

AGN VARIABILITY: INSIGHTS FROM KEPLER

HSC Science Discussions

Princeton, New Jersey

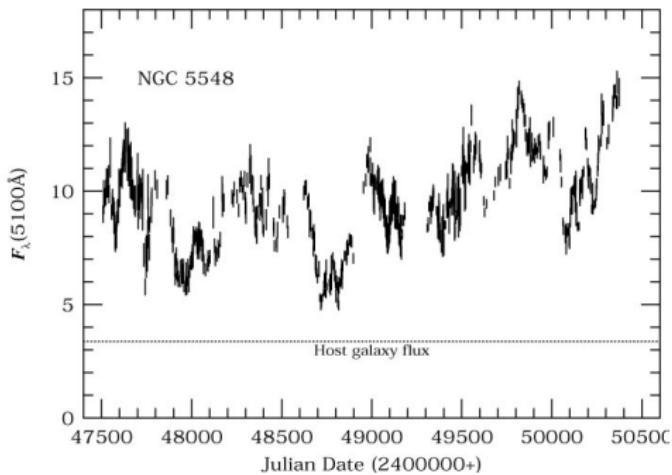
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March 24, 2016

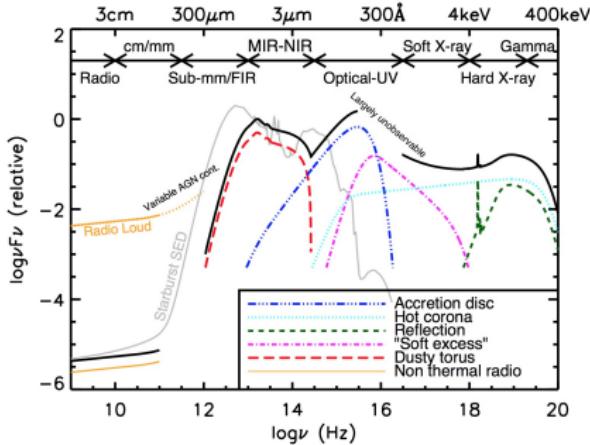
AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



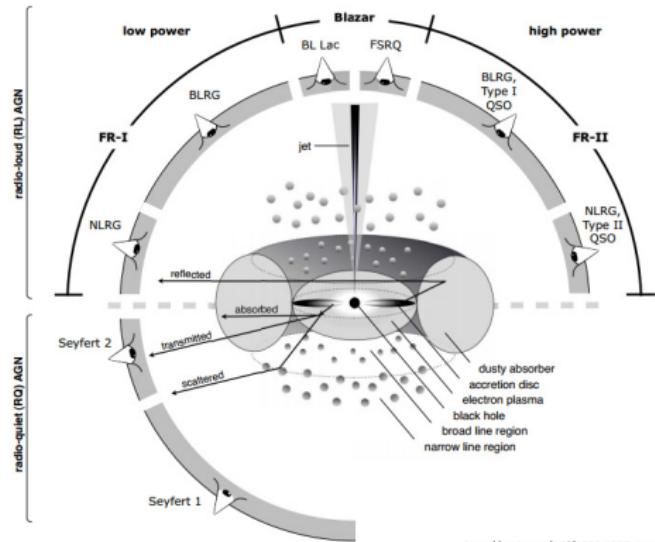
(Peterson et al. 1999)

- * ~ 90 % vary (Sesar et al. 2007)
- * Pan-spectral: shorter $\lambda \Rightarrow$ stronger variability
- * Stochastic! (Peterson 1997)
- * longer λ lag shorter λ

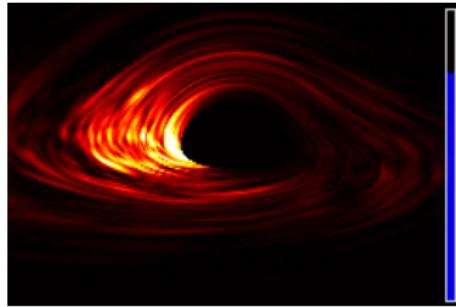
AGN Morphology: Continuum Variations → Origin in Accretion Disk



Chris Harrison

<http://arxiv.org/pdf/1302.1397v1.pdf>

Sources of variability



Armitage & Reynolds (2003)

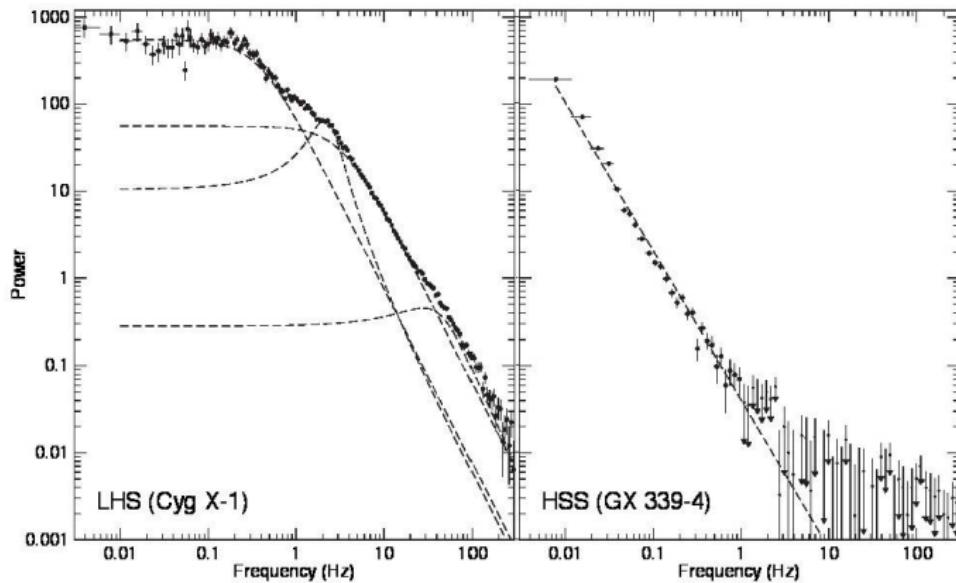
Magnetic Reynolds number:

$R_{\text{magnetic}} = UL/\eta \sim \text{advection vs diffusion.}$

Magnetic diffusivity $\eta = \frac{m_e v_{\text{collision}}}{\mu_0 n_e e^2}.$

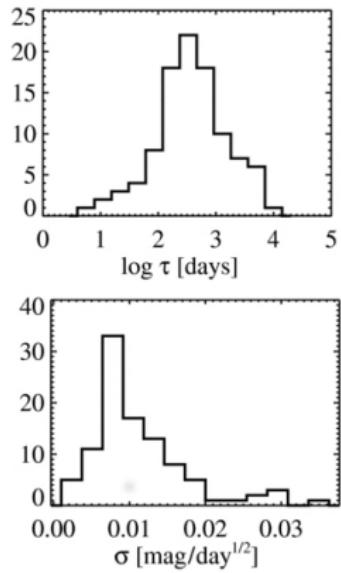
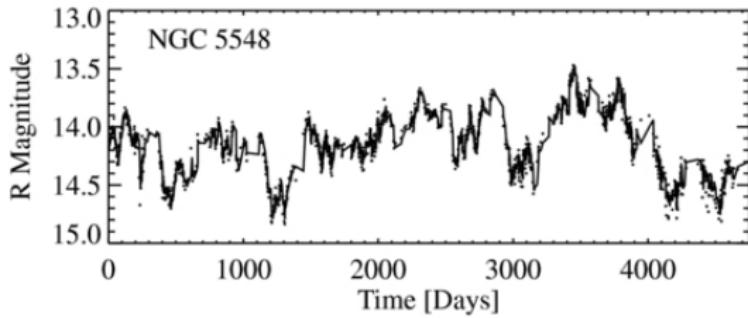
- ✿ λ dependent (X-Ray partially drives Optical) (Uttley & Casella 2014)
- ✿ Shot noise models unlikely (Uttley et al. 2005)
- ✿ MHD turbulence responsible (Nowak & Wagoner 1995)
- ✿ Coronal X-Ray flares possible (Poutanen & Fabian 1999)
- ✿ Propagating fluctuations (Lyubarskii 1997)
 - ✿ Predicts PSD
- ✿ Coronal accretion (Janiuk & Czerny 2007)

Search for timescales in Power Spectral Density (PSD)



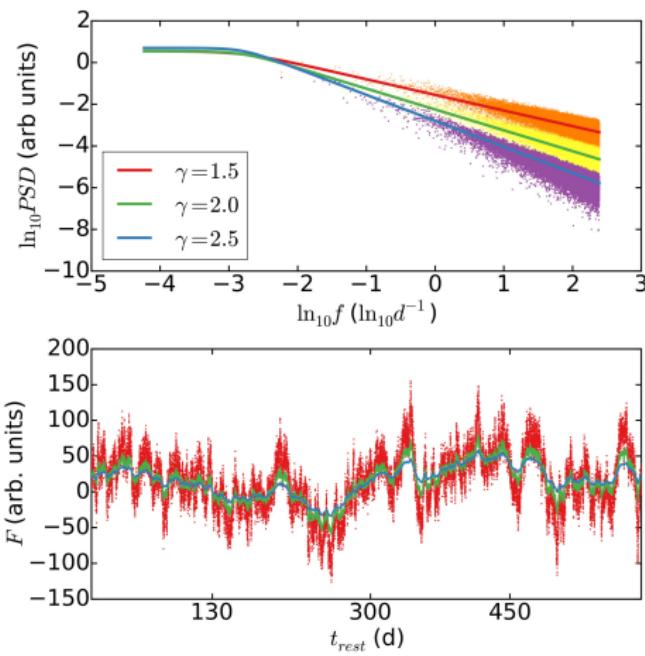
Belloni & Stella (2014)

Kelly et al. (2009): Model variability as DRW



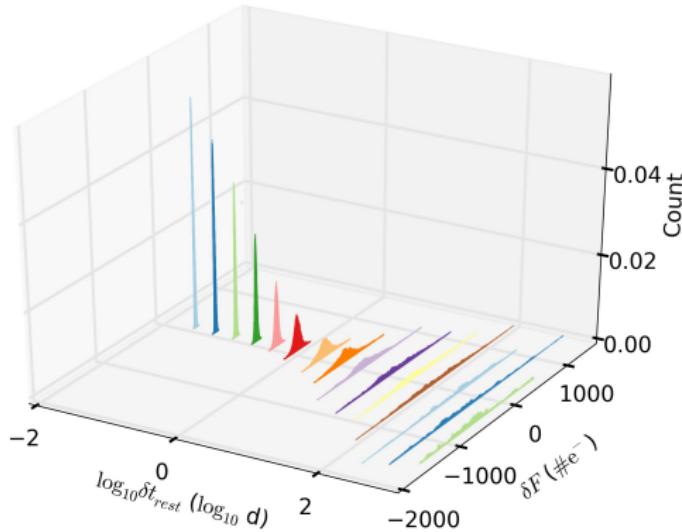
- * Dynamical or thermal processes responsible for variability
- * $\tau \propto M_{\text{BH}} \& L_{\text{AGN}}$ but $\sigma \propto 1/M_{\text{BH}} \& 1/L_{\text{AGN}}$

PSD of the Damped Random Walk



- * $PSD \propto \frac{1}{f^2}$ on short timescales
- * $PSD \propto \frac{1}{f^b} \Rightarrow \sigma_{\alpha-fluc} \propto r^b$
(Lyubarskii 1997)
- * DRW: b is fixed - is this true?
- * Generalize: $PSD \propto \frac{1}{f^\gamma}$ (McHardy et al. 2004)
- * Test with data!

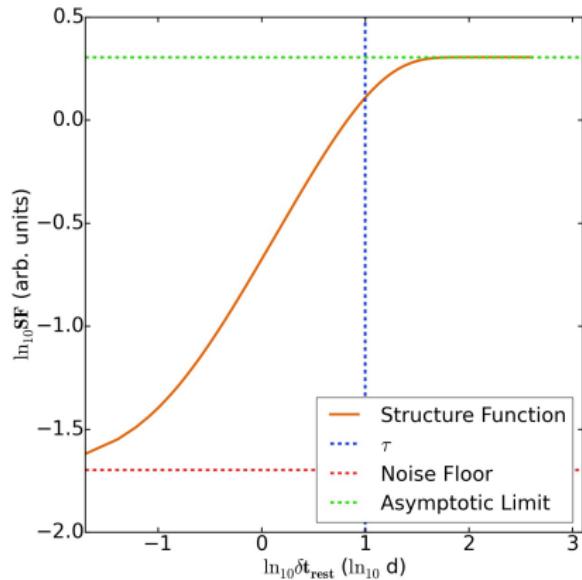
Structure functions



- * 2nd-order statistic.
- * $\delta F = F(t + \delta t) - F(t)$
- * $SF(\delta t) = \langle |\delta F|^2 \rangle_t$
- * Insensitive to edge-effects, aliasing etc...
- * $SF(\delta t) = 2ACVF(0) - 2ACVF(\delta t)$

How does variance of δF vary with δt ?

Structure functions

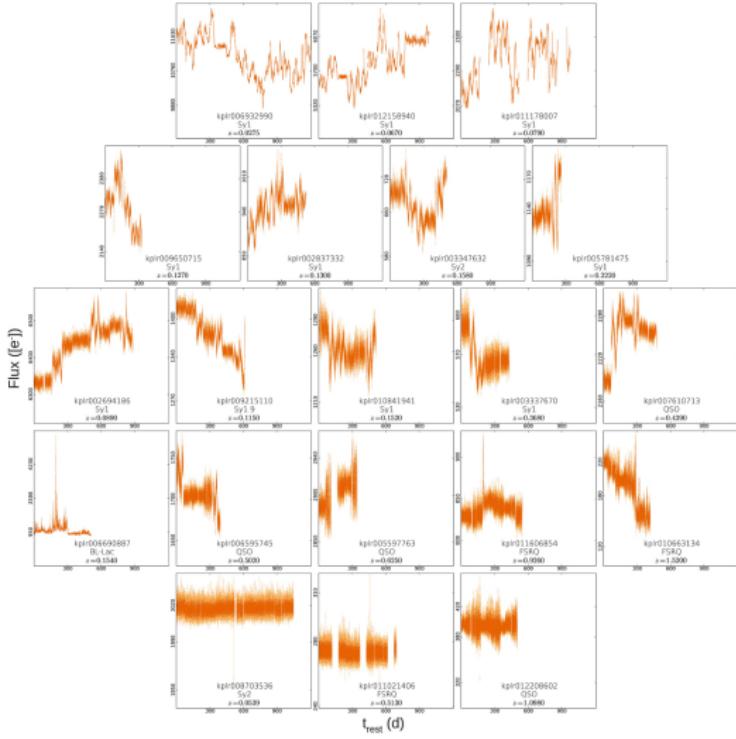


- * Small δt : ‘Noise floor’
- * Slope $\sim \gamma$
- * Big δt : Turnover i.e. damping
- * Spurious breaks & features

(Emmanoulopoulos et al. 2010)

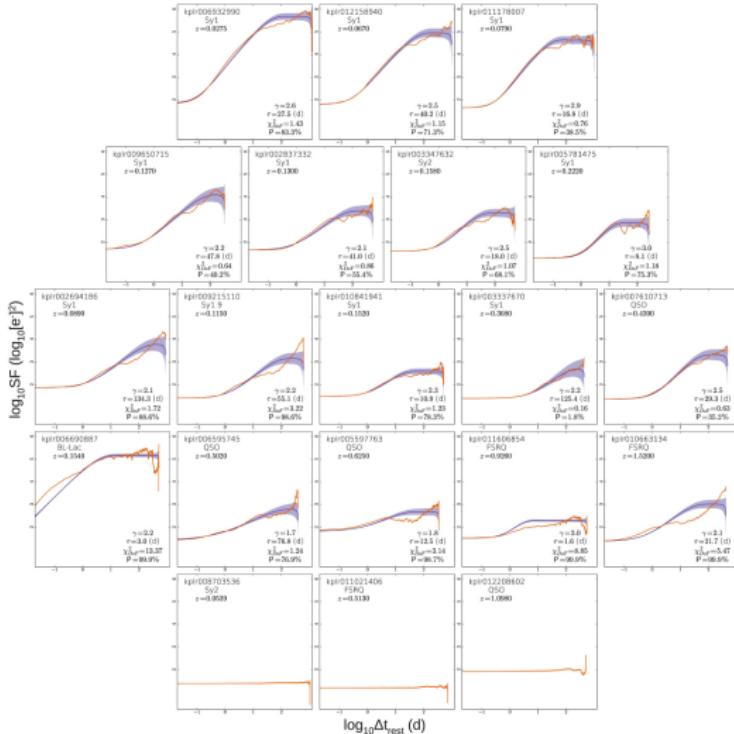
Features in the Structure Function

Full AGN sample



- * $z \sim 0.02\text{-}1.5$
- * $\delta t_{\text{rest}} \sim 14\text{-}28 \text{ min}$
- * $N \sim 16k\text{-}60k$
- * Wide variety of behavior!

Structure function fits

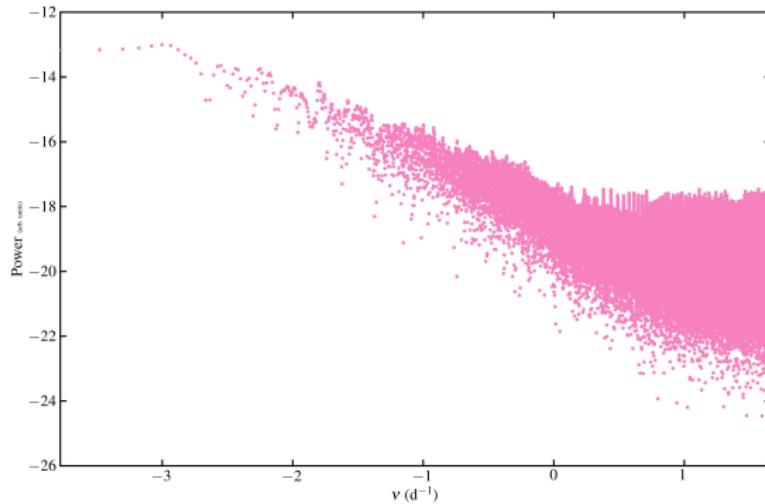


- Not all AGN \sim DRW
- PSD model too simple
- Variability onsets over ~ 1 hr to ~ 1 d

Kasliwal, Vogeley, & Richards (2015a)

Periodogram of Zw 229-15

What model to use?



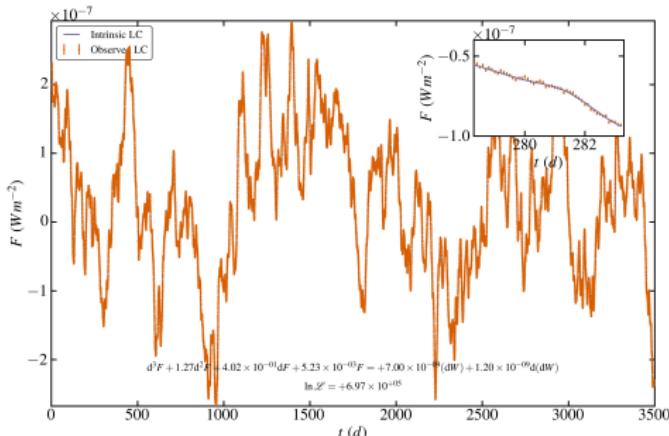
- * Stochastic model must be flexible
- * Amenable to physical interpretation

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

$$dW \sim \mathcal{N}(0, dt)$$

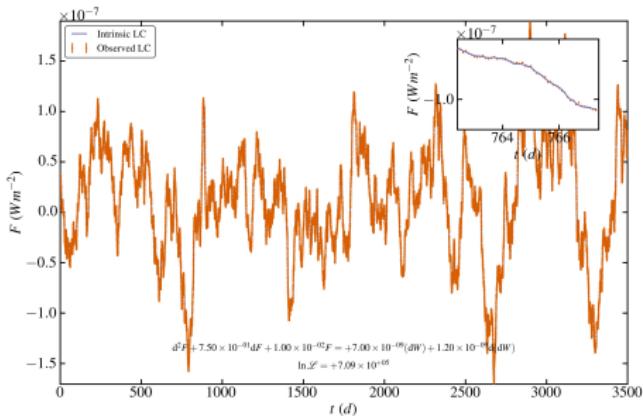
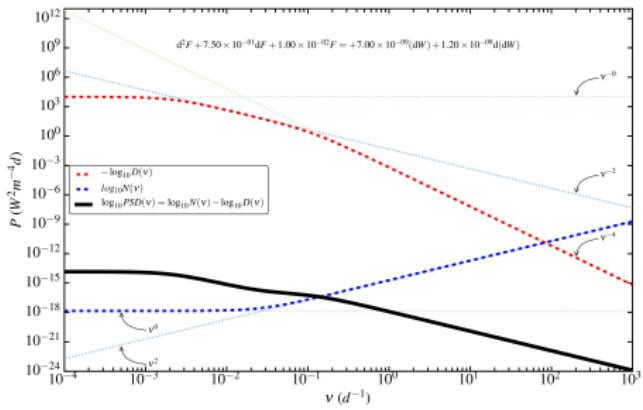
$$d^p x + \alpha_1 d^{p-1} x + \dots + \alpha_{p-1} dx + \alpha_p x = \beta_0(dW) + \dots + \beta_q d^q(dW)$$

- ✿ Itō calculus Brockwell (2014); Davis (2002); Kelly et al. (2014)
- ✿ Drive linearized system with noise
- ✿ PSD is a ratio of even polynomials in frequency



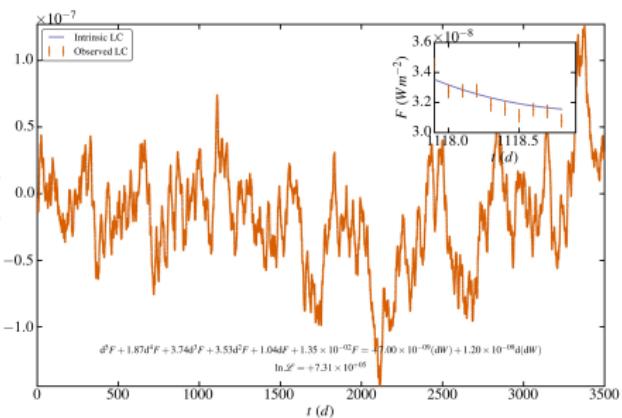
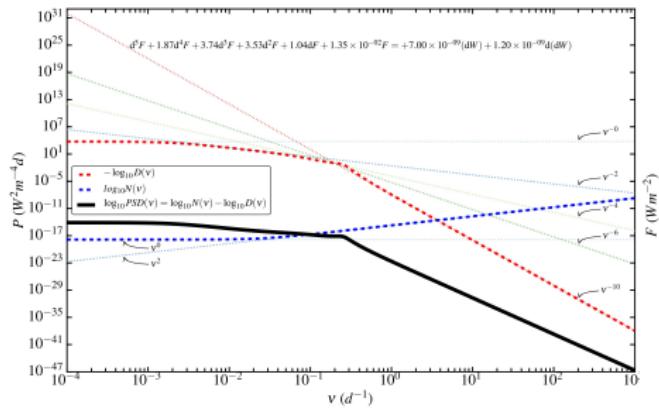
Power Spectral Density

Eg. C-ARMA(2,1)

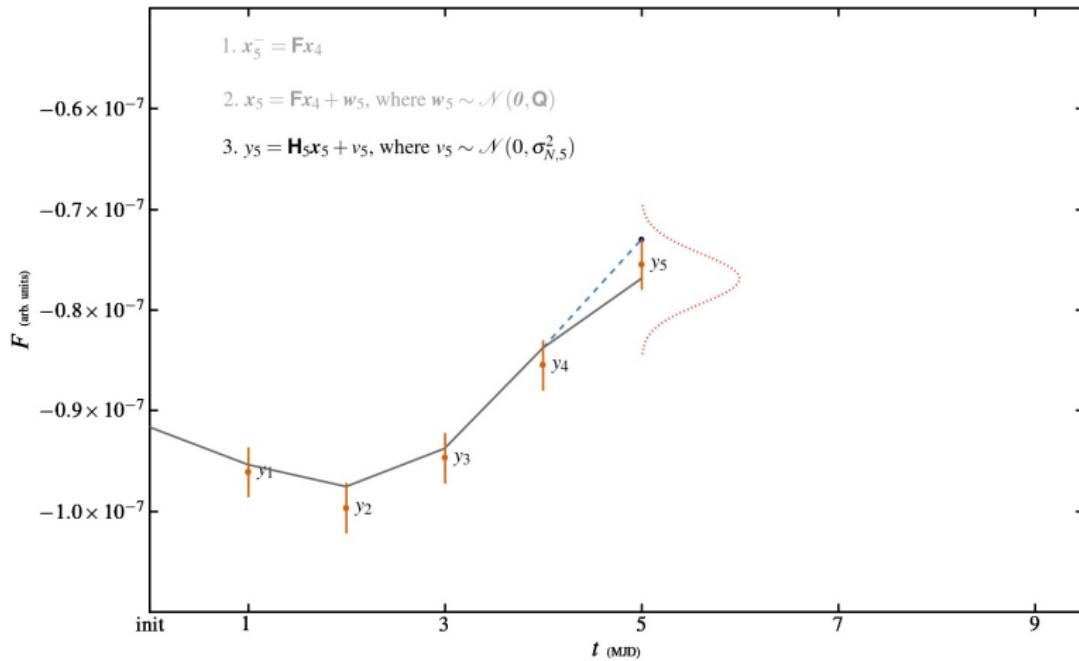


Power Spectral Density

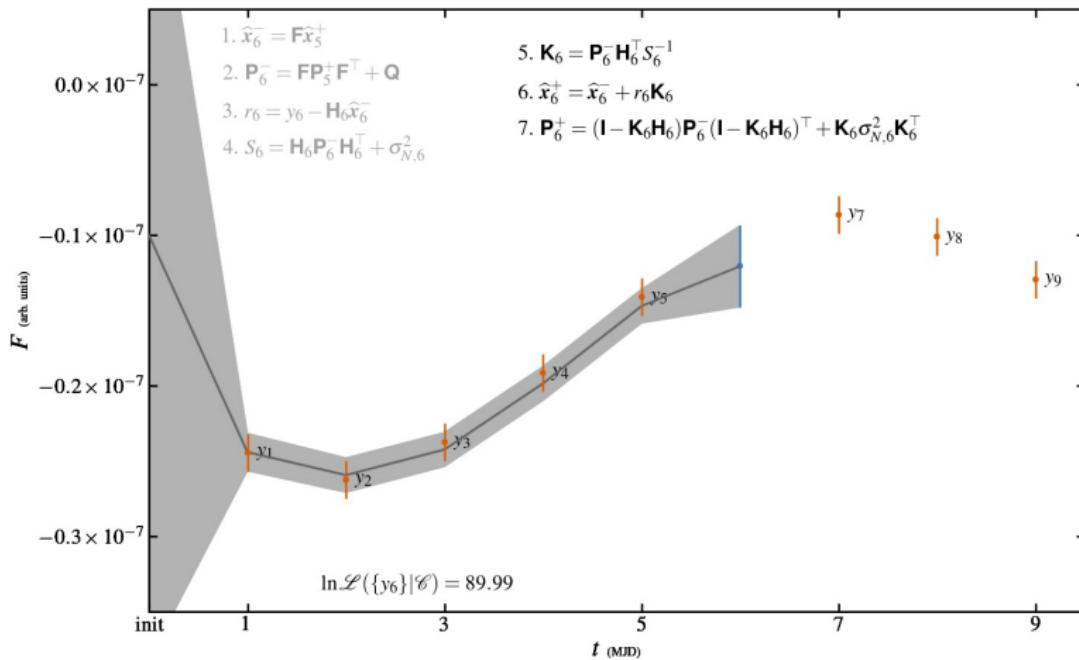
Eg. C-ARMA(5,1)



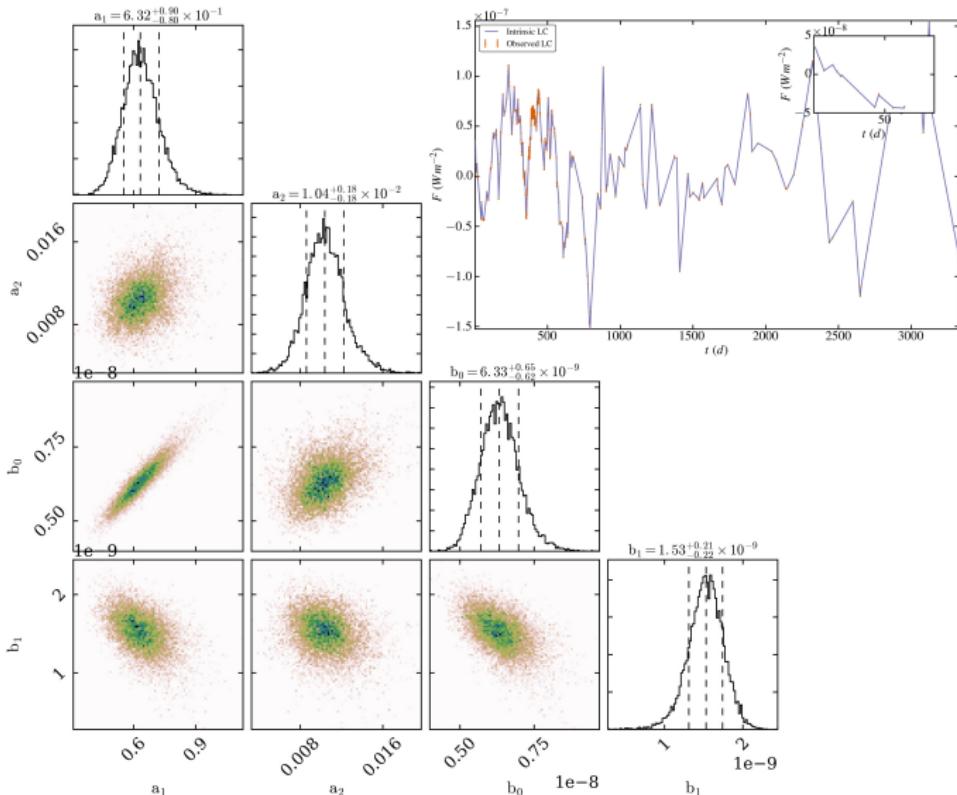
Evolution & observation of light curve state



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

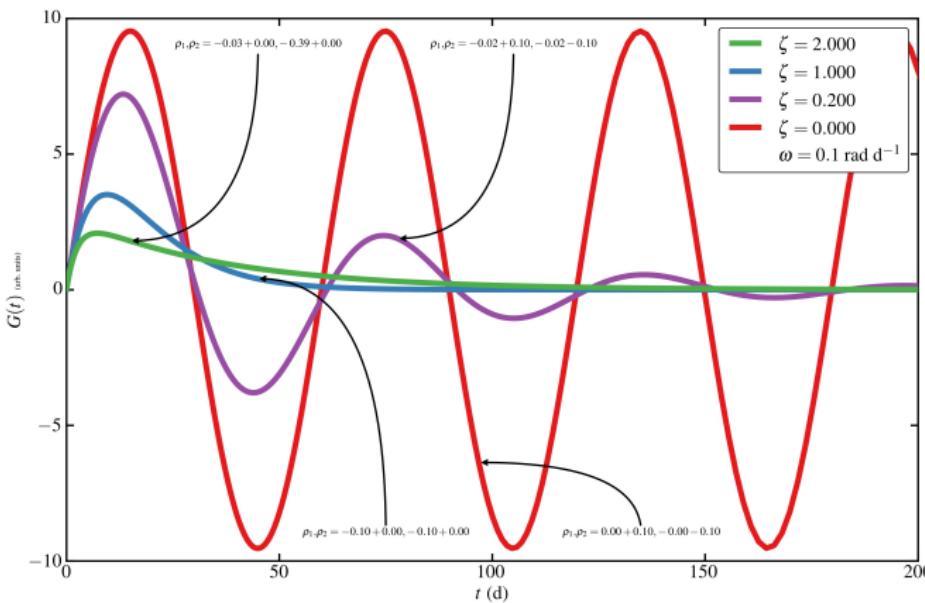


Confidence Interval Estimates

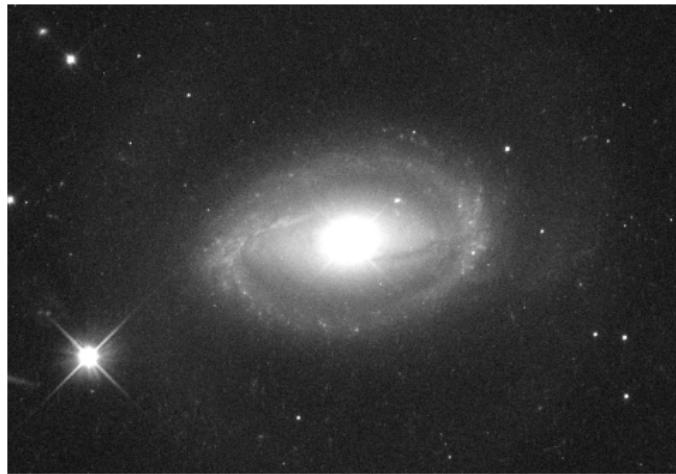


How to Interpret?: Green's Function of LHS (eg. C-ARMA(2,1)...)

$$d^2G + 2\omega\zeta dG + \omega^2 G = \delta(0)$$



Zw 229-15 (kplr006932990)



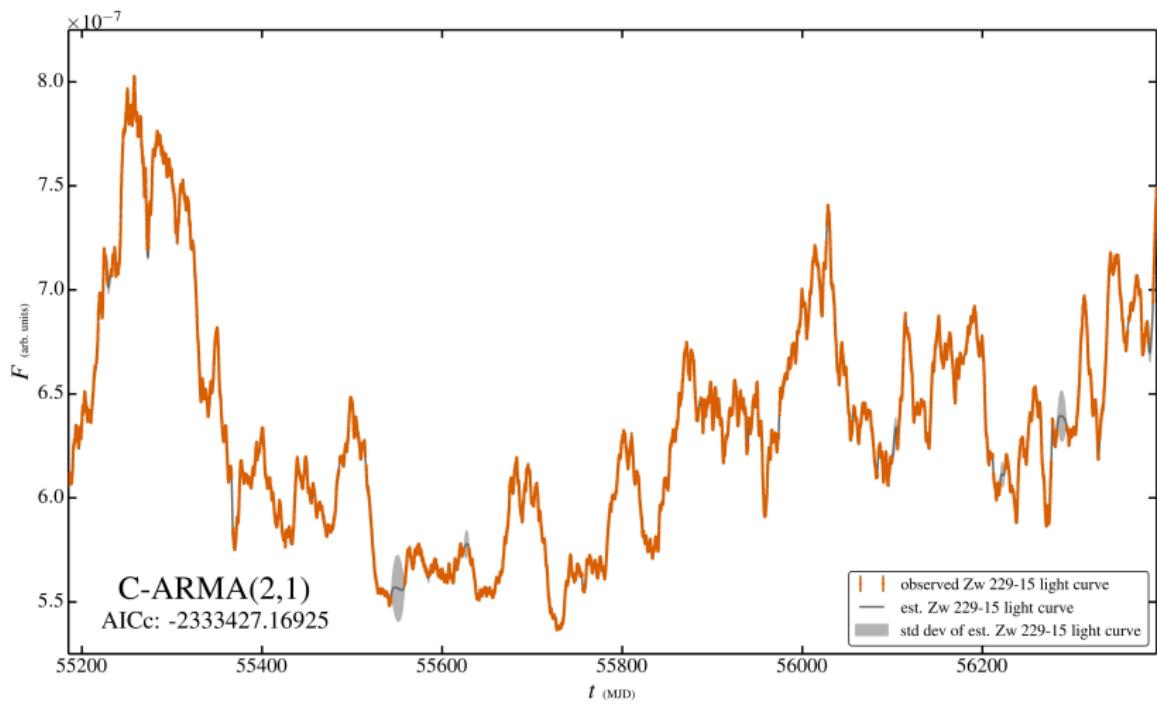
HST Image

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

(Barth et al. 2011)

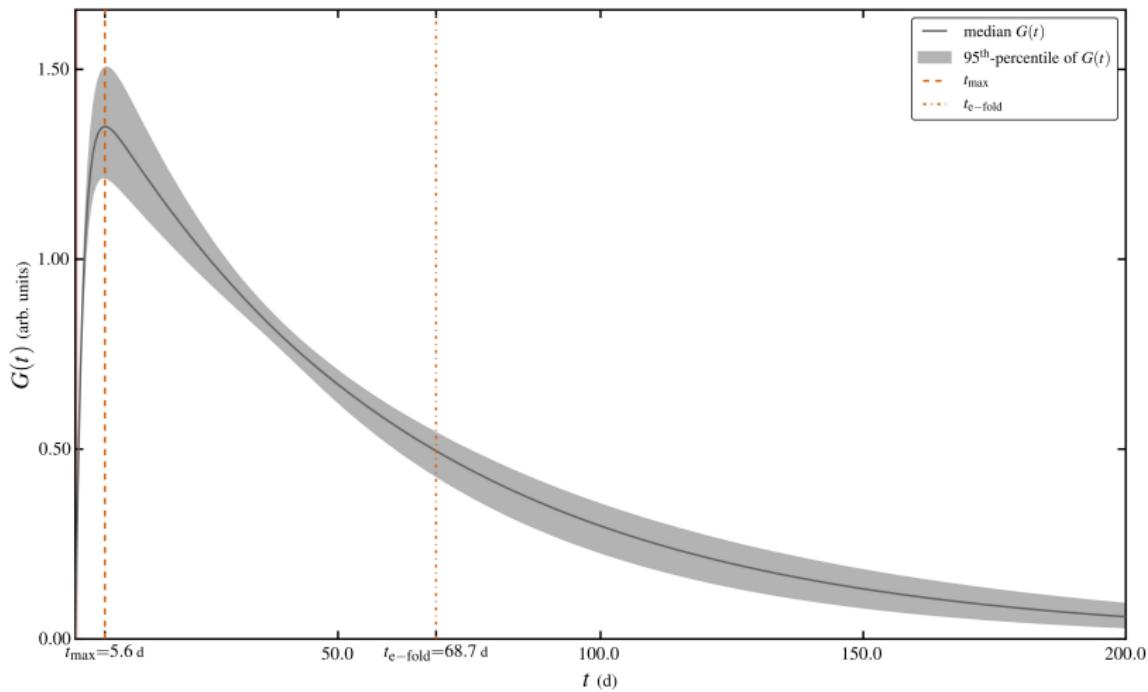
C-ARMA(2,1) model of Zw 229-15

Smoothed light curve



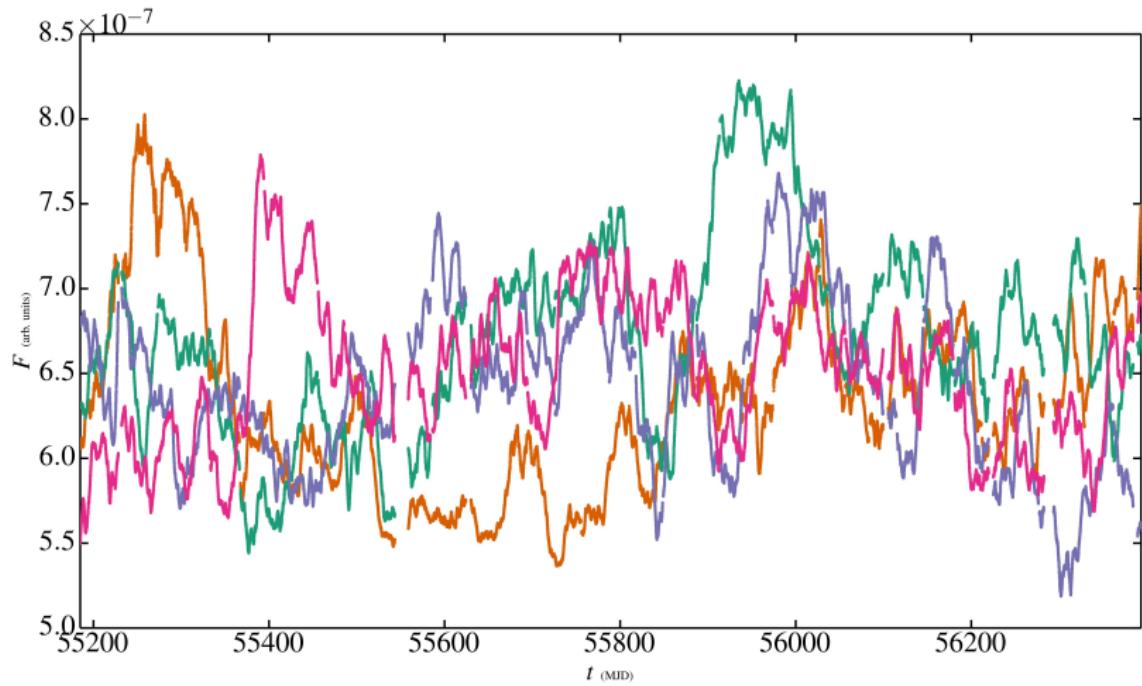
C-ARMA(2,1) model of Zw 229-15

Green's Function



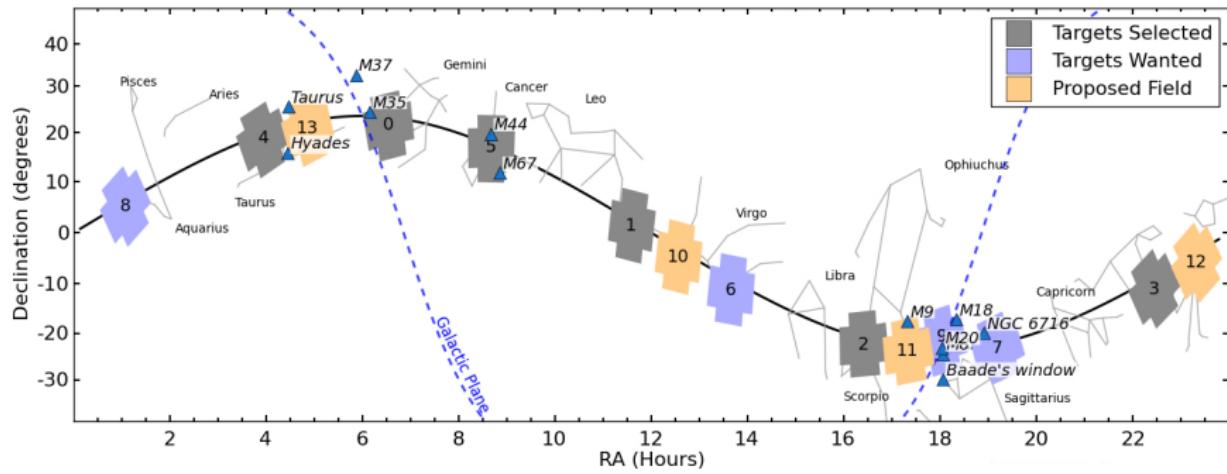
C-ARMA(2,1) model of Zw 229-15

Which is the real light curve?



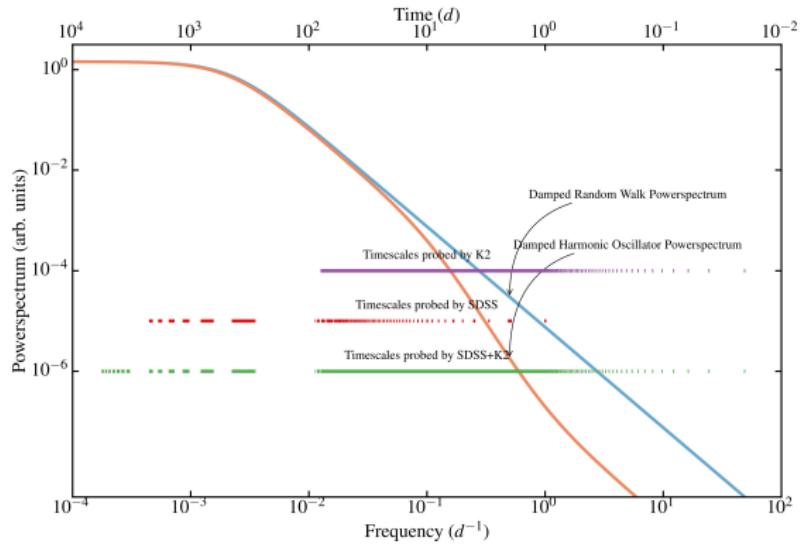
Work in Progress

K2 campaigns



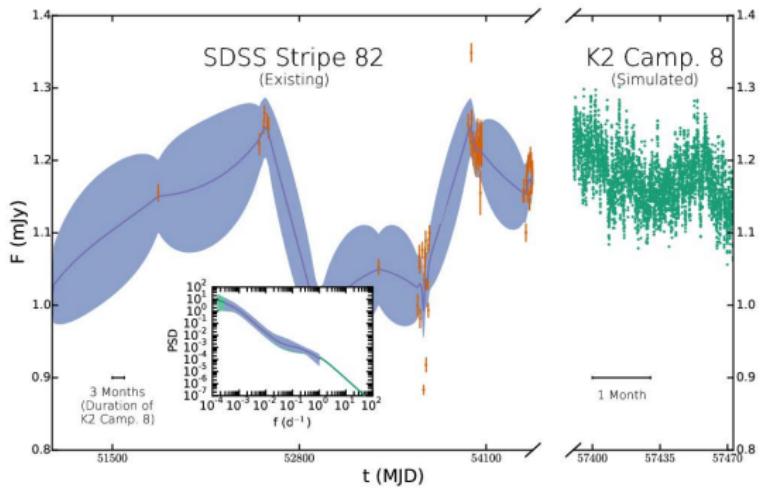
Work in Progress

Power of SDSS+K2



Work in Progress

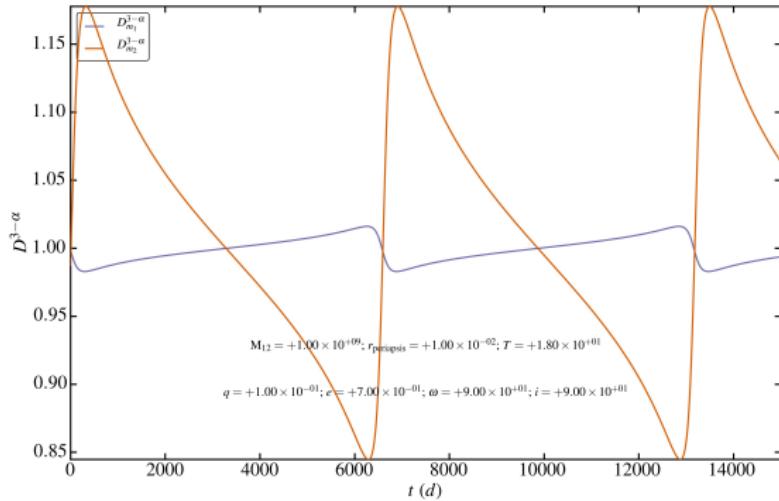
K2 observations of Stripe 82 QSOs



Work in Progress

Beaming from binary SMBHs

Inspired by D'Orazio, Haiman, & Schiminovich (2015)



- * $M_{12} = 10^9 M_\odot$
- * $r_{periapsis} = 0.01 \text{ pc}$

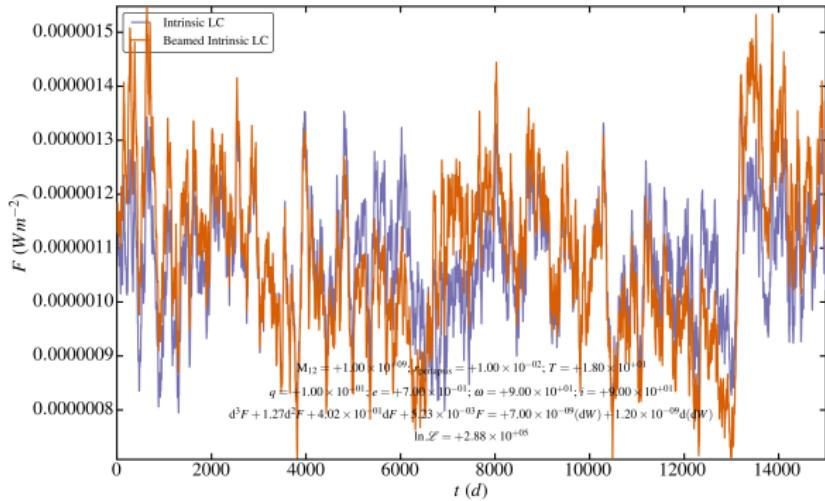
- * $q = 0.1$

- * $e = 0.7$

Work in Progress

Beaming from binary SMBHs

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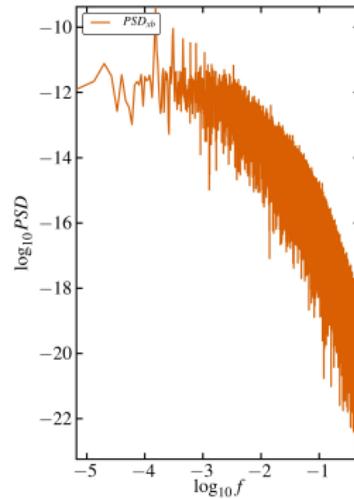
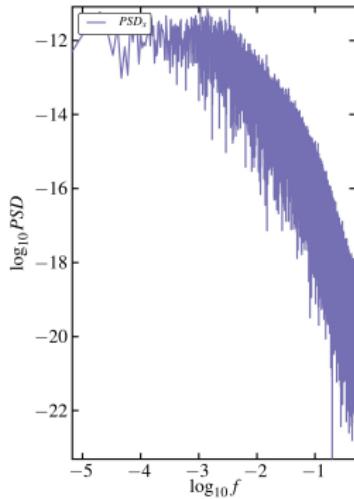
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Work in Progress

Beaming from binary SMBHs

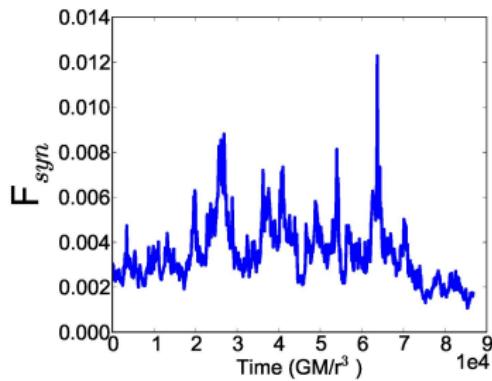
Inspired by D'Orazio, Haiman, & Schiminovich (2015)



- * Do C-ARMA techniques pick up these QPOs?
- * Can we get the binary parameters from observations?

Work in Progress

- ✿ SDSS Stripe 82 + K2 QSO variability
 - ✿ Connection between AGN sub-type and variability
 - ✿ Better time series models for exotic objects (blazars)
 - ✿ Cadence and periodicity requirements of LSST
- ✿ Detection of binary-SMBH via variability
- ✿ Multi-wavelength variability
- ✿ Comparing simulations with observations
- ✿ Stationarity of AGN light curves



J. Drew Hogg

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**

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