Extracting Information from AGN Variability

Kentucky Association for Reasearch with LSST Louisville, KY

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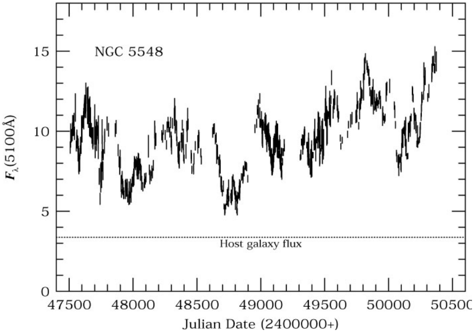
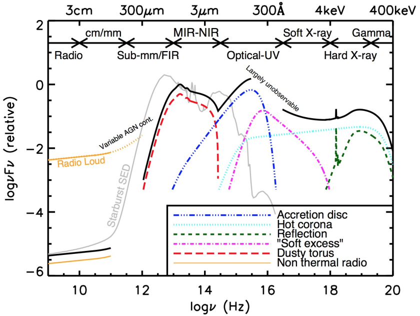
AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



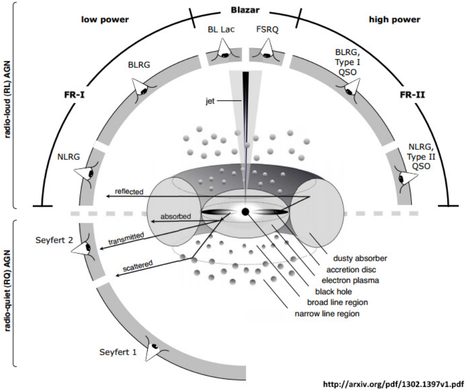
(Peterson et al. 1999)

- $\sim 90\ \%$ 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

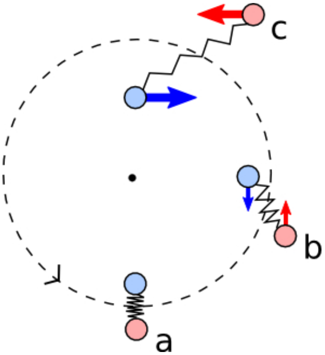


Chris Harrison

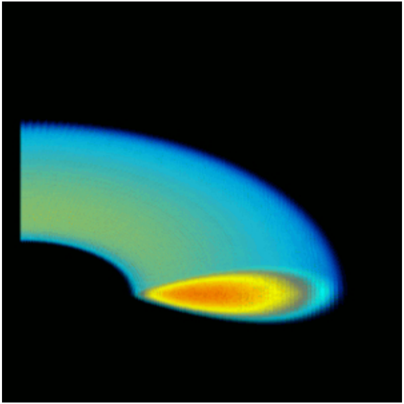


http://arxiv.org/pdf/1302.1397v1.pdf

Accretion Mechanism: The MRI

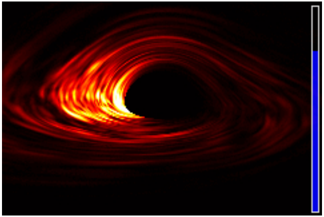


Harvard Astronomy Dept



Hawley & Krolik (2002)

Sources of variability



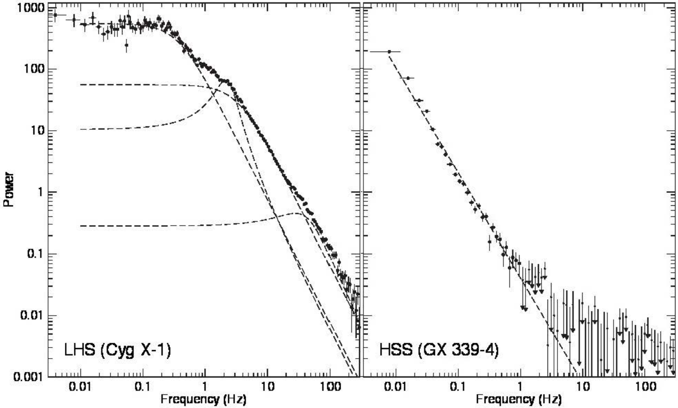
Armitage & Reynolds (2003)

Magnetic Reynolds number: $R_{\mathrm{magnetic}} = UL/\eta$ ~ advection vs diffusion.

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

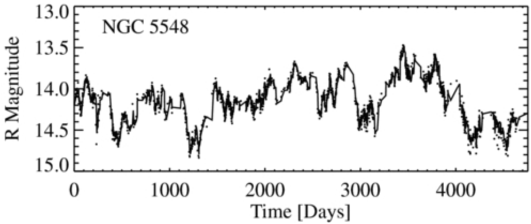
- λ dependent (X-Ray partially drives Optical) (Uttley & Casella 2014)
- Shot noise models unlikely (Uttley et al. 2005)
- MHD turbulence responsible (Nowak & Wagoner 1995)
- Coronal X-Ray flares possible (Poutanen & Fabian 1999)
- Propagating fluctuations (Lyubarskii 1997)
  - Predicts PSD
- Coronal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

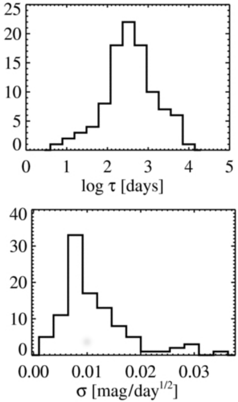
Search for timescales in Power Spectral Density (PSD)



Belloni & Stella (2014)

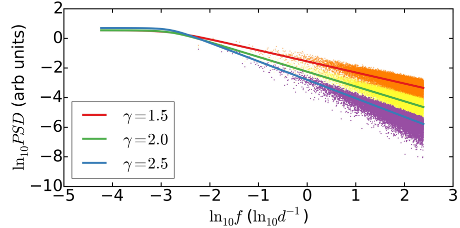
Kelly et al. (2009): Model variability as DRW

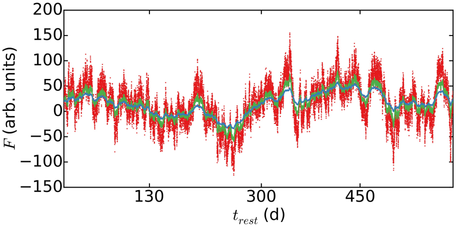




- Dynamical or thermal processes responsible for variability
- $\tau \propto \mathrm{M_{BH}}$ & L_{AGN} but $\sigma \propto 1/\mathrm{M_{BH}}$ & $1/L_{\mathrm{AGN}}$

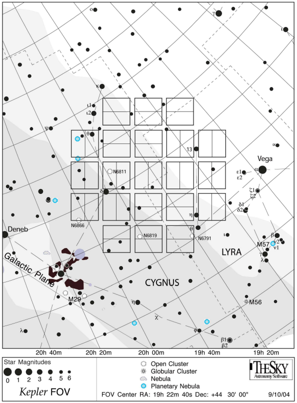
PSD of the Damped Random Walk





- $PSD \propto \frac{1}{f^2}$ 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!

What can we learn from Kepler?

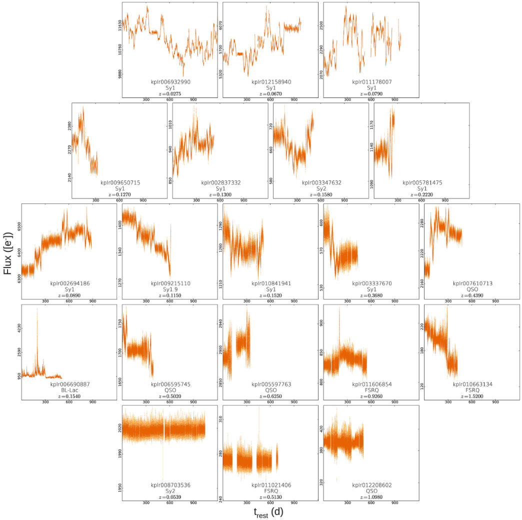


Van Cleve & Caldwell (2009)

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

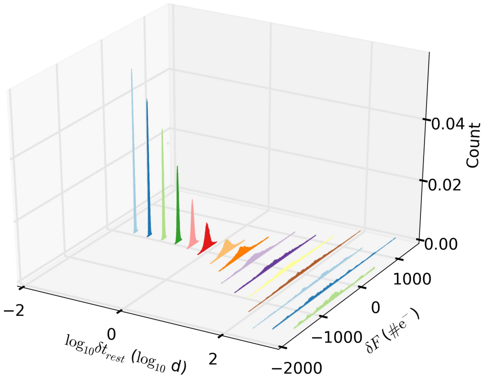
(Mushotzky et al. 2011; Edelson & Malkan 2012; Carini & Ryle 2012; Wehrle et al. 2013; Shaya et al. 2015)

Full AGN sample



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

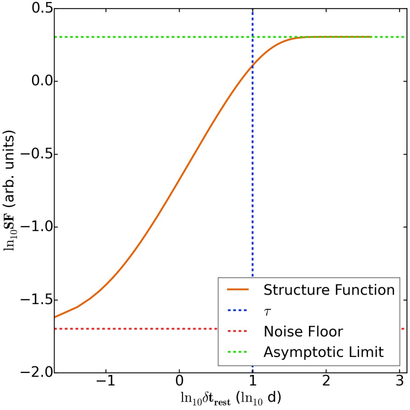
Structure functions



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

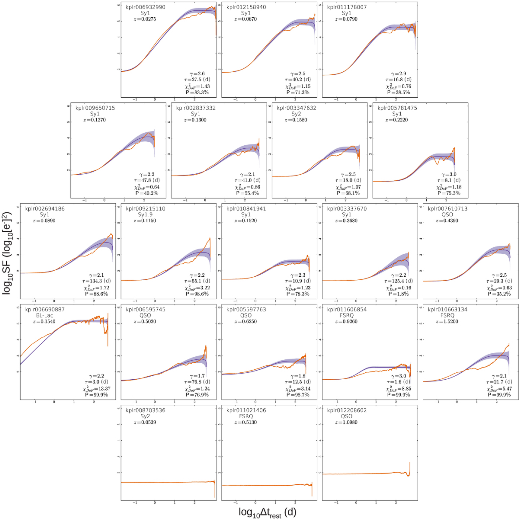


Features in the Structure Function

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

(Emmanoulopoulos et al. 2010)

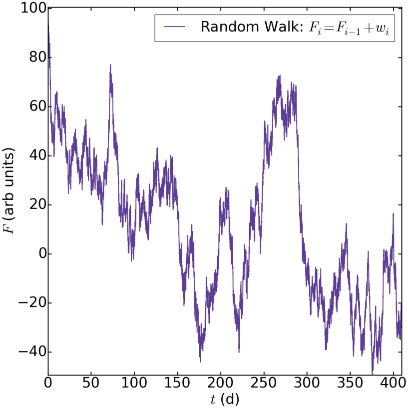
Structure function fits



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

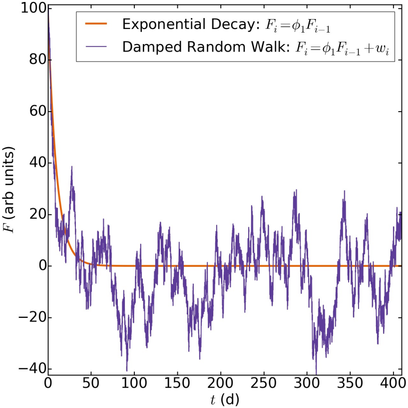
Kasliwal, Vogeley, & Richards (2015)

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.

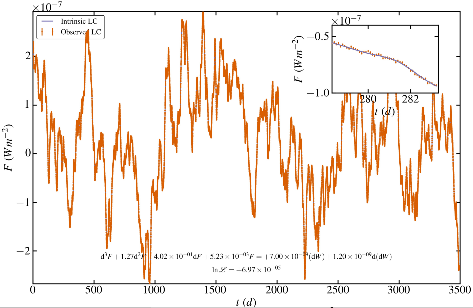
- Exponential decay
  - $F_i = \phi_1 F_{i-1}$
  - $\phi = e^{-\frac{\delta t}{\tau}} < 1$
  - Decays to asymptotic flux level
- Damped Random Walk
  - $F_i = \phi_1 F_{i-1} + w_i$
  - 'Walks around' exponential decay
- Exponential decay driven by Gaussian noise
- 1^{st}-Order Linear Stochastic-DE

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

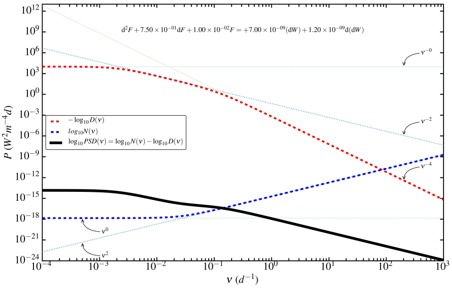
$$\mathrm{d}W \sim \mathcal{N}(0, \mathrm{d}t)$$

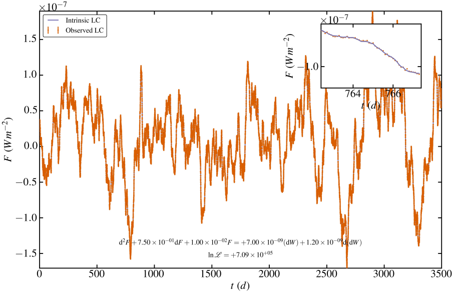
$$\mathrm{d}^p x + \alpha_1 \mathrm{d}^{p-1} x + \ldots + \alpha_{p-1} \mathrm{d}x + \alpha_p x = \beta_0 (\mathrm{d}W) + \ldots + \beta_q \mathrm{d}^q (\mathrm{d}W)$$

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

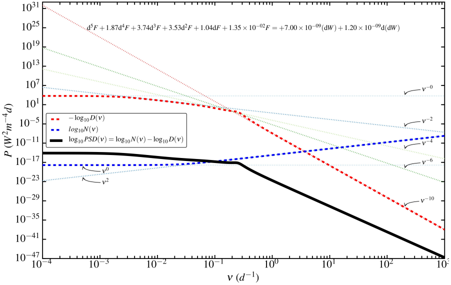


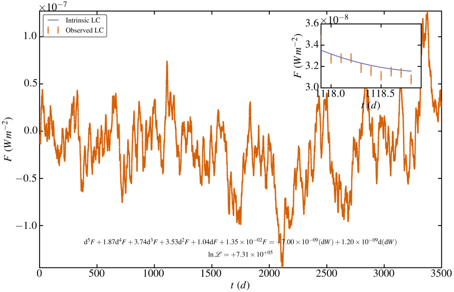
Power Spectral Density
Eg. C-ARMA(2,1)



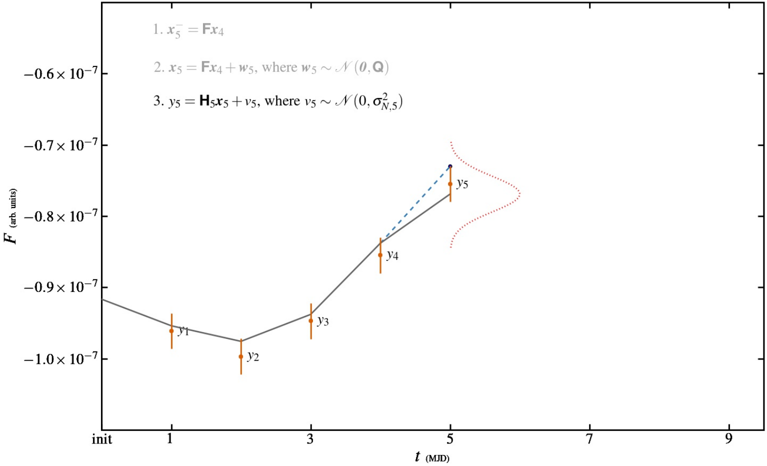


Power Spectral Density
Eg. C-ARMA(5,1)

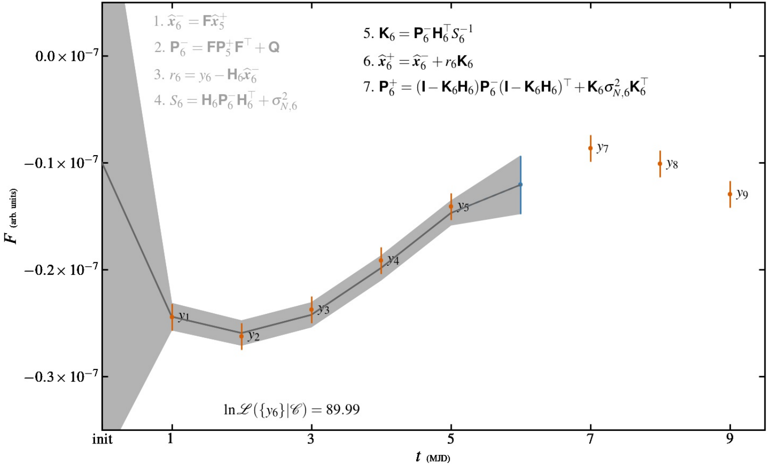




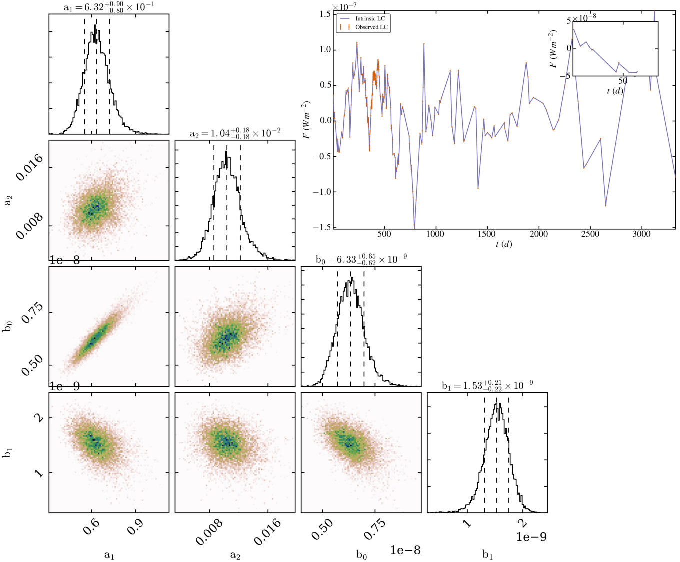
Evolution & observation of light curve state



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

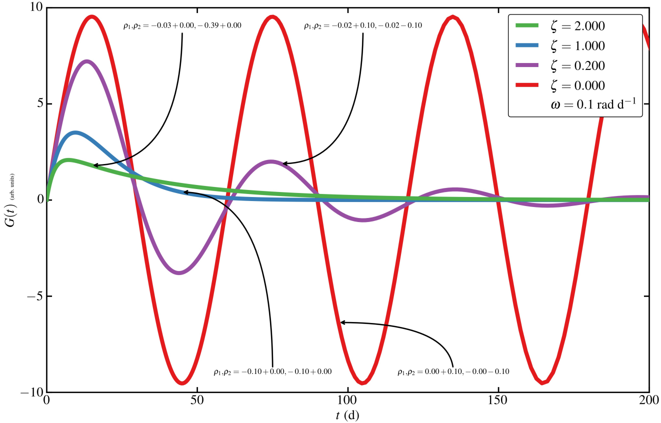


Confidence Interval Estimates



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

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



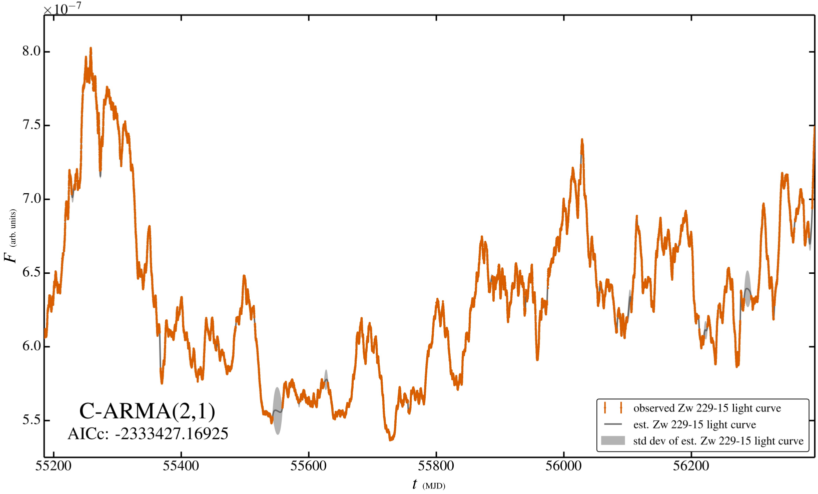
Zw 229-15 (kplr006932990)

HST Image

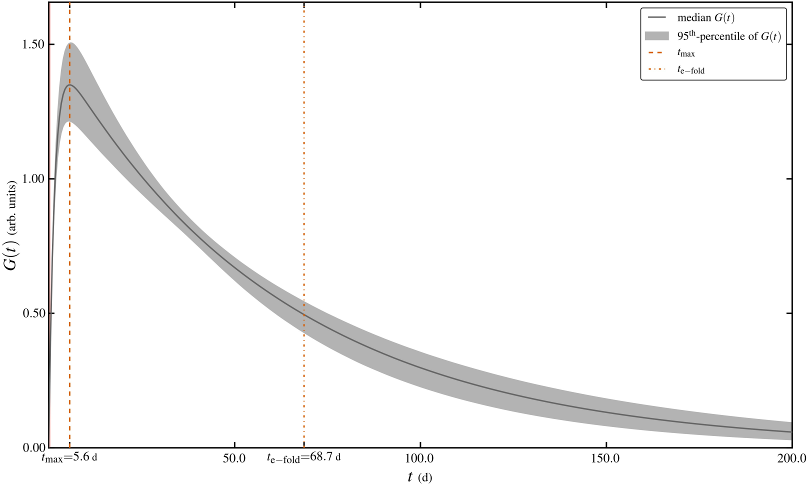
- Sy 1 in Lyra
- $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d
- mag 15.4
- $M_{BH} = 1.00^{+0.19}_{-0.24} \times 10^{7} M_{\odot}$

(Barth et al. 2011)

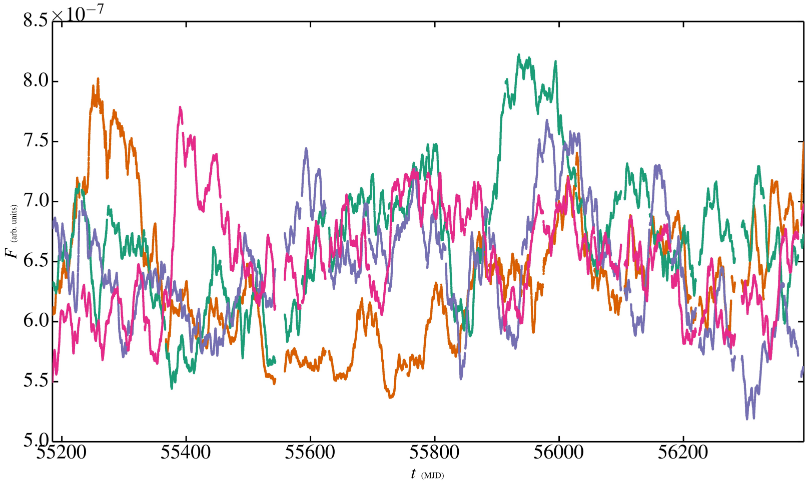
C-ARMA(2,1) model of Zw 229-15
Smoothed light curve



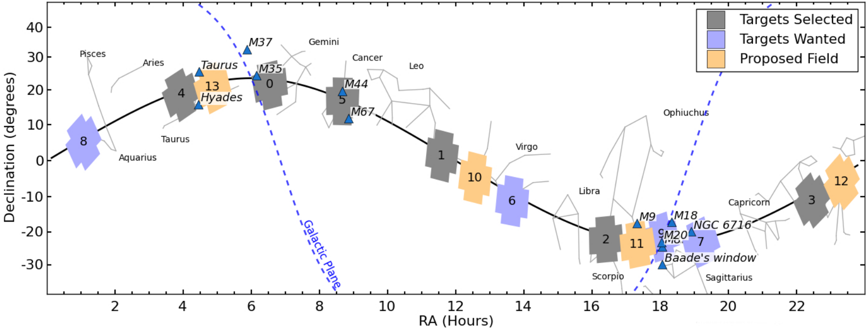
C-ARMA(2,1) model of Zw 229-15 Green's Function



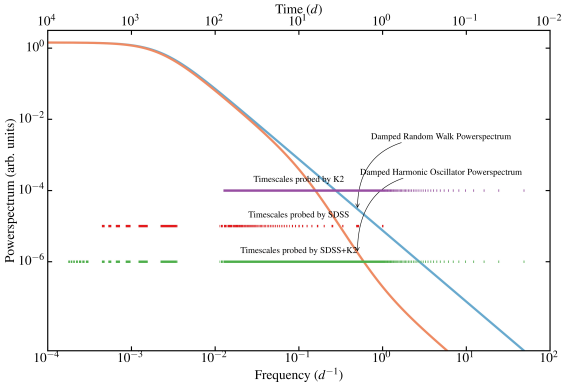
C-ARMA(2,1) model of Zw 229-15
Which is the real light curve?



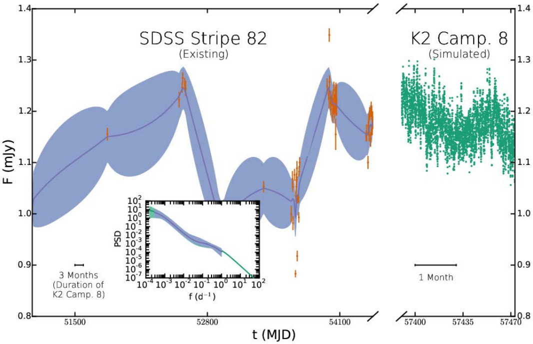
Work in Progress
K2 campaigns



Work in Progress
Power of SDSS+K2

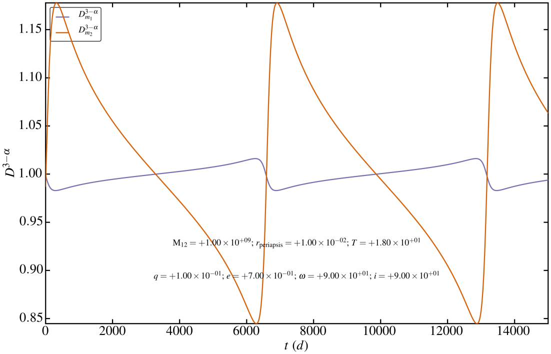


Work in Progress
K2 observations of Stripe 82 QSOs



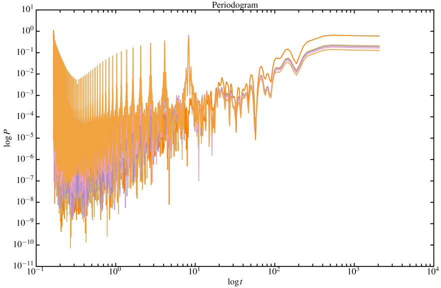
Work in Progress
Beaming from Massive Black Hole Binaries (MBHB)

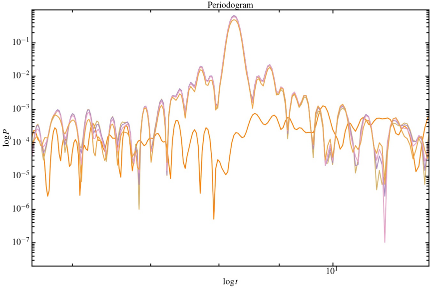
Inspired by D'Orazio, Haiman, & Schiminovich (2015)



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

Work in Progress
Effect on PSD

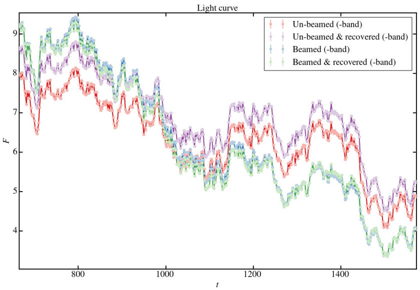


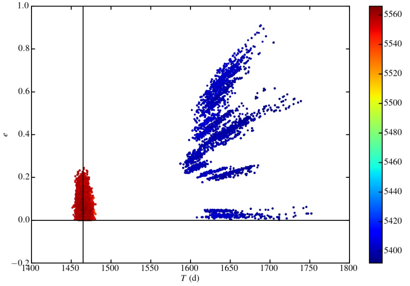


- $a_1 = 10^{-4}$ pc
- $a_2 = 10^{-4}$ pc
- $T = 8.25$ d
- e ranges from 0.0 to 0.75

- $M_{12} = 138.68 \times 10^6 M_\odot$
- $\Omega = 0.0$ degree
- $i = 90.0$ degree

Work in Progress
Inferencing with Kalman Filter



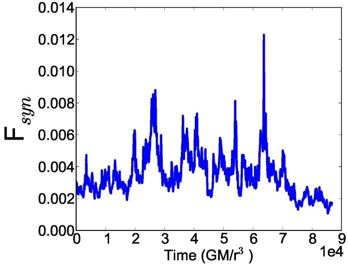


- $a_1 = 10^{-2}$ pc
- $a_2 = 2 \times 10^{-2}$ pc
- $T = 4.0$ yr
- $M_{12} = 14.8 \times 10^9 M_\odot$

- $e = 0.0$
- $\Omega = 0.0$ degree
- $i = 90.0$ degree

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
- Zw 229-15 acts like a **CARMA(2,1)** process (Damped Harmonic Oscillator Driven by Colored Noise)
- Relativistic-beaming from MBHB is **detectable** (un-realistic data quality may be required)

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