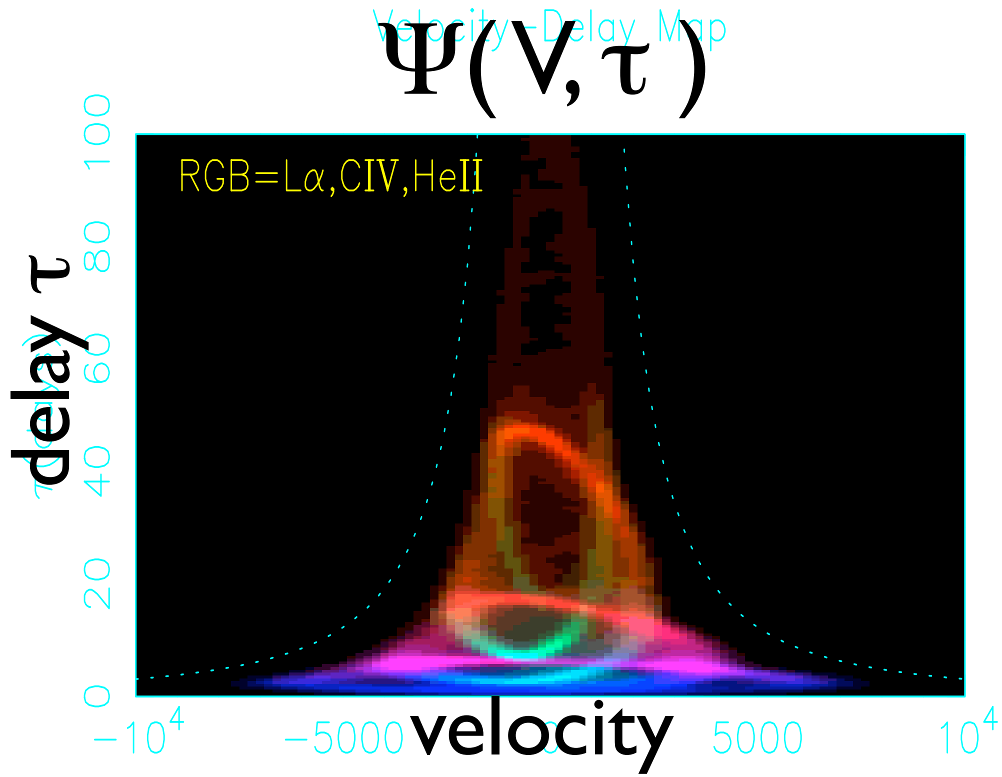
Echo Mapping of Active Galactic Nuclei

Keith Horne: (SUPA St Andrews)

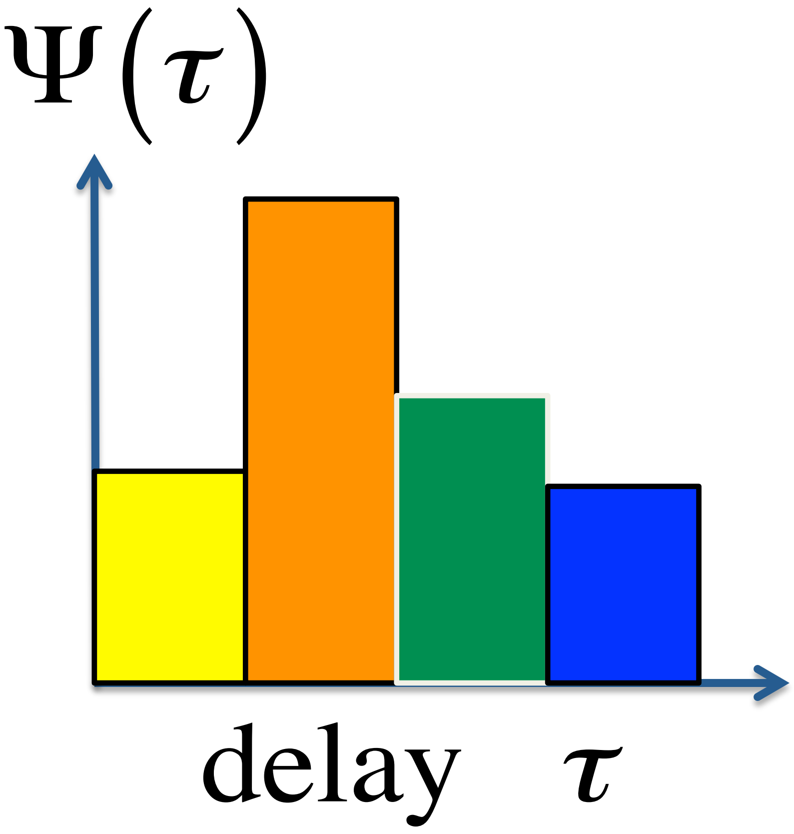
- ***Indirect imaging*** *using light travel* ***time delays*** *and* ***doppler shifts****.*
- ***Micro-arcsecond*** *maps of accretion flows onto AGN black holes.*
- *Black Hole masses.*
- *Geometry, Kinematics, Ionisation structure of their Accretion Flows..*

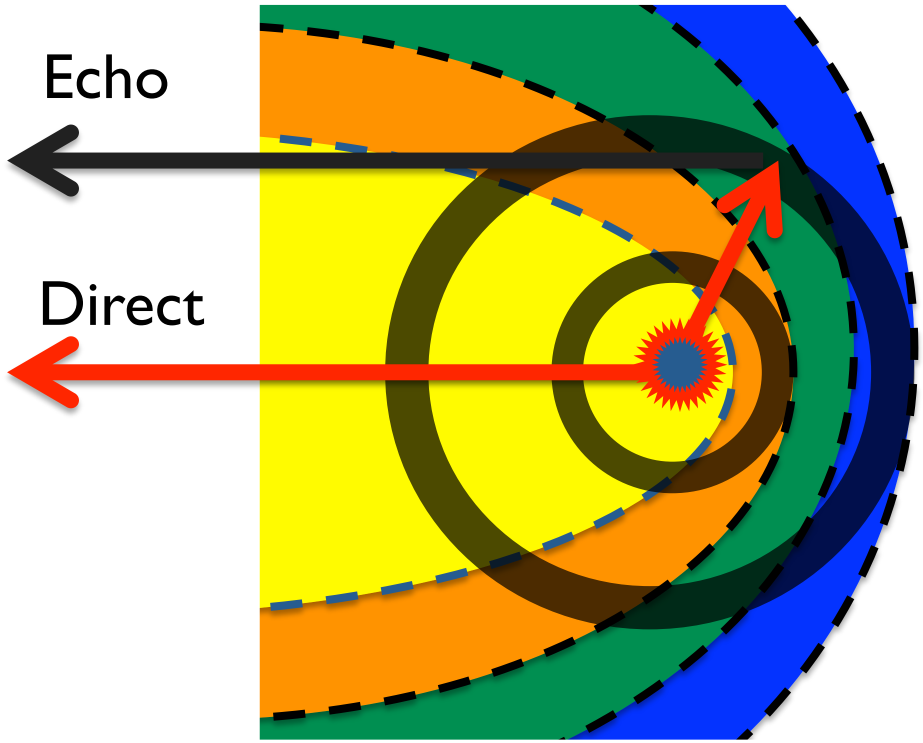
"Model-independent" projection of the 6-D phase space, resolved on doppler shift V and time delay τ, for different emission lines.



Echo Tomography:
f(λ, t) => Ψ(V, τ)

Light travel time delay τ "slices up" the region on iso-delay paraboloids.

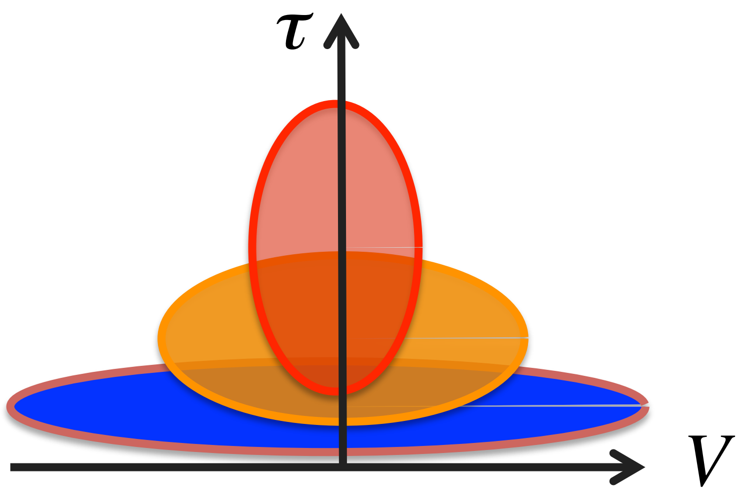


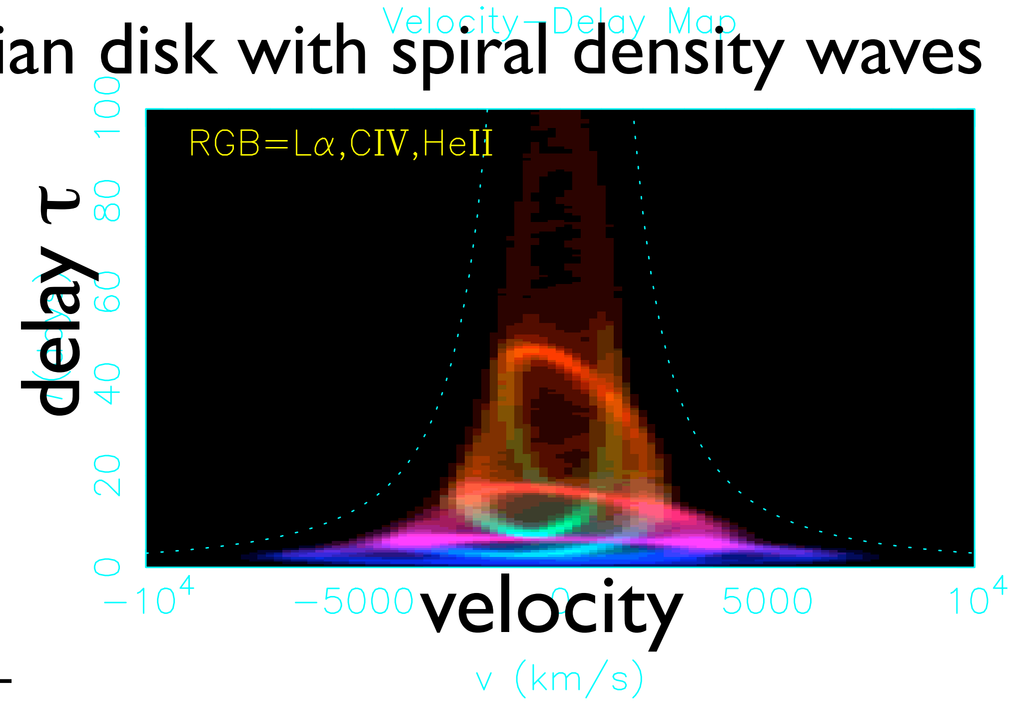


$$\tau = \frac{R}{c}\left(1+\cos\theta\right)$$

Velocity-Delay Maps $\Psi(V, \tau)$

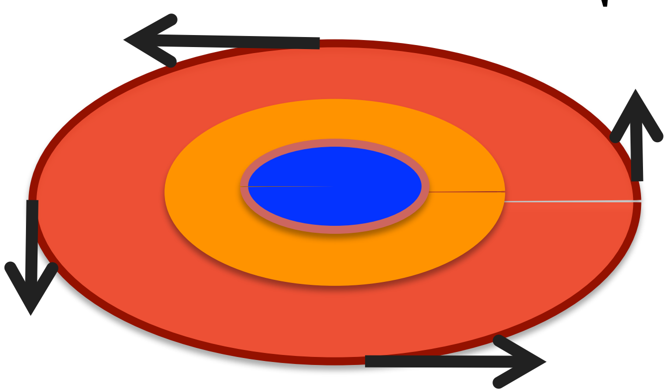
Simulation: Photo-ionised Keplerian disk with spiral density waves

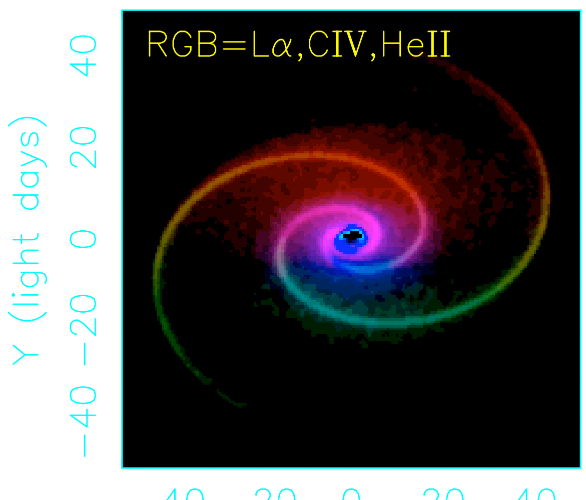




$$\tau = \frac{R}{c}\left(1 + \sin i \cos\theta\right) \qquad V = \sqrt{\frac{GM}{R}} \sin i \sin\theta$$

Sky view:



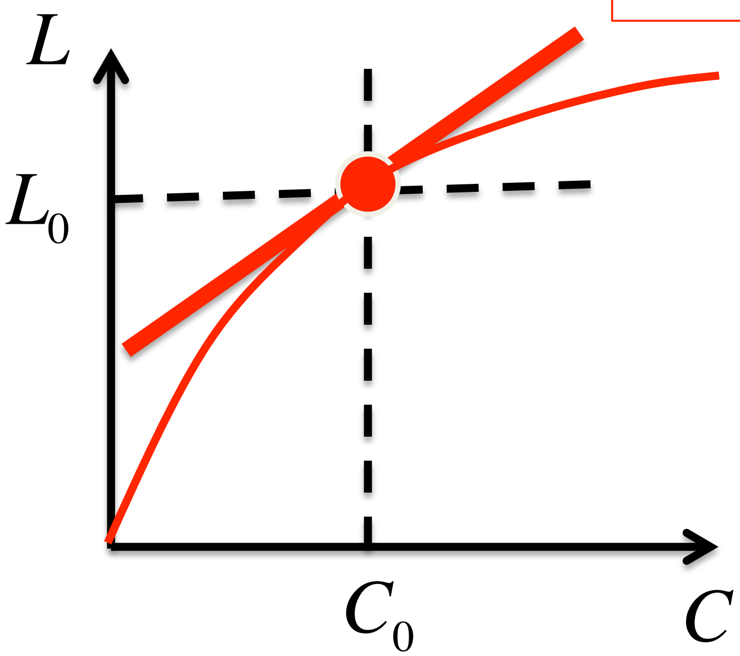


Linearised Echo Model

Lightcurve model:

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

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



Tangent-curve approximation to ***non-linear*** *responses of photo-ionised emission lines to continuum variations.*

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

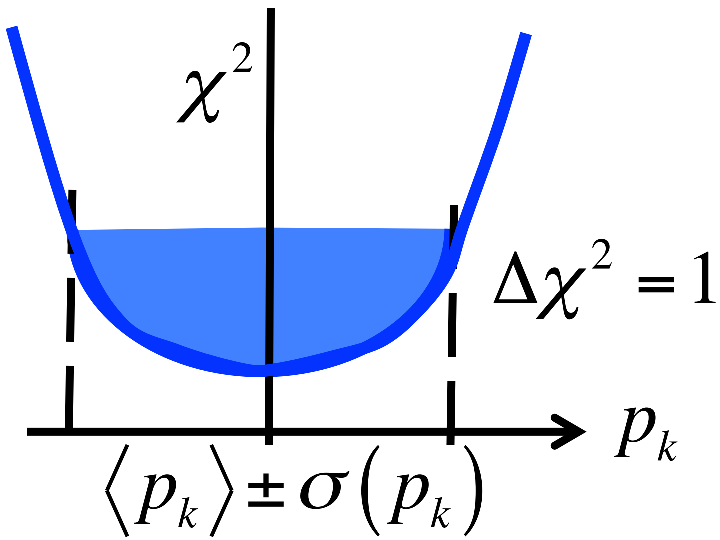
$$\text{model parameters}: \quad C(t),\ L_0,\ \Psi(\tau)\ .$$

MEMECHO : Maximum Entropy Fits

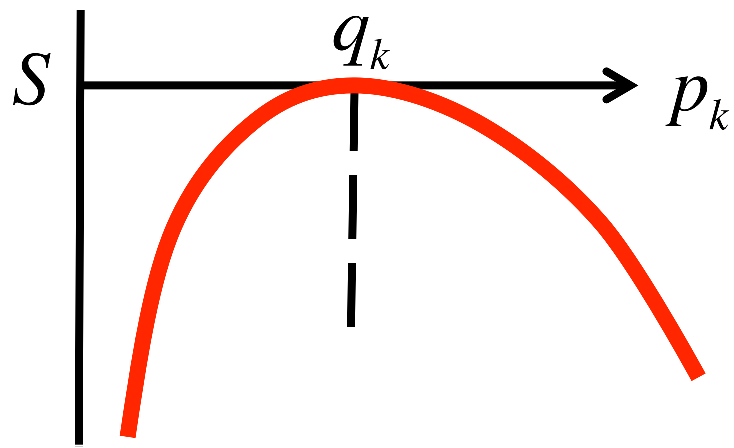
$$\Pr(\text{Model} \mid \text{Data}) \propto \exp\{-\chi^2/2\}\ \exp\{\alpha S/2\}$$

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

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

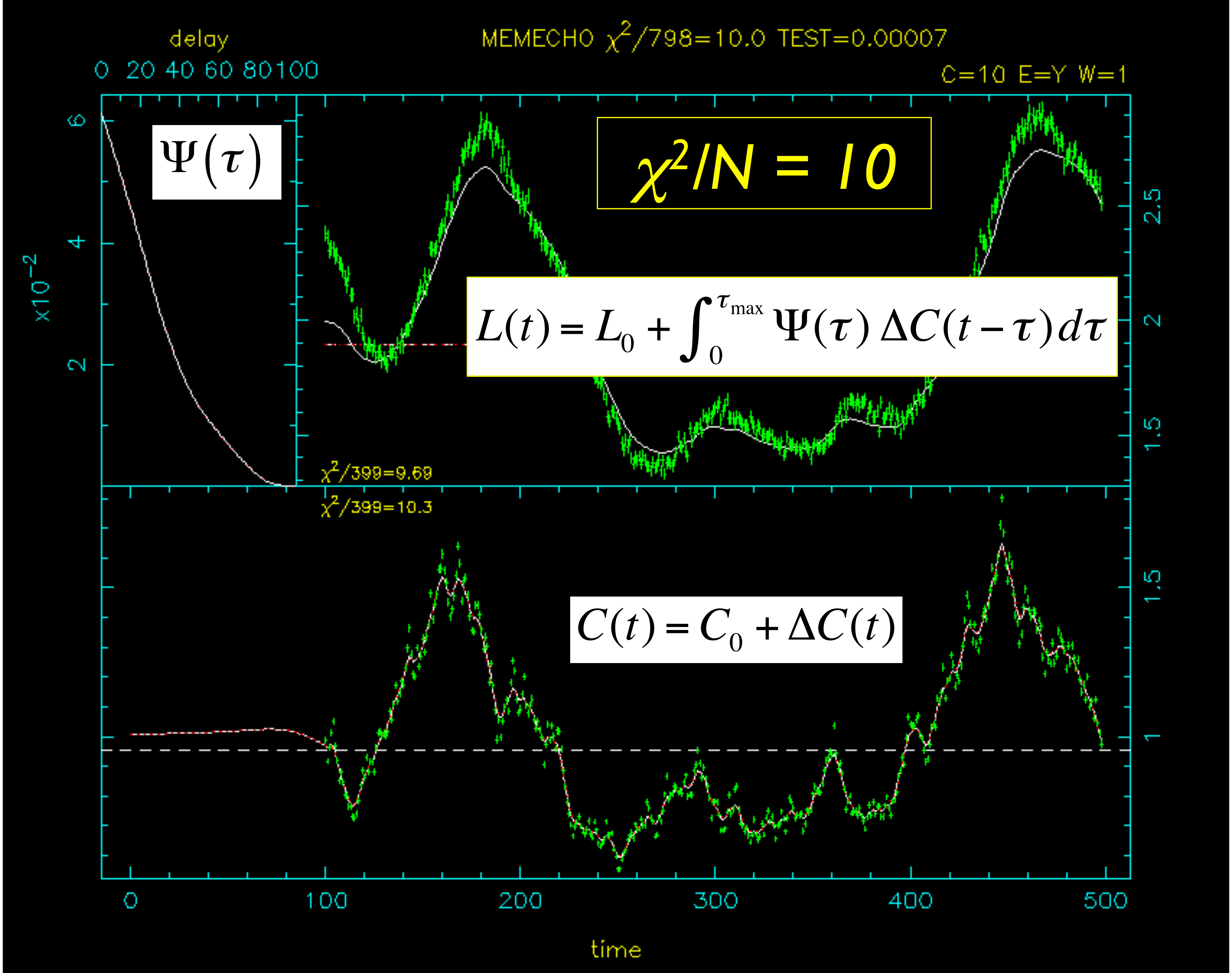


2. **Keep it "simple".** $\alpha \Rightarrow \infty$

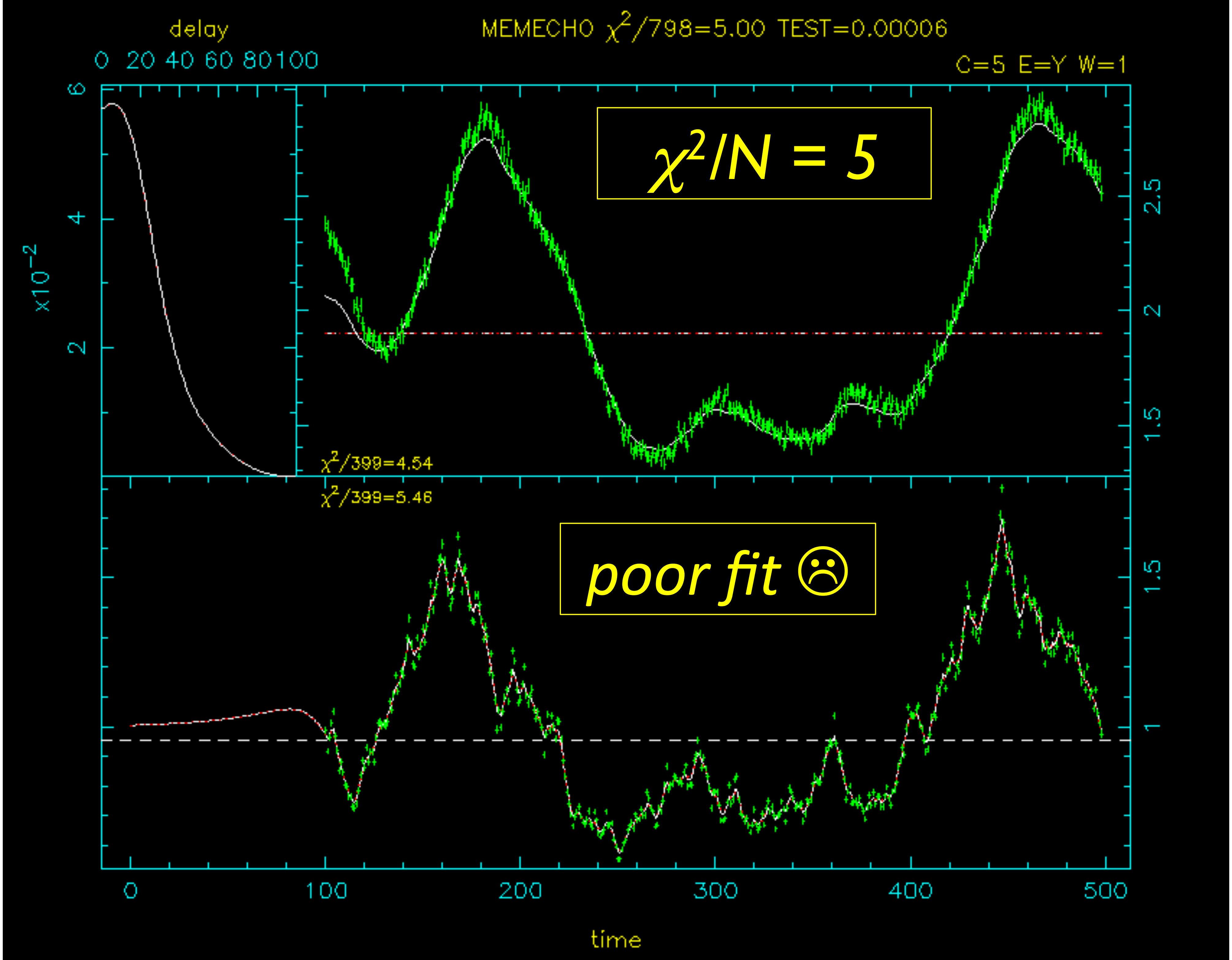


$p_k > 0$. $S_{\max} = 0$, when $p_k = q_k$.

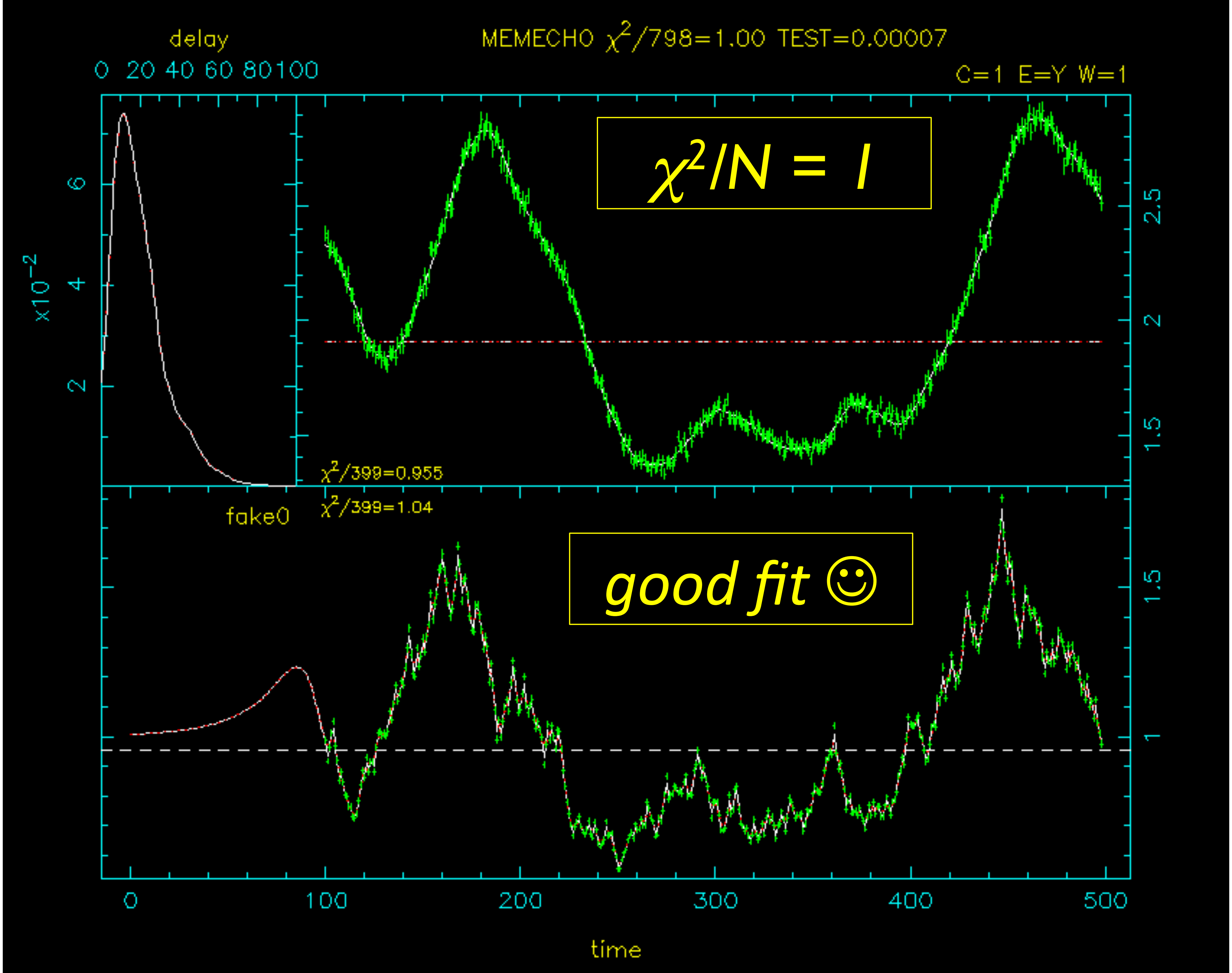
default values: e.g. $q_k = (p_{k-1} p_{k+1})^{1/2}$



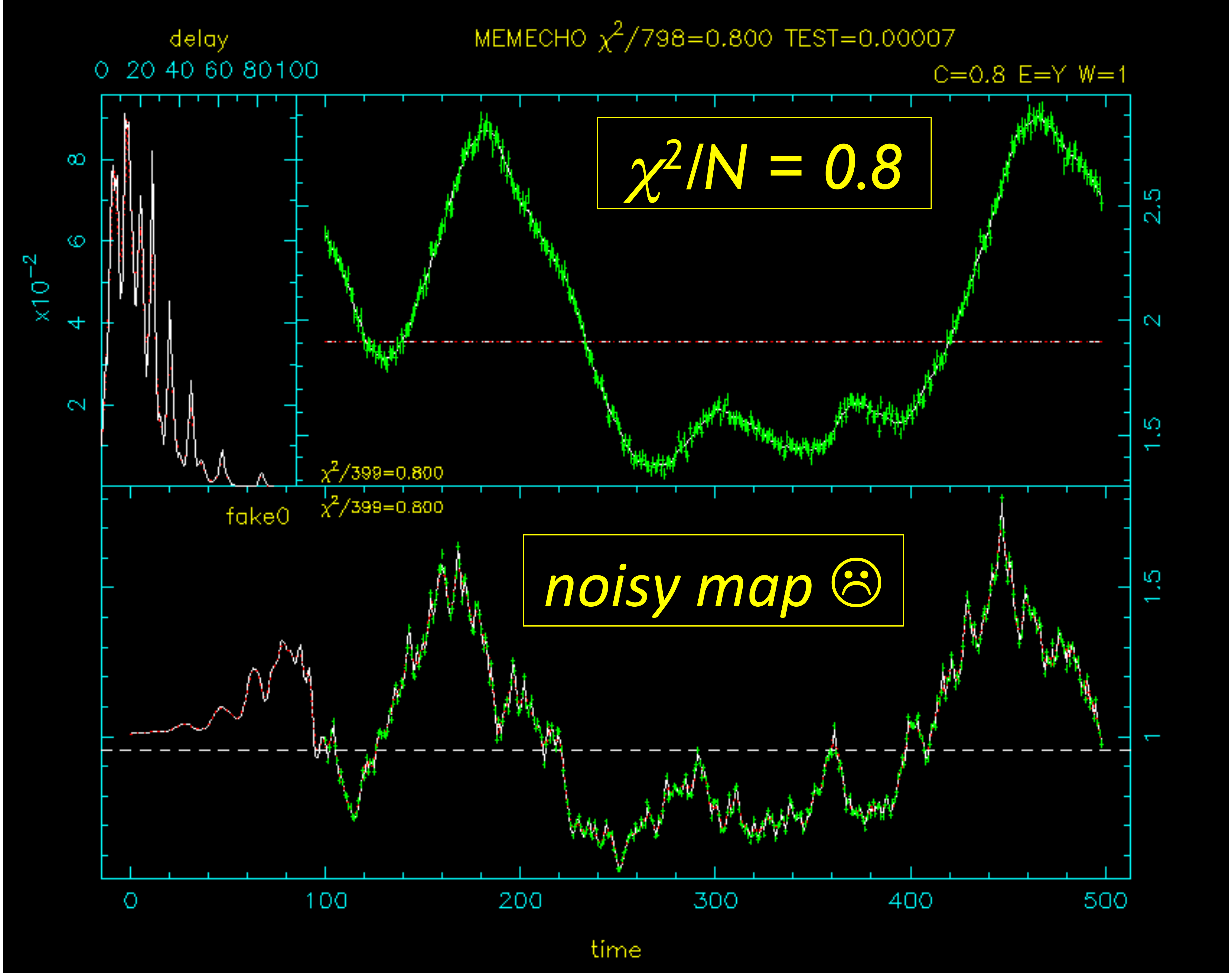
delay
0 20 40 60 80100
MEMECHO $\chi^2/798=10.0$ TEST=0.00007
C=10 E=Y W=1
$\Psi(\tau)$
$\chi^2/N = 10$
$L(t) = L_0 + \int_0^{\tau_{max}} \Psi(\tau)\, \Delta C(t-\tau)\, d\tau$
$C(t) = C_0 + \Delta C(t)$
$\chi^2/399=9.69$
$\chi^2/399=10.3$
x10^{-2}
6
4
2
2.5
2
1.5
1.5
1
0
100
200
300
400
500
time



delay
0 20 40 60 80 100
MEMECHO χ^2/798=5.00 TEST=0.00006
C=5 E=Y W=1
$\chi^2/N = 5$
χ^2/399=4.54
χ^2/399=5.46
poor fit ☹
x10^{-2}
2
4
6
2.5
2
1.5
1
0 100 200 300 400 500
time



delay
0 20 40 60 80100
MEMECHO χ2/798=1.00 TEST=0.00007
C=1 E=Y W=1
x10−2
6
4
2
2.5
2
1.5
χ2/N = 1
χ2/399=0.955
fake0
χ2/399=1.04
good fit ☺
1.5
1
0
100
200
300
400
500
time

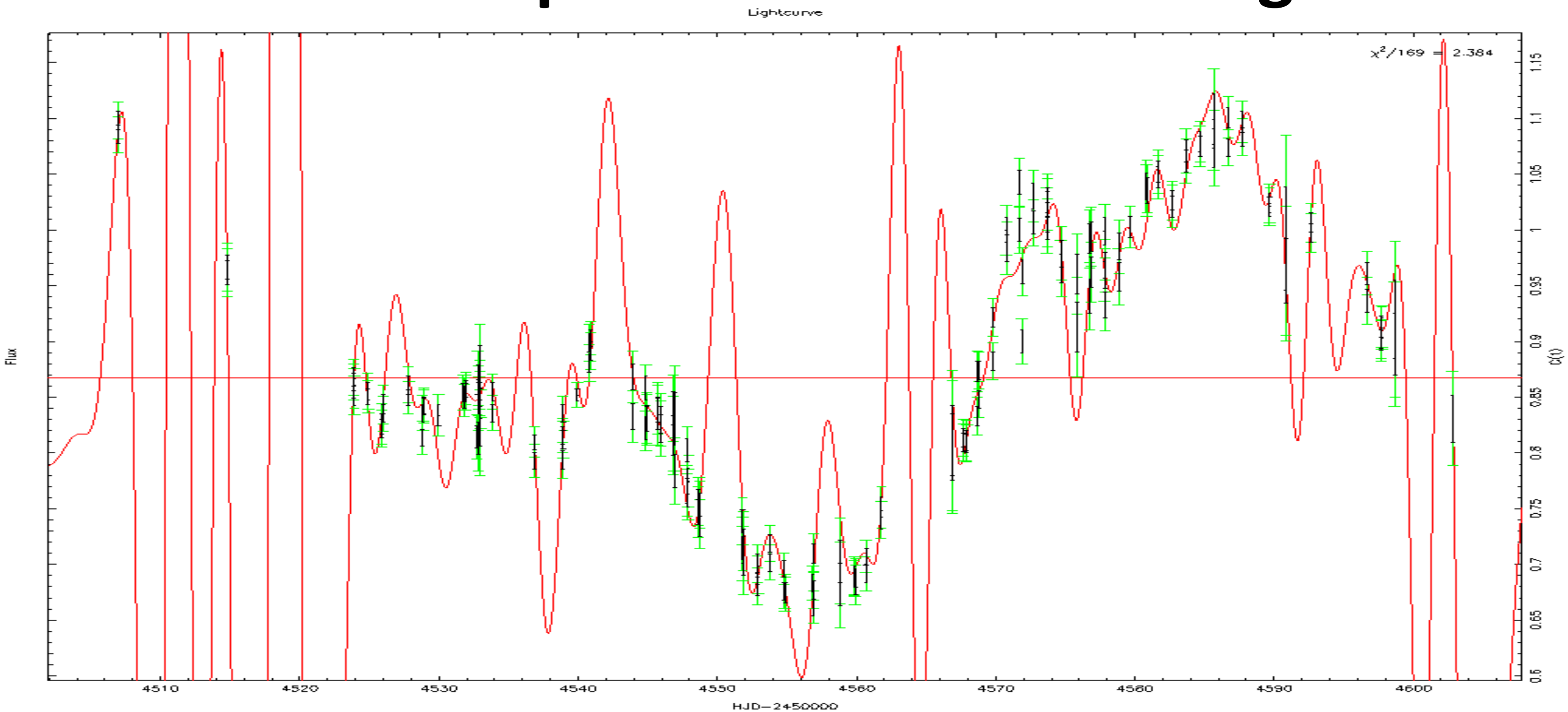


MEMECHO χ^2/798=0.800 TEST=0.00007
C=0.8 E=Y W=1
delay
0 20 40 60 80 100
$\times 10^{-2}$
2
4
6
8
1.5
2
2.5
$\chi^2/N = 0.8$
χ^2/399=0.800
χ^2/399=0.800
fake0
noisy map ☹
1
1.5
0
100
200
300
400
500
time

Problem: $\chi^2 - \alpha S$ fails to control the lightcurve model in data gaps and extrapolation regions.

Solution: 1: Use **good data** with **good error bars**.

2: Use **prior info about AGN lightcurves**.



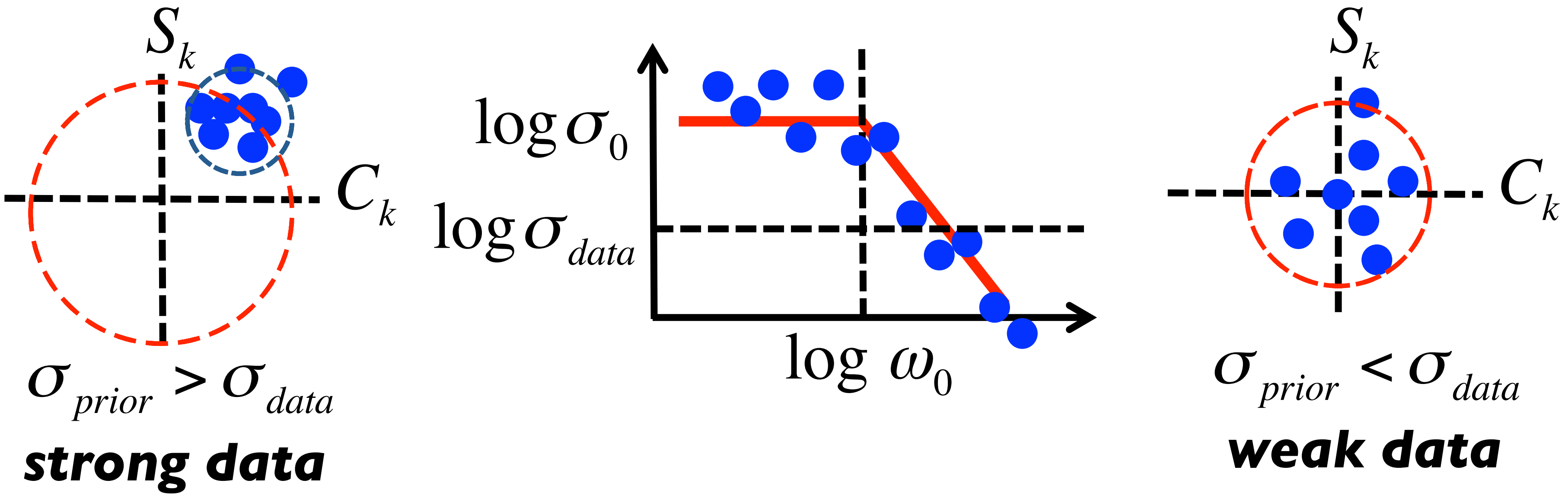
Cure: Power Spectrum Prior

Lightcurve model: $\mu(t) = \sum_{k=1}^{K} C_k \cos(2\pi\omega_k t) + S_k \sin(2\pi\omega_k t)$

Gaussian priors on fourier amplitudes, **power - law power spectrum**:

$$\text{Prior}(C_k, S_k) = \frac{1}{2\pi\sigma_k^2} \exp\left\{-\frac{C_k^2 + S_k^2}{2\sigma_k^2}\right\} \qquad \sigma_k^2 = \frac{\sigma_0^2}{1+(\omega_k/\omega_0)^\alpha}$$

Parameters: $C_k, S_k,$ $\sigma_0^2, \omega_0, \alpha$

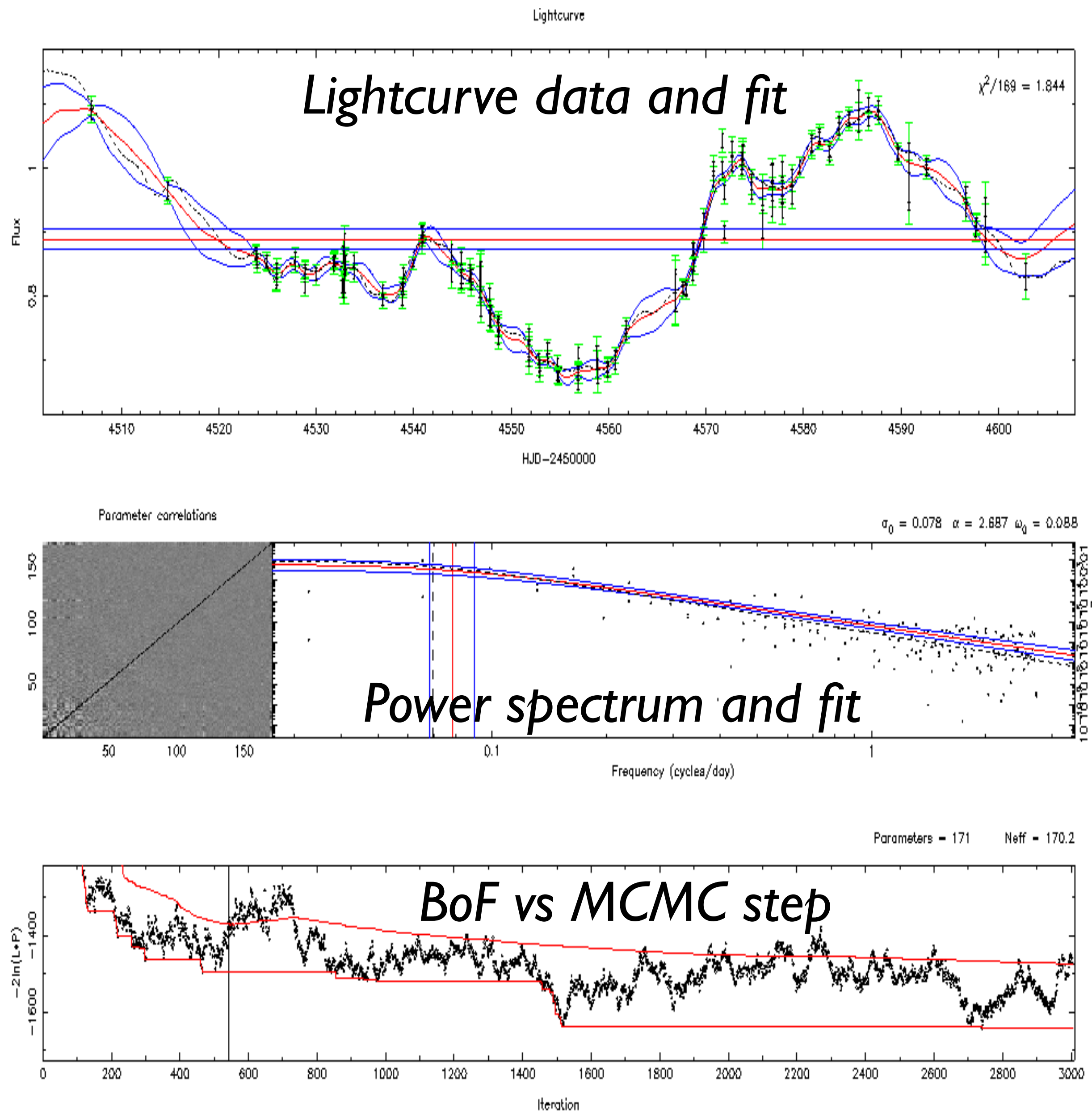


MCMC fit with Power-Spectrum Prior

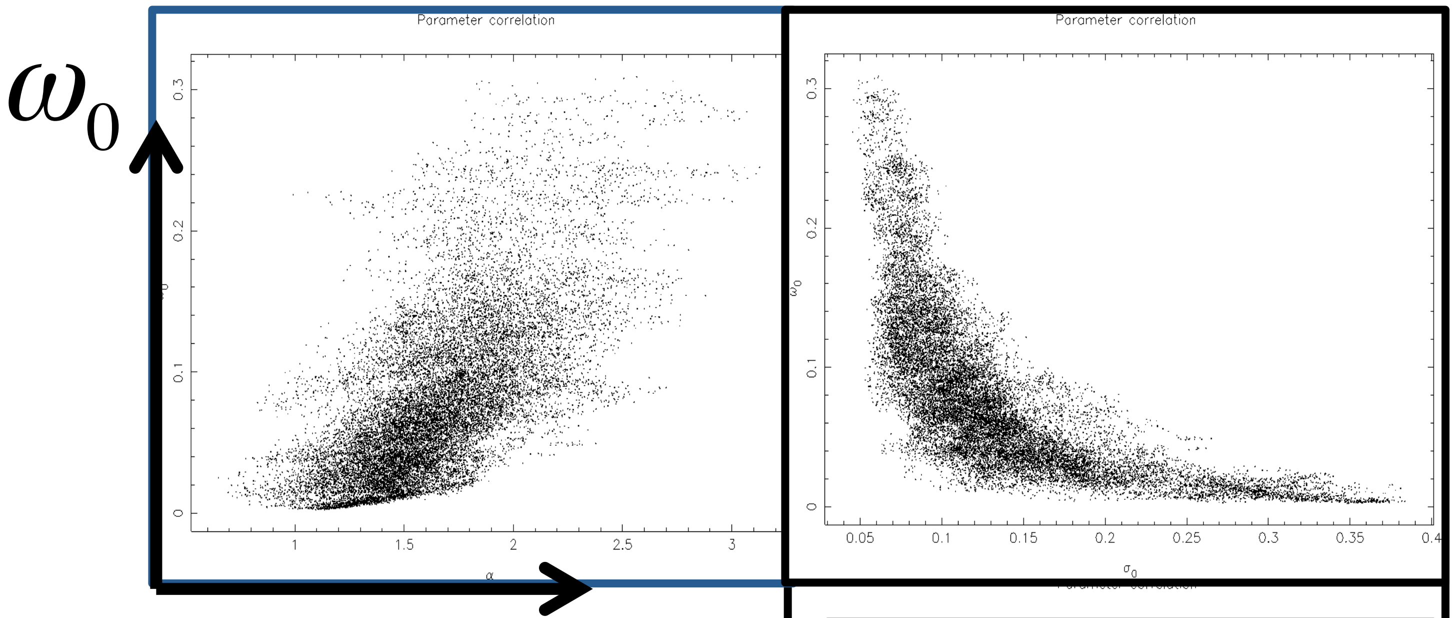
MCMC fit *explores the full range of parameters that fit the data.*

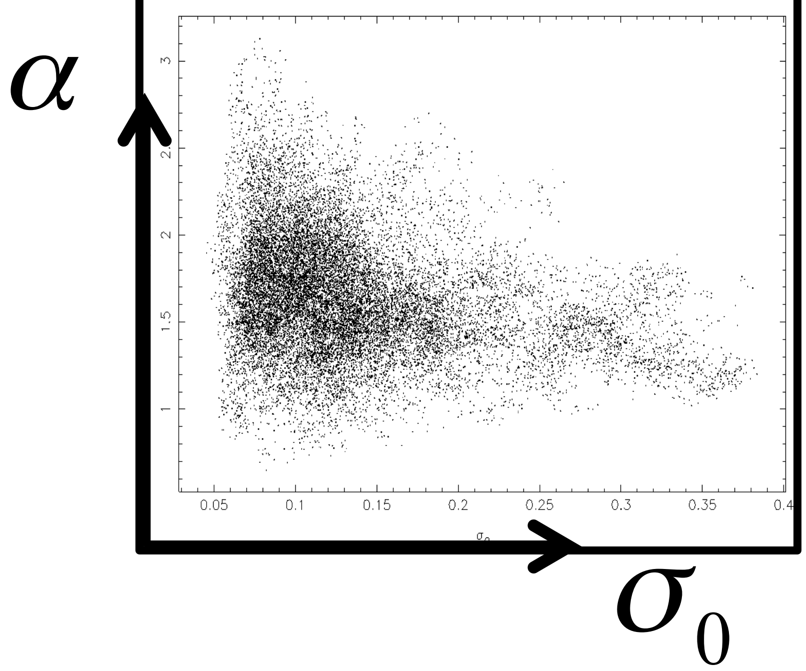
Power-spectrum prior
cures "flailing" in the data gaps.

Error bars on the fit
Optimal average of dense data,
Error envelope expands
in data gaps and extrapolations.



MCMC: Parameter Co-Variances



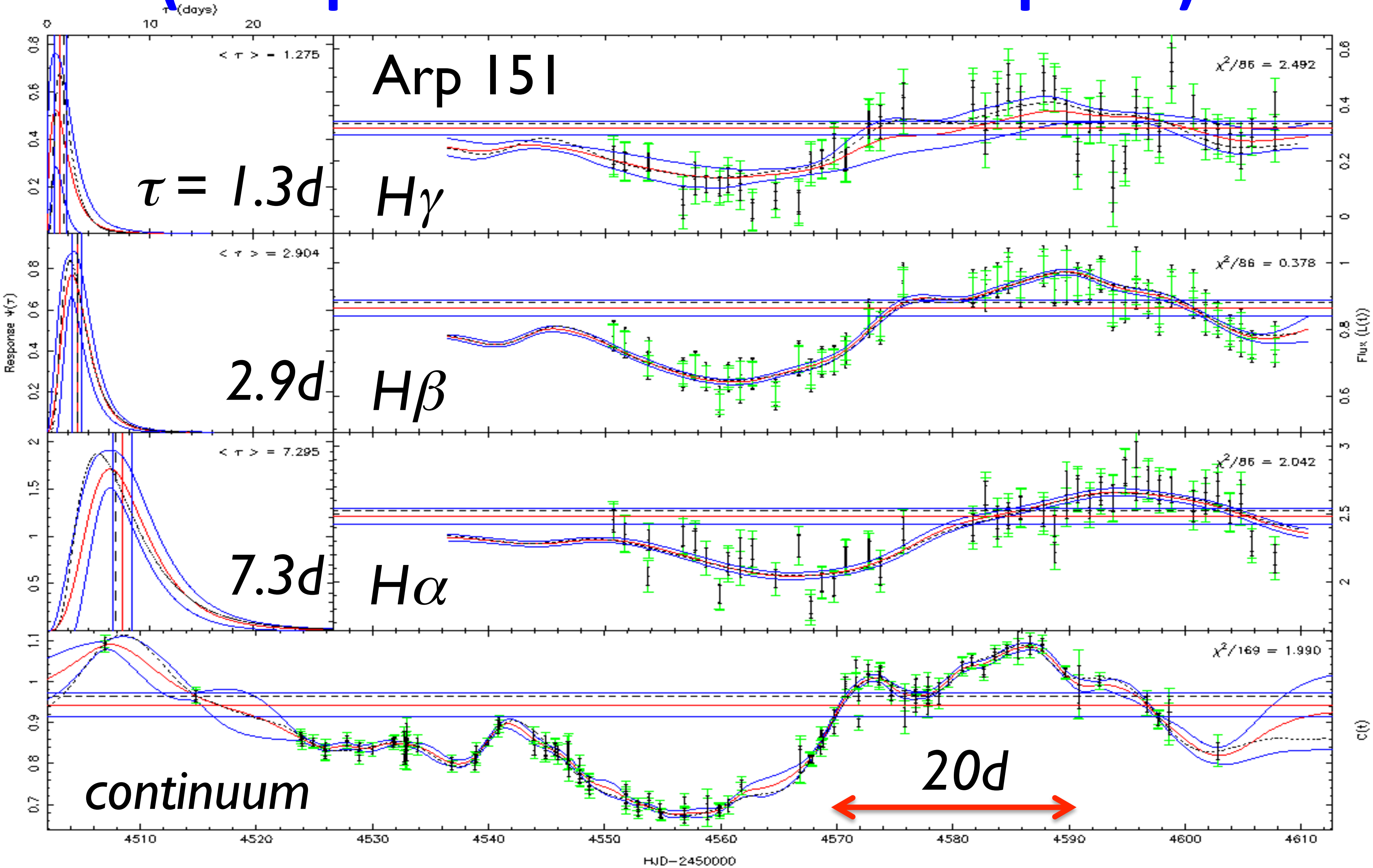


Power Spectrum Prior:

$$\sigma^2(\omega) = \frac{\sigma_0^2}{1+\left(\omega / \omega_0\right)^{\alpha}}$$

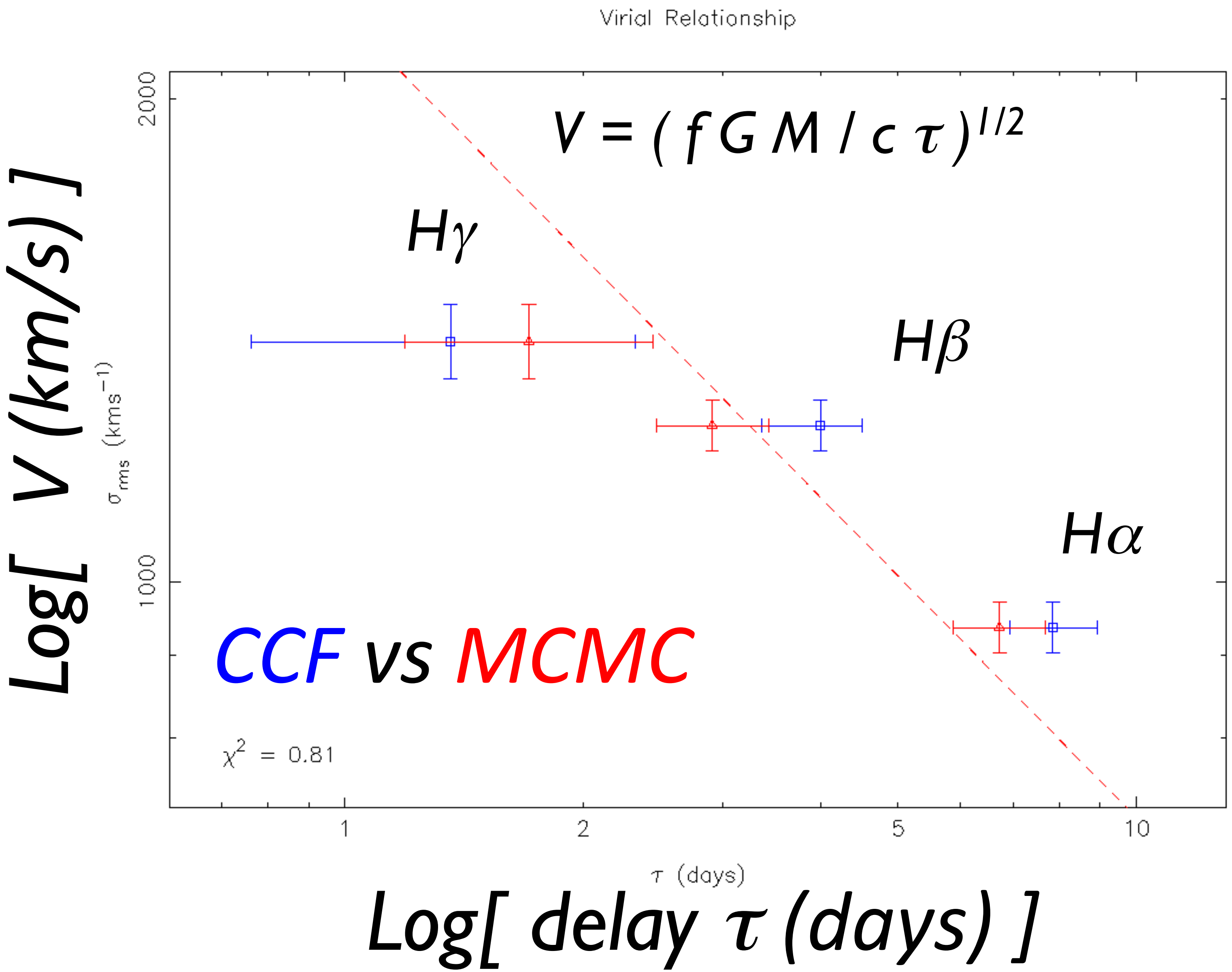
3 parameters: $\sigma_0, \omega_0, \alpha$

MCMC: log-normal delay maps of Arp 151
(complete with error envelopes !)



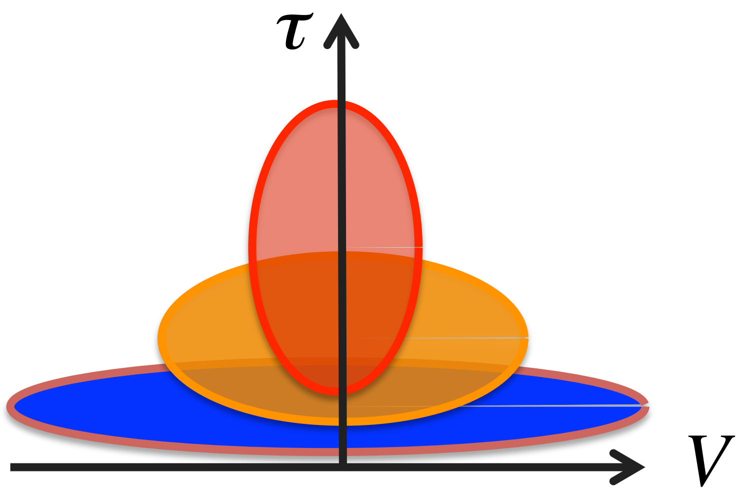
2008 LAMP data, MCMC fit by J.Simpson

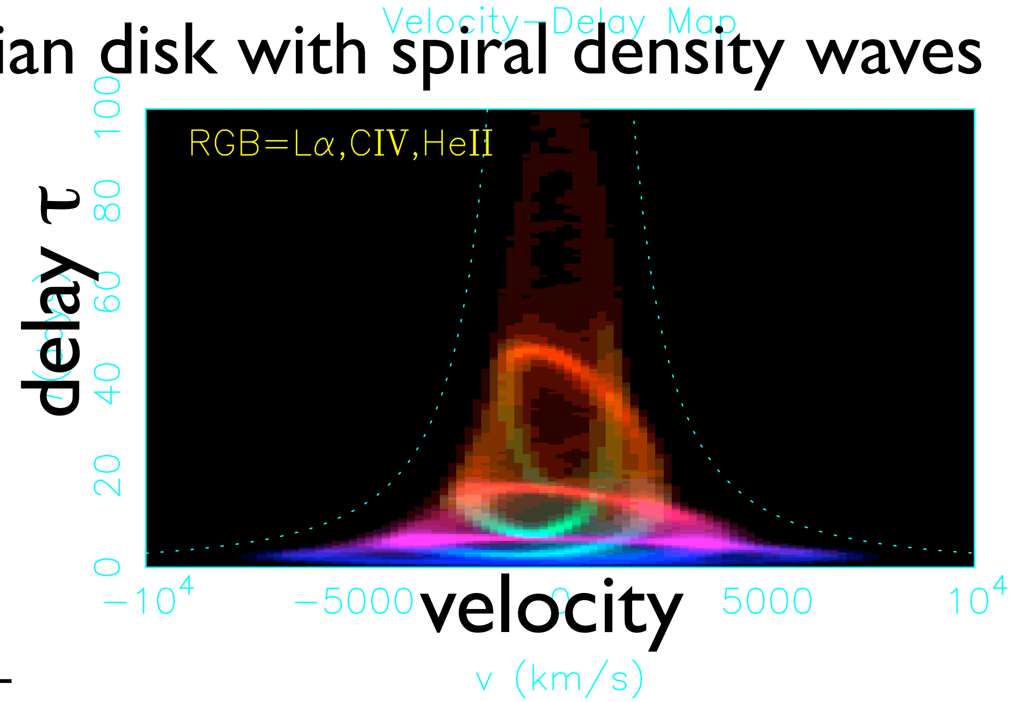
Test of Virial Gas Motions



Velocity-Delay Maps $\Psi(V, \tau)$

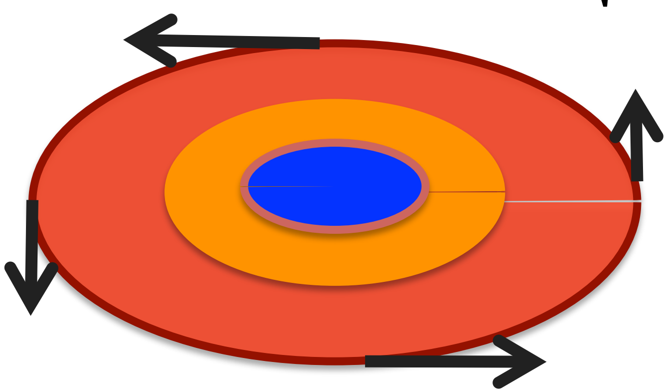
Simulation: Photo-ionised Keplerian disk with spiral density waves

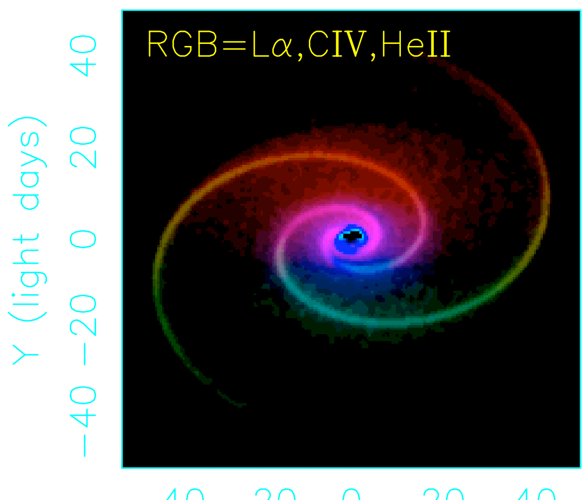




$$\tau = \frac{R}{c}\left(1 + \sin i \cos\theta\right) \qquad V = \sqrt{\frac{GM}{R}} \sin i \sin\theta$$

Sky view:



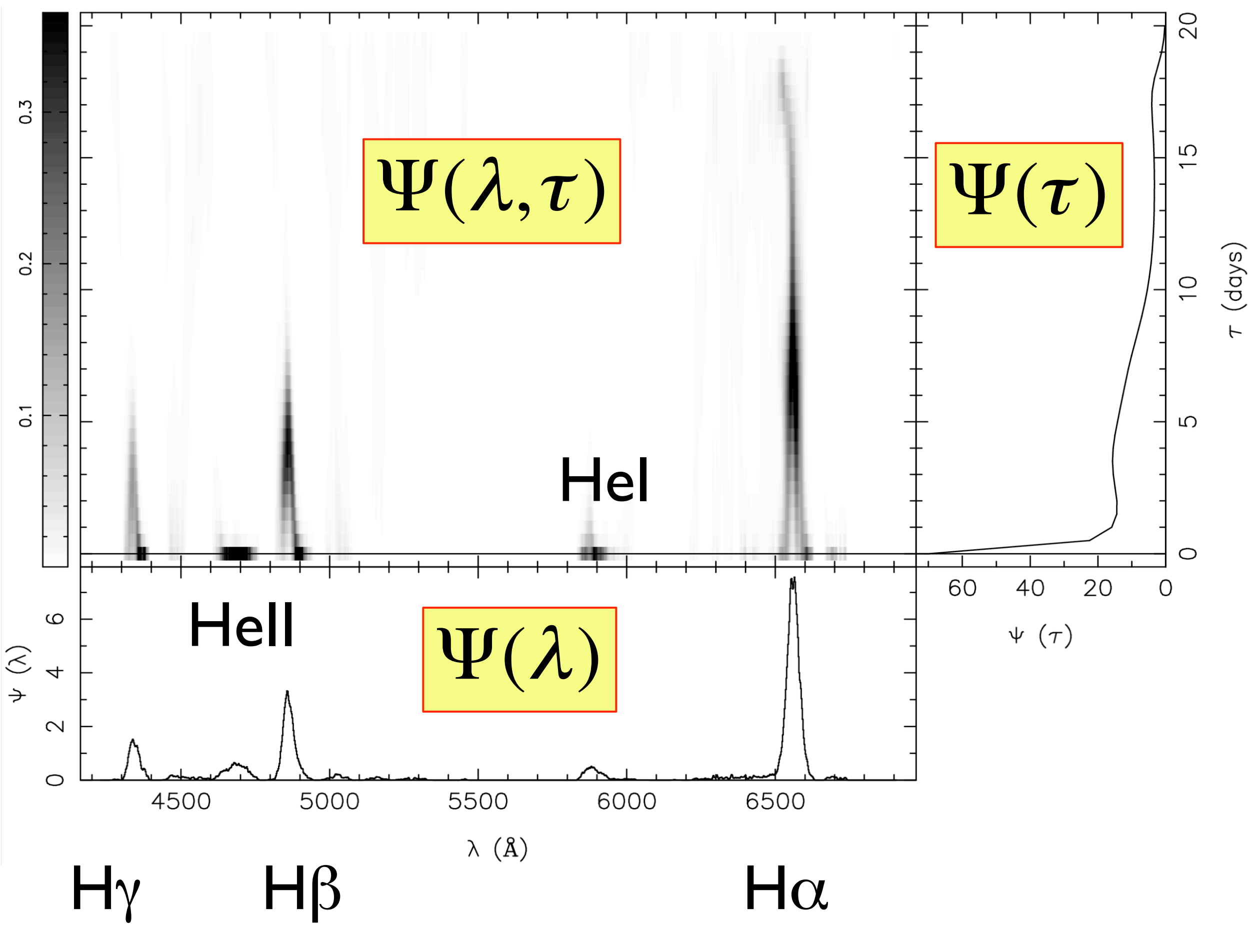


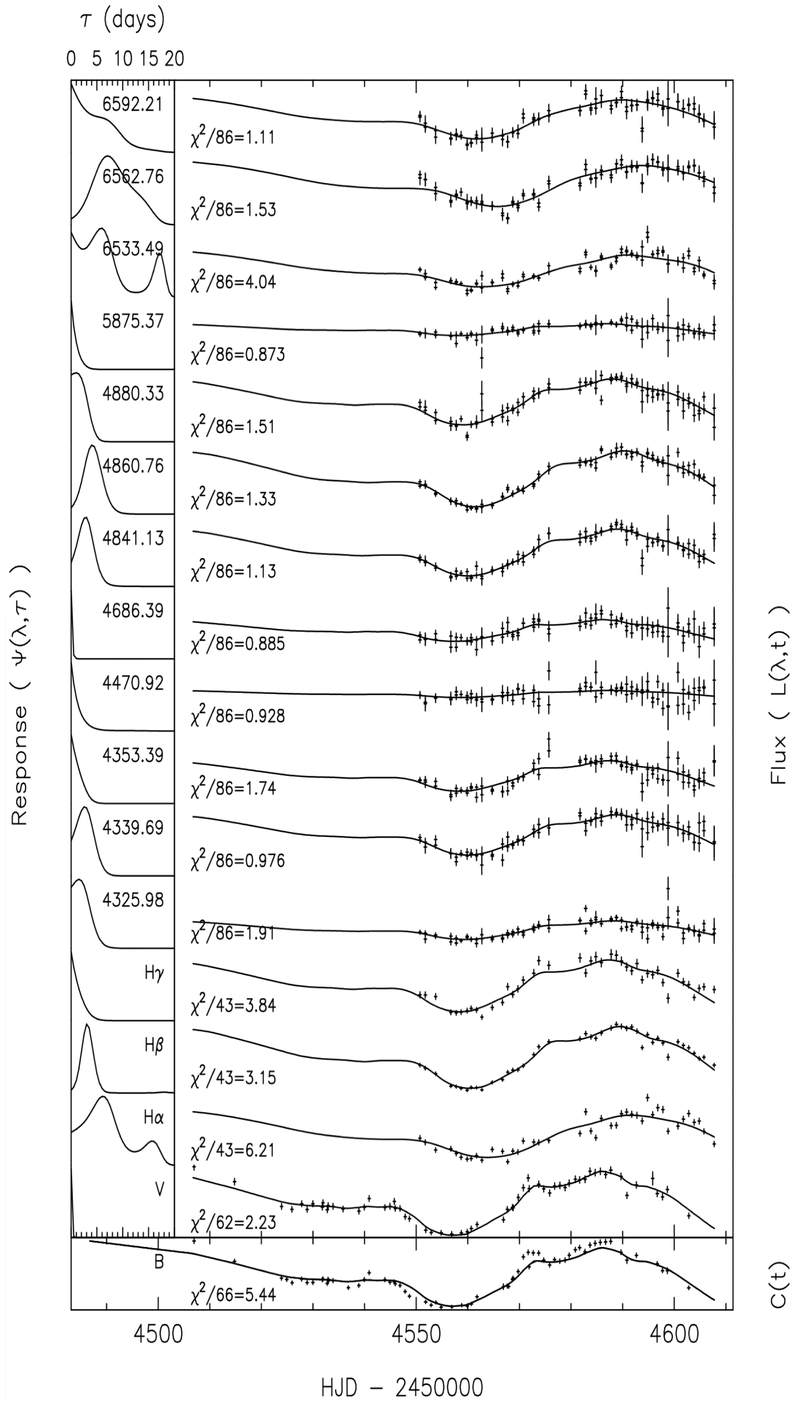
Arp 151 Maps: Ψ(λ, τ)

MEMECHO *fits to 2008* LAMP *data*

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

$$f(\lambda,t) = f_0(\lambda,t) + \int_0^{\tau_{max}} \Psi(\lambda,\tau)\,\Delta C(t-\tau)\,d\tau$$

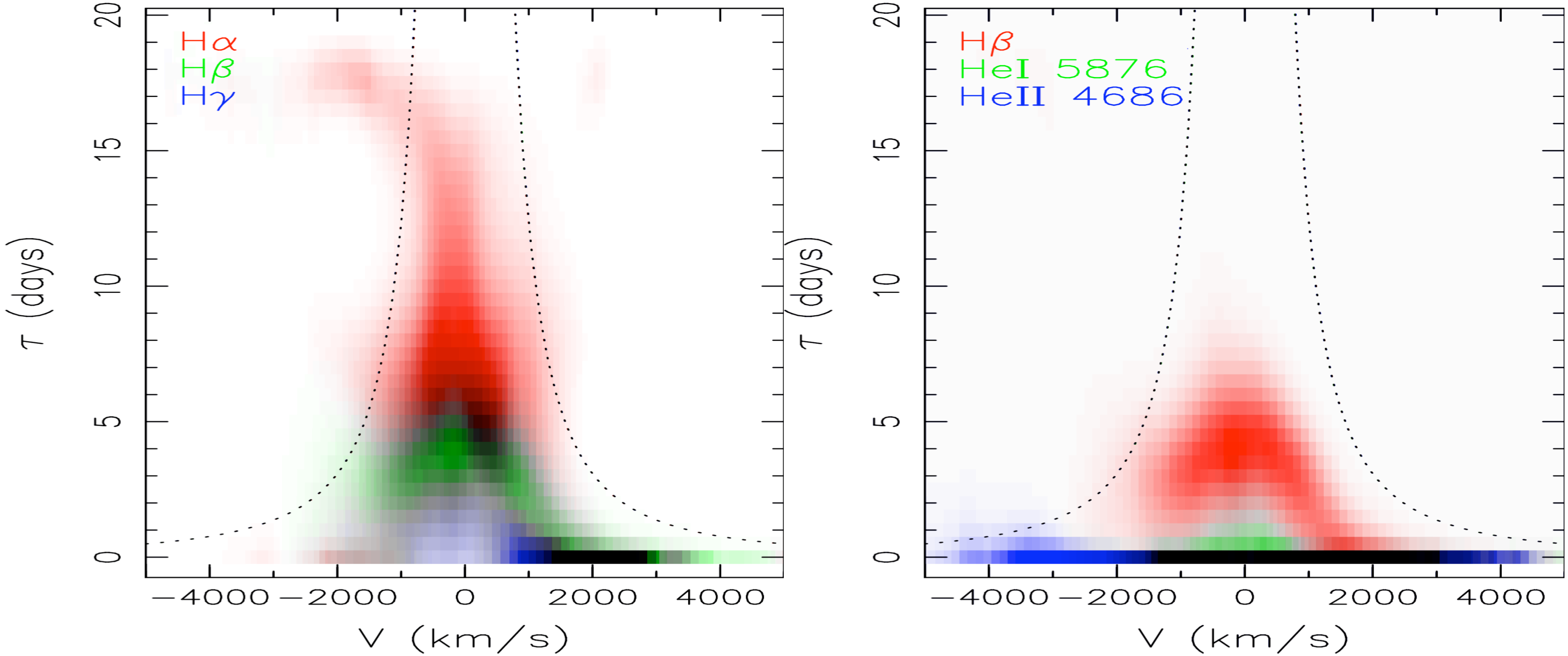




Bentz, et al. 2010

Arp 151 Maps: $\Psi(v, \tau)$

MEMECHO *fits to 2008* LAMP *data*



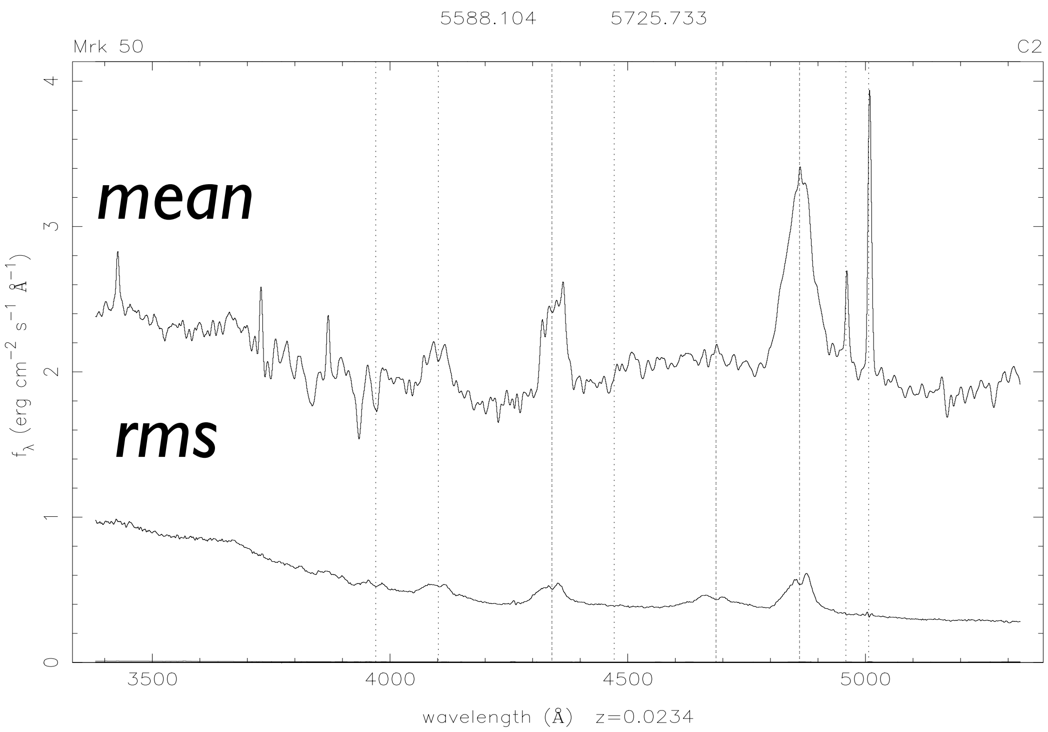
Virial envelope V ~ $\tau^{-1/2}$
Balmer lines stratified.
Prompt response on red wing.
(disk, far side enhanced, inflow)

HeI and HeII
Barely resolved in τ

Bentz, et al. 2010

Mrk 50 :   2011 LAMP data

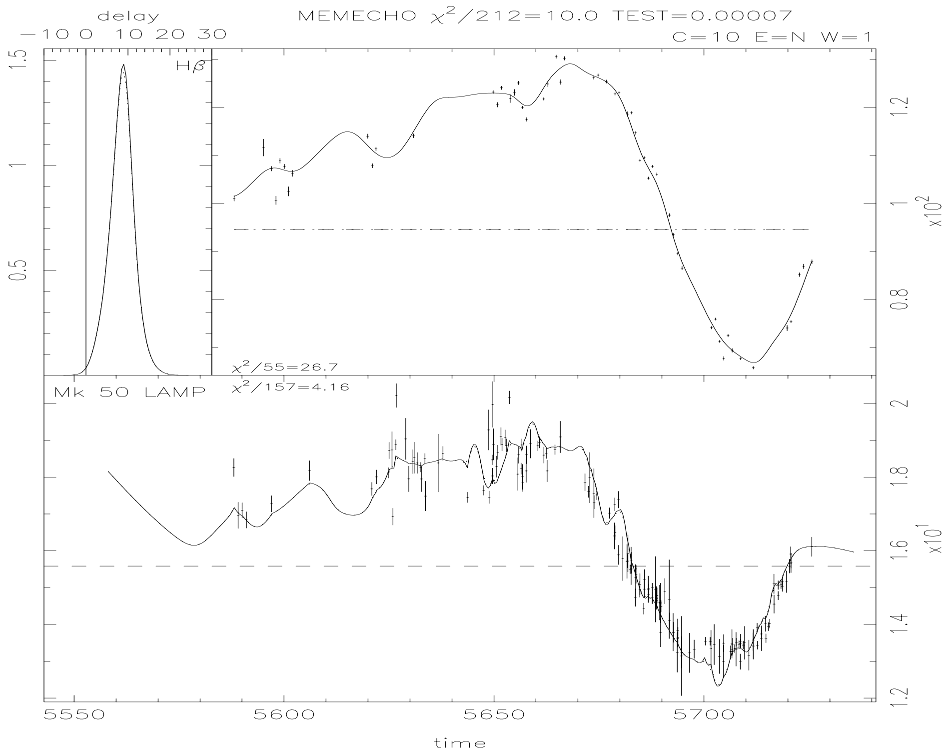
Mean and RMS spectra



MEMECHO *fit of* $\Psi(\tau)$

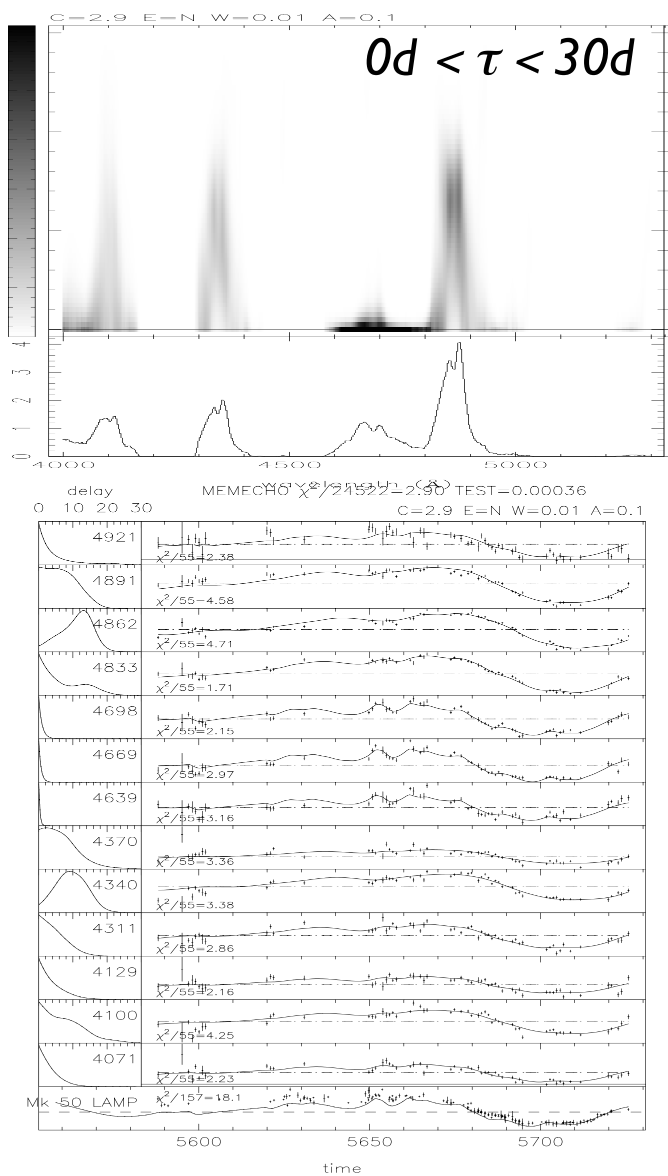
Hβ vs continuum

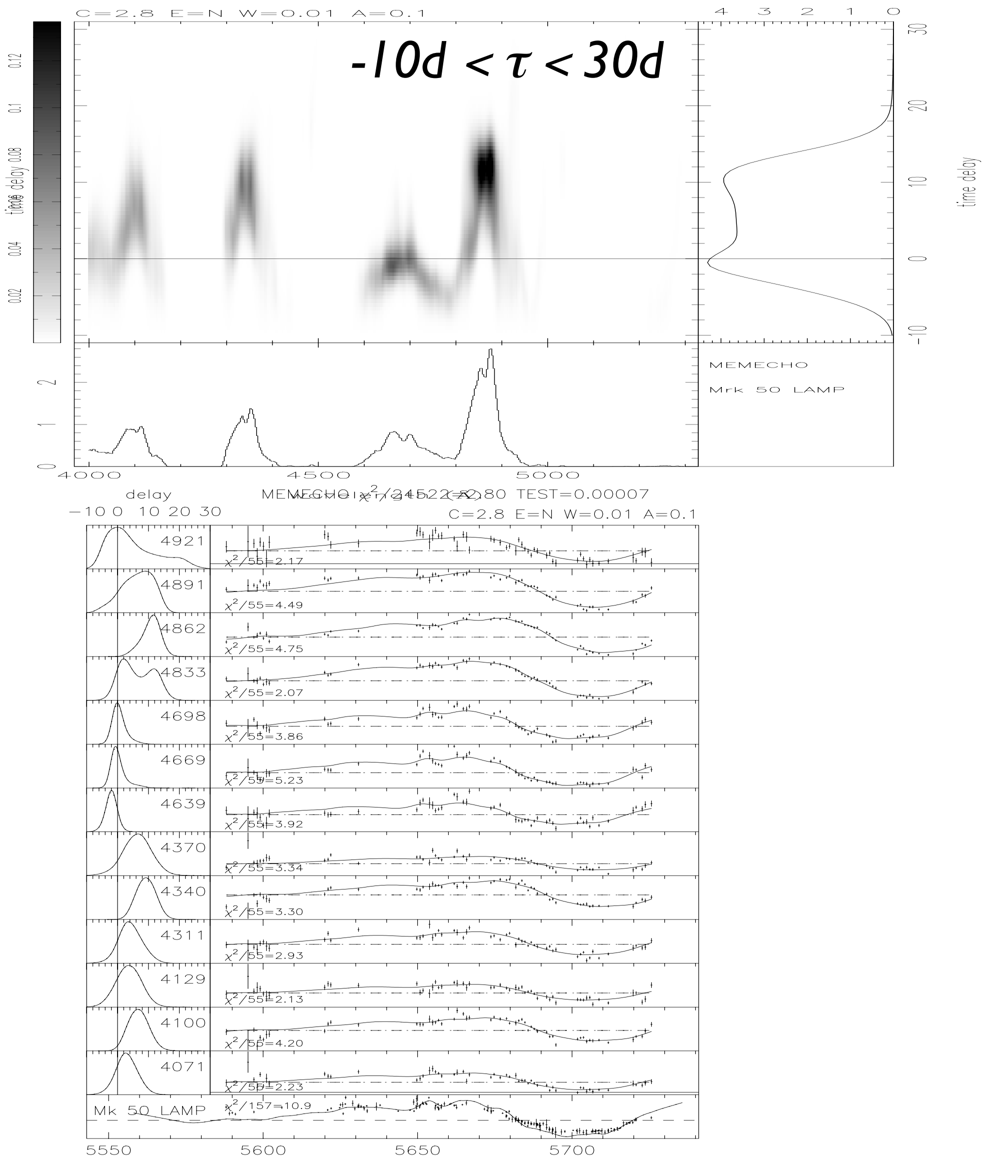
$\tau \sim 10d$



Mrk 50: Velocity-Delay Maps

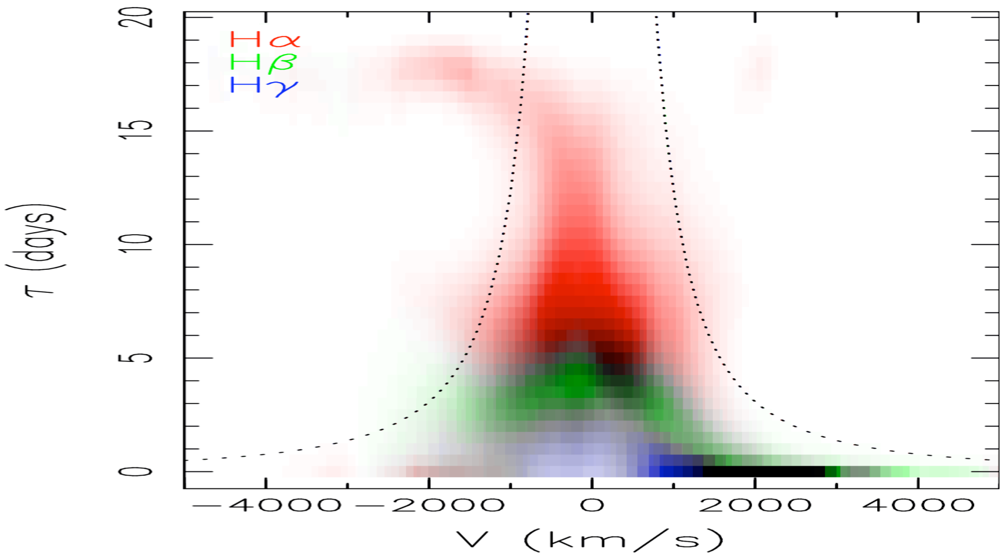
MEMECHO *fits of* Ψ(λ, τ) *to 2011* LAMP *data*

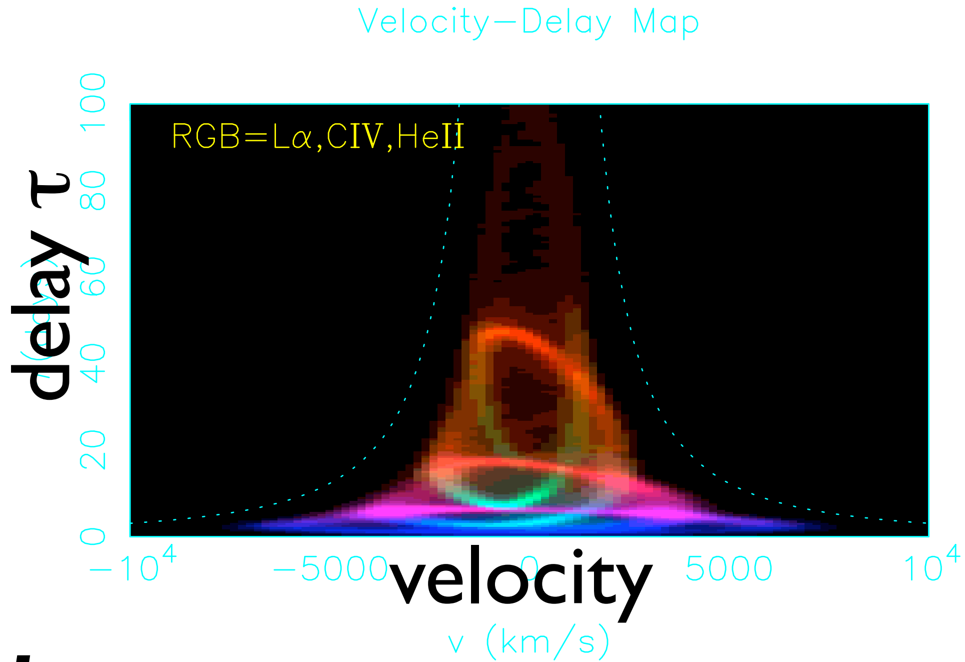




Does HeII precede the continuum?

STORM campaign on NGC 5548

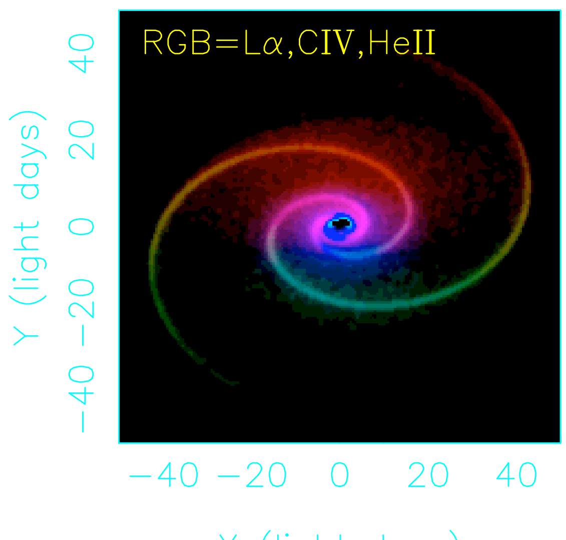




Delay resolution limited by S/N, cadence, duration, systematic errors.

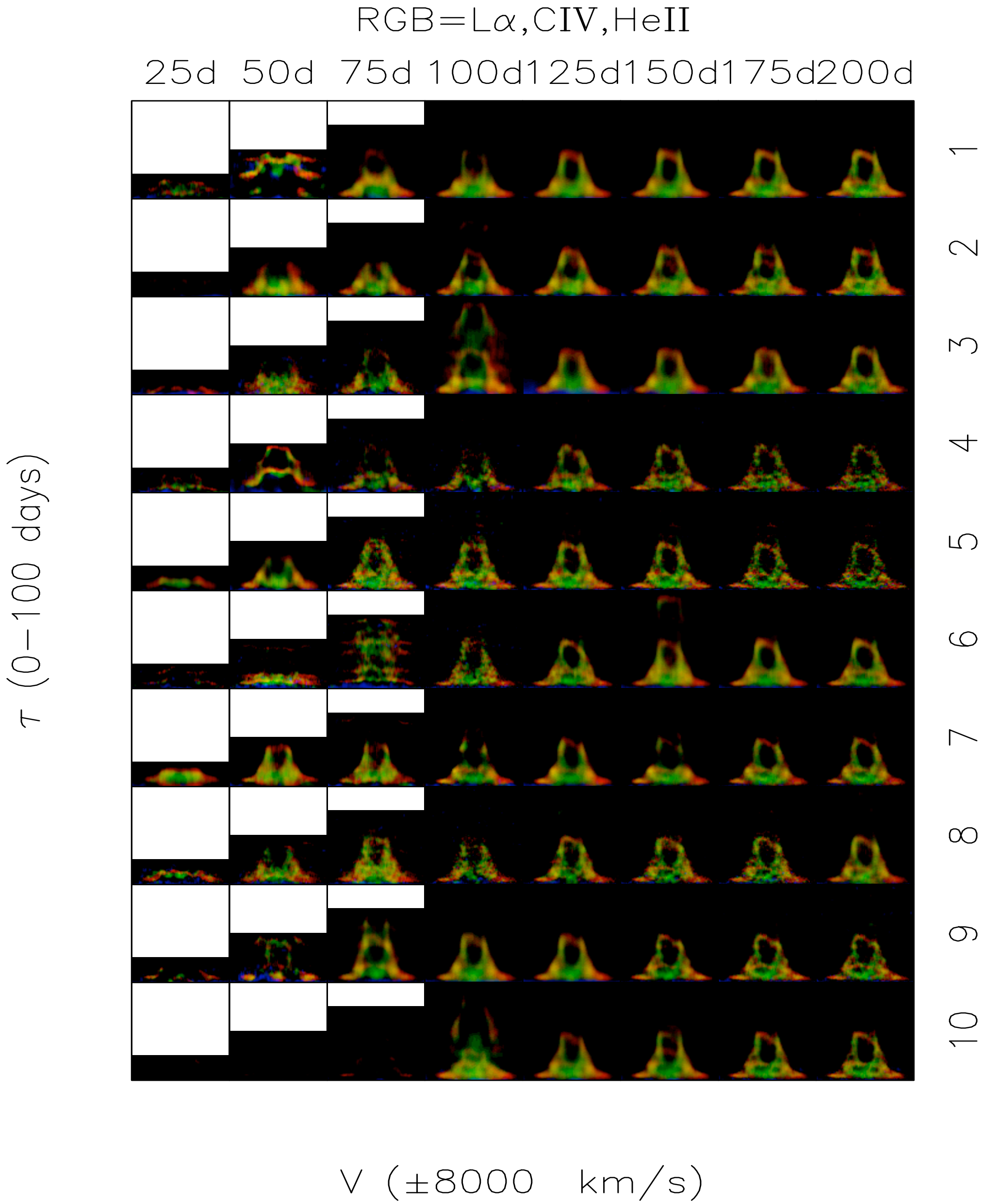
Better time sampling => sharper maps.

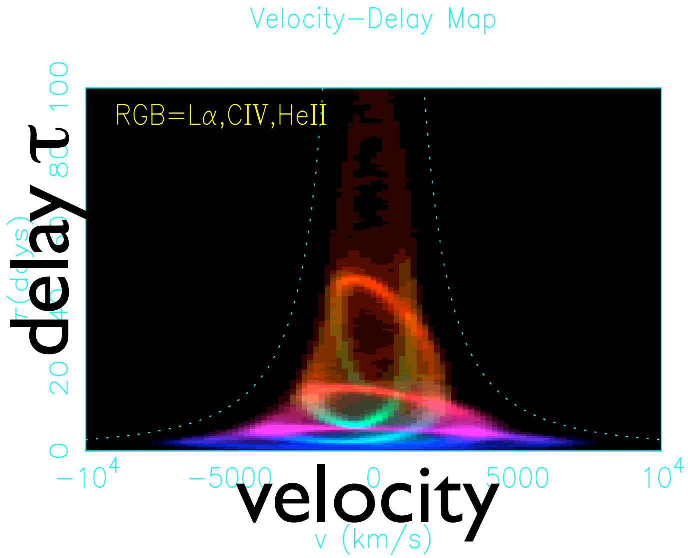
Sky view:

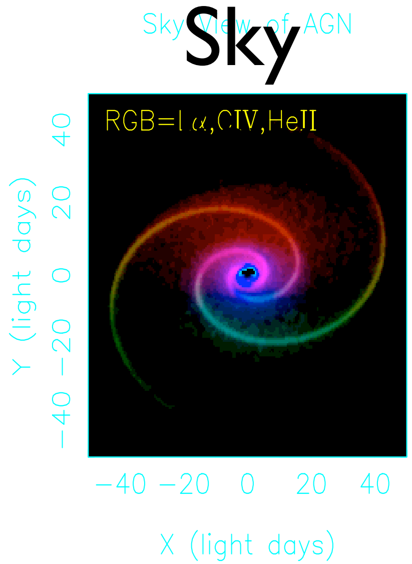


HST/COS 180 epochs at 1d sampling.
SWIFT 8hr sampling.
Ground-based photometry and spectroscopy.

MEMECHO recovery of Ψ(V, τ) maps from simulated HST/COS data







Prelim analysis of 5548 HST data

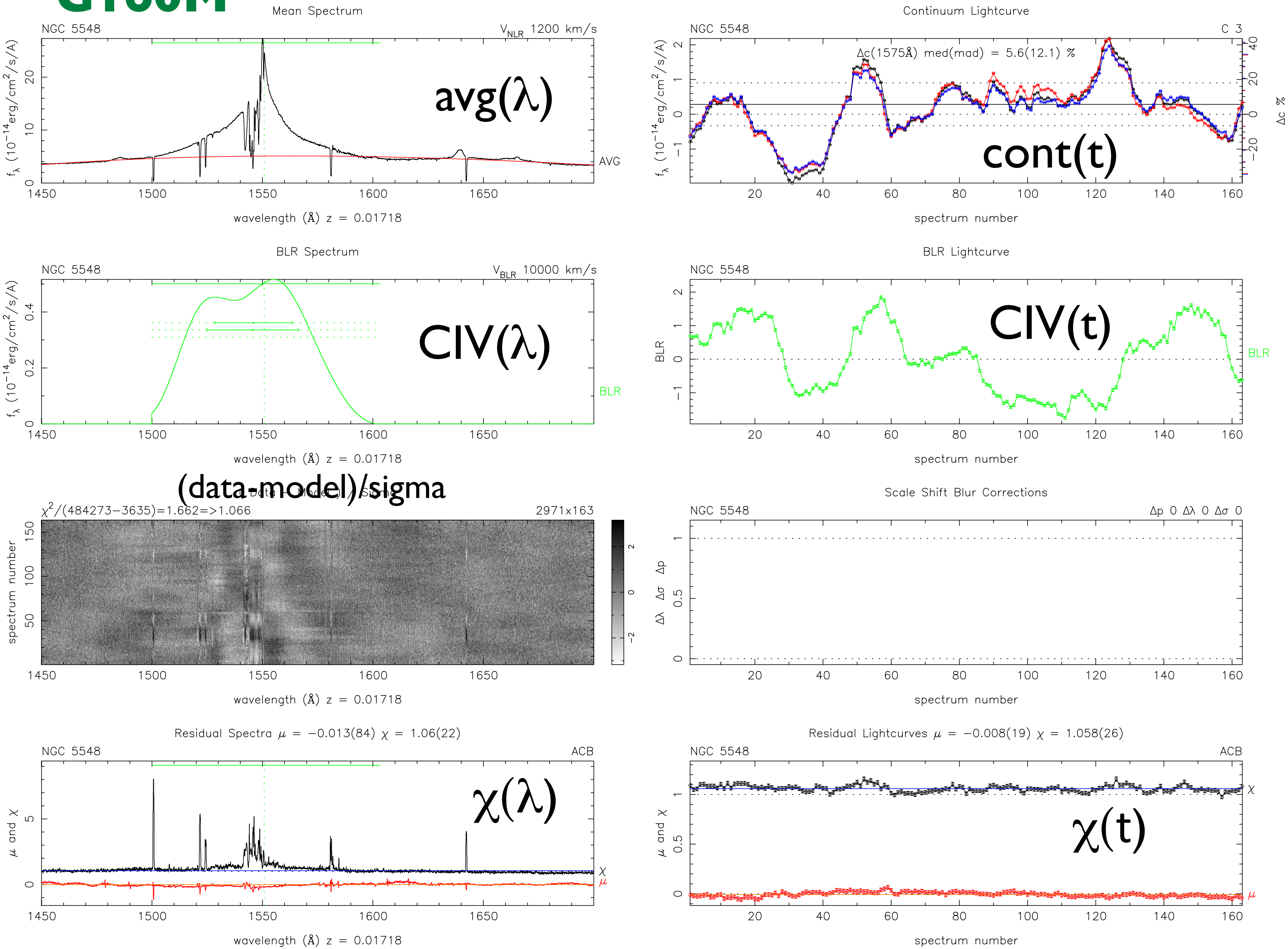
- **No delay maps yet** ☹
  - Absorption lines complicating the analysis.
- **PrepSpec** fits a simple separable model:

$$F(\lambda,t) = avg(\lambda) + cont(\lambda,t) + BLR(\lambda)\, BLR(t)$$

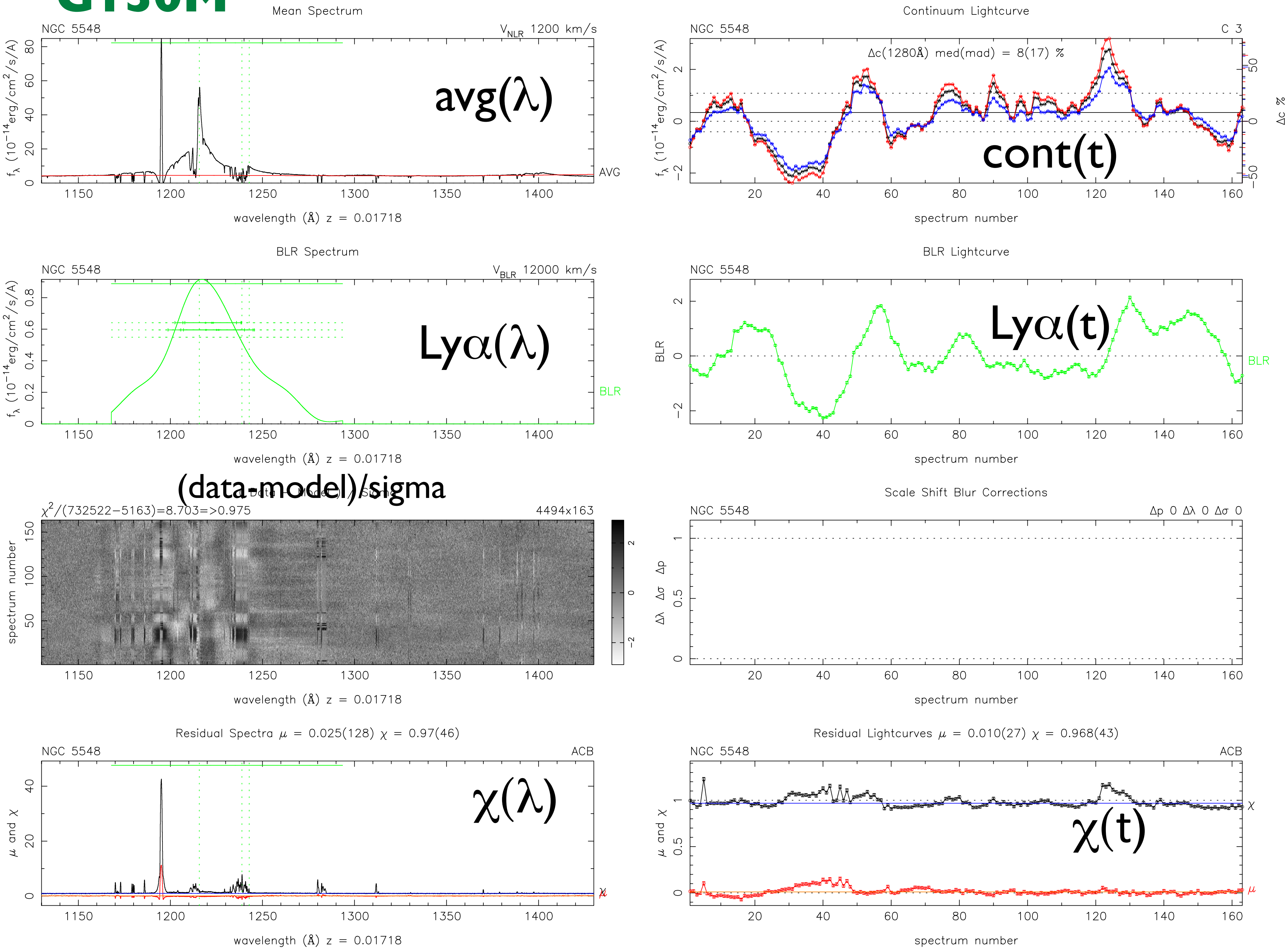
  - Mean spectrum **avg(λ)**
  - Continuum lightcurves **cont(λ,t)**
  - BLR lightcurves **BLR(t)**
  - Variable BLR velocity profiles **BLR(λ)**

  - Residuals show subtle features (not yet analysed).

G160M

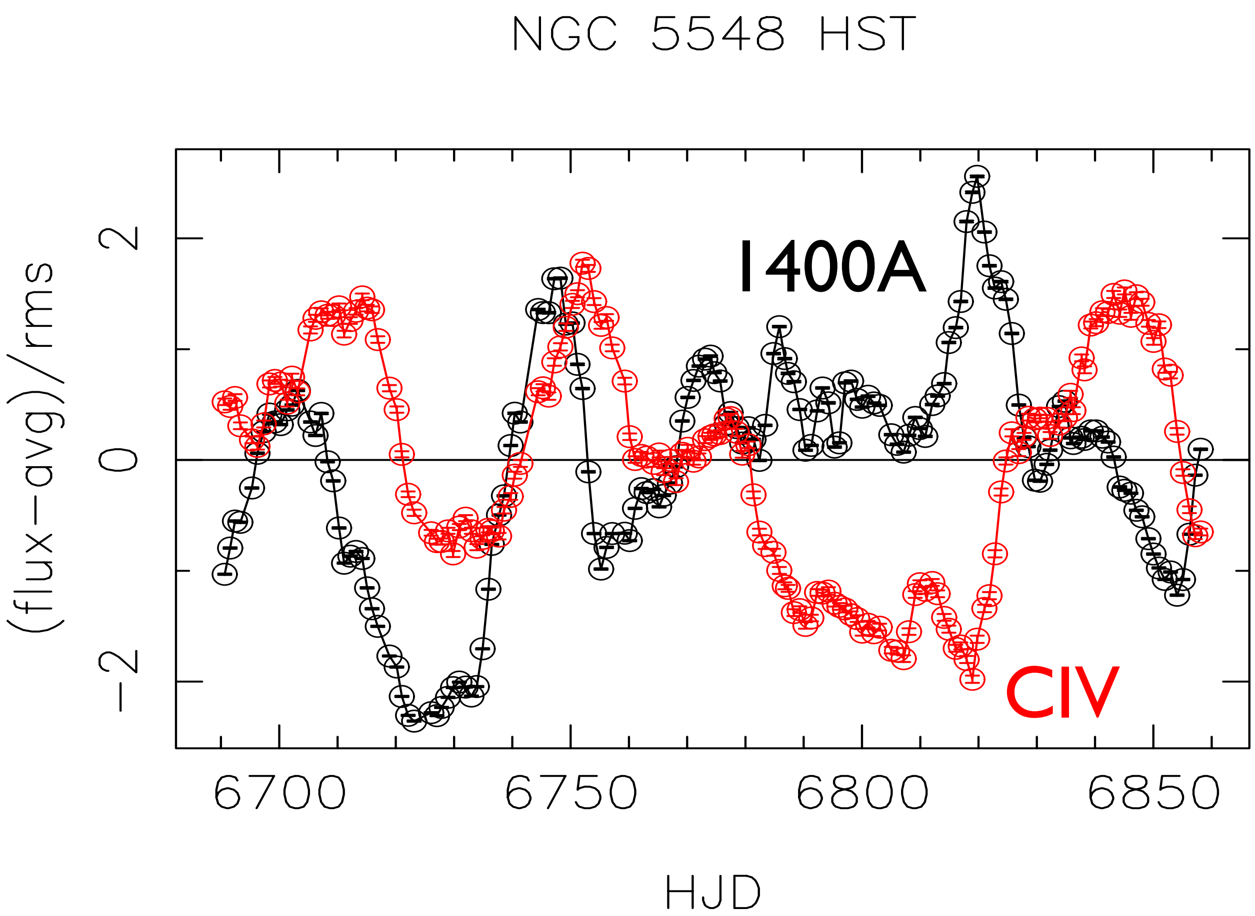

Mean Spectrum
NGC 5548
V_NLR 1200 km/s
avg(λ)
AVG
wavelength (Å) z = 0.01718
Continuum Lightcurve
C 3
Δc(1575Å) med(mad) = 5.6(12.1) %
cont(t)
Δc %
spectrum number
BLR Spectrum
V_BLR 10000 km/s
CIV(λ)
BLR
BLR Lightcurve
CIV(t)
(data-model)/sigma
χ²/(484273−3635)=1.662=>1.066
2971x163
Scale Shift Blur Corrections
Δp 0 Δλ 0 Δσ 0
Residual Spectra μ = −0.013(84) χ = 1.06(22)
ACB
χ(λ)
μ and χ
Residual Lightcurves μ = −0.008(19) χ = 1.058(26)
χ(t)

G130M



Mean Spectrum
NGC 5548
V_{NLR} 1200 km/s
avg(λ)
AVG
f_λ (10^{-14}erg/cm^2/s/A)
wavelength (Å) z = 0.01718
Continuum Lightcurve
NGC 5548
C 3
Δc(1280Å) med(mad) = 8(17) %
cont(t)
Δc %
spectrum number
BLR Spectrum
NGC 5548
V_{BLR} 12000 km/s
Lyα(λ)
BLR
BLR Lightcurve
NGC 5548
Lyα(t)
BLR
(data-model)/sigma
χ^2/(732522−5163)=8.703=>0.975
4494x163
spectrum number
Scale Shift Blur Corrections
NGC 5548
Δp 0 Δλ 0 Δσ 0
Δλ Δσ Δp
Residual Spectra μ = 0.025(128) χ = 0.97(46)
NGC 5548
ACB
χ(λ)
μ and χ
Residual Lightcurves μ = 0.010(27) χ = 0.968(43)
NGC 5548
ACB
χ(t)

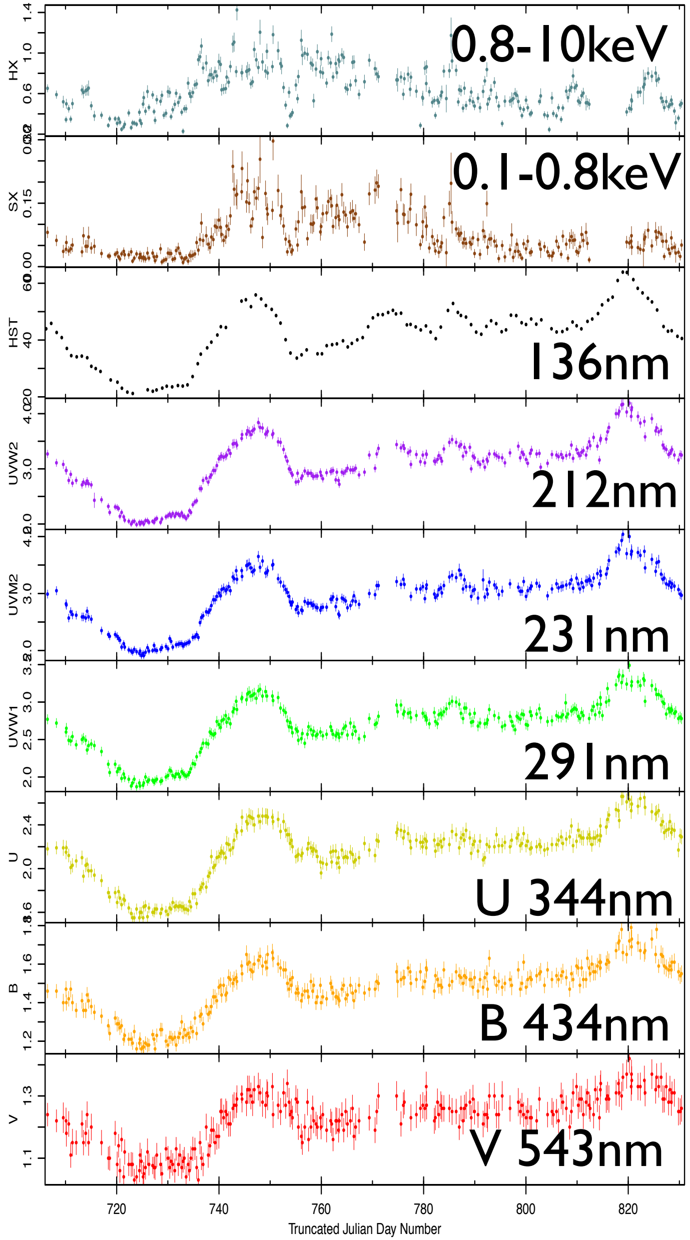
CIV variations complicated



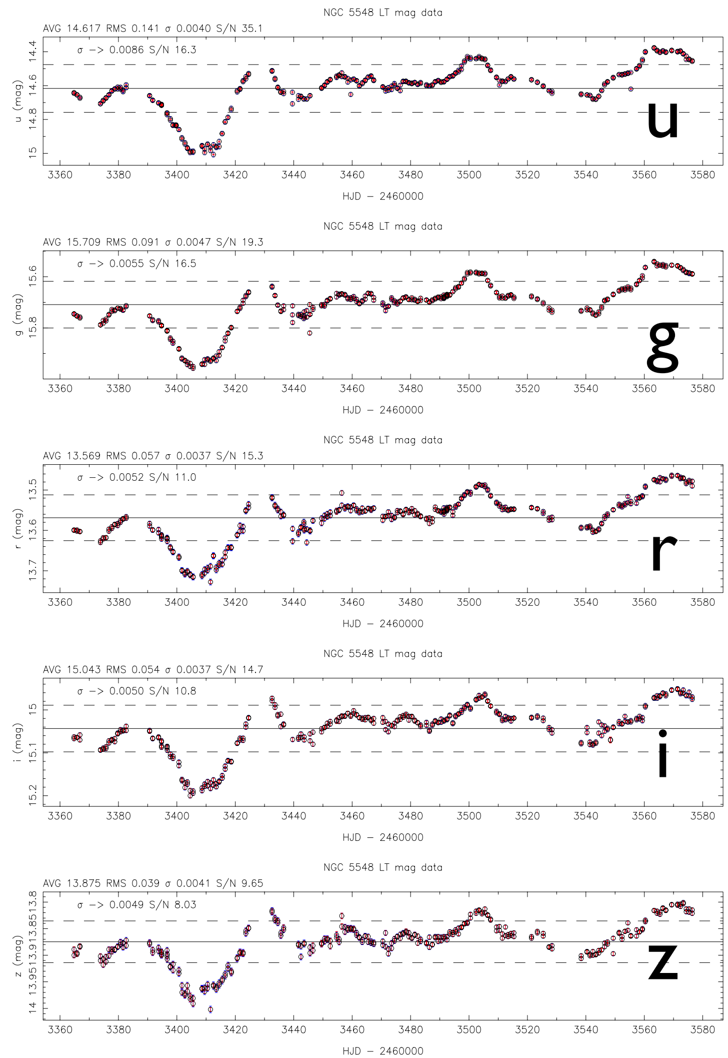
- Fast (5-20d) variations correlate, with clear (5-10d) lags.
- Slow (100d) variations may anti-correlate.
- Linerarised echo model may be inadequate.
  - Negative CIV response on 100d timescales?

N5548 Photometric Lightcurves

Swift lightcurves

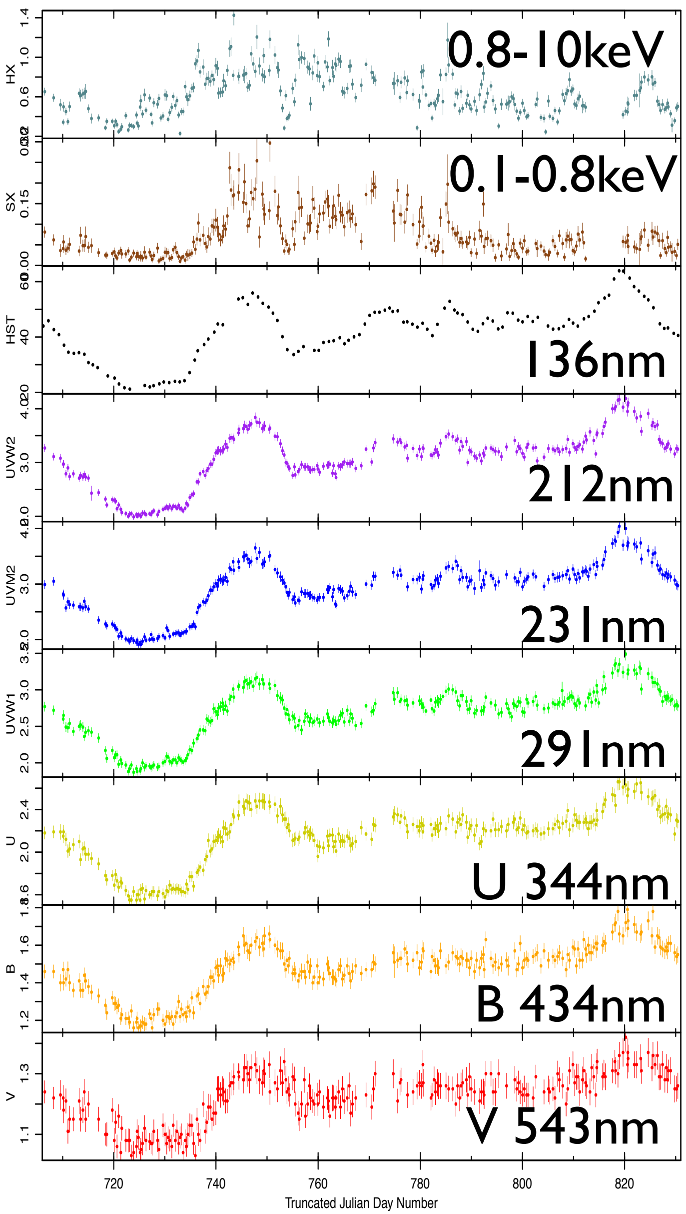


Liverpool 2m robotic telescope ugriz lightcurves

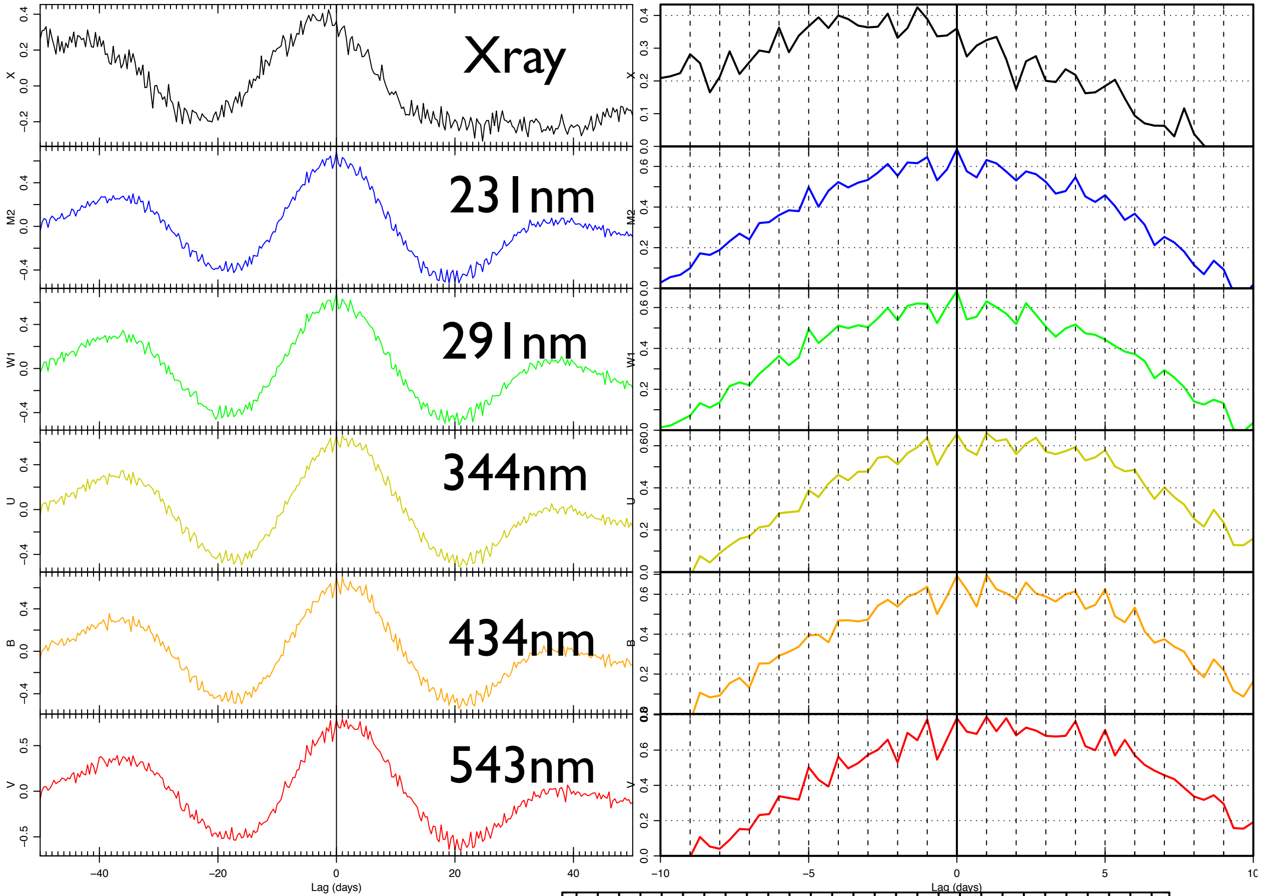


SWIFT lags (Edelson et al. in prep)

Swift lightcurves

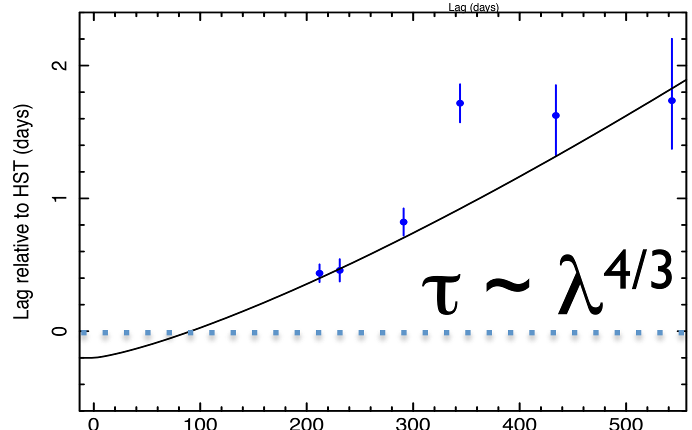


Swift CCF vs 212nm



Steady disk

$T \sim R^{-3/4}$



Summary

- Analysis techniques well developed
- Datasets now support velocity-delay mapping.
- 5548 HST, Swift, rich datasets under analysis.

- Future:
- Robotic telescopes (LCOGT) deliver photometry.
- IFU spectrographs (better control of systematics)
- SDSS-RM   800 AGN in parallel.