Probing Accretion Processes Through Variability

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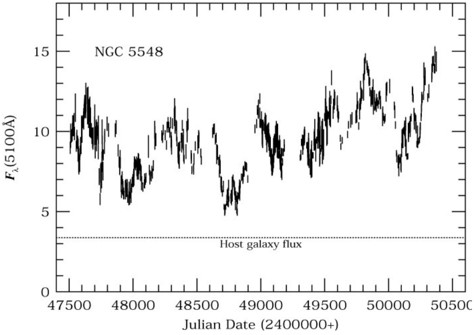
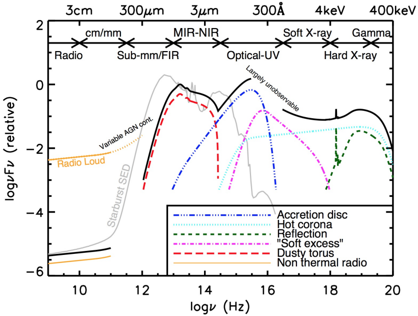
AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



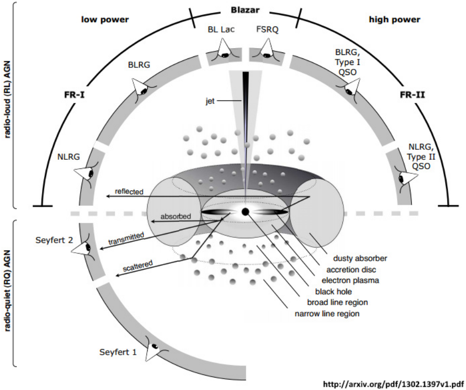
(Peterson et al. 1999)

- $\sim 90\ \%$ 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

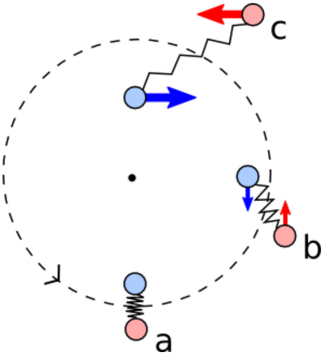


Chris Harrison

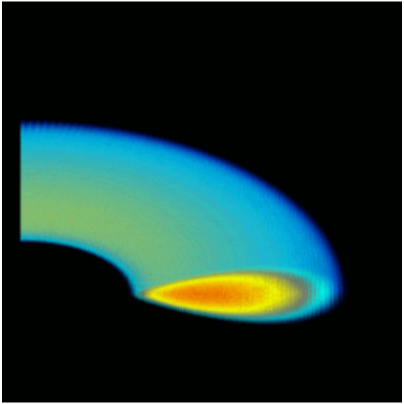


http://arxiv.org/pdf/1302.1397v1.pdf

Accretion Mechanism: The MRI

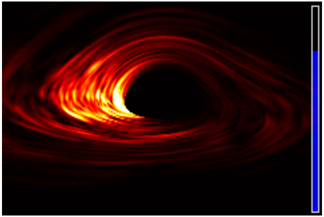


Harvard Astronomy Dept



Hawley & Krolik (2002)

Sources of variability

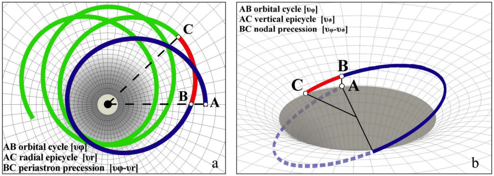


Armitage & Reynolds (2003)

Magnetic Reynolds number: $R_{\mathrm{magnetic}} = UL/\eta$ ~ advection vs diffusion.
Magnetic diffusivity $\eta = \frac{m_e \nu_{\mathrm{collision}}}{\mu_0 n_e e^2}$.

- 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)

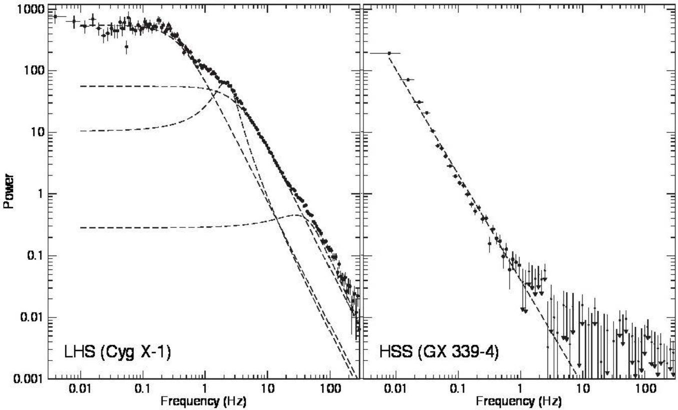
Timescales that *may* be found in AGN



Belloni & Stella (2014)

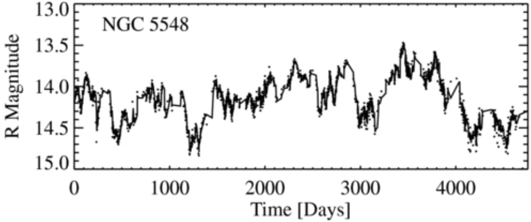
- $t_{\rm dyn} = \sqrt{\frac{r^3}{GM_{\rm BH}}} \sim$ 1-1500 d
- $t_{\rm therm} = \frac{t_{\rm dyn}}{\alpha} \sim$ 1 d - 5 yr
- $t_{\rm visc} = \frac{t_{\rm dyn}}{\alpha (H/r)^2} \sim$ 1-10 yr

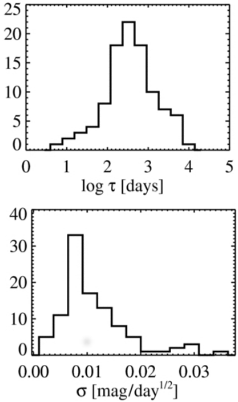
Search for timescales in Power Spectral Density (PSD)



Belloni & Stella (2014)

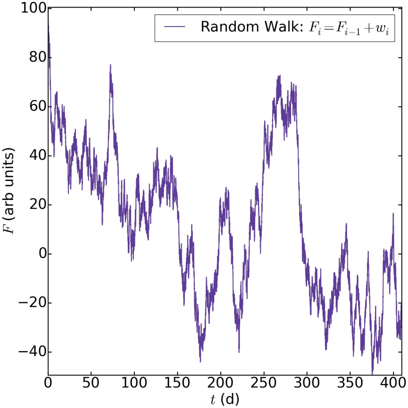
Kelly et al. (2009): Model variability as DRW





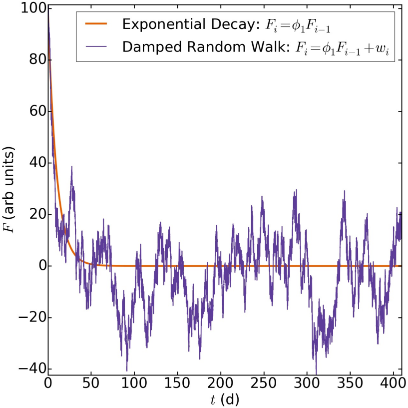
- Dynamical or thermal processes responsible for variability
- $\tau \propto \mathrm{M_{BH}}$ & L_{AGN} but $\sigma \propto 1/\mathrm{M_{BH}}$ & $1/L_{\mathrm{AGN}}$

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'

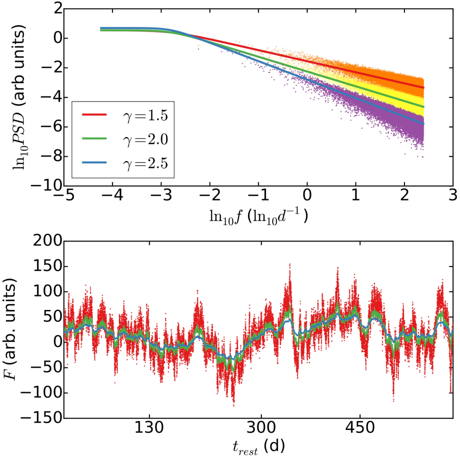
The Damped Random Walk



$\tau = 1$ d.

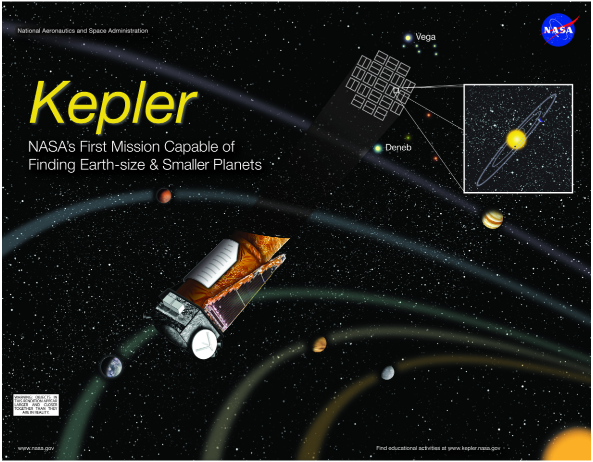
- Exponential decay
  - $F_i = \phi_1 F_{i-1}$
  - $\phi = e^{-\frac{\delta t}{\tau}} < 1$
  - Decays to asymptotic flux level
- Damped Random Walk
  - $F_i = \phi_1 F_{i-1} + w_i$
  - 'Walks around' exponential decay
- Exponential decay driven by Gaussian noise
- 1^{st}-Order Linear Stochastic-DE

PSD of the Damped Random Walk

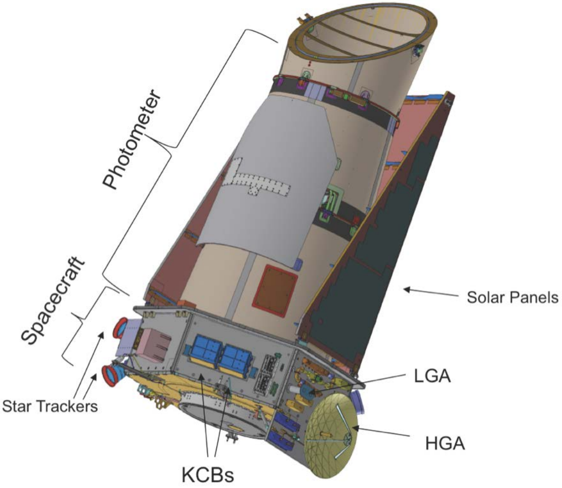


- $PSD \propto \frac{1}{f^2}$ on short timescales
- $PSD \propto \frac{1}{f^b} \Rightarrow \sigma_{\alpha-fluc} \propto r^b$ (Lyubarskii 1997)
- DRW: b is fixed - is this true?
- Generalize: $PSD \propto \frac{1}{f^\gamma}$ (McHardy et al. 2004)
- Test with data!

Serendipitous AGN science with Kepler

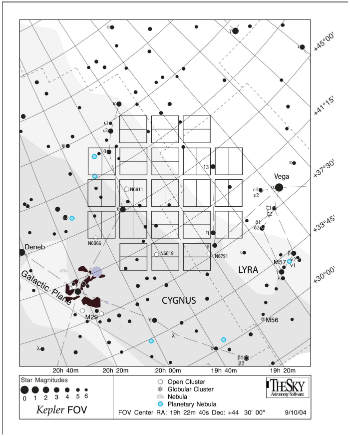


Kepler Instrument Design



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

What can we learn from Kepler?

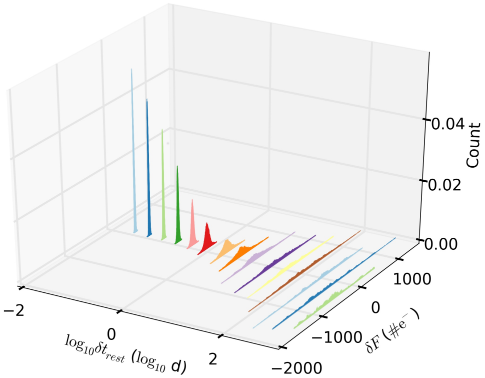


Van Cleve & Caldwell (2009)

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

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

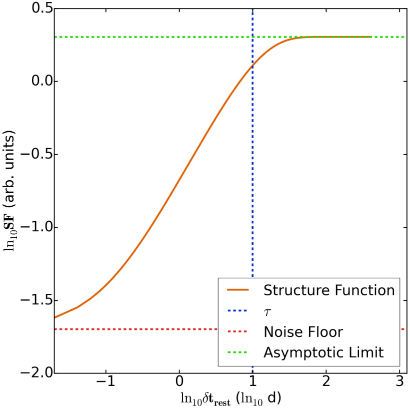
Structure functions



How does variance of δF vary with δt?

- 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...
- $SF(\delta t) = 2ACVF(0) - 2ACVF(\delta t)$

Structure functions

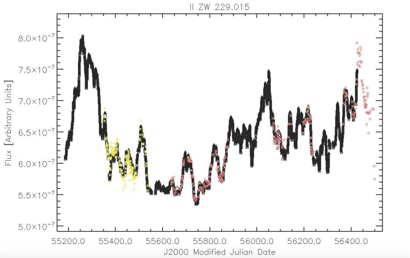


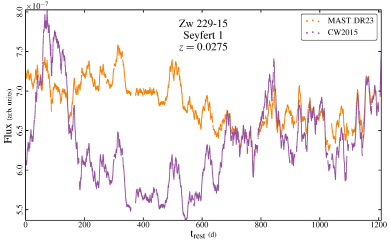
Features in the Structure Function

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

(Emmanoulopoulos et al. 2010)

Are the MAST light curves accurate?



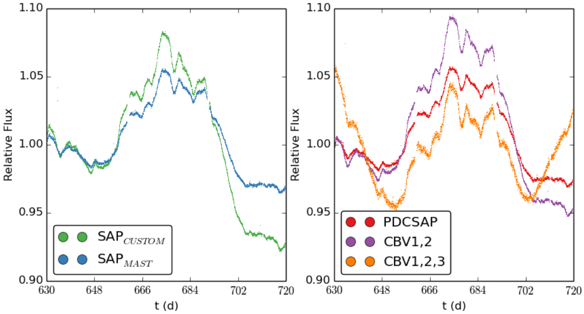


Williams & Carini (2015)

- Incorrect photometric aperture

- Spacecraft induced systematics

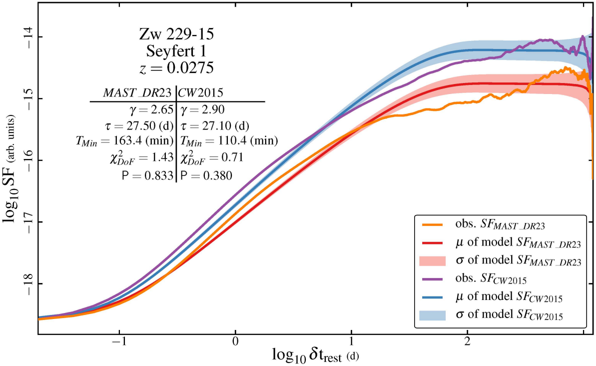
Photometric aperture definition & de-trending



Jackeline Moreno

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

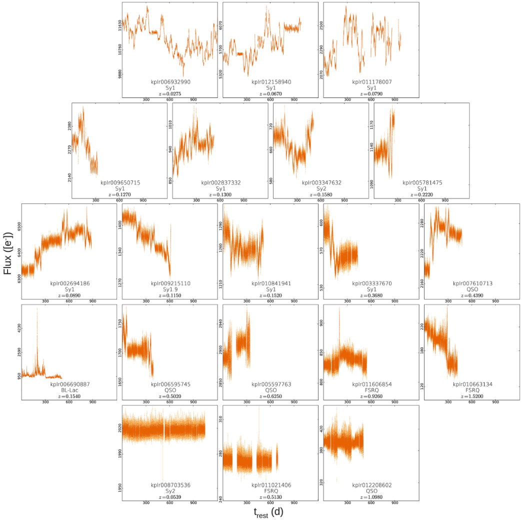
Effect on Structure Functions Analysis



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

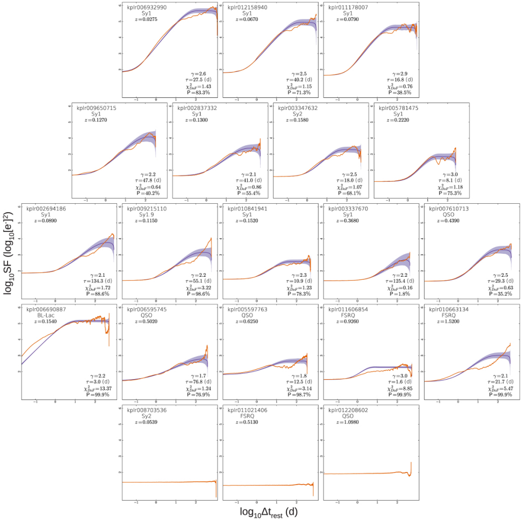
Kasliwal et al. (2015b)

Full AGN sample



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

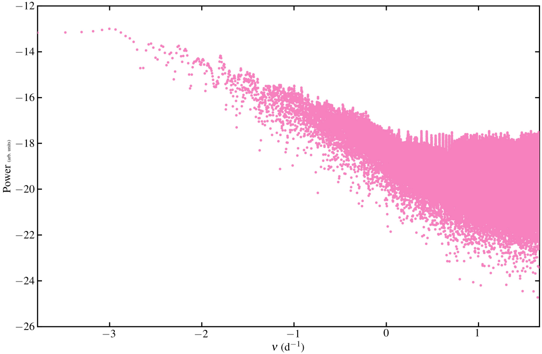
Structure function fits



- Not all AGN ~ 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?

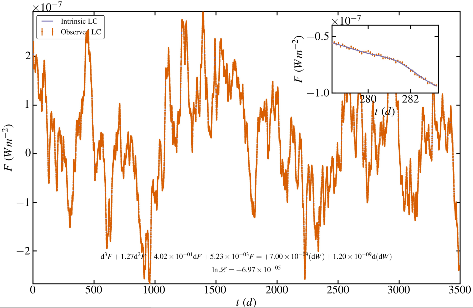


- Stochastic model must be flexible
- Amenable to physical interpretation

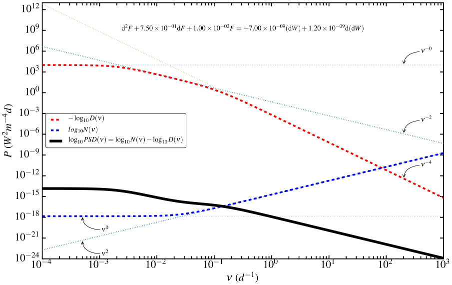
Continuous-time AutoRegressive Moving Average (C-ARMA) Processes

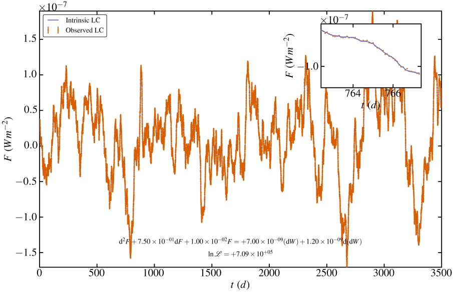
$$\mathrm{d}W \sim \mathcal{N}(0, \mathrm{d}t)$$
$$\mathrm{d}^p x + \alpha_1 \mathrm{d}^{p-1} x + \ldots + \alpha_{p-1} \mathrm{d}x + \alpha_p x = \beta_0(\mathrm{d}W) + \ldots + \beta_q \mathrm{d}^q(\mathrm{d}W)$$

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

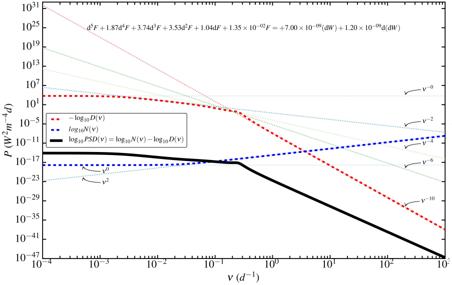


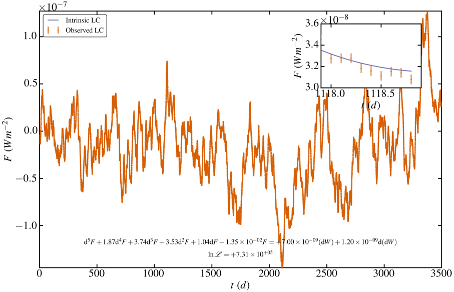
Power Spectral Density
Eg. C-ARMA(2,1)





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





State Space Representation

State equation:

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

with

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

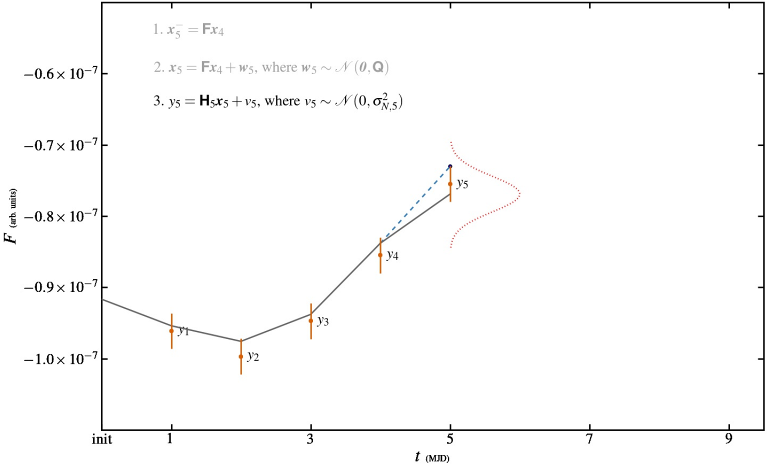
Observation equation:

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

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

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

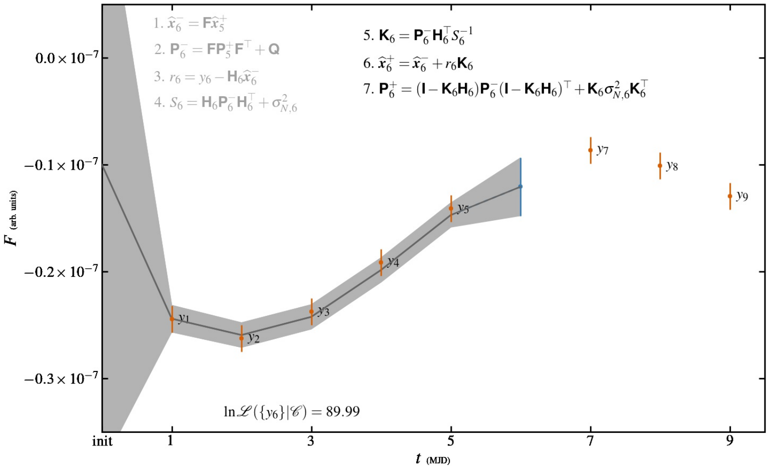
Evolution & observation of light curve state



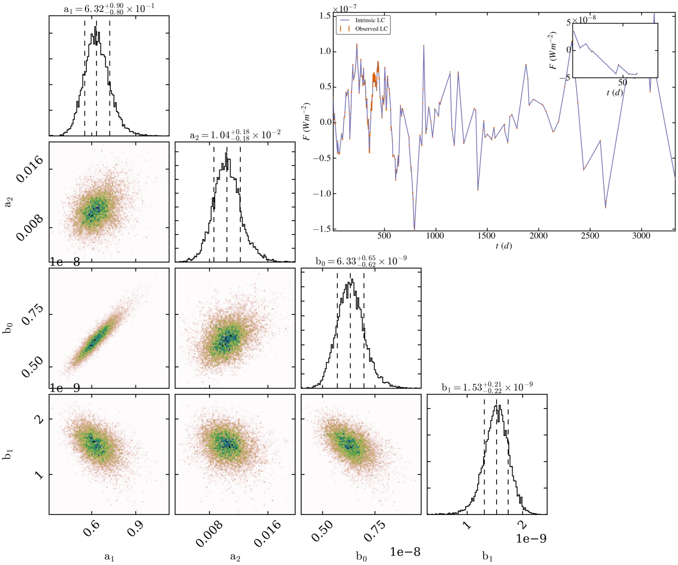
The Kalman Filter

- Linear quadratic estimator of $\boldsymbol{x}$.
- 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

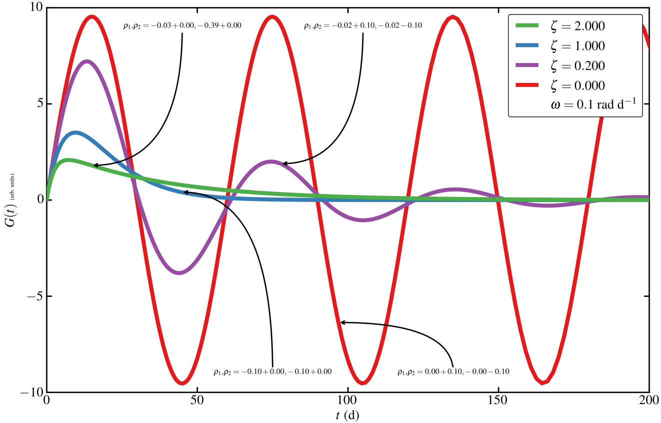


Confidence Interval Estimates



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

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



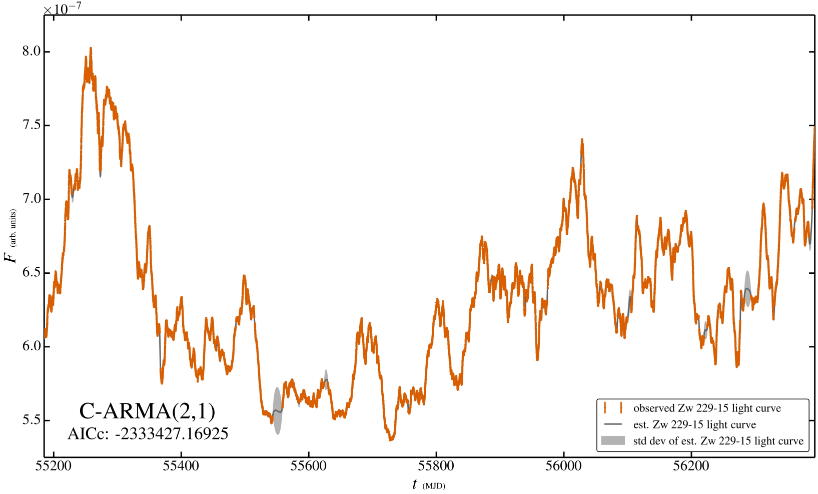
Zw 229-15 (kplr006932990)

HST Image

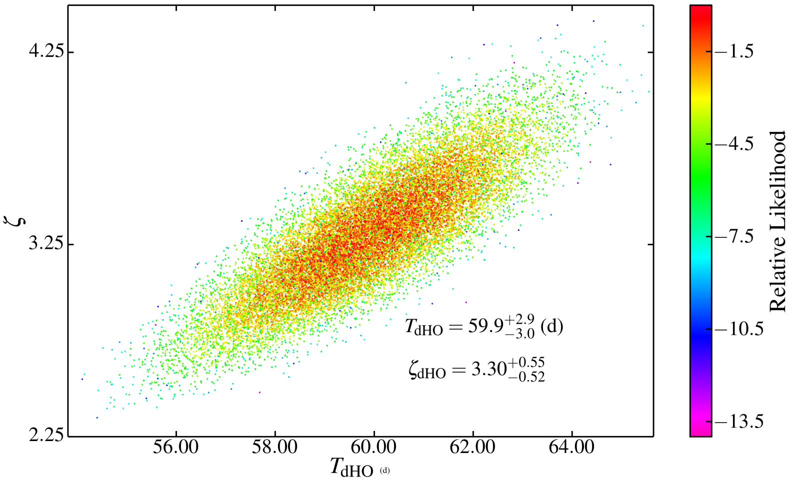
- Sy 1 in Lyra
- $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d
- mag 15.4
- $\mathrm{M_{BH}} = 1.00^{+0.19}_{-0.24} \times 10^7 \mathrm{M}_\odot$

(Barth et al. 2011)

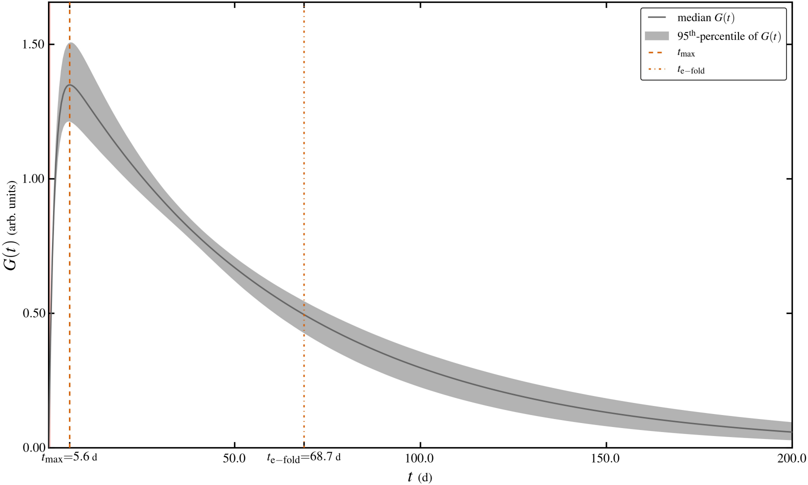
C-ARMA(2,1) model of Zw 229-15 Smoothed light curve



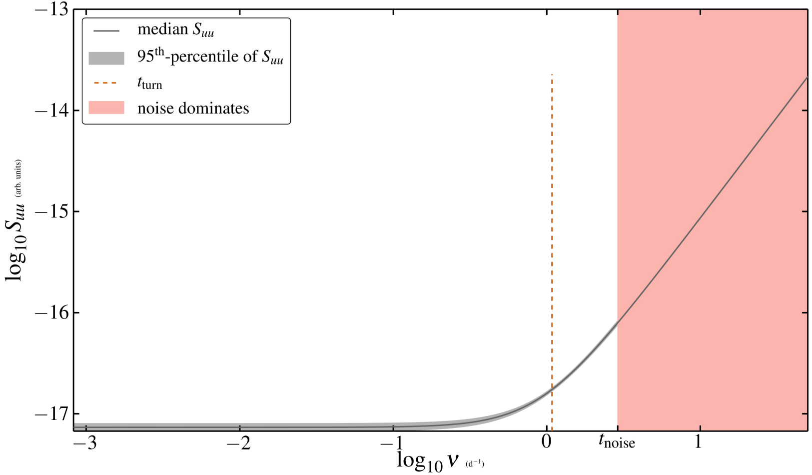
C-ARMA(2,1) model of Zw 229-15
Damped Harmonic Oscillator



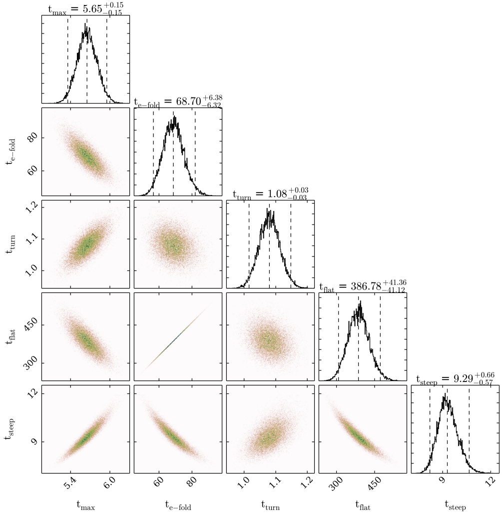
C-ARMA(2,1) model of Zw 229-15 Green's Function



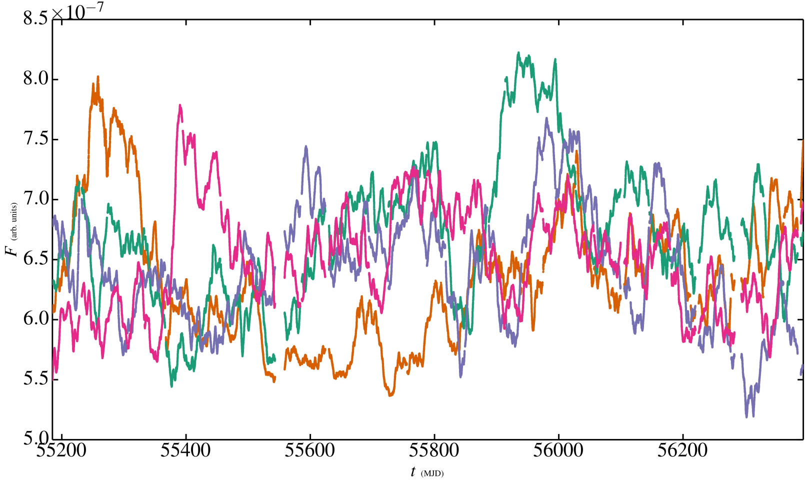
C-ARMA(2,1) model of Zw 229-15 Disturbance PSD



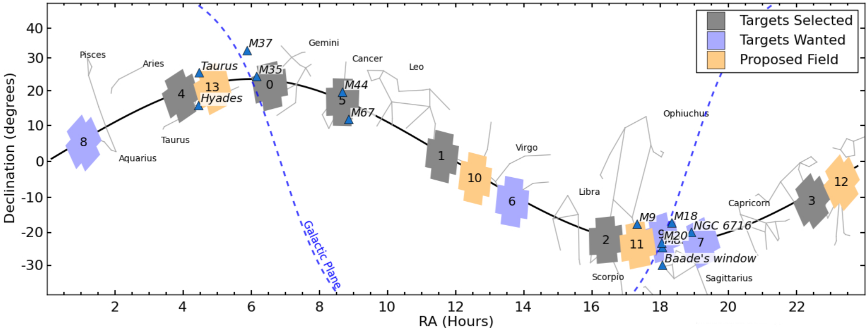
C-ARMA(2,1) model of Zw 229-15 Timescales



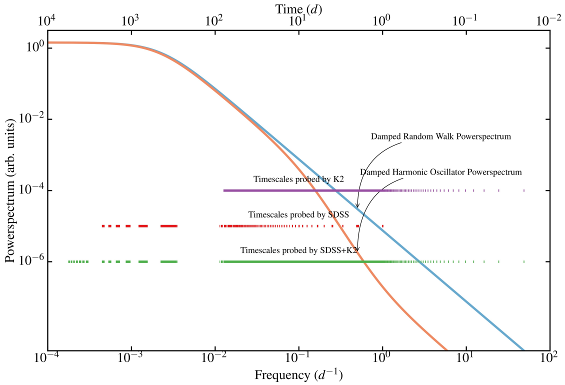
C-ARMA(2,1) model of Zw 229-15
Which is the real light curve?



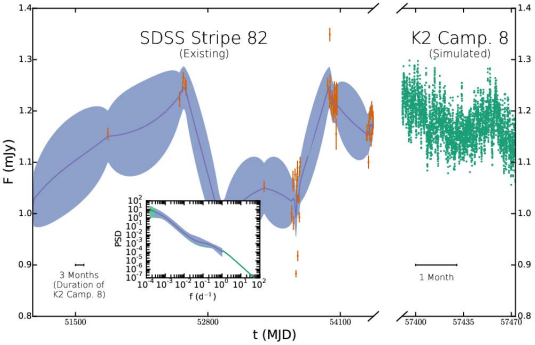
Work in Progress
K2 campaigns



Work in Progress
Power of SDSS+K2



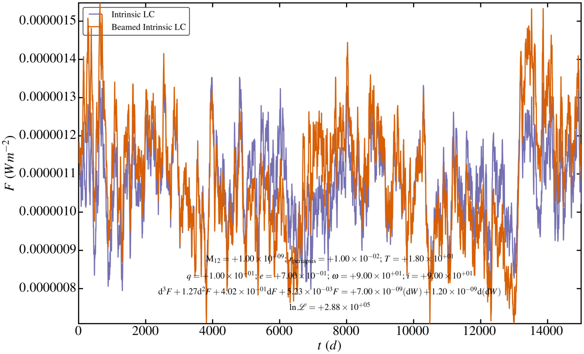
Work in Progress
K2 observations of Stripe 82 QSOs



- 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

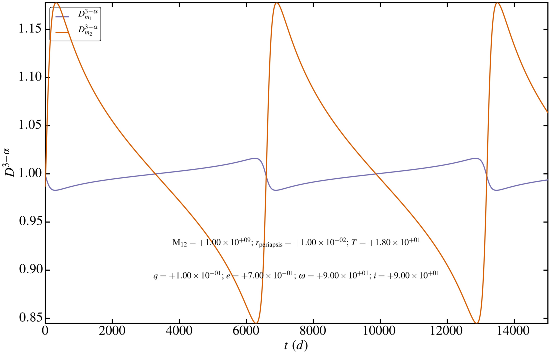
Inspired by D'Orazio, Haiman, & Schiminovich (2015)



- $M_{12} = 10^9 M_\odot$
- $q = 0.1$
- $r_{\text{periapsis}} = 0.01$ pc
- $e = 0.7$

Work in Progress
Beaming from binary SMBHs

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



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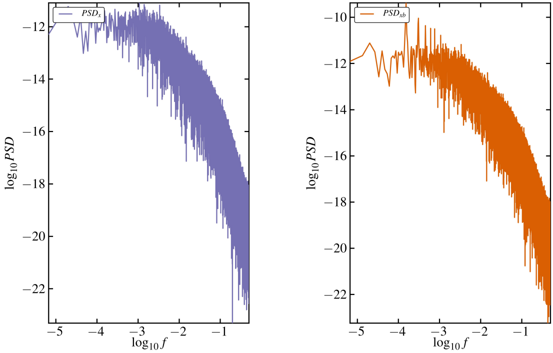
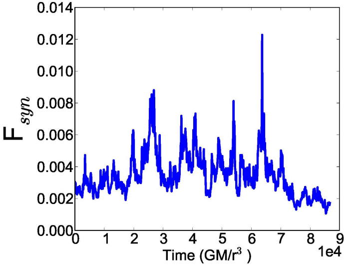


- Do C-ARMA techniques pick up these QPOs?
- Can we get the binary parameters from observations?

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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