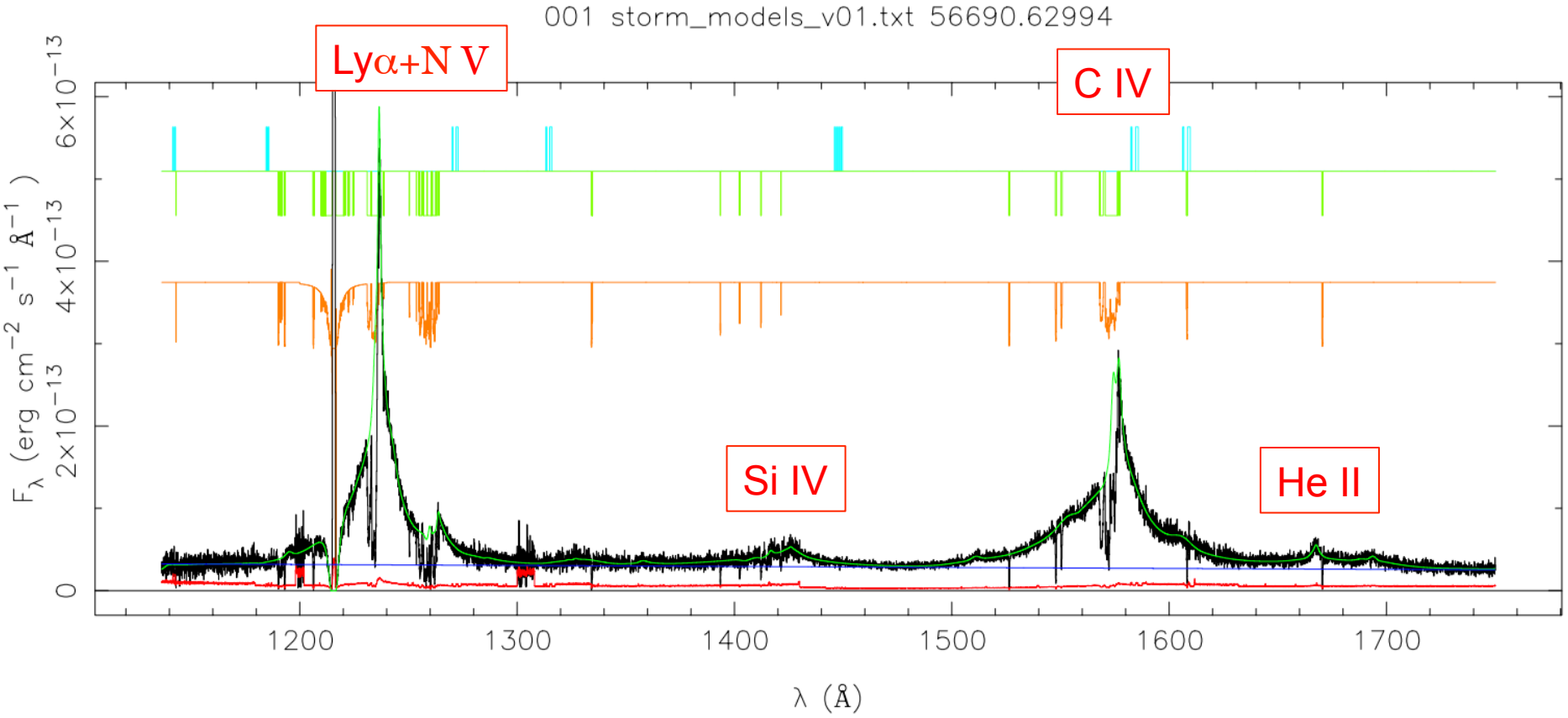
Narrow Absorption Lines

- See the same continuum that we do.
- Response time is recombination time.
- Vary in strength with continuum flux *at their ionization energy*.
- Track changes in the ionising SED

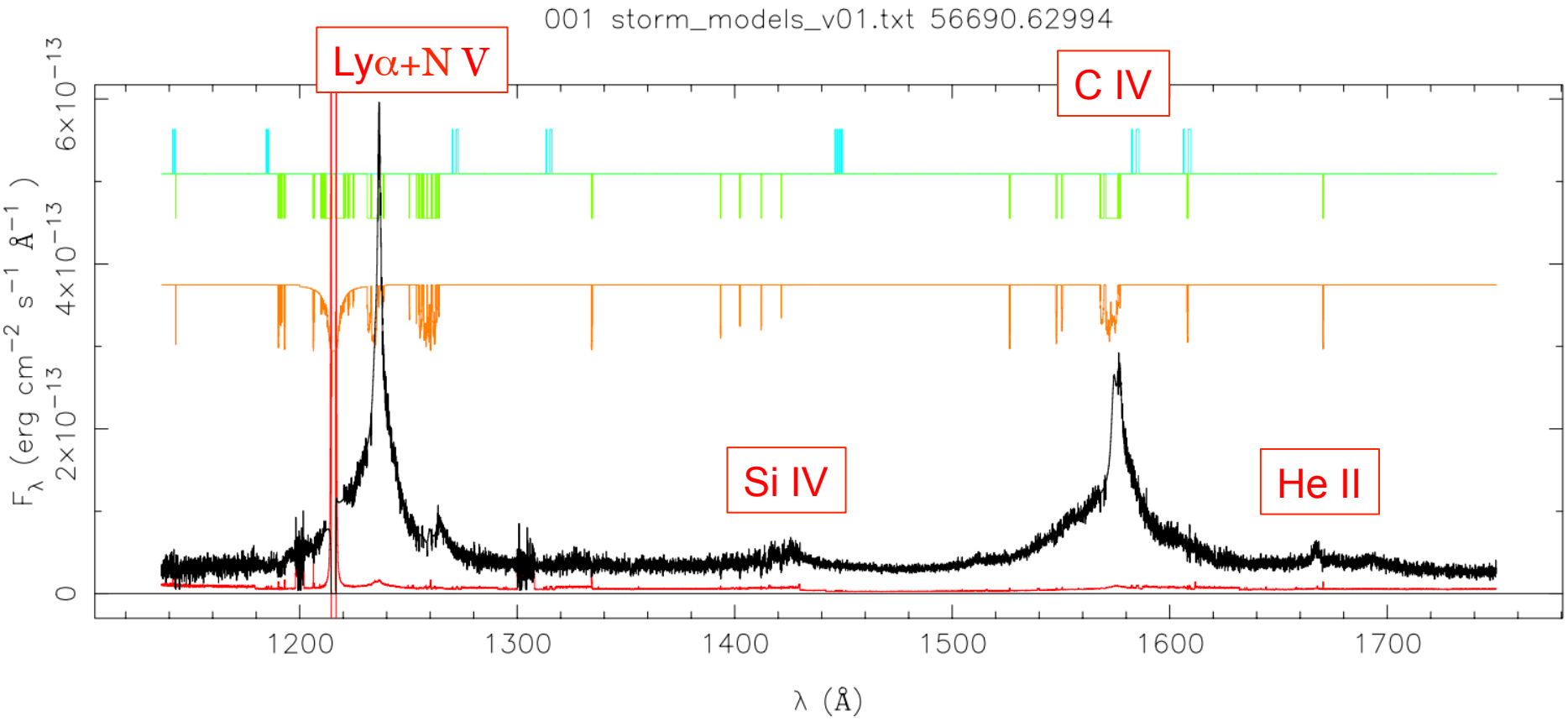


Kriss et al. in prep

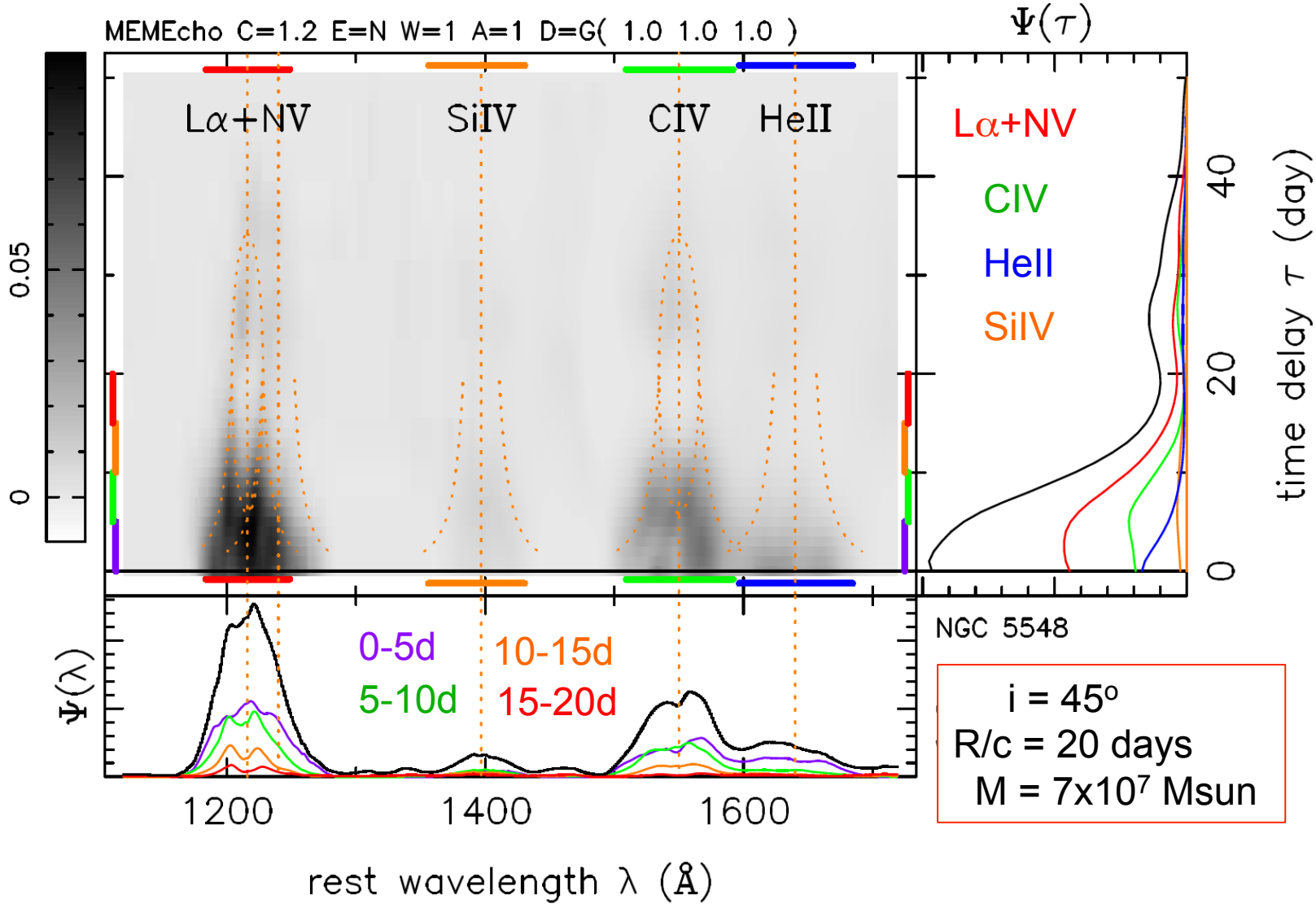
Absorption Lines Modeled



Absorption Lines Removed ☺

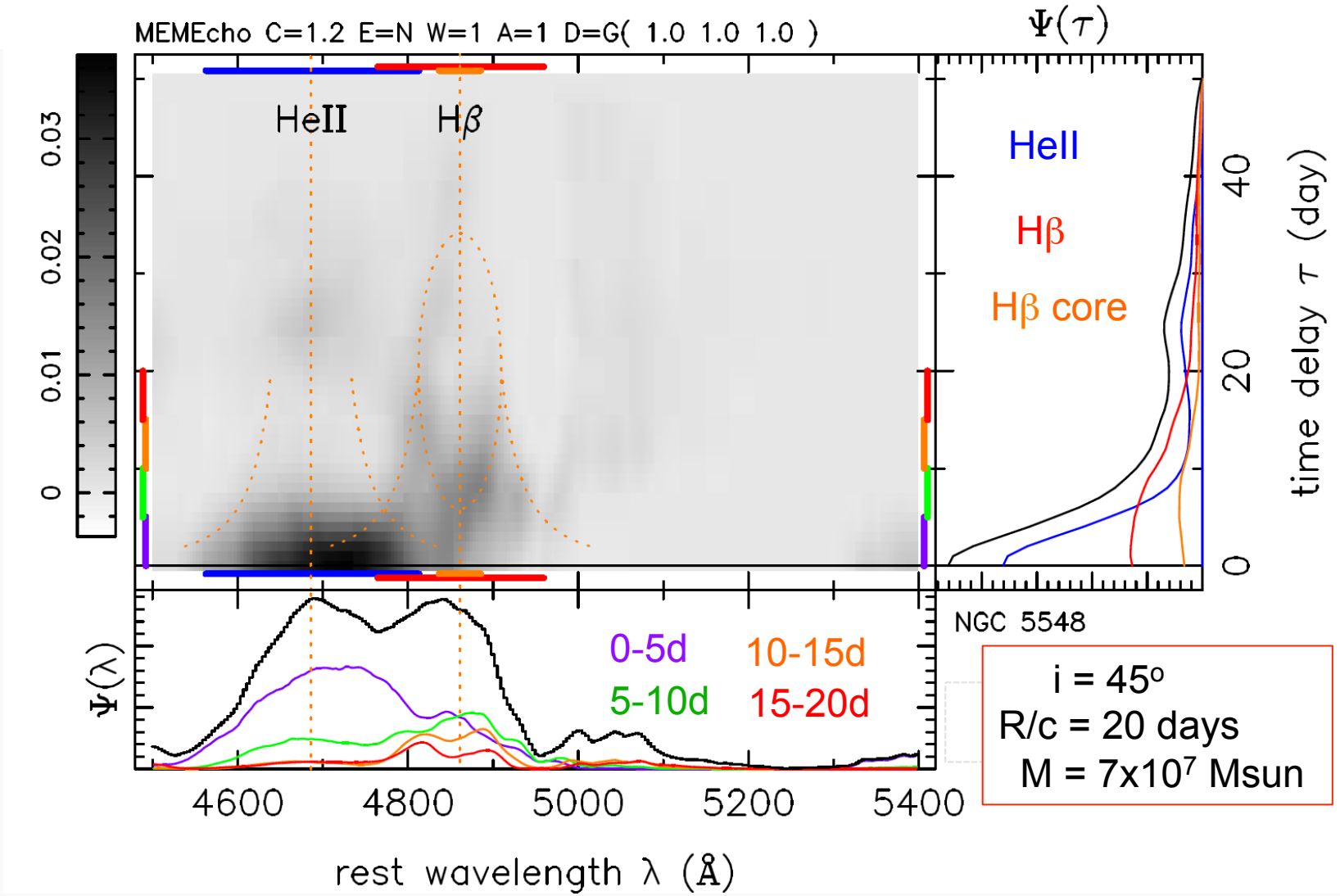


HST (UV lines) Velocity-Delay Map

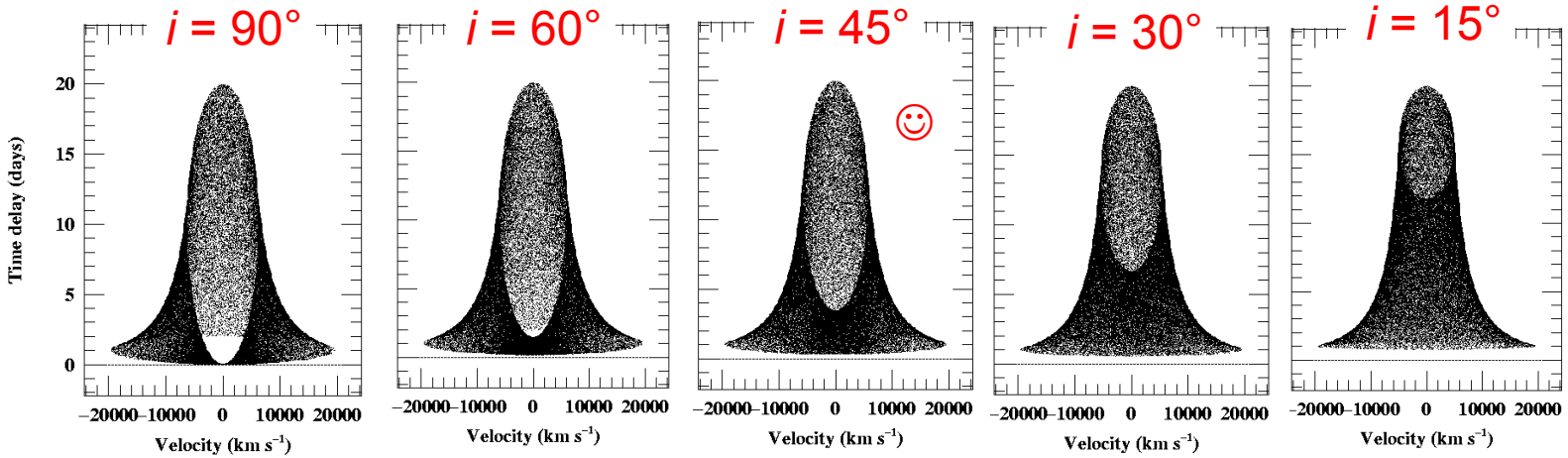


Optical lines : Velocity-Delay Map

MEMEcho fit to MDM data from *Pei et al, submitted*.

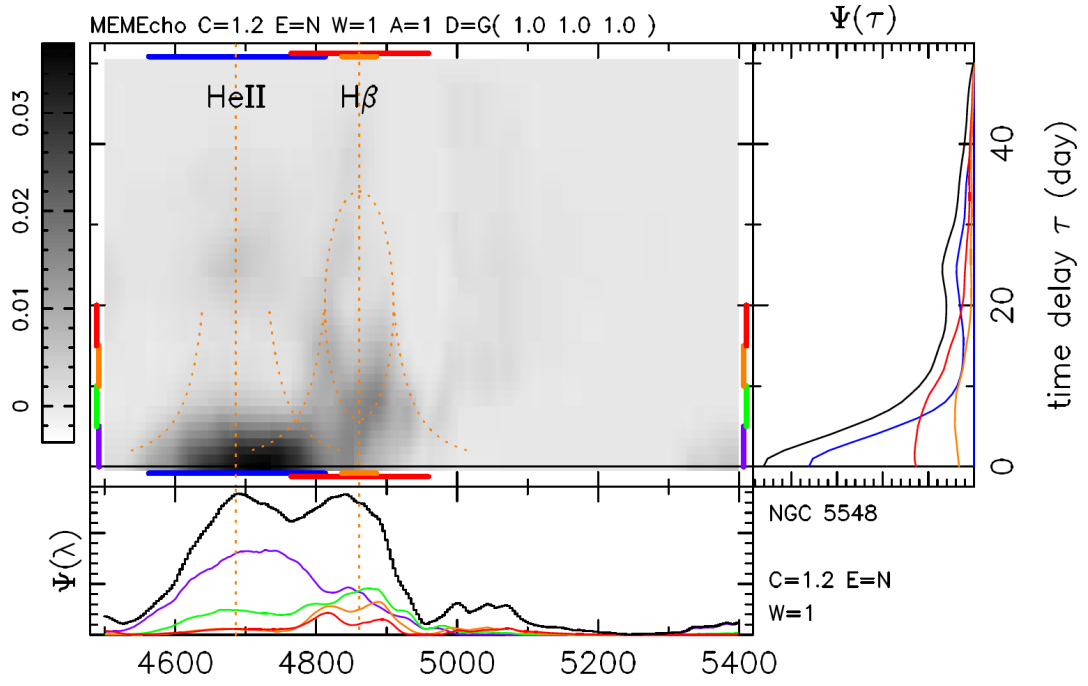


Comparison with Toy Models



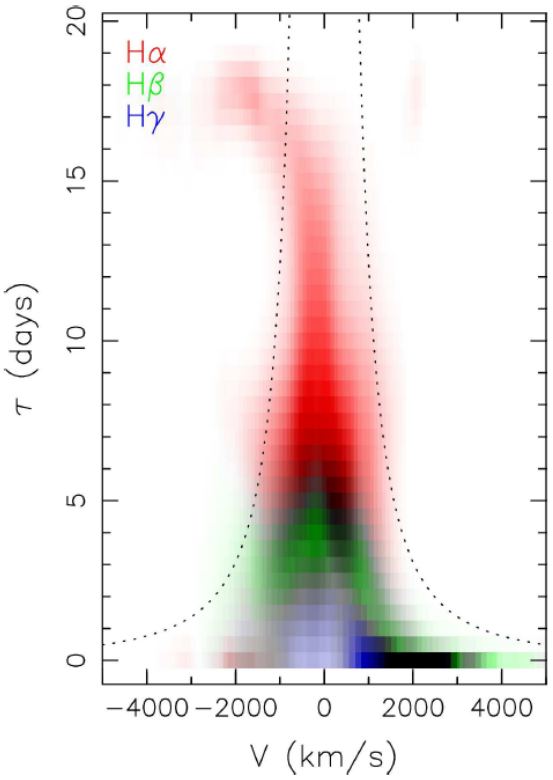
Keplerian Envelope
+ Elliptical Ring
➔
Disk-like Geometry
and Kinematics
2 to 20 light days

i = 45°
R/c = 20 days
M = 7x10^7 Msun

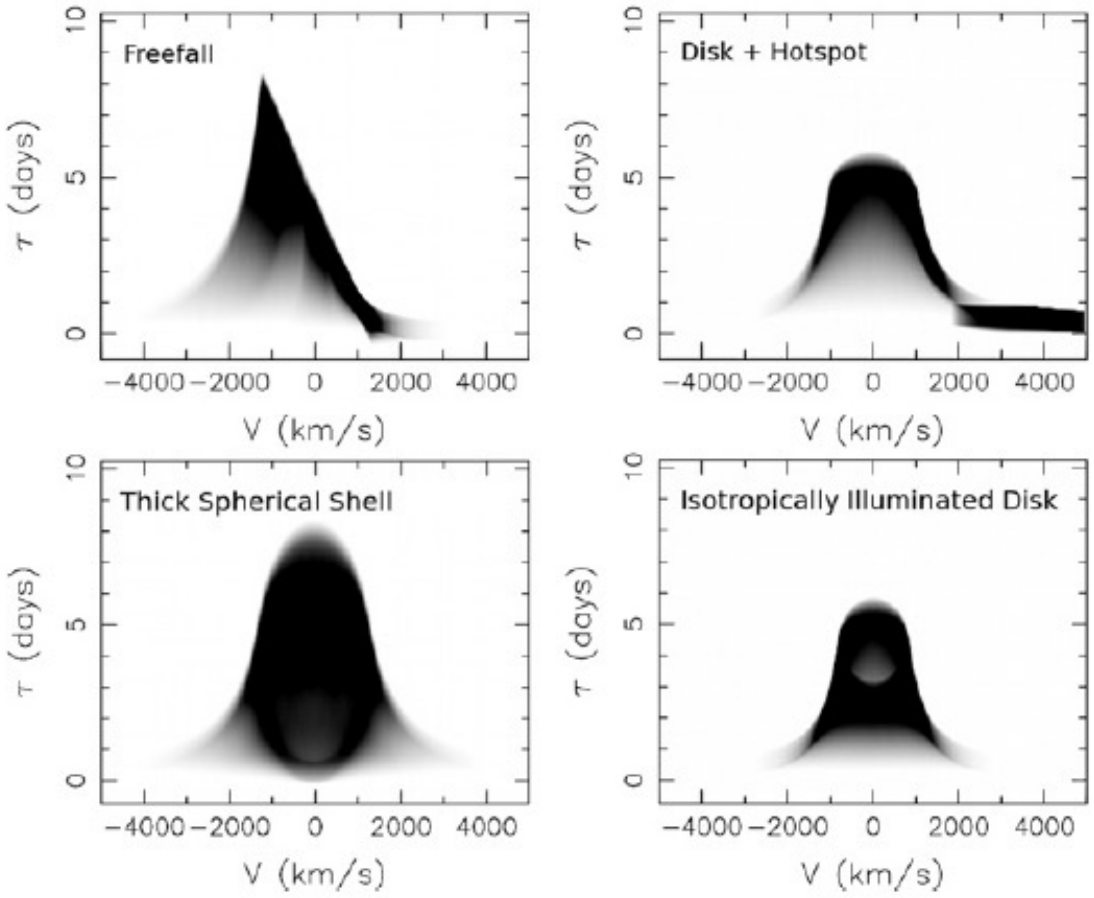


Arp 151 : BLR Maps and Toy Models

Arp 151 LAMP data :

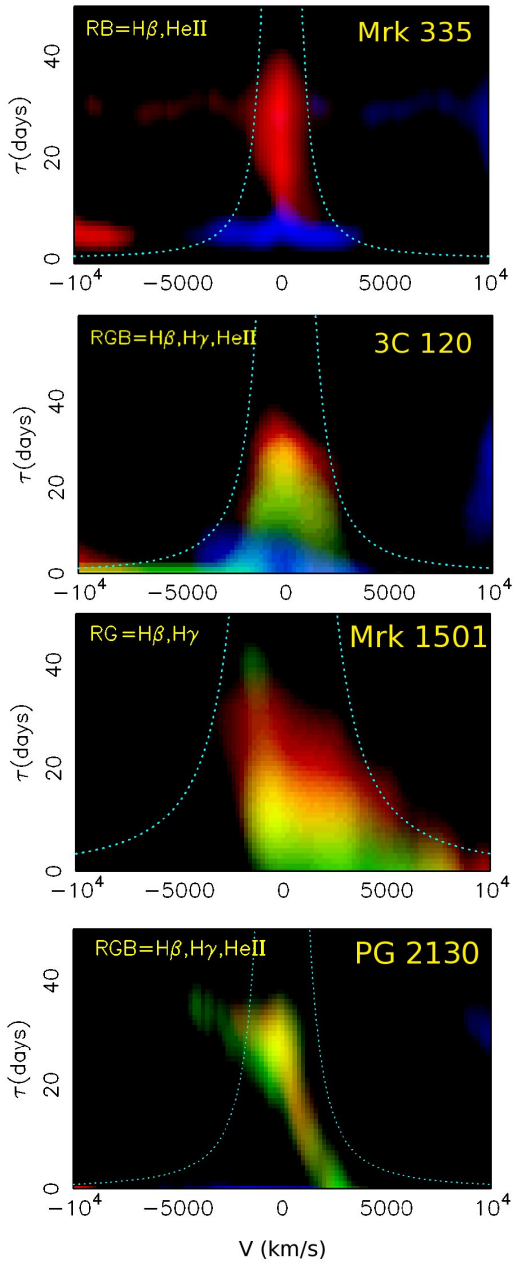


Bentz et al. 2010

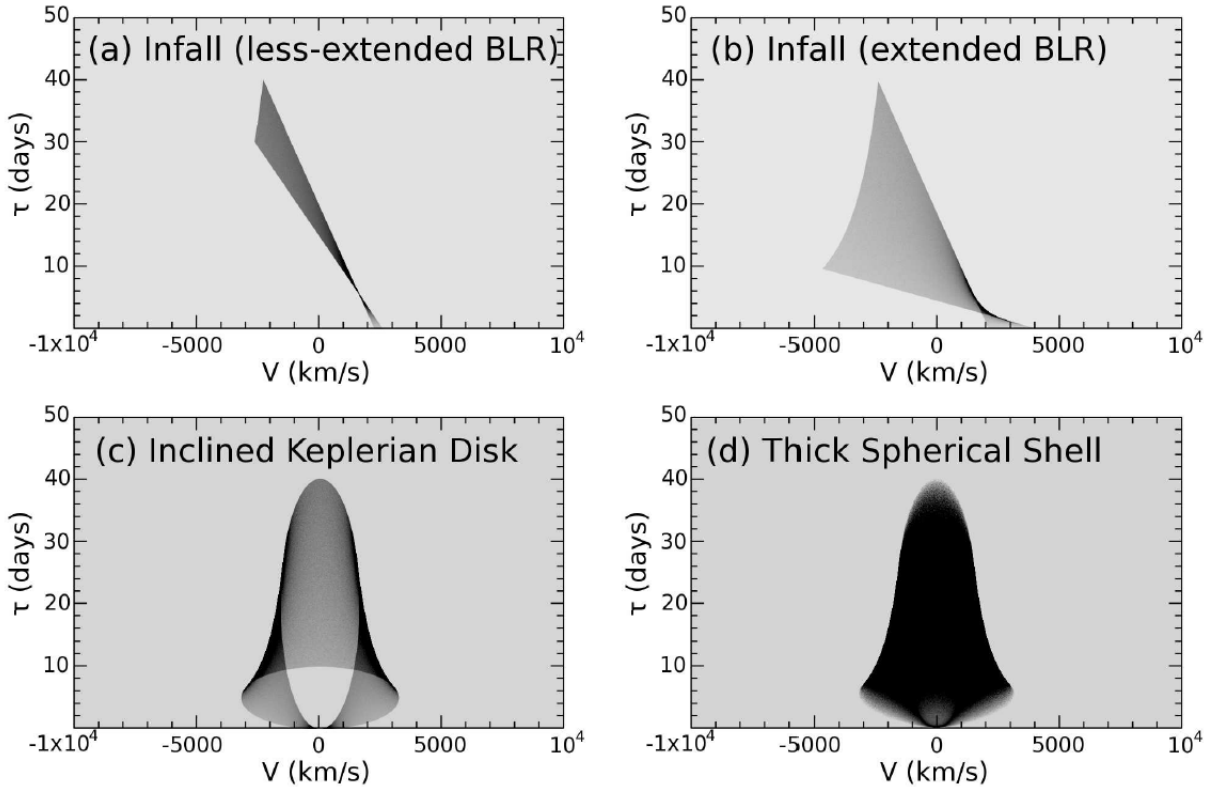


BLR Diversity

A variety of velocity-delay structures is seen.
How reliable / repeatable are these maps?
Is every AGN flow different ?



Grier et al. 2013, ApJ 764, 47



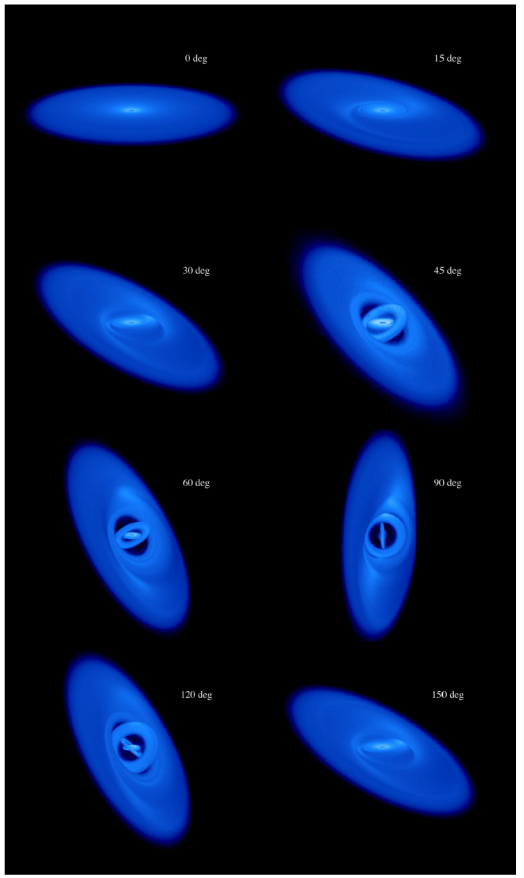
Lamp Post => Tilted Inner Disk ?

- Black hole spin mis-aligned (expected)
  - Bardeen-Petterson effect : Lens-Thirring torques align inner disk with BH spin
- Self-illumination (as in close binary stars)
  - X-FUV : multiple reprocessing increases and smears reprocessing time.
  - UV-IR : $T(r)$ steeper than $r^{-3/4}$
- Anisotropic irradiation pattern
  - $T(r) => T(r, \theta)$
  - $\Psi(V, \tau)$ red/blu asymmetry sans in/out flow
  - Object-object diversity
- Precession ?
  - Observable?

Starkey et al. in prep

Nealon, Price, Nixon 2015 MNRAS

3d SPH simulations



Thanks for Listening