

AGN VARIABILITY: INSIGHTS FROM KEPLER

HSC Science Discussions

Princeton, New Jersey

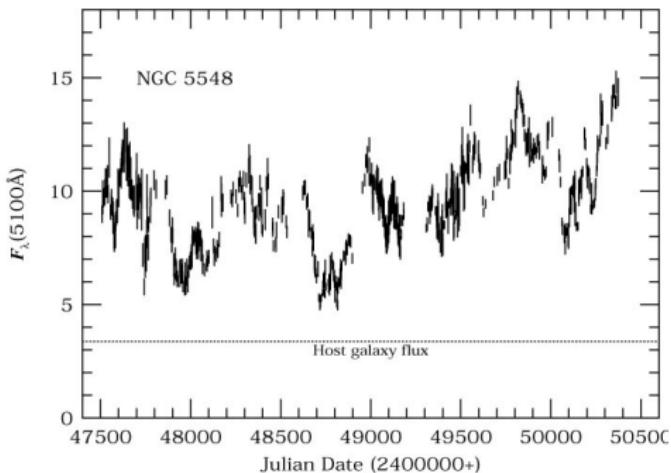
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March 24, 2016

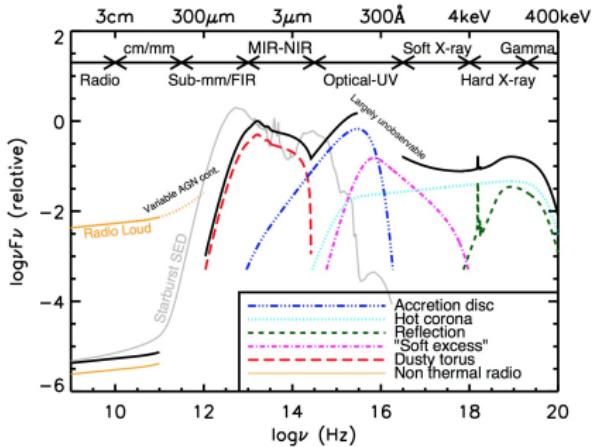
AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



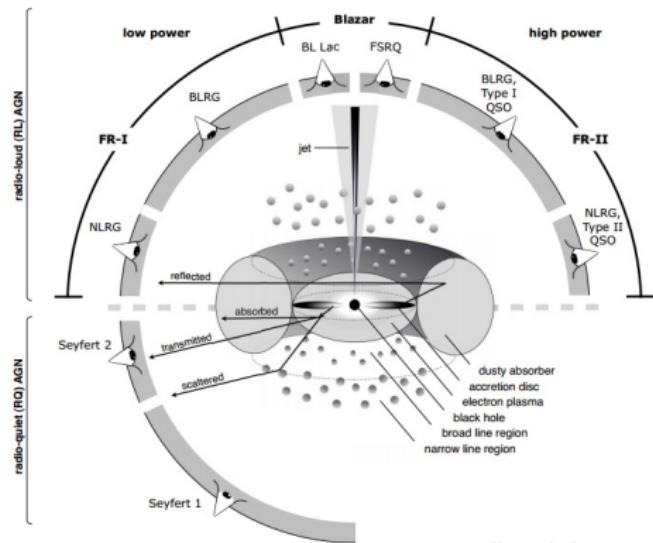
(Peterson et al. 1999)

- * ~ 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

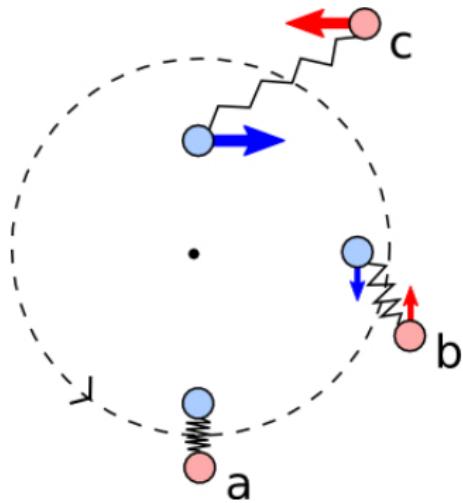


Chris Harrison

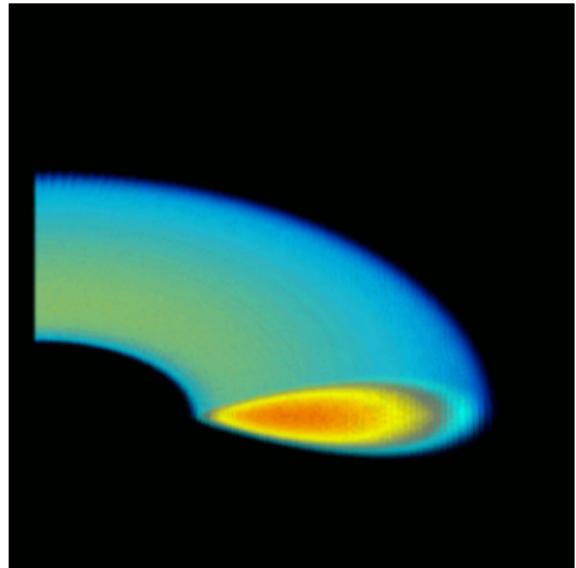


<http://arxiv.org/pdf/1302.1397v1.pdf>

Accretion Mechanism: The MRI

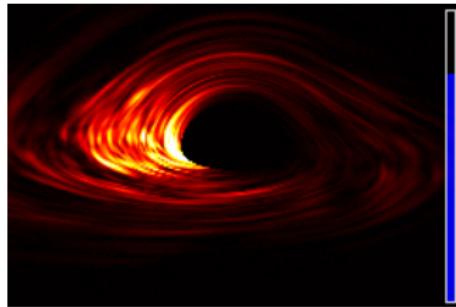


Harvard Astronomy Dept



Hawley & Krolik (2002)

Sources of variability



Armitage & Reynolds (2003)

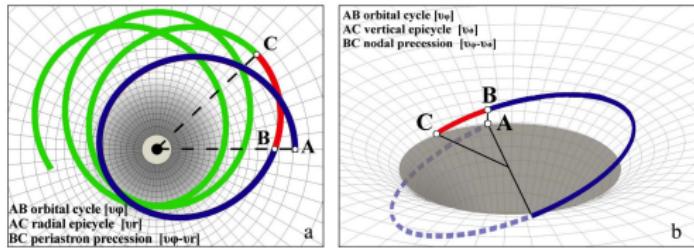
Magnetic Reynolds number:

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

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

- * 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)

Timescales that *may* be found in AGN



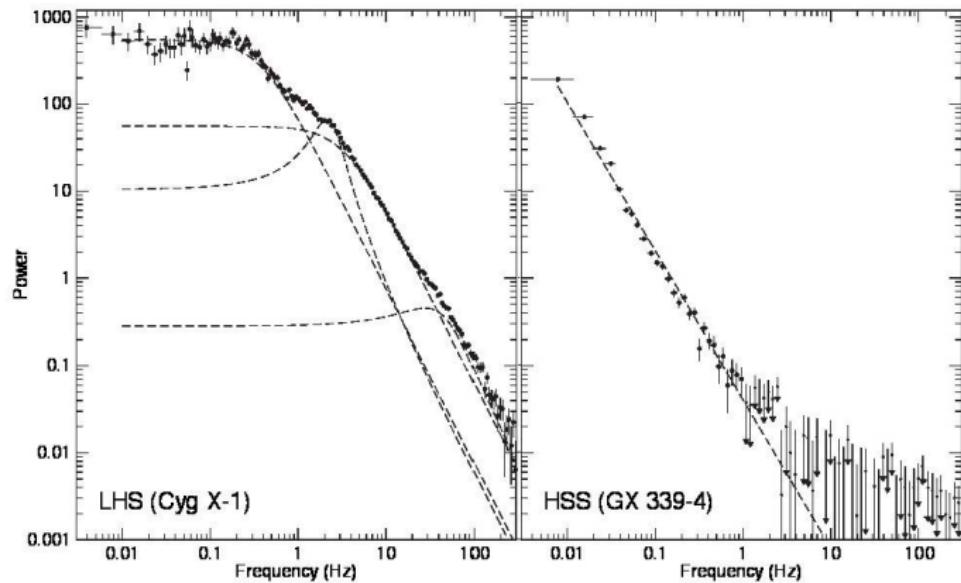
Belloni & Stella (2014)

$$\ast \quad t_{\text{dyn}} = \sqrt{\frac{r^3}{GM_{\text{BH}}}} \sim 1-1500 \text{ d}$$

$$\ast \quad t_{\text{therm}} = \frac{t_{\text{dyn}}}{\alpha} \sim 1 \text{ d} - 5 \text{ yr}$$

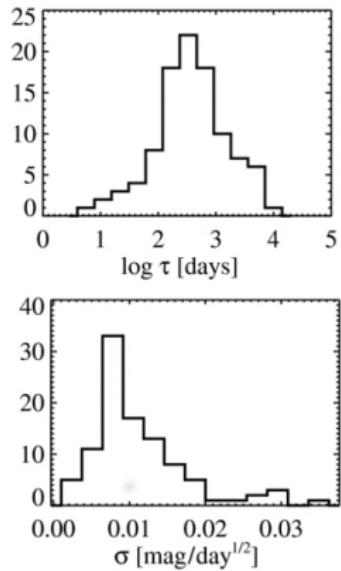
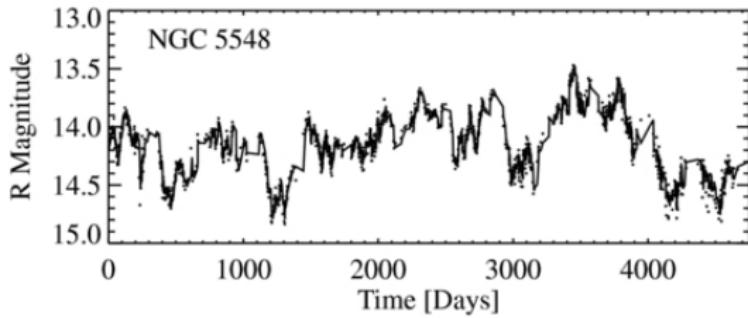
$$\ast \quad t_{\text{visc}} = \frac{t_{\text{dyn}}}{\alpha(H/r)^2} \sim 1-10 \text{ yr}$$

Search for timescales in Power Spectral Density (PSD)



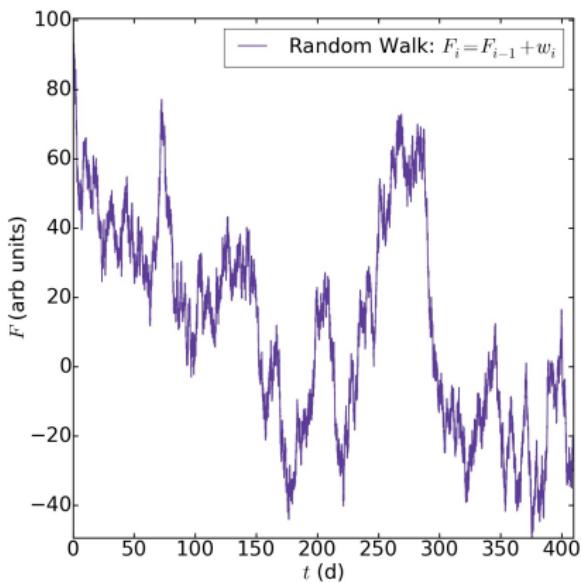
Belloni & Stella (2014)

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



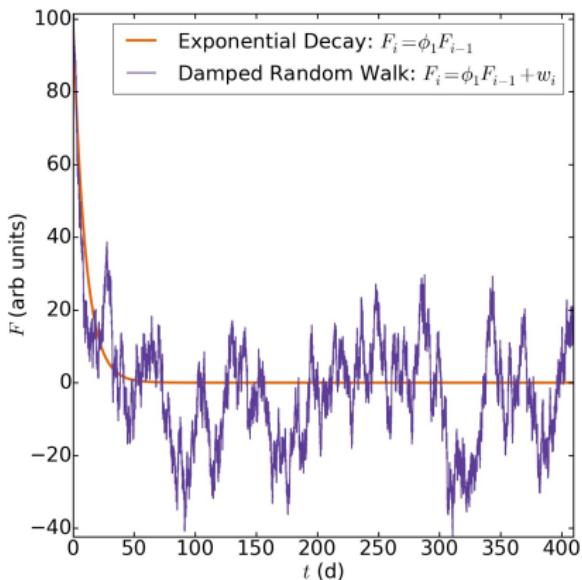
- * Dynamical or thermal processes responsible for variability
- * $\tau \propto M_{\text{BH}} \& L_{\text{AGN}}$ but $\sigma \propto 1/M_{\text{BH}} \& 1/L_{\text{AGN}}$

Random Walks



- * Accretion disk: MHD ‘Hot-spots’
- * Random ‘disturbances’
 - * $w_i \sim \mathcal{N}(0, \sigma^2)$
- * $F_{i+1} = F_i + w_i$
- * Not stationary - flux ‘walks away’

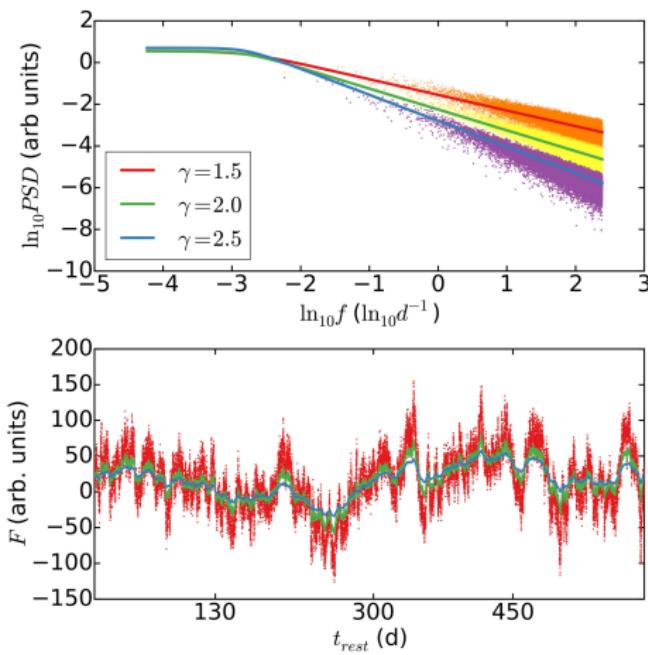
The Damped Random Walk



$\tau = 1$ d.

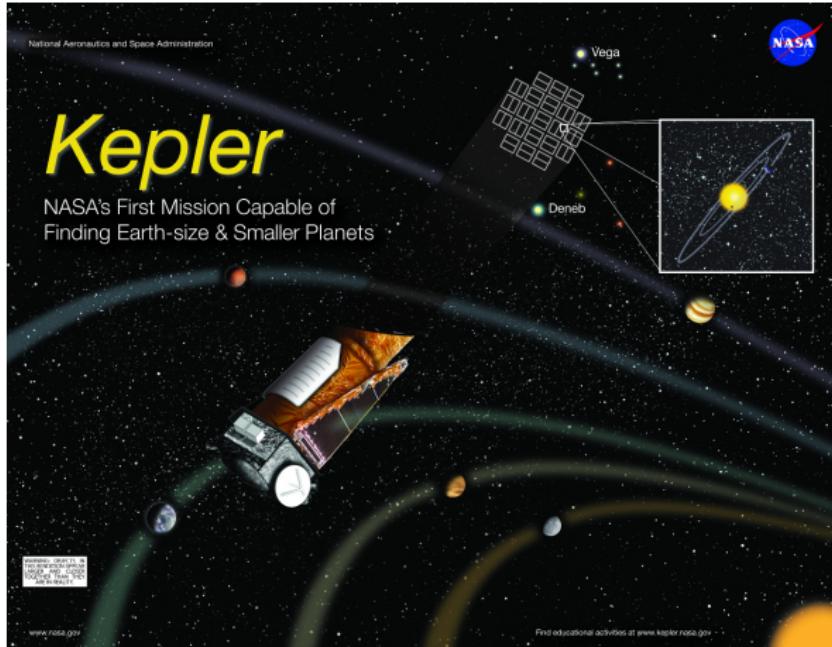
- * Exponential decay
 - * $F_i = \phi_1 F_{i-1}$
 - * $\phi = e^{-\frac{\delta t}{\tau}} < 1$
 - * Decays to asymptotic flux level
- * Damped Random Walk
 - * $F_i = \phi_1 F_{i-1} + w_i$
 - * ‘Walks around’ exponential decay
- * Exponential decay driven by Gaussian noise
- * 1st-Order Linear Stochastic-DE

PSD of the Damped Random Walk

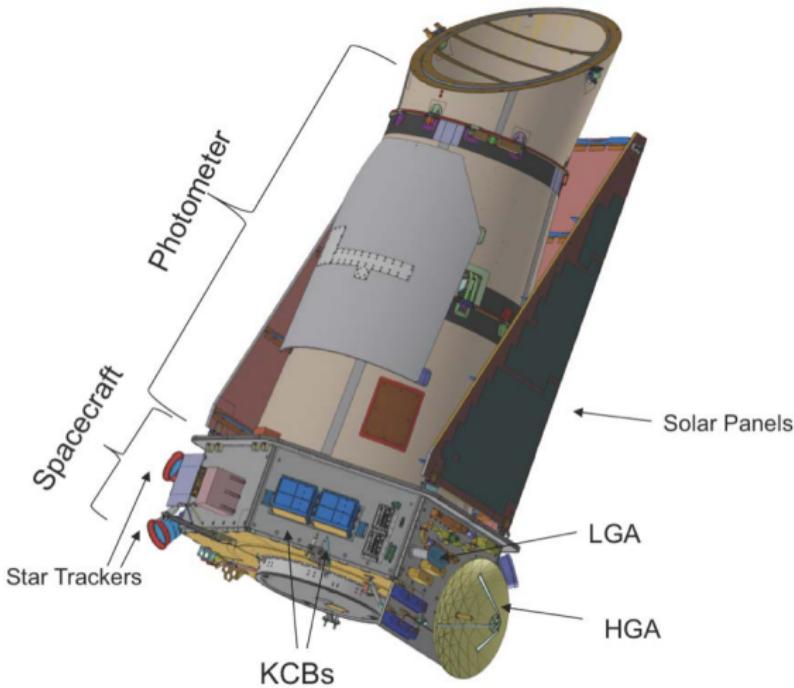


- * PSD $\propto \frac{1}{f^2}$ on short timescales
- * PSD $\propto \frac{1}{f^b} \Rightarrow \sigma_{\alpha-fluc} \propto r^b$
(Lyubarskii 1997)
- * DRW: b is fixed - is this true?
- * Generalize: PSD $\propto \frac{1}{f^\gamma}$ (McHardy et al. 2004)
- * Test with data!

Serendipitous AGN science with Kepler

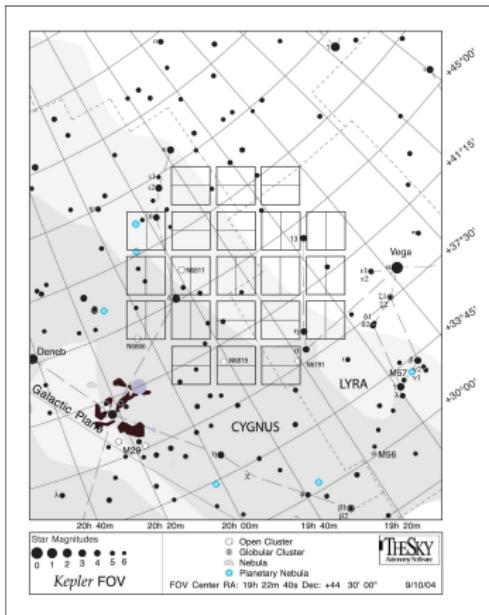


Kepler Instrument Design



- * Schmidt camera
- * 0.95 m clear aperture
- * Fast f/1.473 optics
- * Plate scale
3.98 arcsec/pixel
- * PSF: 95-percent EED
 ~ 6.4 pixel
- * Photometric Precision: 35 ppm (mag 12 star)

What can we learn from Kepler?

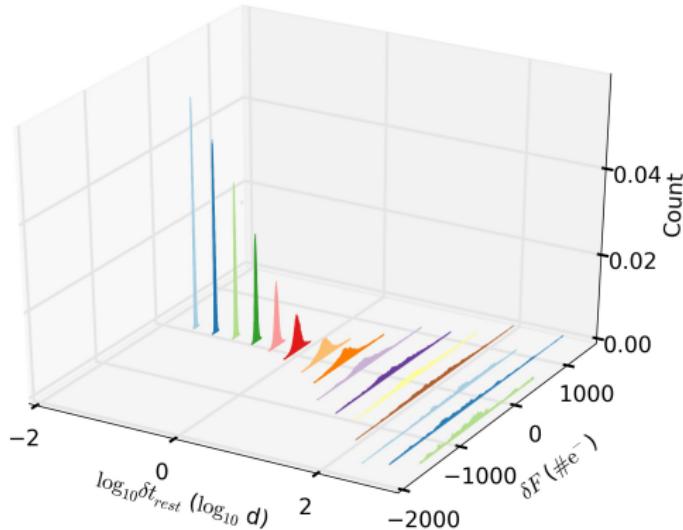


- ✿ Very precise: $S/N \sim 10^5$
 - ✿ Long baseline: $T = 3.5$ yr
 - ✿ Rapid sampling: $\delta t_{\text{obs}} = 29.4$ min
 - ✿ 110 deg 2 FOV
 - ✿ ~ 80 AGN

(Mushotzky et al. 2011; Edelson & Malkan 2012; Carini & Ryle 2012; Wehrle et al. 2013; Shaya et al. 2015)

Van Cleve & Caldwell (2009)

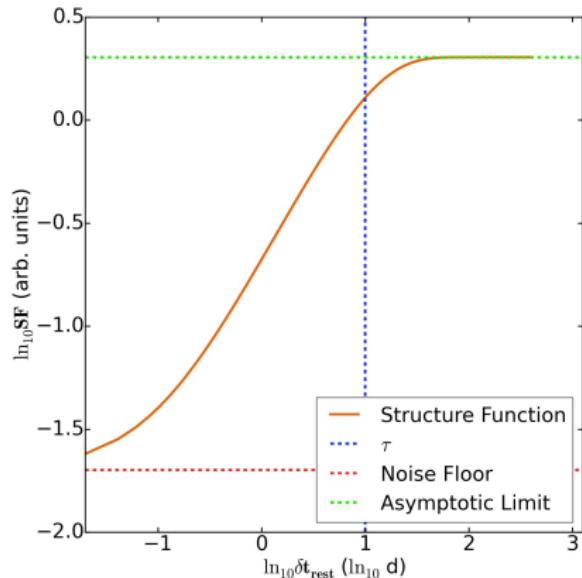
Structure functions



- * 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

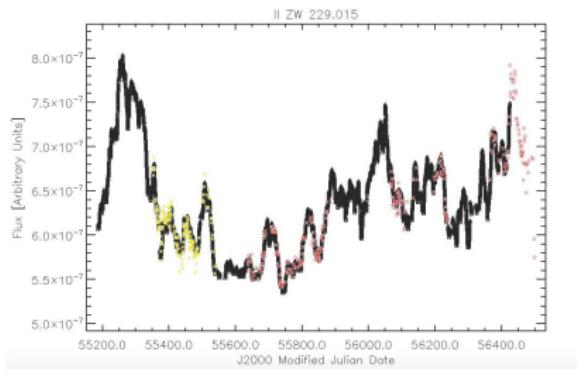


- * Small δt : ‘Noise floor’
- * Slope $\sim \gamma$
- * Big δt : Turnover i.e. damping
- * Spurious breaks & features

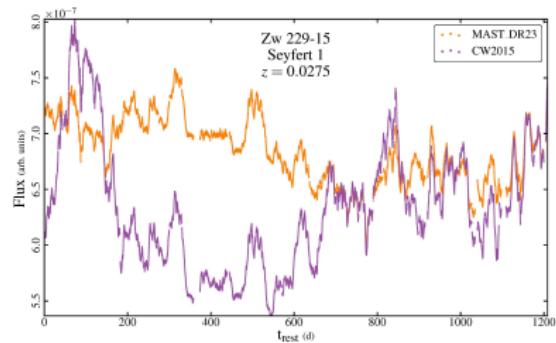
(Emmanoulopoulos et al. 2010)

Features in the Structure Function

Are the MAST light curves accurate?



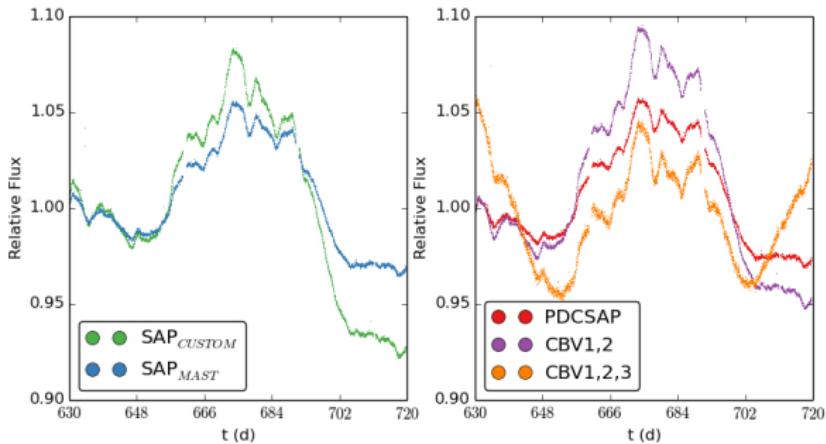
Williams & Carini (2015)



* Spacecraft induced systematics

* Incorrect photometric aperture

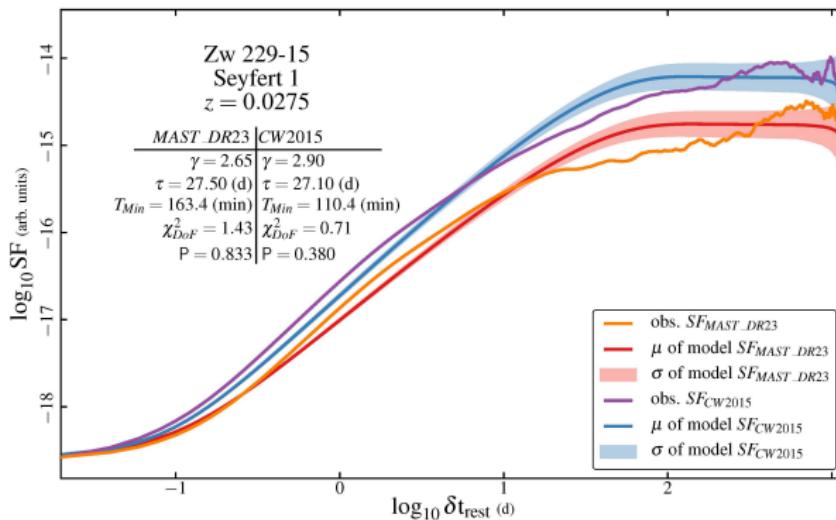
Photometric aperture definition & de-trending



Jackeline Moreno

- * Flux re-extraction possible
- * De-trending can be re-done

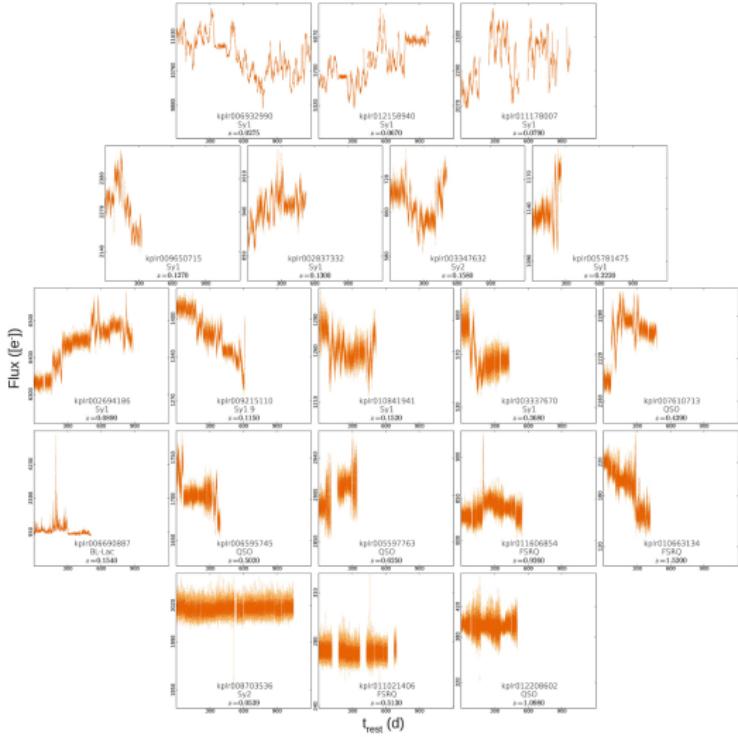
Effect on Structure Functions Analysis



- Instrumentation not responsible for non-DRW behavior
- Ground-based supplementary data crucial

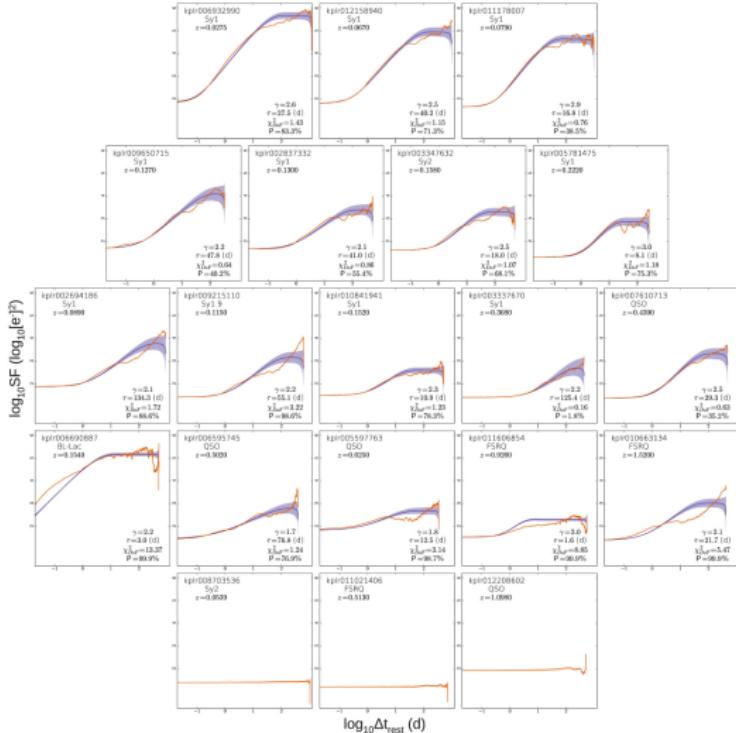
Kasliwal et al. (2015b)

Full AGN sample



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

Structure function fits

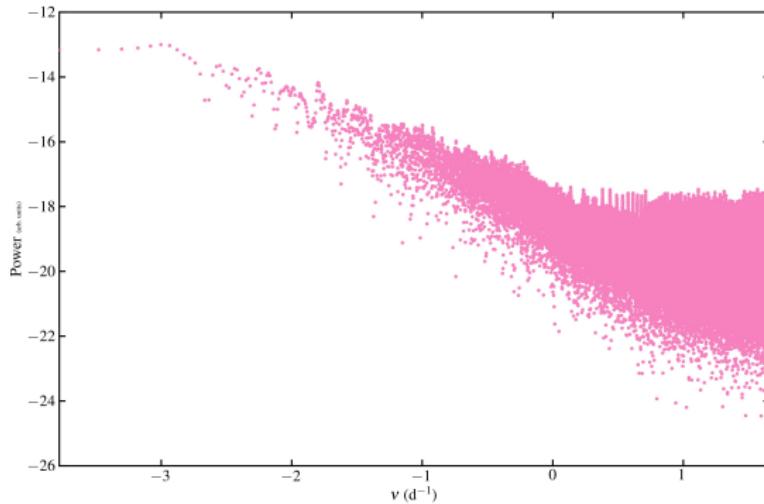


- * Not all AGN \sim DRW
- * PSD model too simple
- * Variability onsets over ~ 1 hr to ~ 1 d

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

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

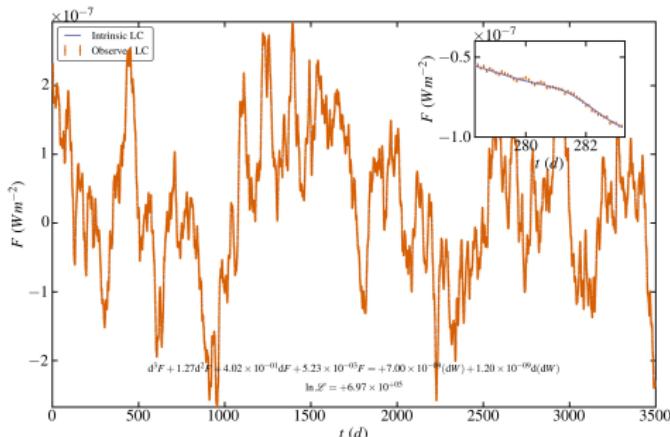
$$d^p x + \alpha_1 d^{p-1} x + \dots + \alpha_{p-1} dx + \alpha_p x = \beta_0(dW) + \dots + \beta_q d^q(dW)$$

- * Uses Itô calculus Brockwell (2014); Davis (2002); Kelly et al. (2014)

- * LHS comes from linear perturbations of non-linear system

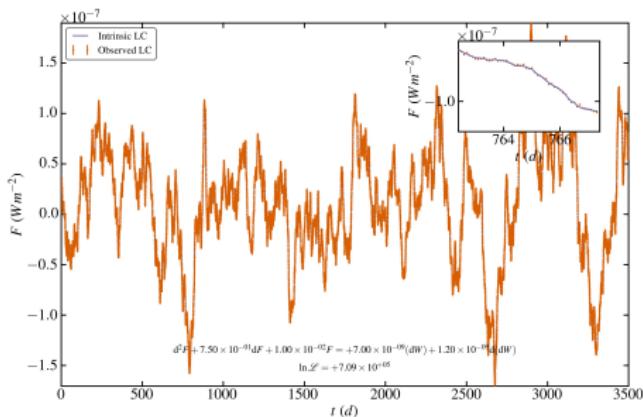
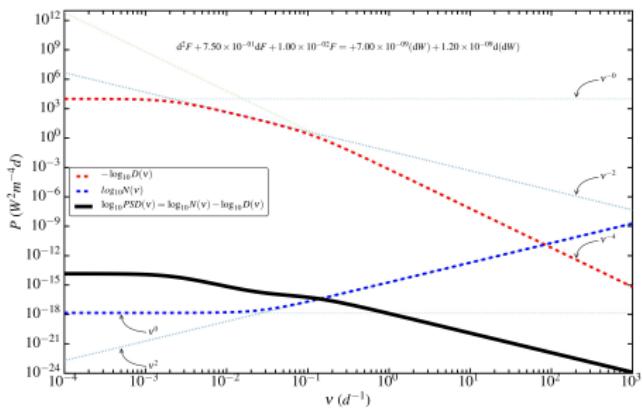
* C-ARMA $\xrightarrow{\text{sample}}$ ARMA

- * PSD is a ratio of even polynomials in frequency



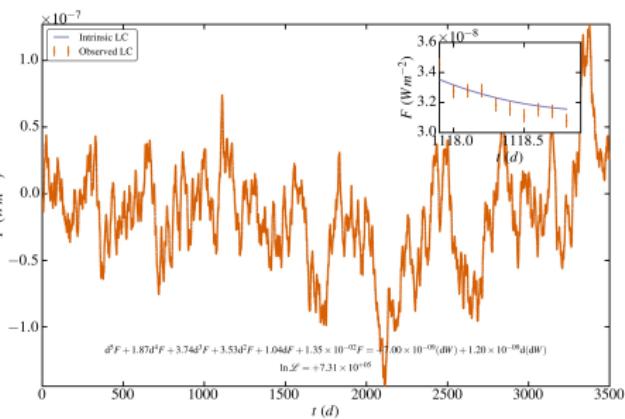
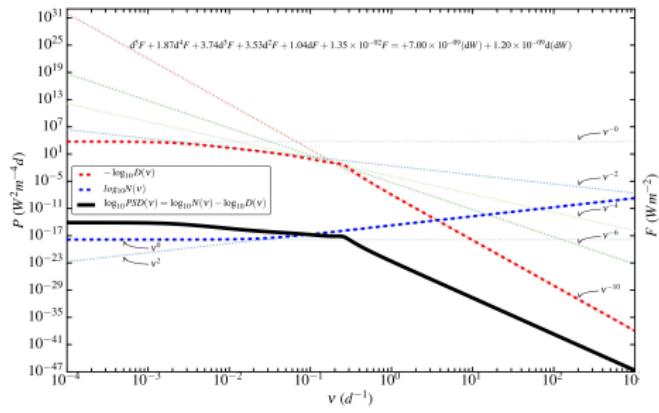
Power Spectral Density

Eg. C-ARMA(2,1)



Power Spectral Density

Eg. C-ARMA(5,1)



State Space Representation

State equation:

$$\mathrm{d}\boldsymbol{x}(t) = \mathbf{A}\boldsymbol{x} + \mathbf{B}\mathrm{d}W \xrightarrow{\text{integrate \& sample}} \boldsymbol{x}_{k+1} = \mathbf{F}\boldsymbol{x}_k + \boldsymbol{w}_k$$

with

$$\mathbf{F} = e^{\mathbf{A}\delta t}; \boldsymbol{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}); \mathbf{Q} = \int_0^{\delta t} e^{\mathbf{A}\xi} \mathbf{B} \mathbf{B}^\top e^{\mathbf{A}^\top \xi} \mathrm{d}\xi$$

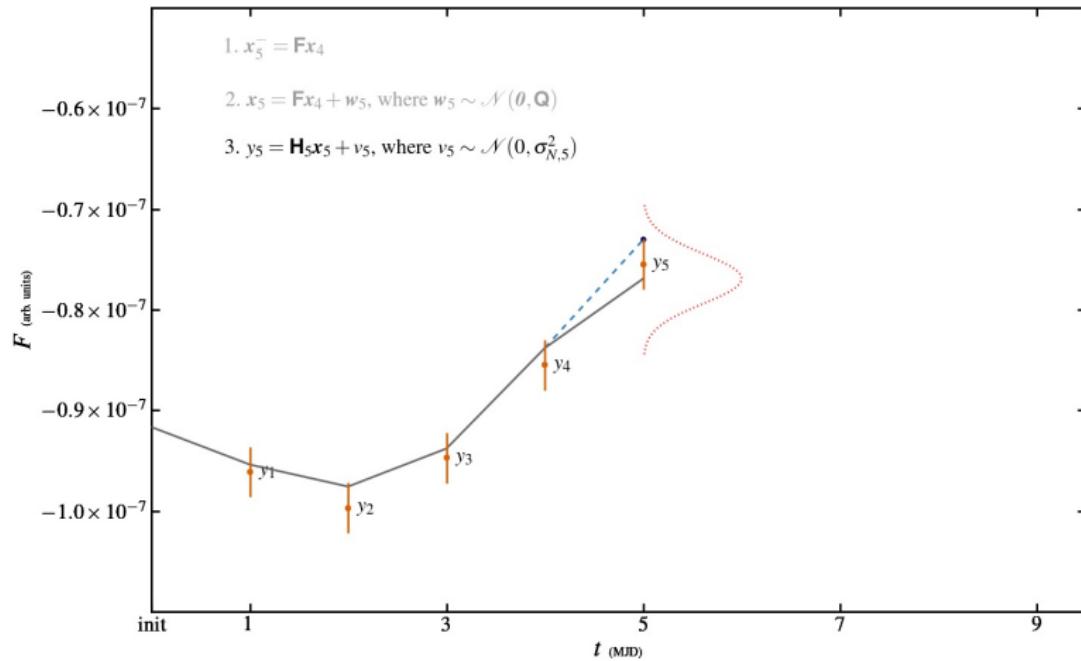
Observation equation:

$$\boldsymbol{x}_{k,\text{obs}} = \mathbf{H}_k \boldsymbol{x}_k + \boldsymbol{v}_k$$

$$\boldsymbol{v}_k \sim \mathcal{N}(0, \sigma_{N,k}^2)$$

- * **F**: Transition matrix & **Q**: Disturbance matrix
- * **H**: Observation matrix
- * Observation noise in-built via \boldsymbol{v}_k !
- * Well studied by engineers (Control systems) and economists

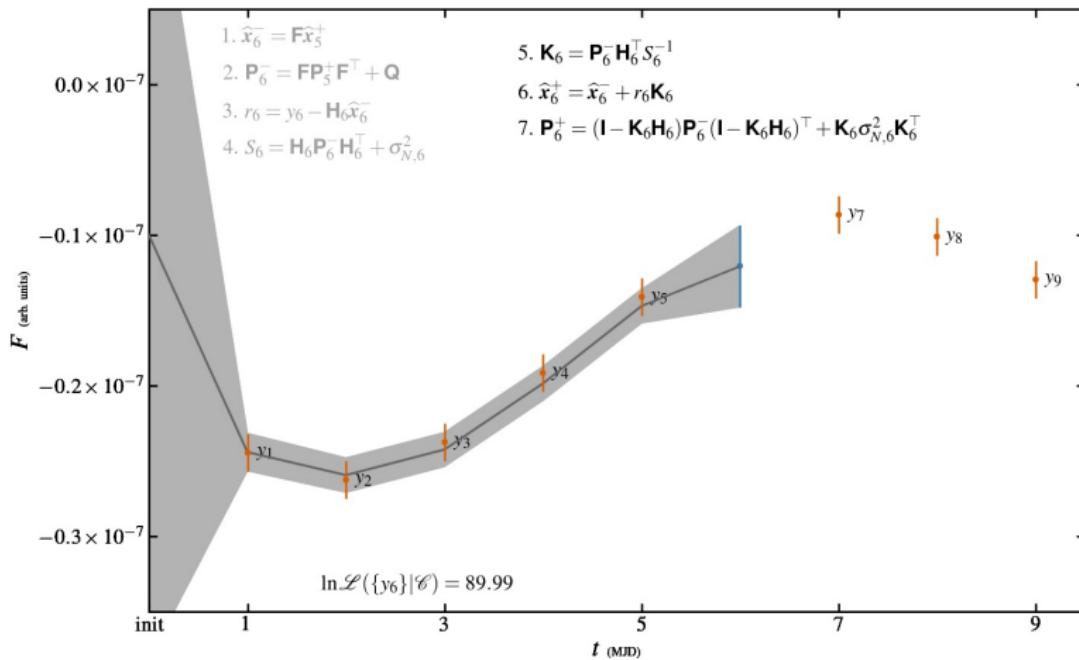
Evolution & observation of light curve state



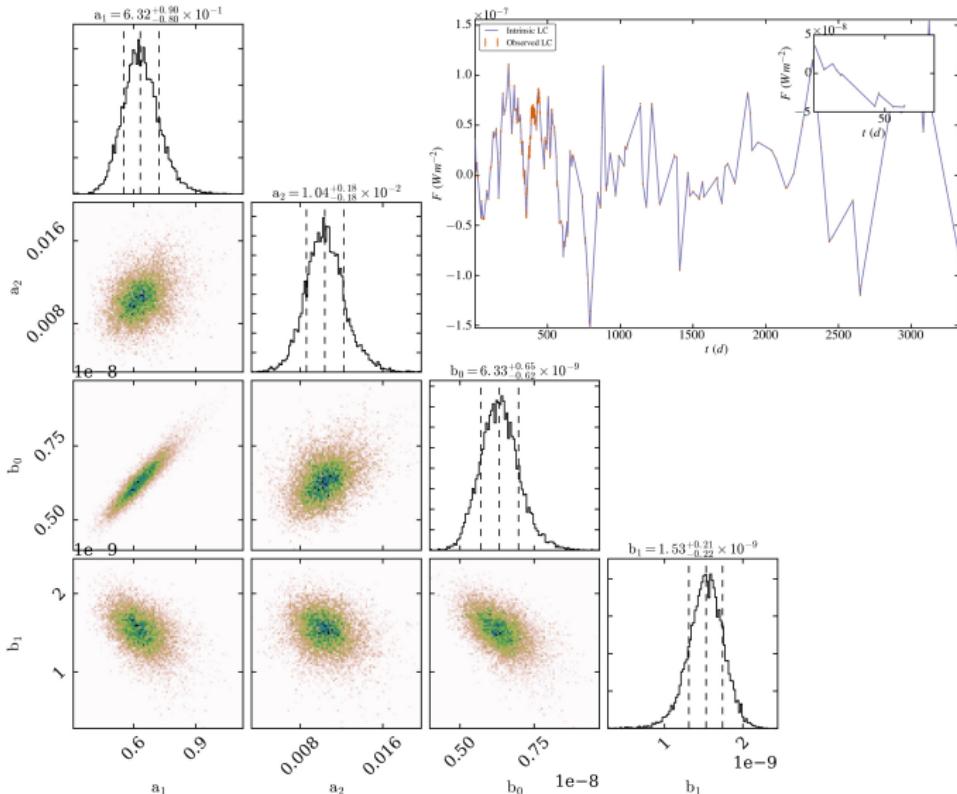
The Kalman Filter

- * Linear quadratic estimator of x .
- * Kalman filter + Linear-quadratic regulator (LQR) = Linear-quadratic Gaussian control: First used to guide Apollo.
- * Predictor-Corrector algorithm.
- * **Predict:** Where should the system go?
- * **Compute:** Compute the log-likelihood of the data given the prediction.
- * **Correct:** Update the system based on the prediction & observation.

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

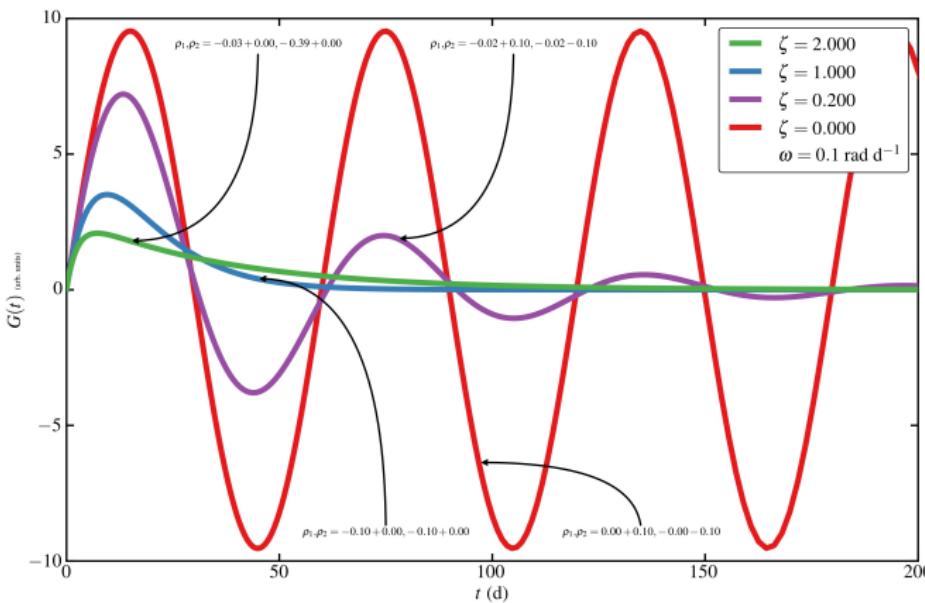


Confidence Interval Estimates

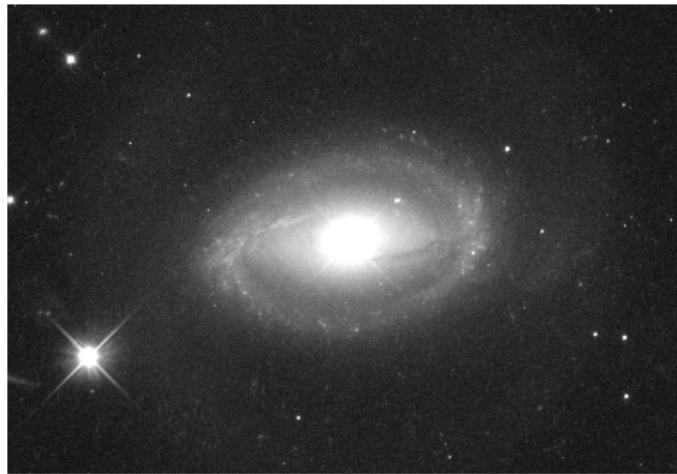


How to Interpret?: Green's Function of LHS (eg. C-ARMA(2,1)...)

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



Zw 229-15 (kplr006932990)



HST Image

* Sy 1 in Lyra

* $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d

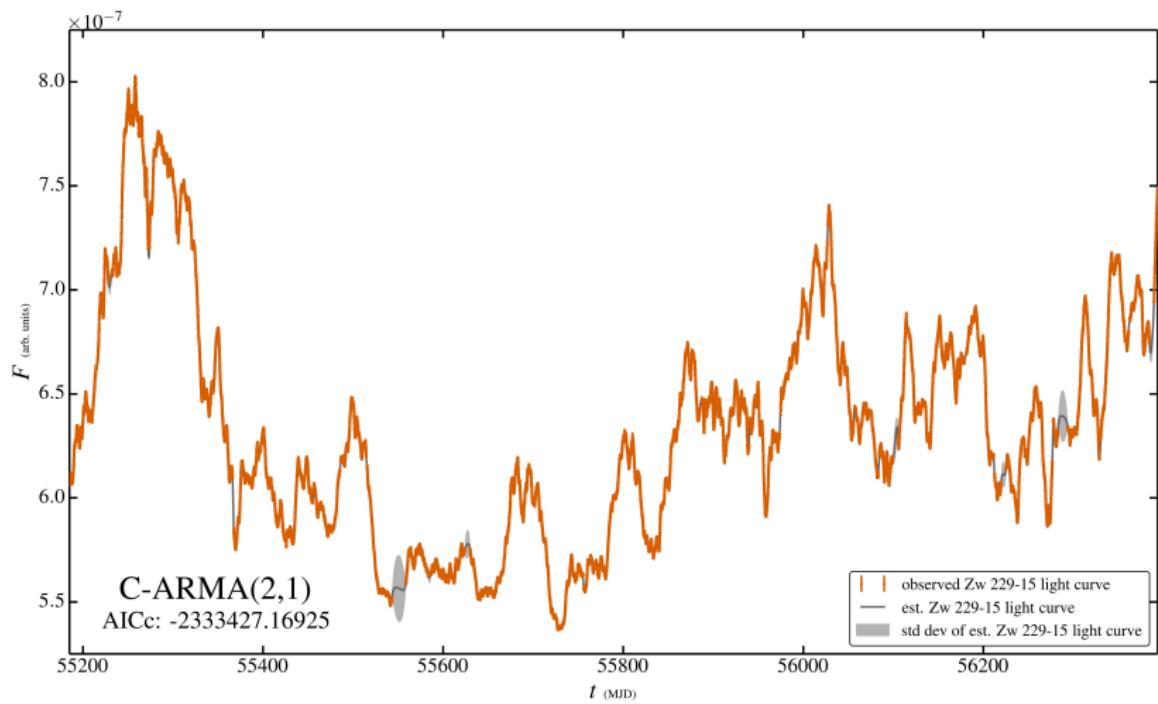
* mag 15.4

* $M_{BH} = 1.00^{+0.19}_{-0.24} \times 10^7 M_\odot$

(Barth et al. 2011)

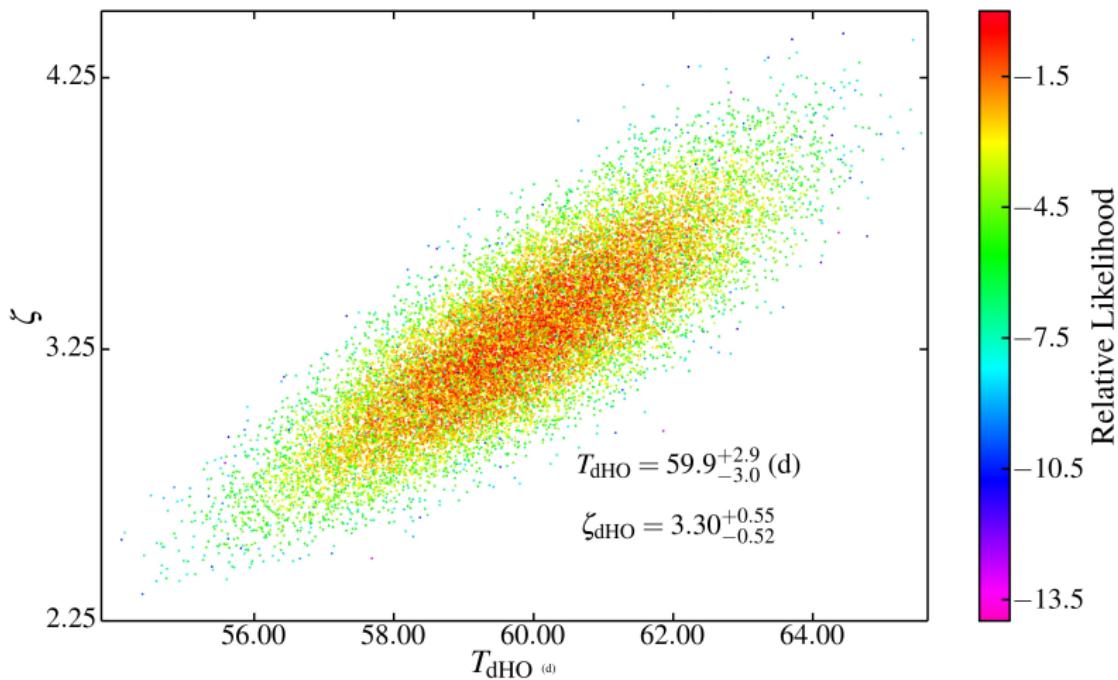
C-ARMA(2,1) model of Zw 229-15

Smoothed light curve

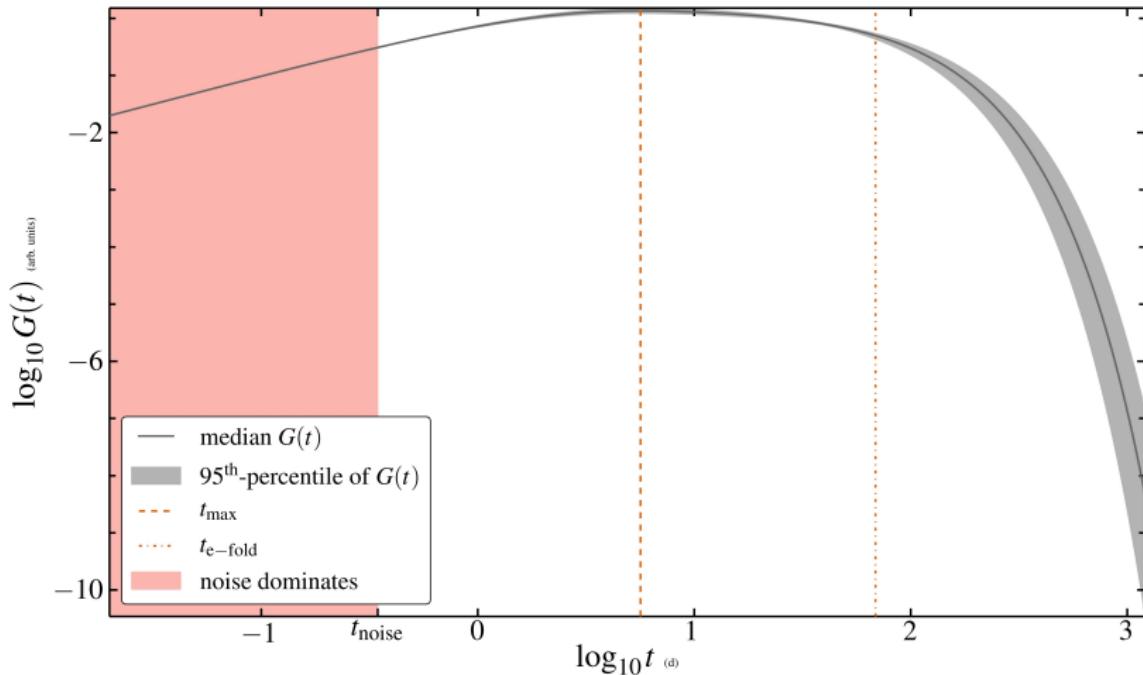


C-ARMA(2,1) model of Zw 229-15

Damped Harmonic Oscillator

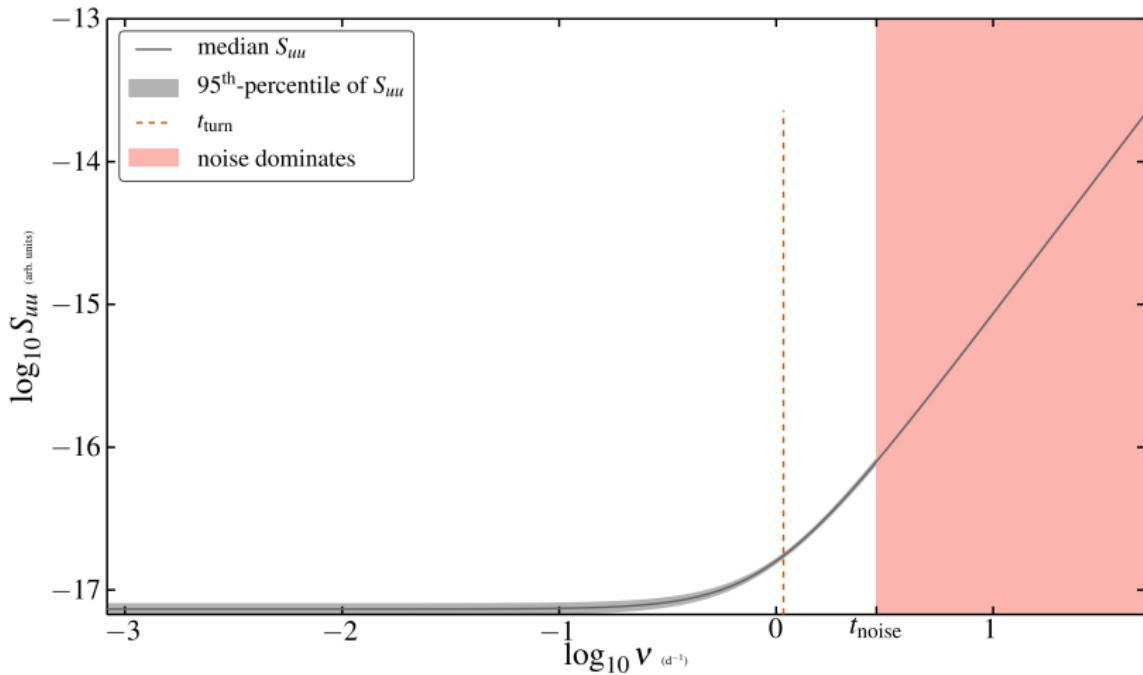


C-ARMA(2,1) model of Zw 229-15 Green's Function



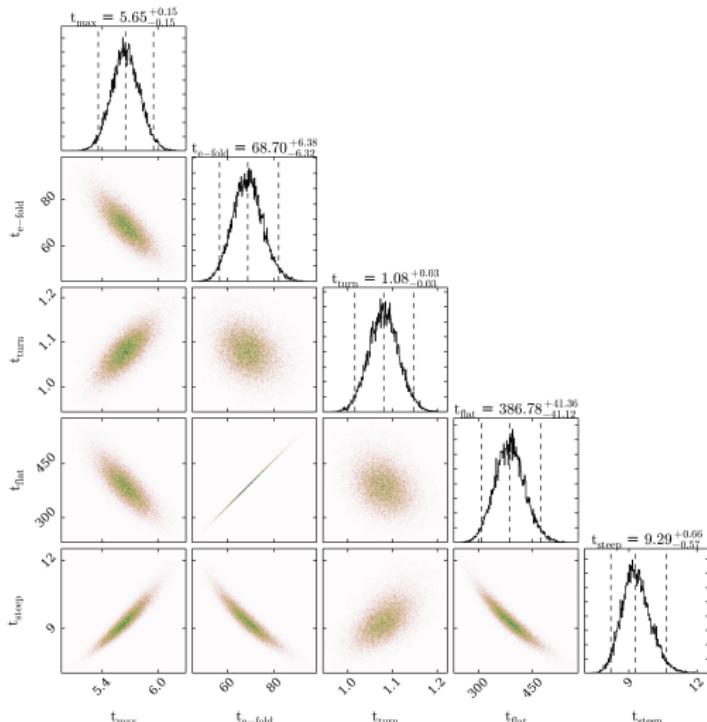
C-ARMA(2,1) model of Zw 229-15

Disturbance PSD



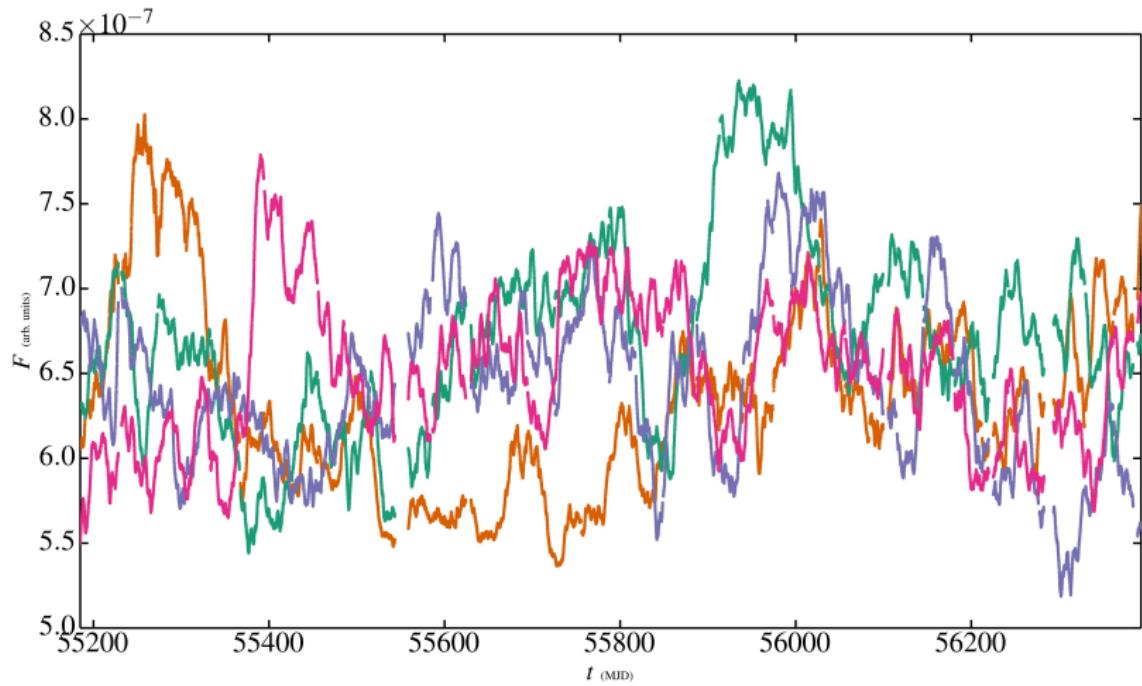
C-ARMA(2,1) model of Zw 229-15

Timescales



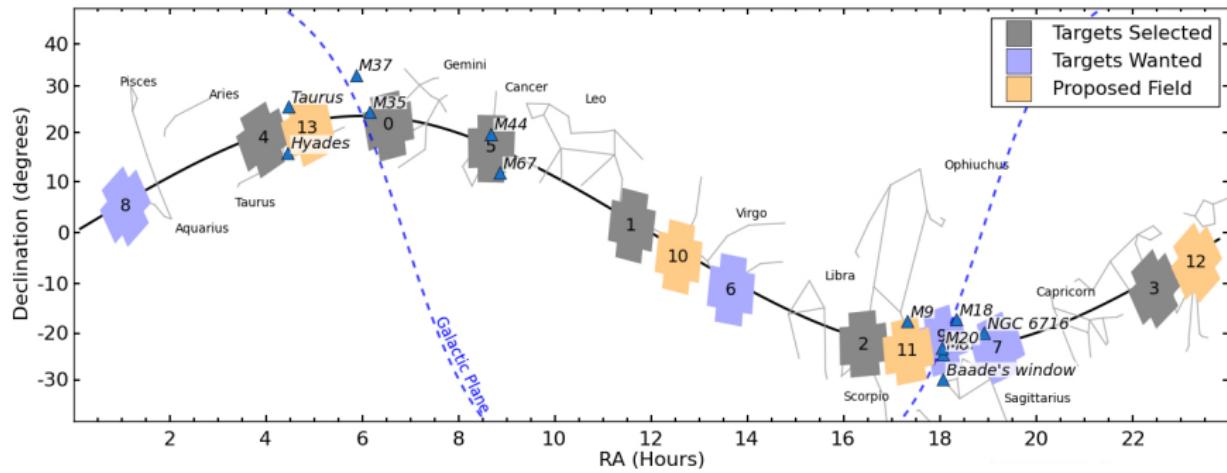
C-ARMA(2,1) model of Zw 229-15

Which is the real light curve?



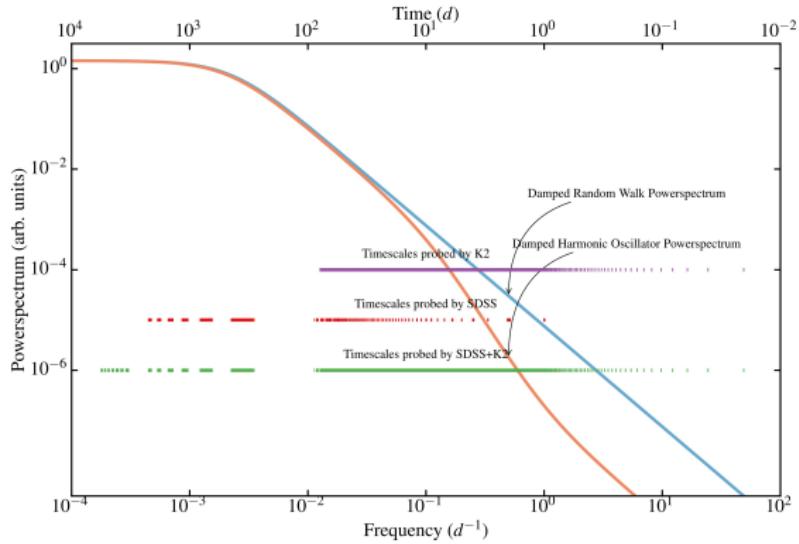
Work in Progress

K2 campaigns



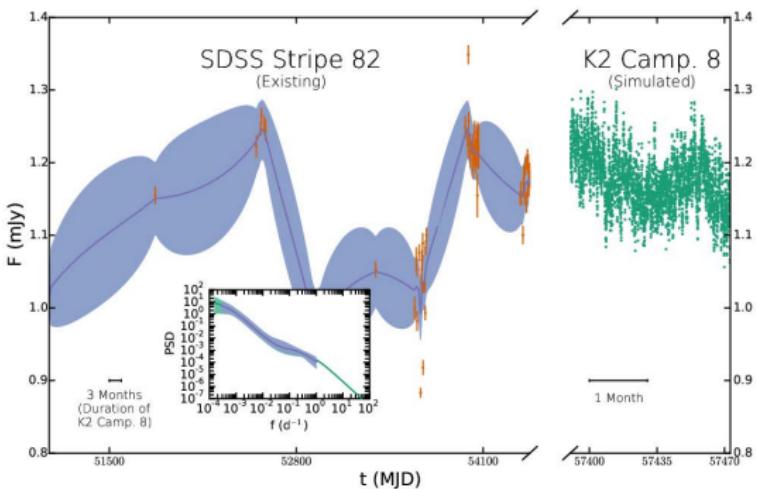
Work in Progress

Power of SDSS+K2



Work in Progress

K2 observations of Stripe 82 QSOs

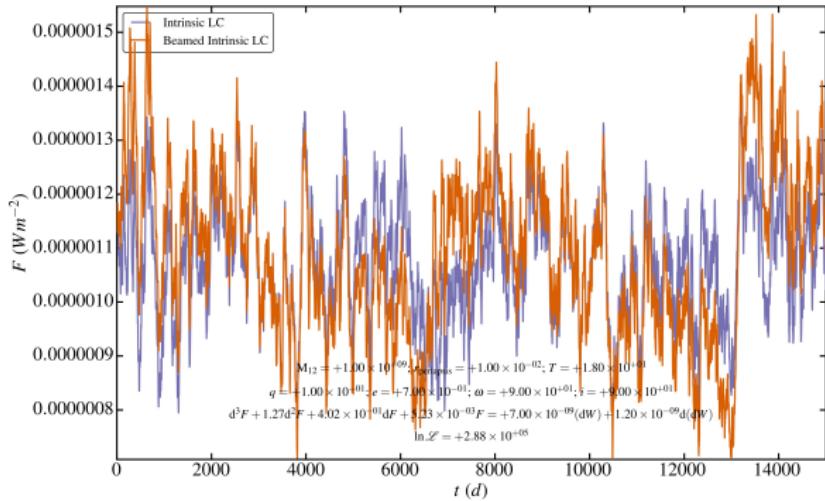


- * Add HSC data from Stripe 82.
- * Is it concurrent with K2 Campaign 12?
- * Can it be used to help calibrate Campaign 12?

Work in Progress

Beaming from binary SMBHs

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



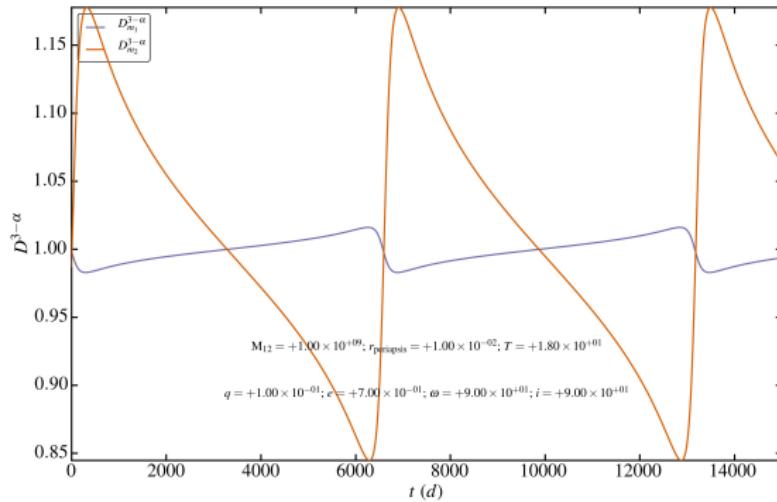
- * $M_{12} = 10^9 M_\odot$
- * $r_{periapsis} = 0.01 \text{ pc}$

- * $q = 0.1$
- * $e = 0.7$

Work in Progress

Beaming from binary SMBHs

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



- * $M_{12} = 10^9 M_\odot$
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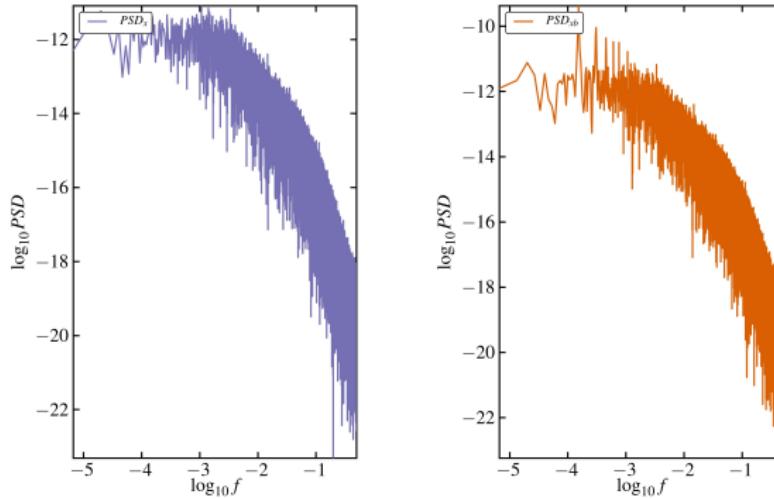
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Work in Progress

Beaming from binary SMBHs

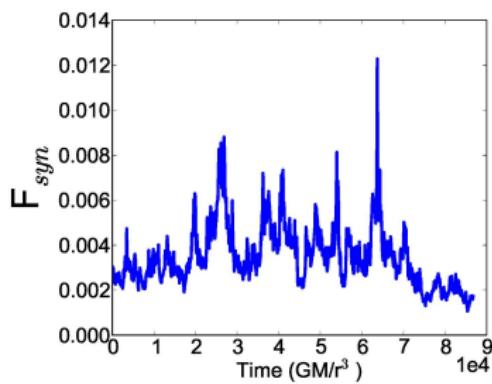
Inspired by D'Orazio, Haiman, & Schiminovich (2015)



- * 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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