Probing AGN Accretion Physics through AGN Variability: Insights from Kepler

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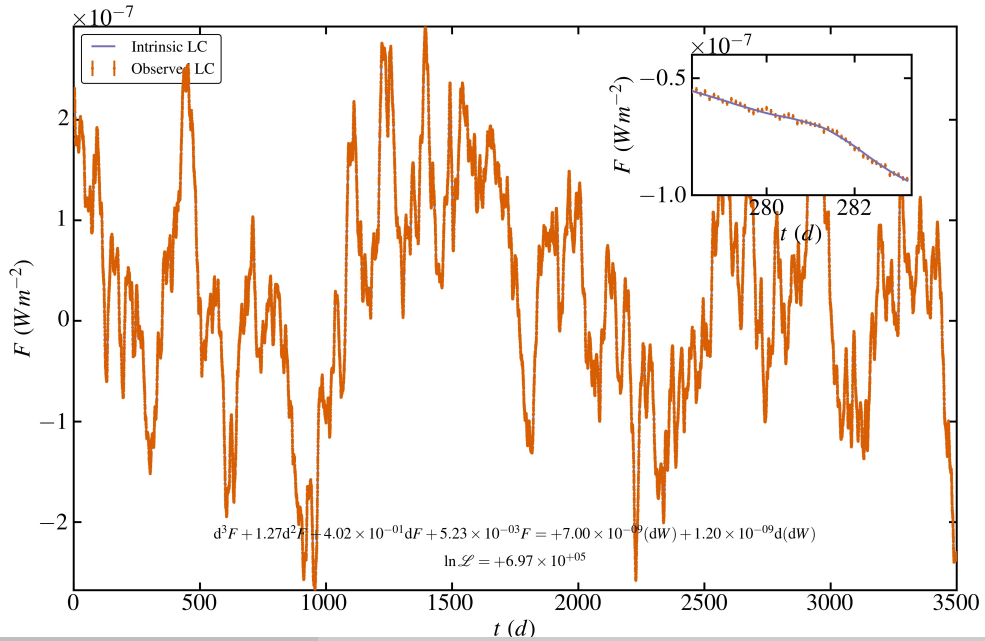
Continuous-time AutoRegressive Moving Average (C-ARMA) Processes

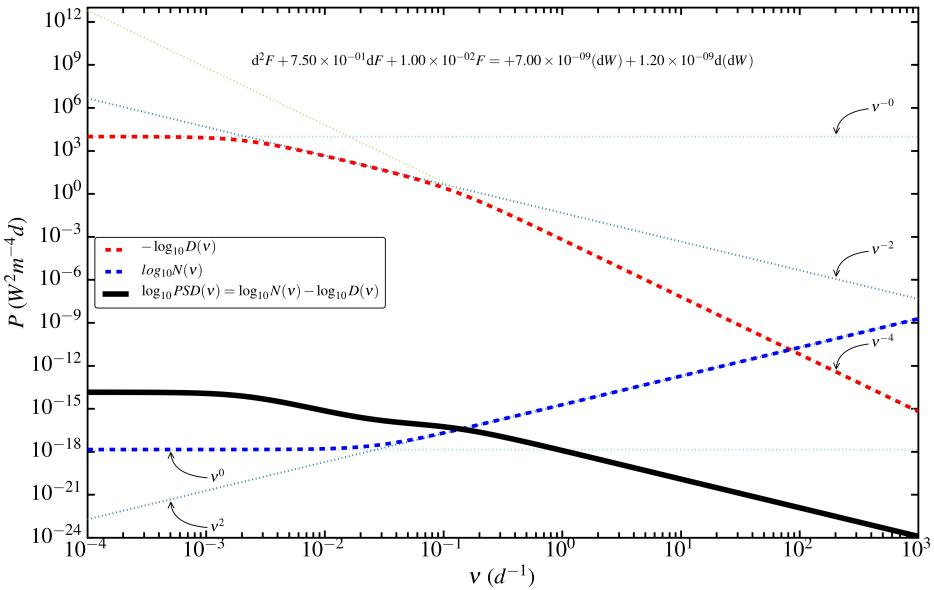
$$\mathrm{d}W \sim \mathcal{N}(0, \mathrm{d}t)$$

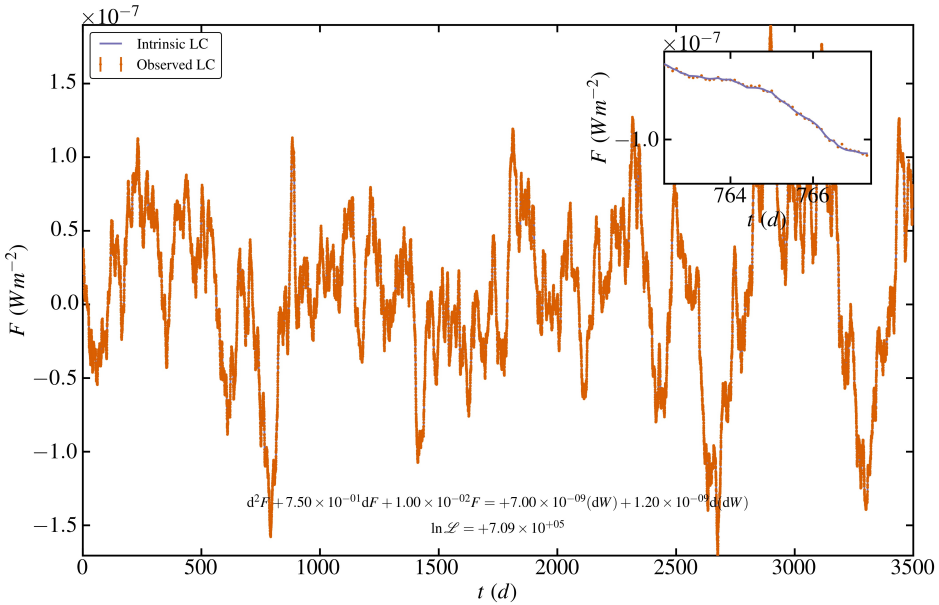
$$\mathrm{d}^p x + \alpha_1 \mathrm{d}^{p-1} x + \ldots + \alpha_{p-1} \mathrm{d}x + \alpha_p x = \beta_0 (\mathrm{d}W) + \ldots + \beta_q \mathrm{d}^q (\mathrm{d}W)$$

- Uses Itō calculus Brockwell (2014); Davis (2002); Kelly et al. (2014)
- LHS comes from linear perturbations of non-linear system
- C-ARMA $\overset{\text{sample}}{\longrightarrow}$ ARMA
- PSD is a ratio of even polynomials in frequency

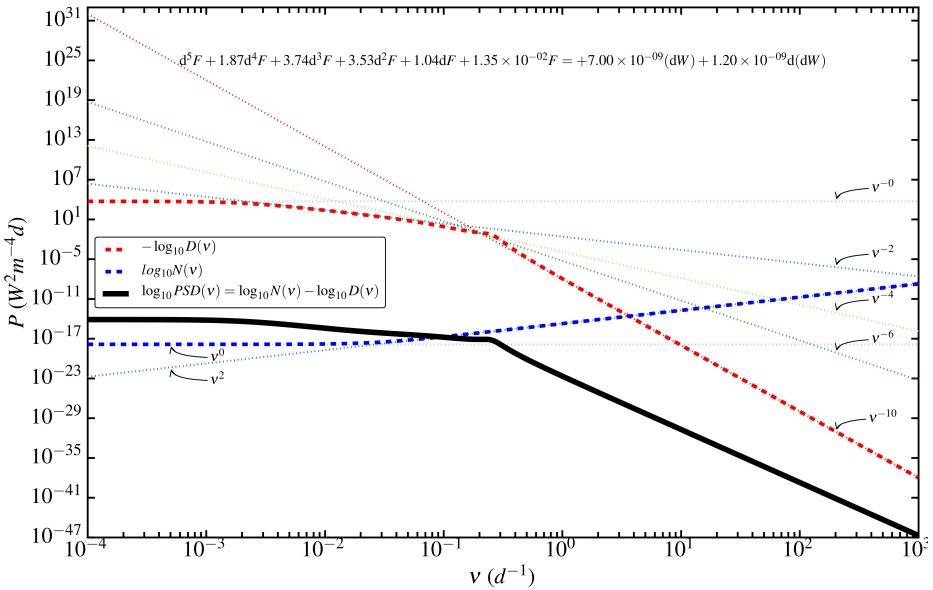


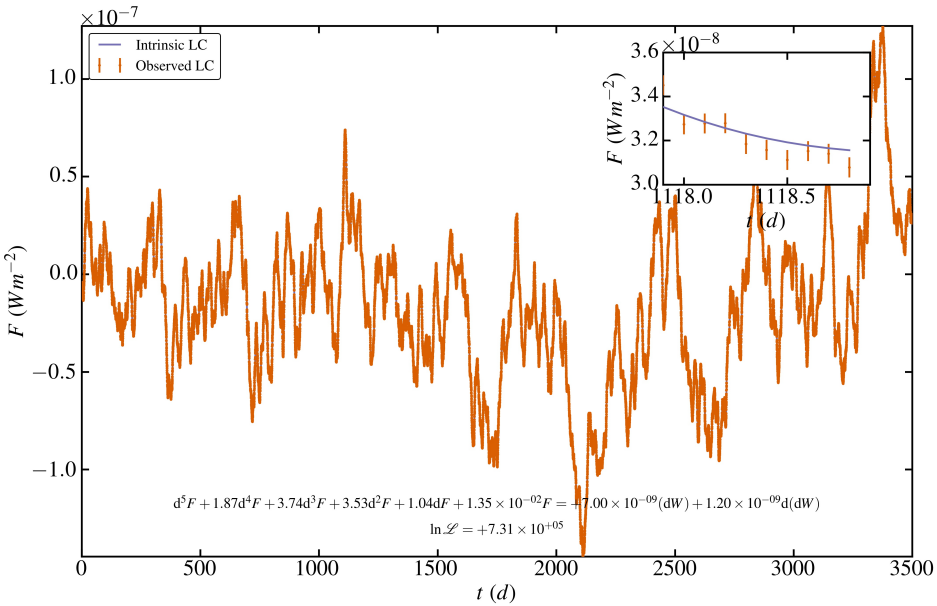
Power Spectral Density
Eg. C-ARMA(2,1)





Power Spectral Density
Eg. C-ARMA(5,1)





State Space Representation

State equation:

$$\boldsymbol{x}_{k+1} = \mathbf{F}\boldsymbol{x}_k + \boldsymbol{w}_k$$

$$\boldsymbol{w}_k \sim \mathcal{N}(\boldsymbol{0}, \mathbf{Q})$$

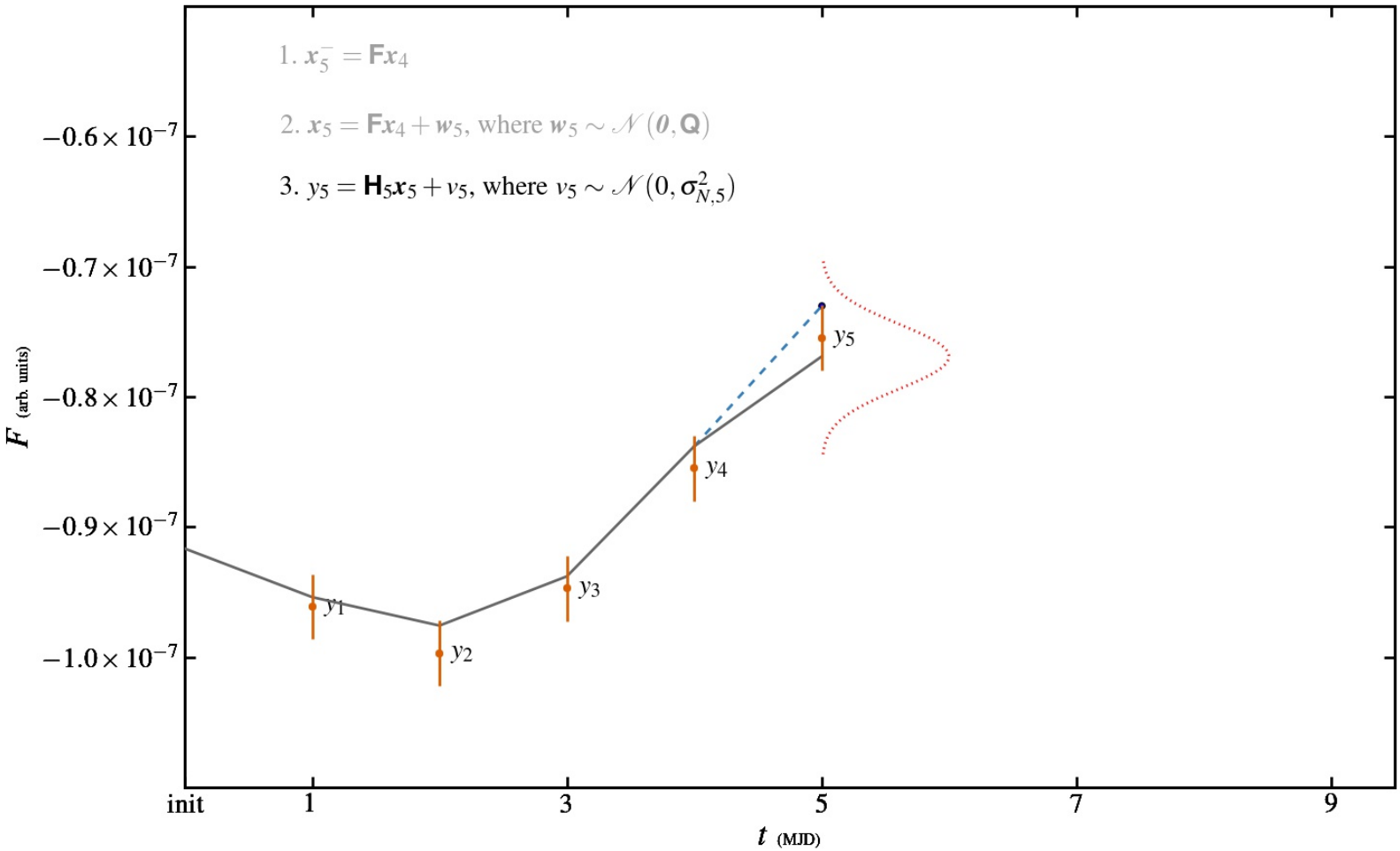
Observation equation:

$$x_{k,\mathrm{obs}} = \mathbf{H}_k\boldsymbol{x}_k + v_k$$

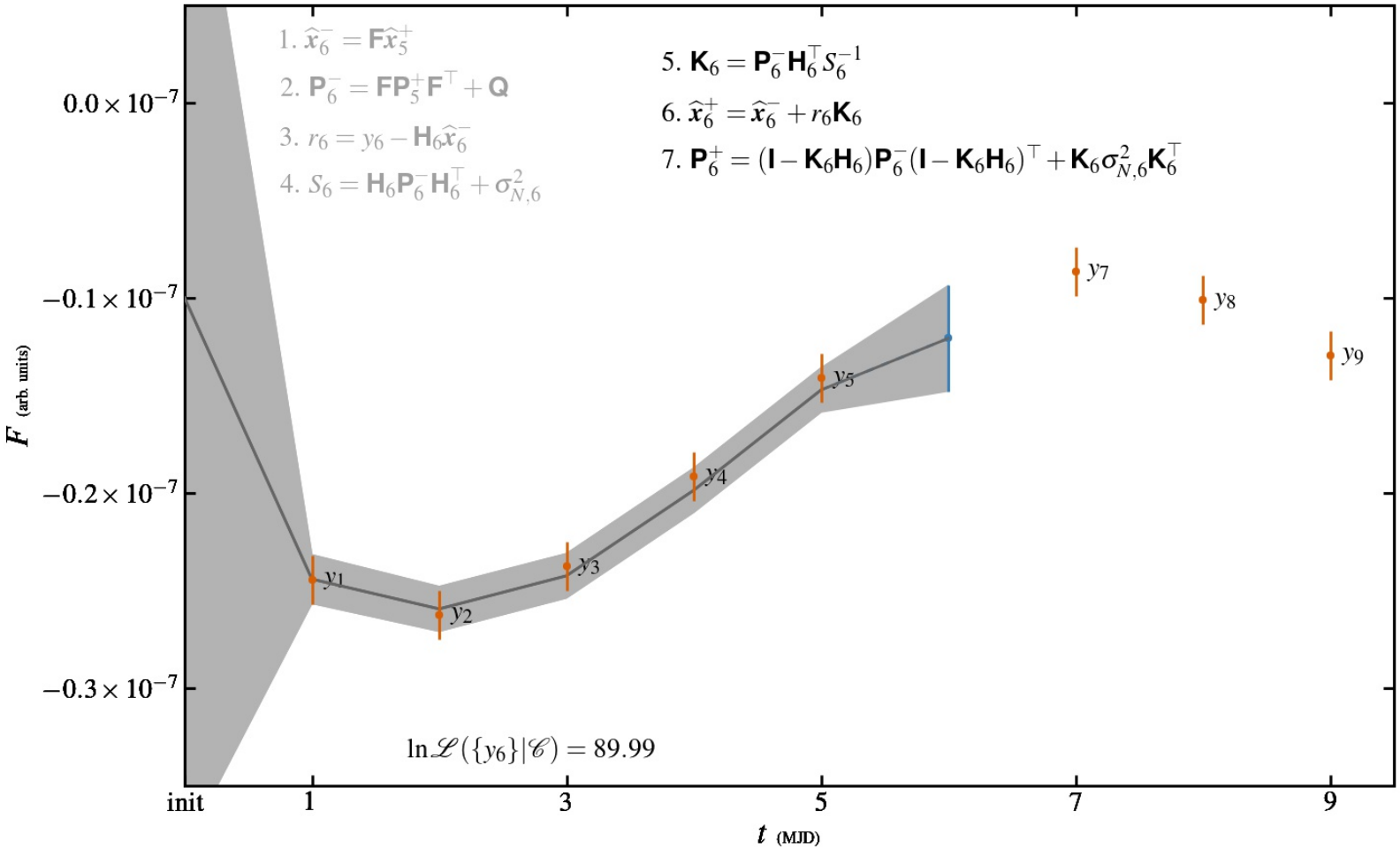
$$v_k \sim \mathcal{N}(0, \sigma^2_{N,k})$$

- **F**: Transition matrix & **Q**: Disturbance matrix
- **H**: Observation matrix
- Observation noise in-built via v_k !
- Well studied by engineers (Control systems) and economists

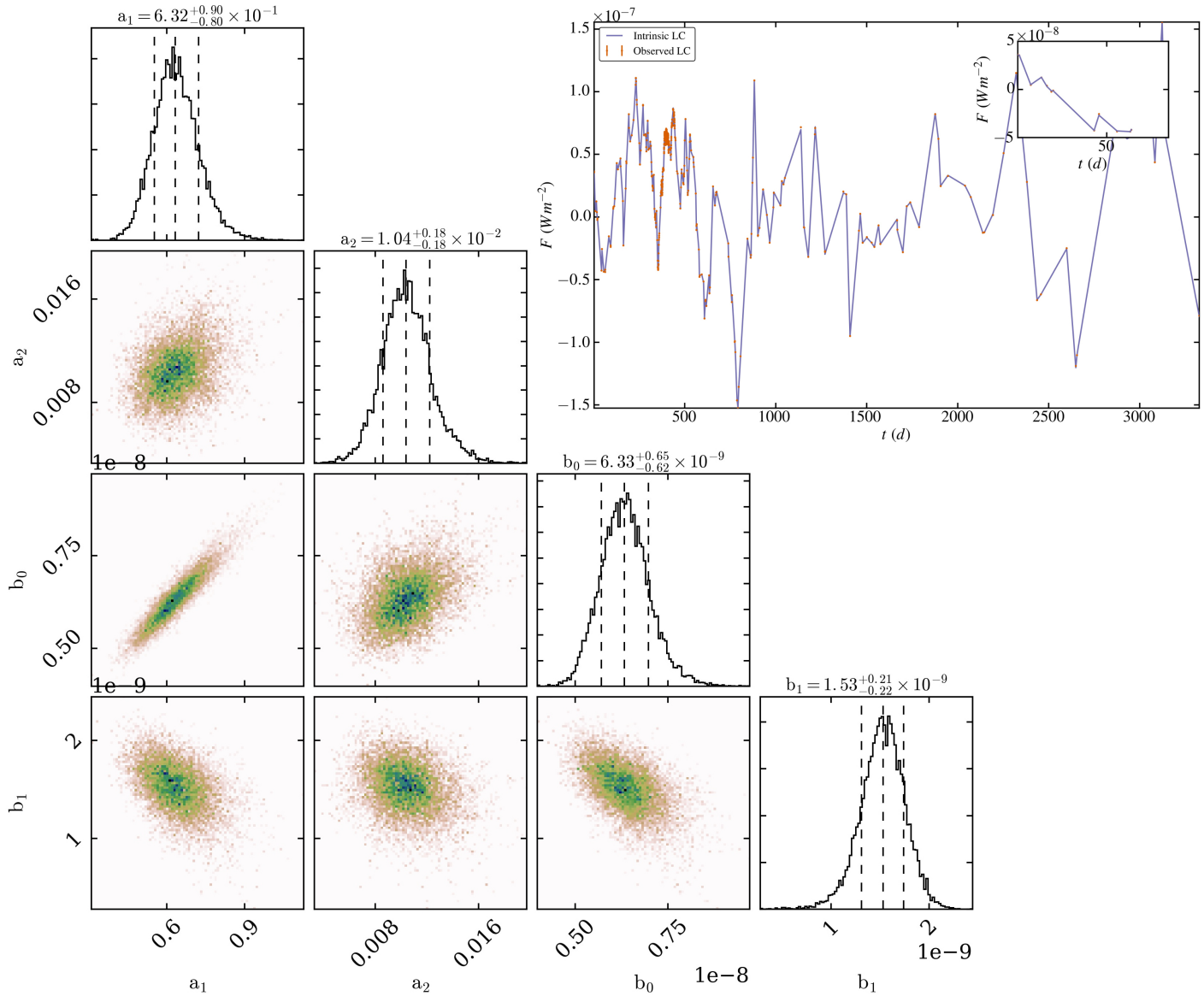
Evolution & observation of light curve state



$\ln \mathcal{L}$ via Kalman filter

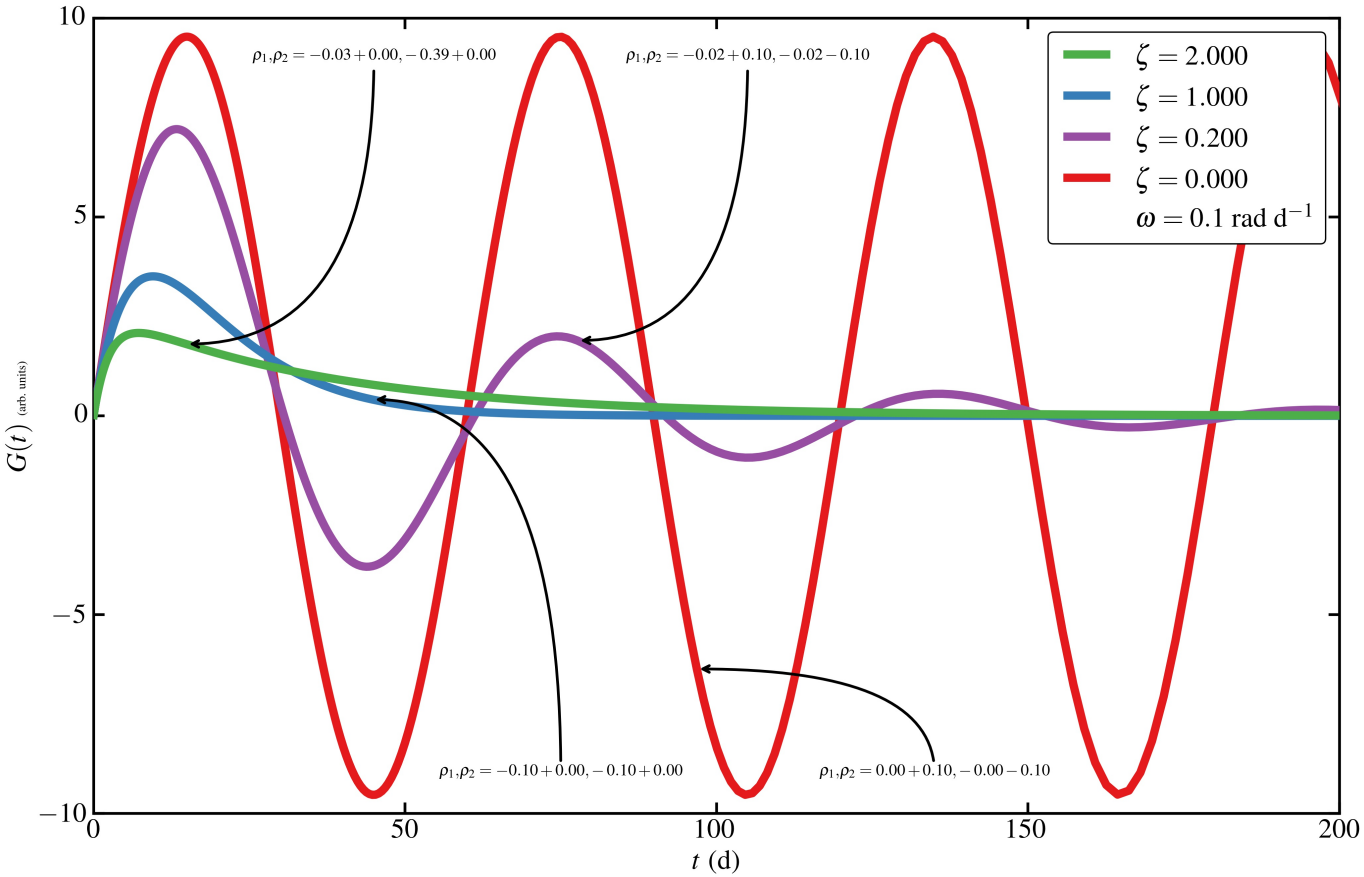


Confidence Interval Estimates

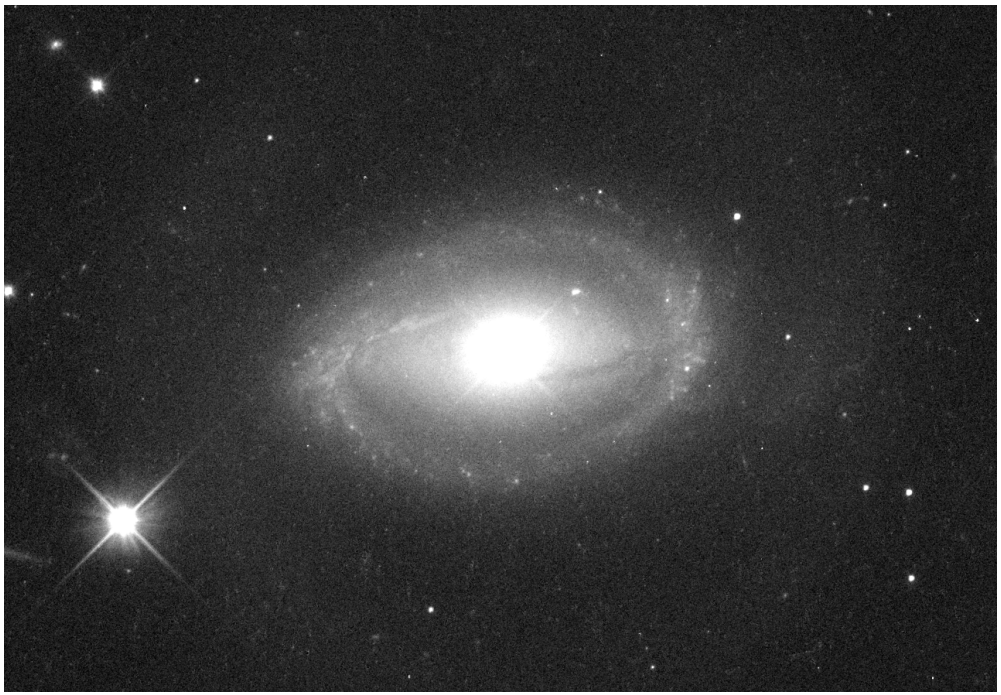


How to Interpret?: Green's Function of LHS (eg. C-ARMA(2,1)...)

$$\mathrm{d}^2G + 2\omega\zeta \mathrm{d}G + \omega^2 G = \delta(0)$$



Zw 229-15 (kplr006932990)

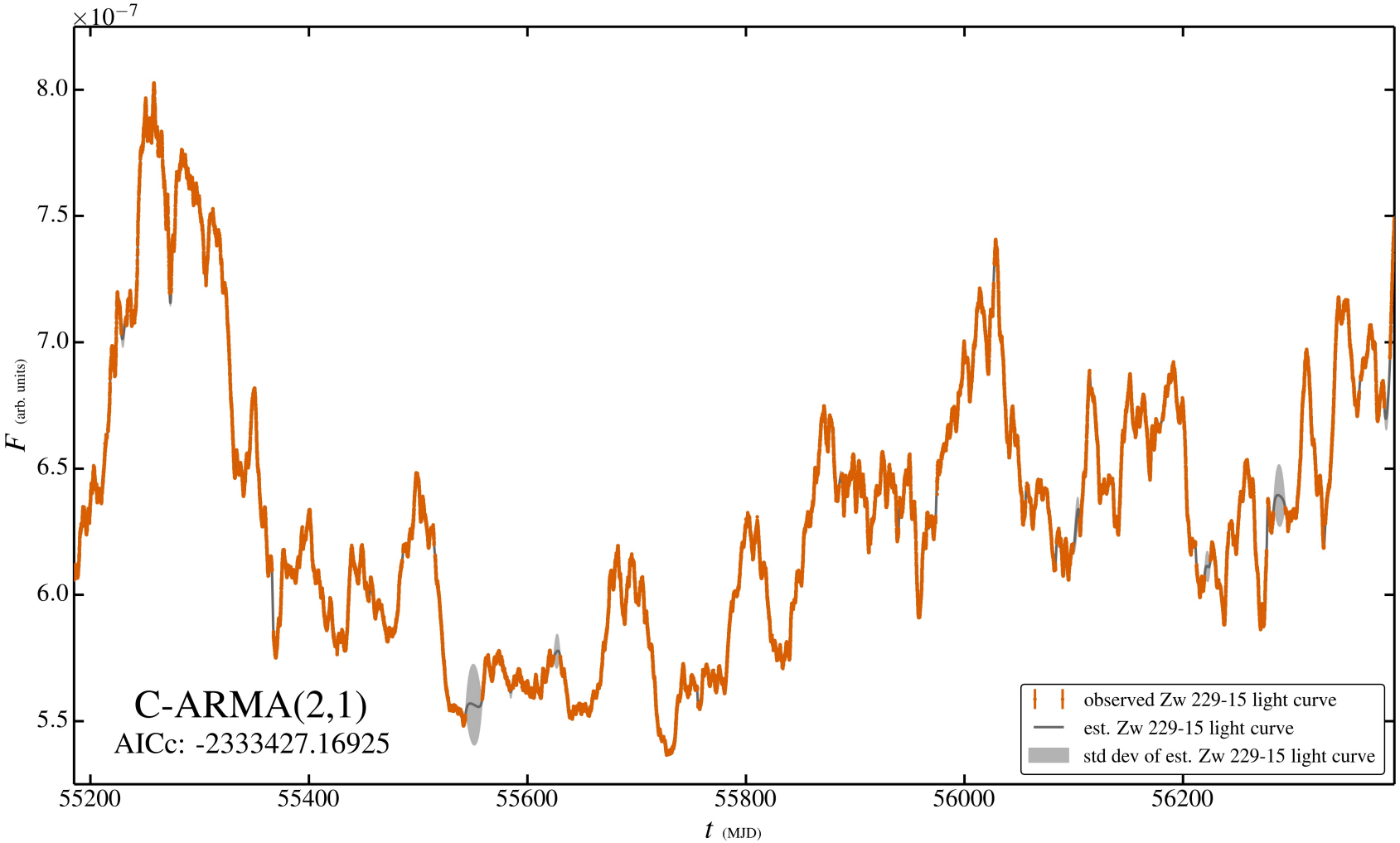


HST Image

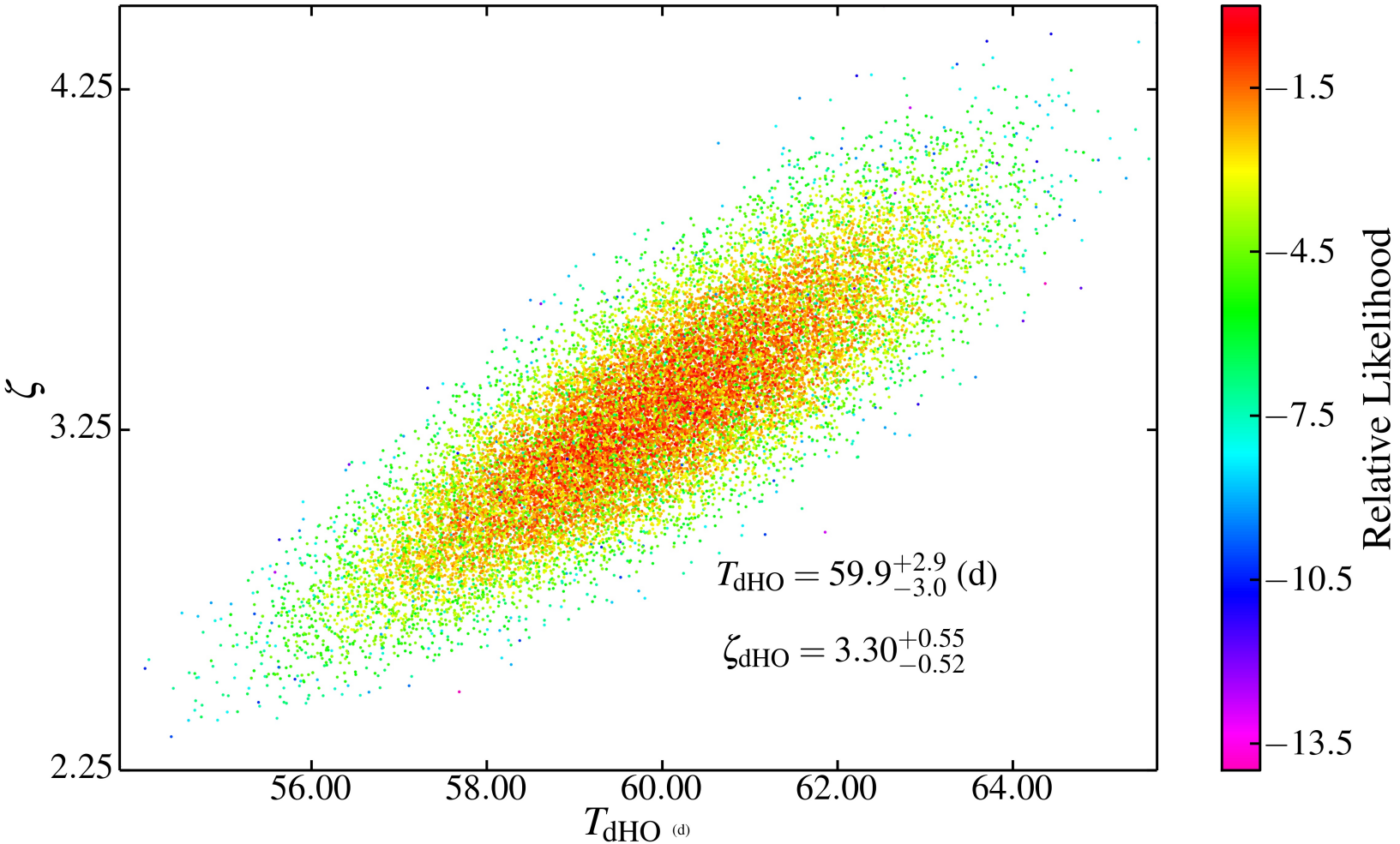
- Sy 1 in Lyra
- $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d
- mag 15.4
- $\mathrm{M_{BH}} = 1.00^{+0.19}_{-0.24} \times 10^7 \mathrm{M}_\odot$

(Barth et al. 2011)

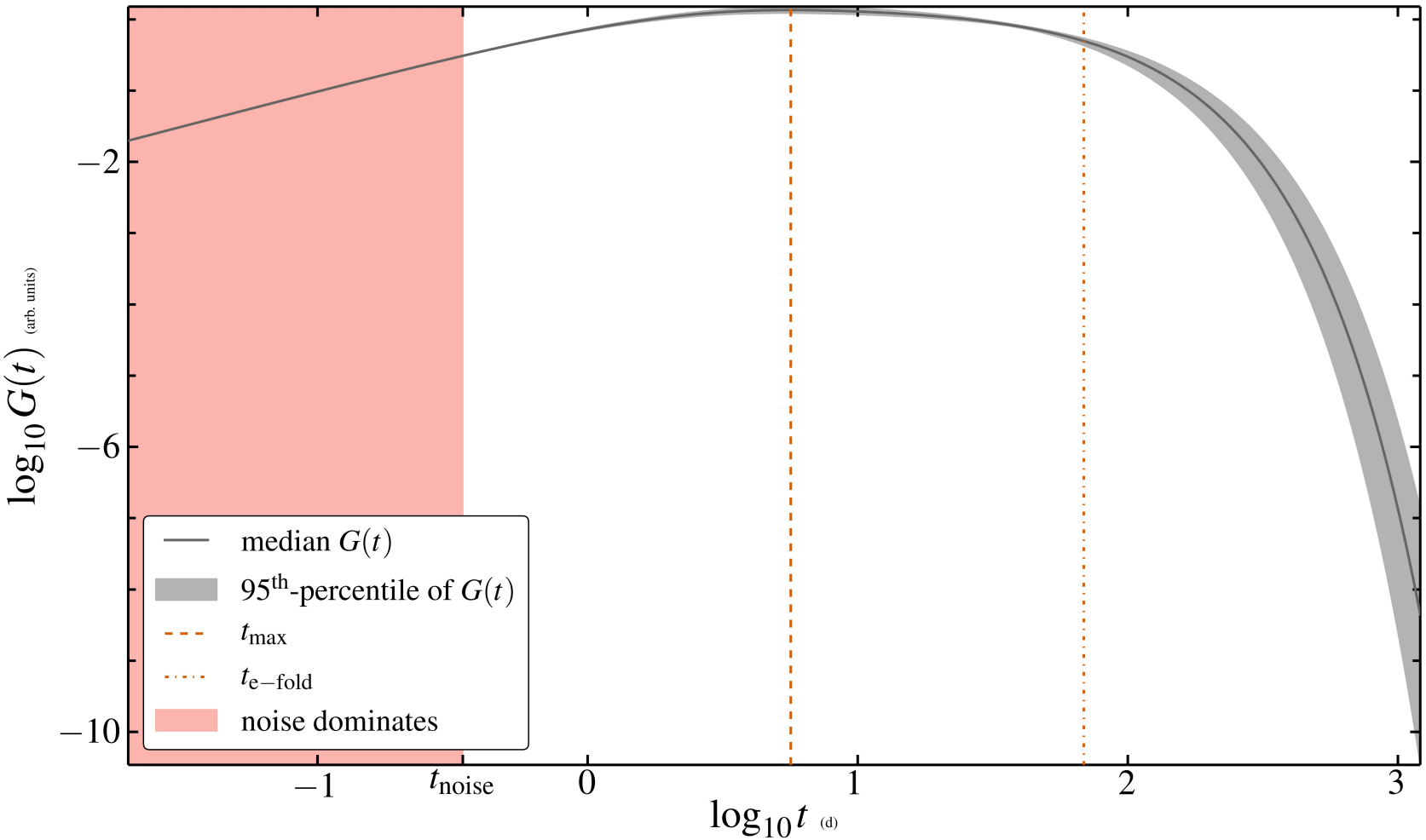
C-ARMA(2,1) model of Zw 229-15
Smoothed light curve



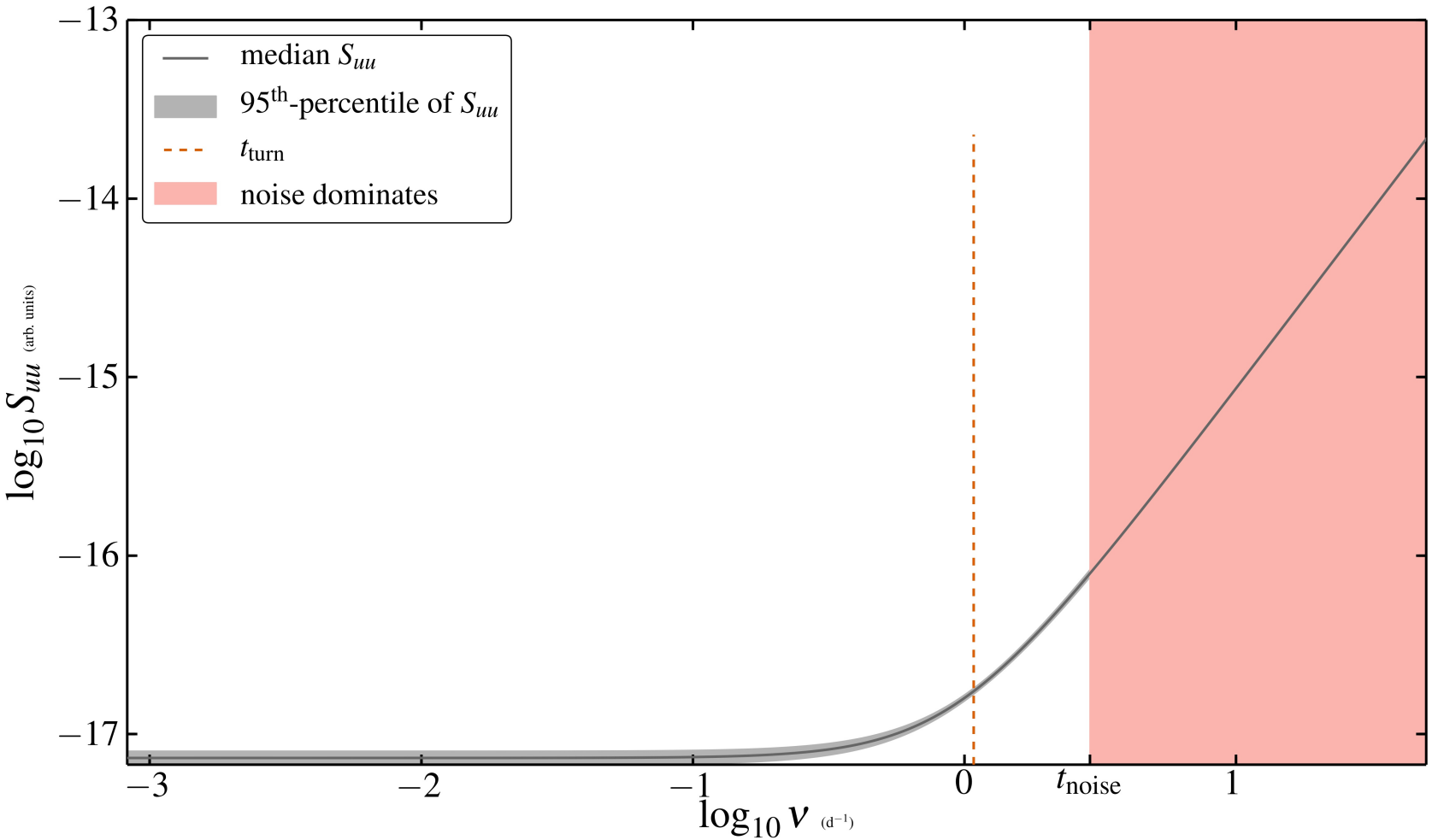
C-ARMA(2,1) model of Zw 229-15
Damped Harmonic Oscillator



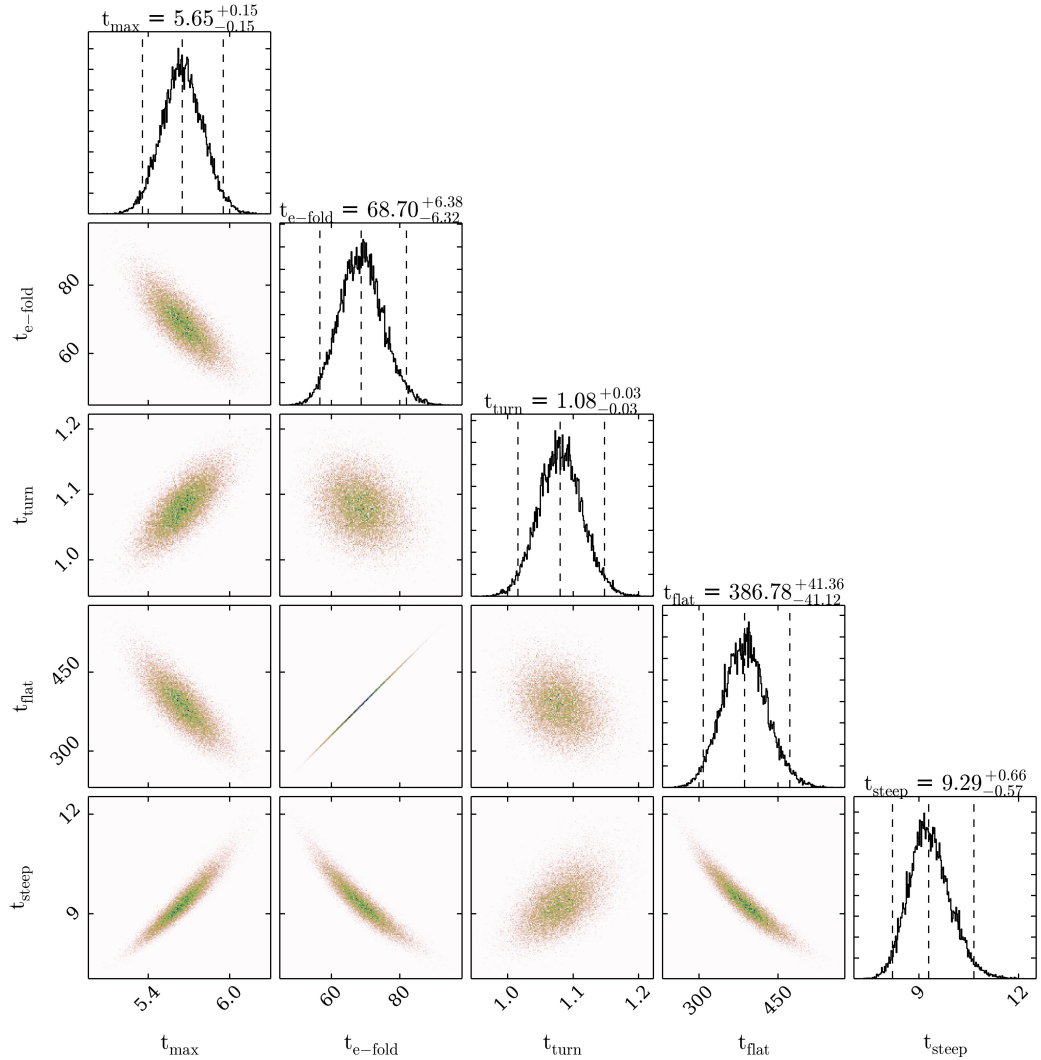
C-ARMA(2,1) model of Zw 229-15
Green's Function



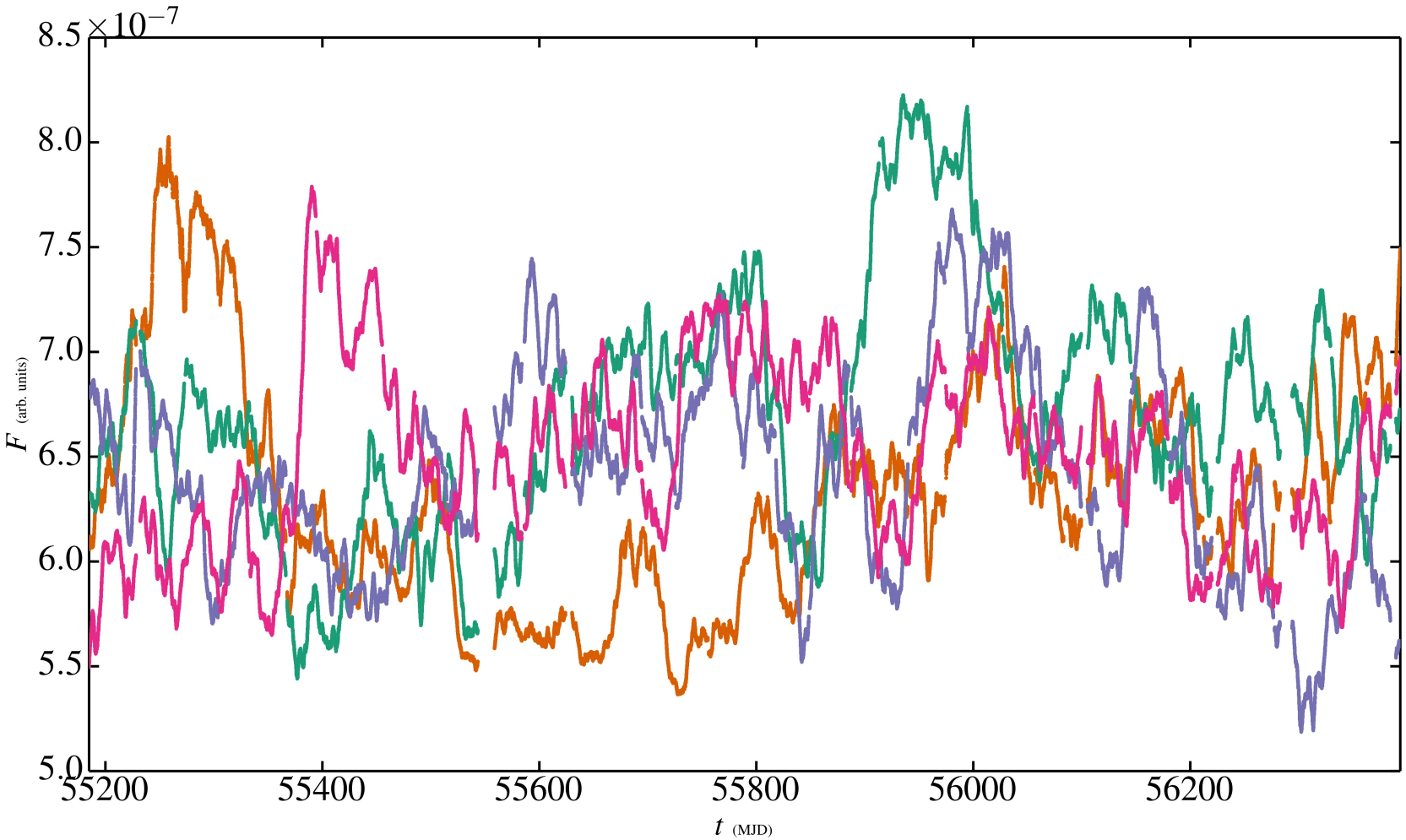
C-ARMA(2,1) model of Zw 229-15
Disturbance PSD



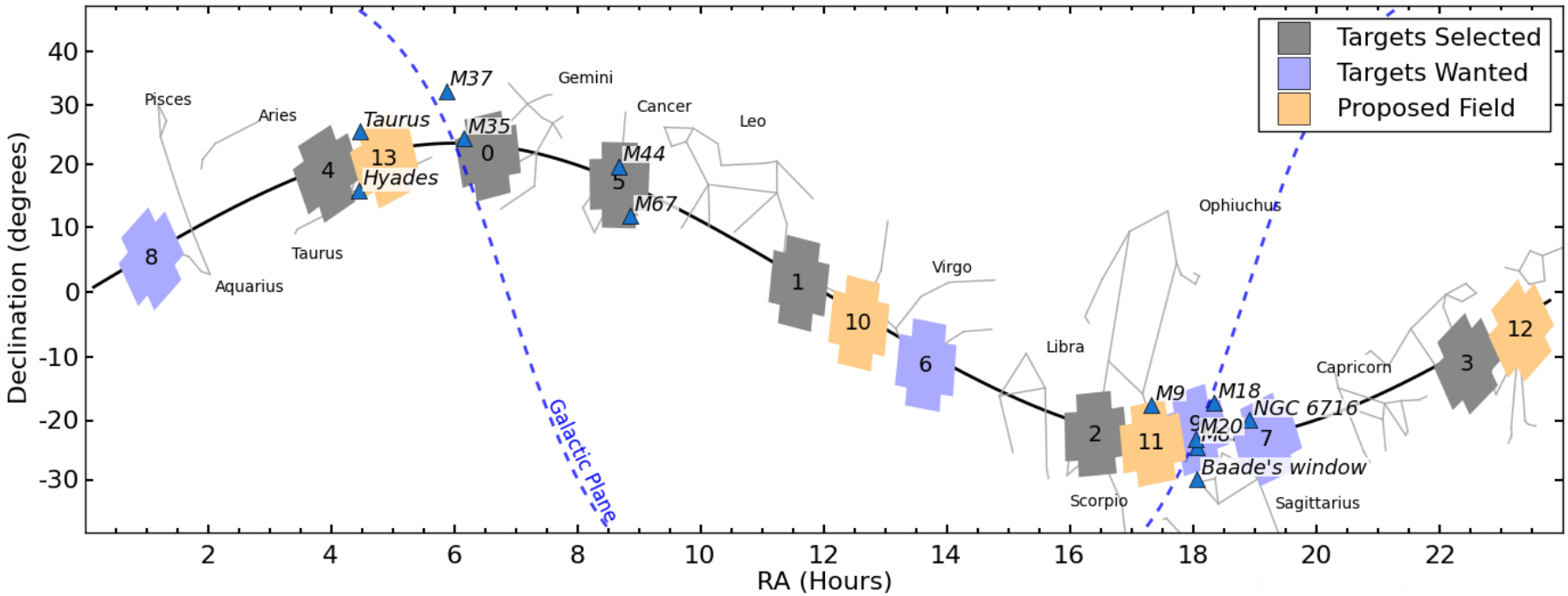
C-ARMA(2,1) model of Zw 229-15
Timescales



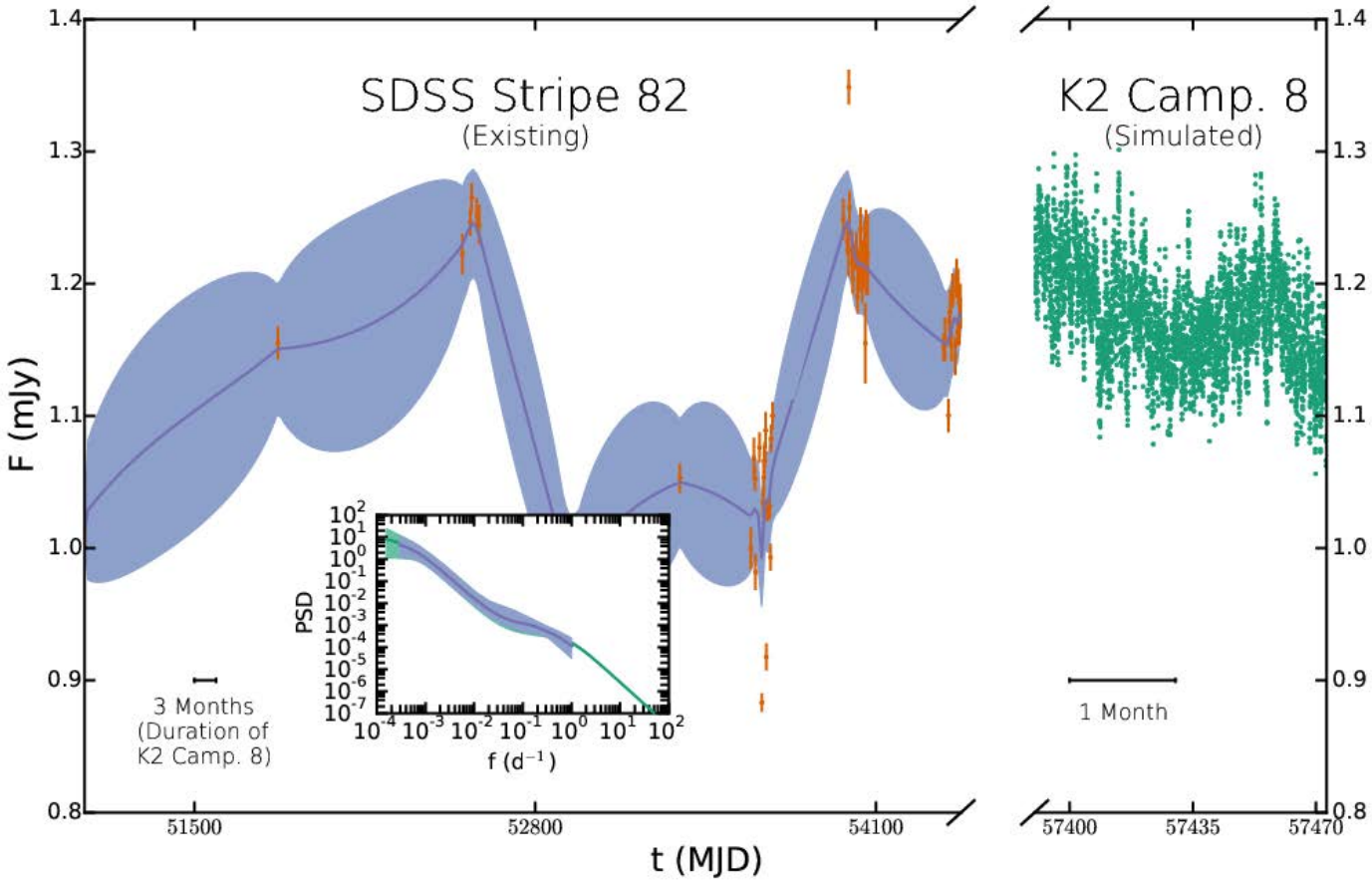
C-ARMA(2,1) model of Zw 229-15
Which is the real light curve?



Work in Progress
K2 campaigns

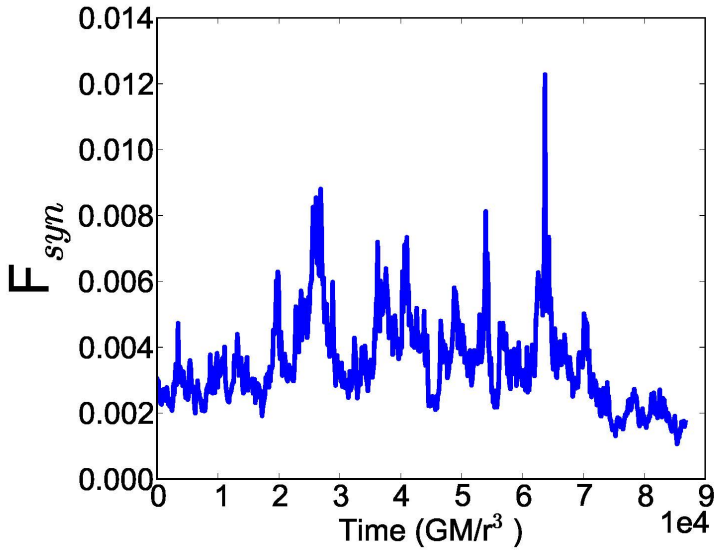


Work in Progress
K2 observations of Stripe 82 QSOs



Work in Progress

- SDSS Stripe 82 + K2 QSO variability
- Connection between AGN sub-type and variability
- Stationarity of AGN light curves
- More sophisticated time series models
- Comparing simulations with observations
- Cadence and periodicity requirements of LSST
- Multi-wavelength variability



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Conclusions

- Kepler AGN exhibit a **wide variety** of behavior (flares & possibly QPOs)
- DRW does **not work** for all AGN
- AGN variability can be modelled as a C-ARMA process
- Kalman filter can be used to infer C-ARMA parameters
- C-ARMA(2,1) process is an **appropriate model** of variability for Zw 229-15
- Zw 229-15 acts like a **Damped Harmonic Oscillator Driven by Colored Noise**

Barth, A. J., Nguyen, M. L., Malkan, M. A., et al. 2011, ApJ, 732, 121

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Davis, J. H. 2002, Foundations of Deterministic and Stochastic Control (Birkhäuser)

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