# AGN Variability: Insights from Kepler

Hot Wiring the Transient Universe V

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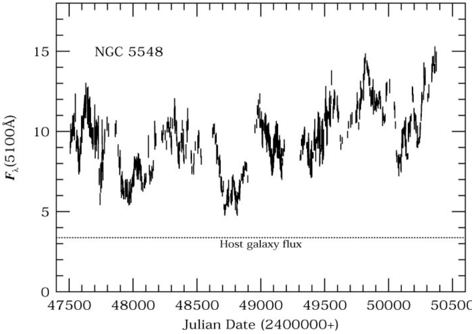
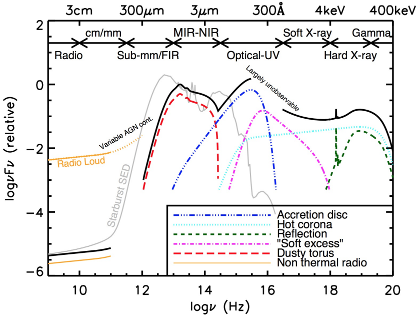
# AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



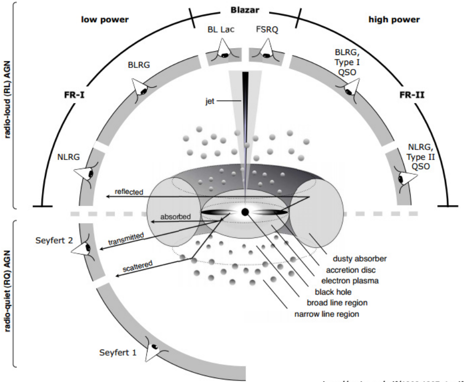

(Peterson et al. 1999)

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

# AGN Morphology: Continuum Variations → Origin in Accretion Disk

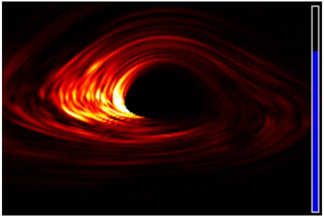



Chris Harrison




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

# Sources of variability



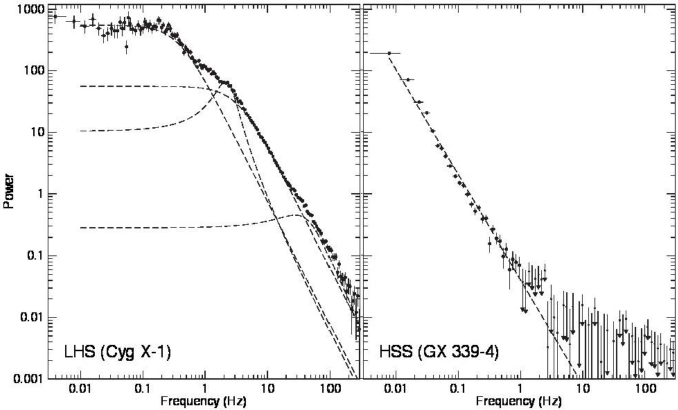
Armitage & Reynolds (2003)

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

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

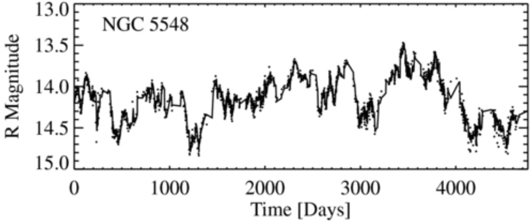
- $\lambda$ dependent (X-Ray partially drives Optical) (Uttley & Casella 2014)
- Shot noise models unlikely (Uttley et al. 2005)
- MHD turbulence responsible (Nowak & Wagoner 1995)
- Coronal X-Ray flares possible (Poutanen & Fabian 1999)
- Propagating fluctuations (Lyubarskii 1997)
    - Predicts PSD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

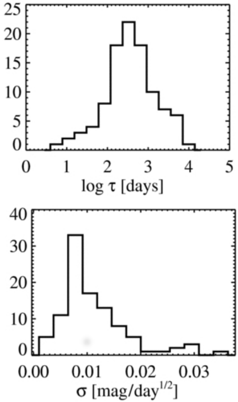
# Search for timescales in Power Spectral Density (PSD)




Belloni & Stella (2014)

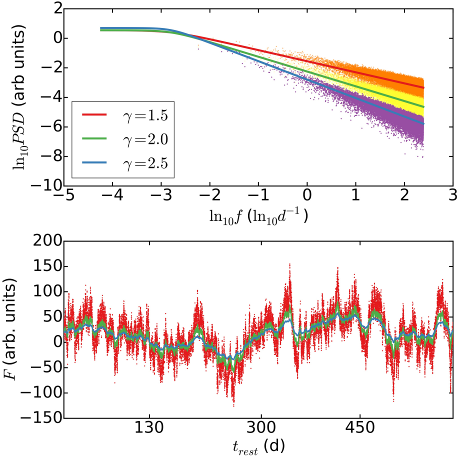
# Kelly et al. (2009): Model variability as DRW



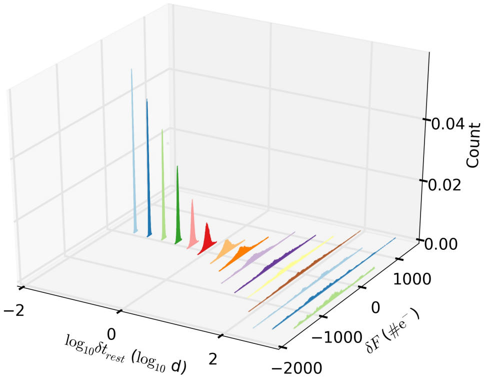

- Dynamical or thermal processes responsible for variability
- $\tau \propto \mathrm{M_{BH}}$ & $L_{\mathrm{AGN}}$ but $\sigma \propto 1/\mathrm{M_{BH}}$ & $1/L_{\mathrm{AGN}}$

# 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!

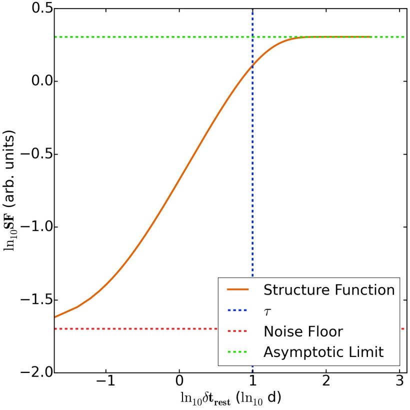
# Structure functions




How does variance of $\delta F$ vary with $\delta t$?

- $2^{nd}$-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

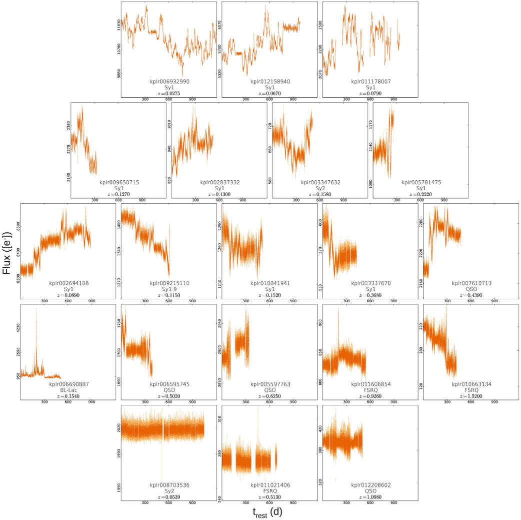



Features in the Structure Function

- Small $\delta t$: 'Noise floor'
- Slope $\sim \gamma$
- Big $\delta t$: Turnover i.e. damping
- Spurious breaks & features

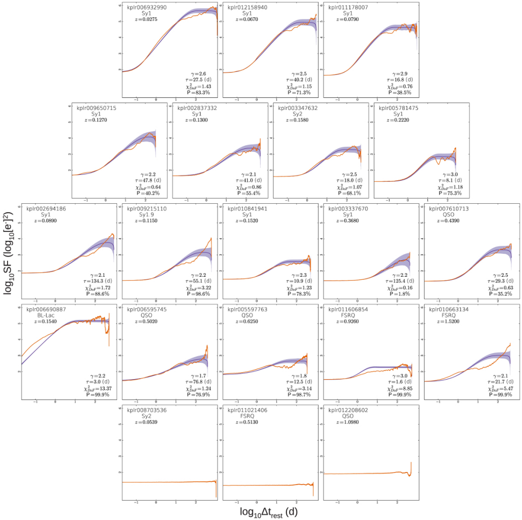
(Emmanoulopoulos et al. 2010)

# Full AGN sample




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

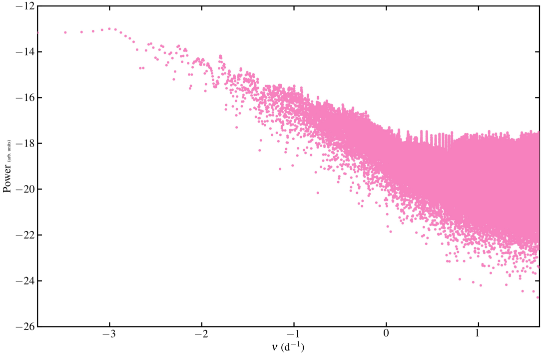
# Structure function fits




- 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?



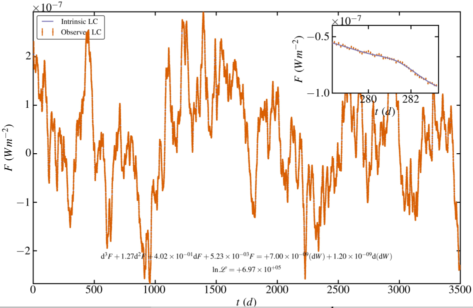

- Stochastic model must be flexible
- Amenable to physical interpretation

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

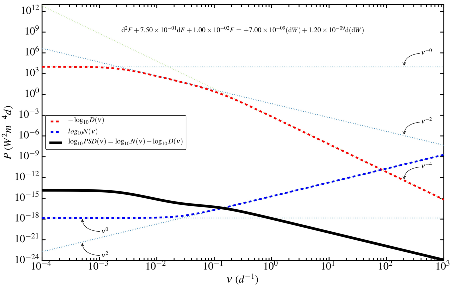
$$\mathrm{d}W \sim \mathcal{N}(0, \mathrm{d}t)$$

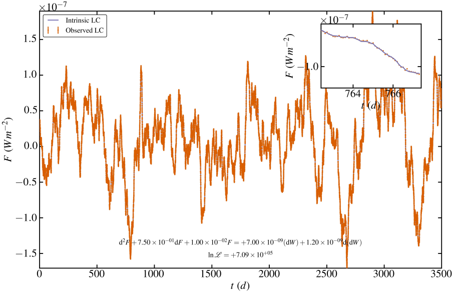
$$\mathrm{d}^p x + \alpha_1 \mathrm{d}^{p-1} x + \ldots + \alpha_{p-1} \mathrm{d}x + \alpha_p x = \beta_0(\mathrm{d}W) + \ldots + \beta_q \mathrm{d}^q(\mathrm{d}W)$$

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

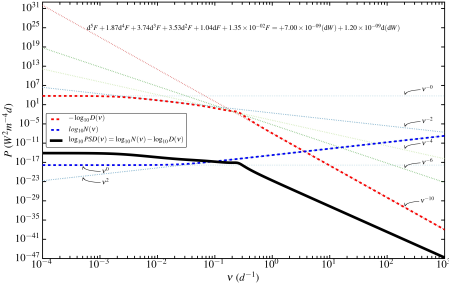


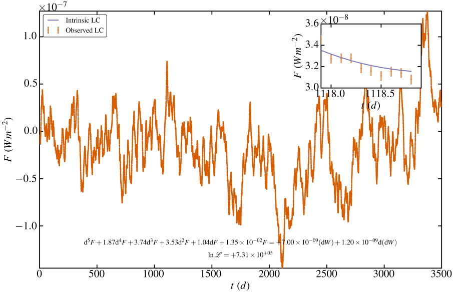
# Power Spectral Density
# Eg. C-ARMA(2,1)



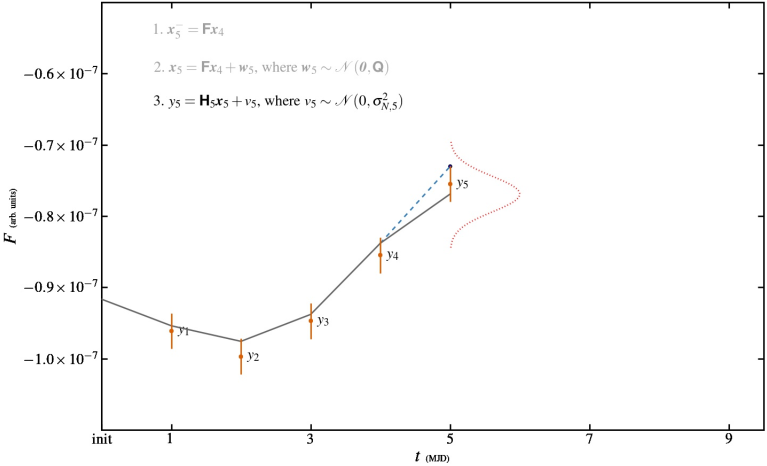



# Power Spectral Density
# Eg. C-ARMA(5,1)

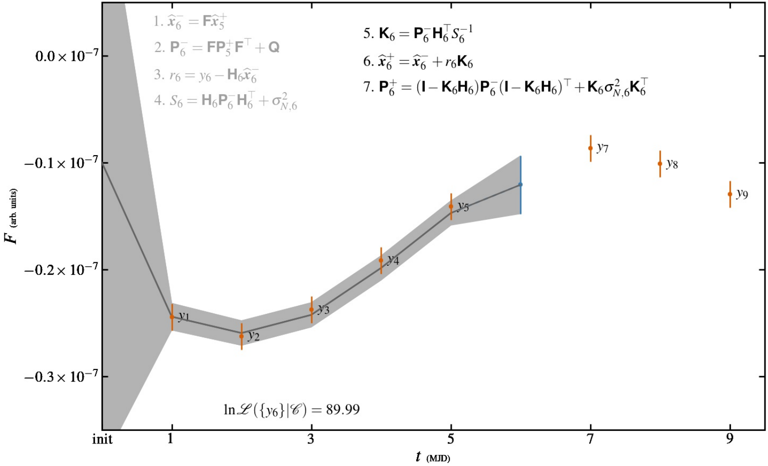


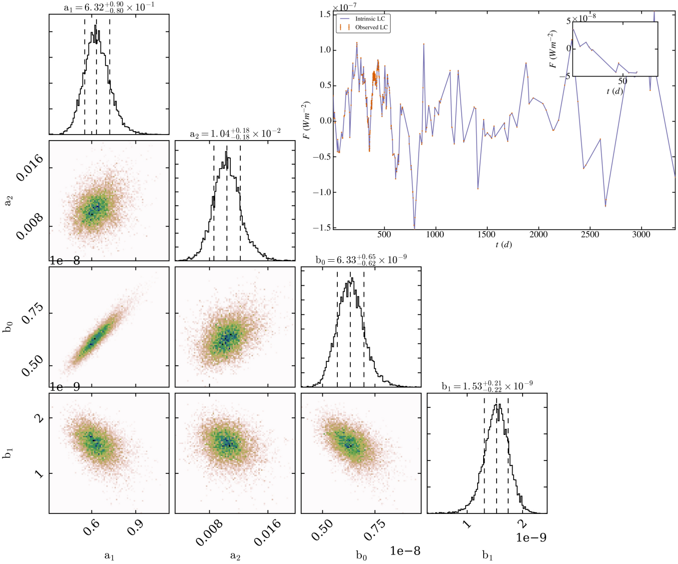
# Evolution & observation of light curve state



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

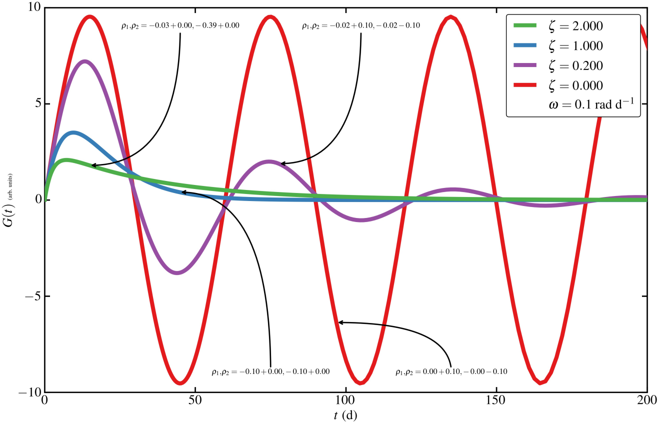


# Confidence Interval Estimates



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

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



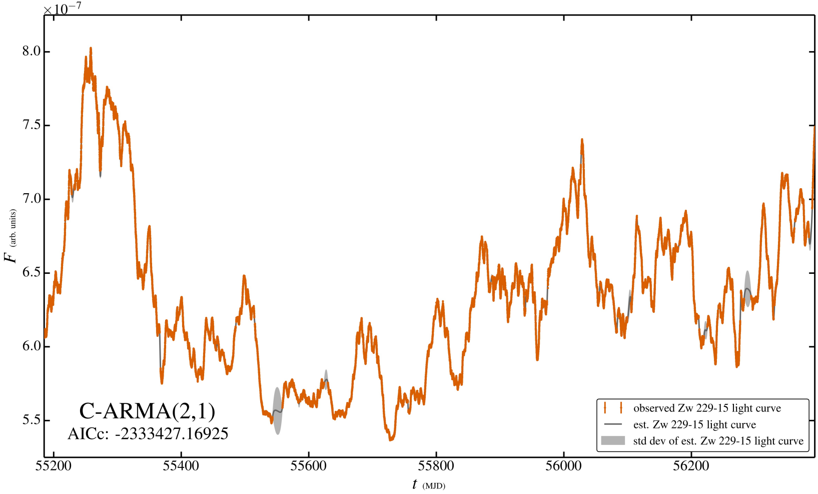
# Zw 229-15 (kplr006932990)

HST Image

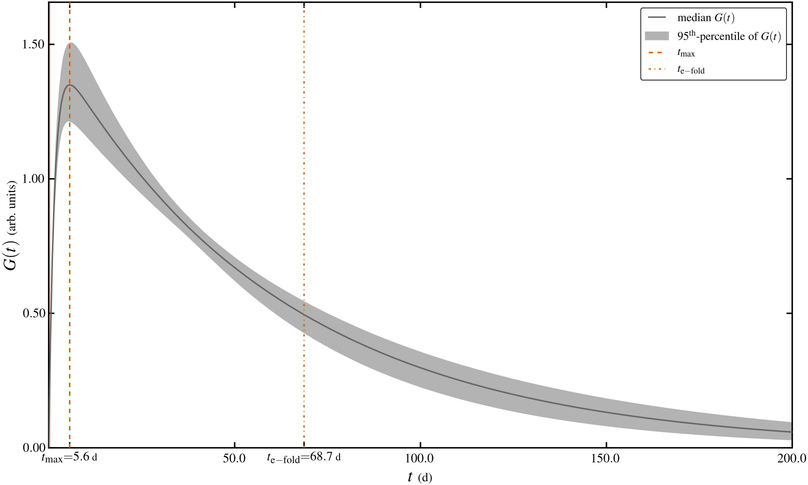
- Sy 1 in Lyra
- $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d
- mag 15.4
- $\mathrm{M_{BH}} = 1.00^{+0.19}_{-0.24} \times 10^7 \mathrm{M}_\odot$

(Barth et al. 2011)

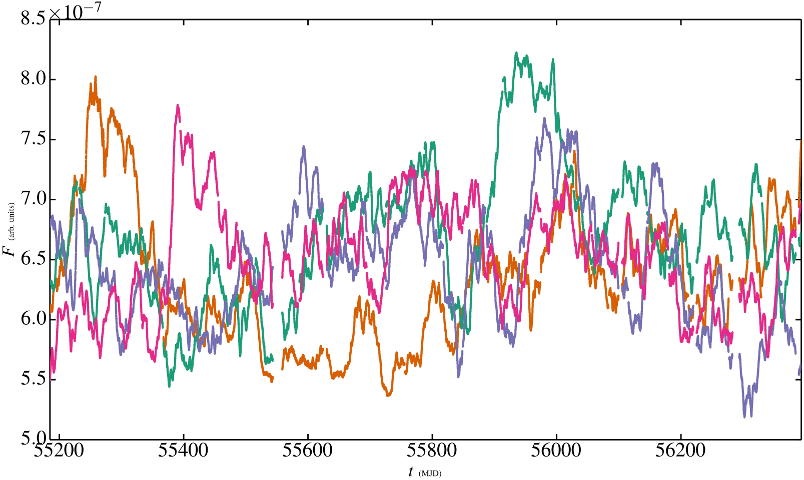
# C-ARMA(2,1) model of Zw 229-15 Smoothed light curve



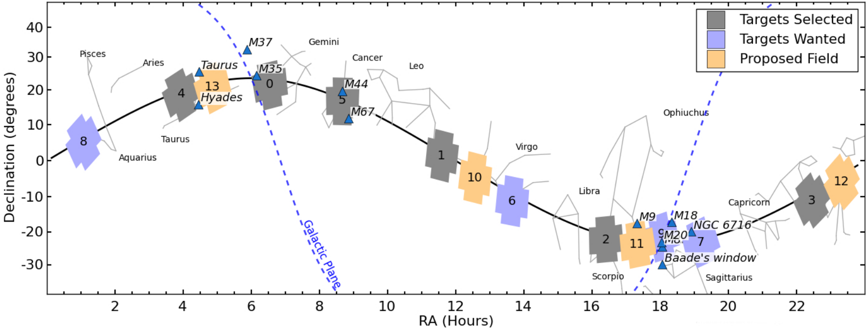
# C-ARMA(2,1) model of Zw 229-15 Green's Function



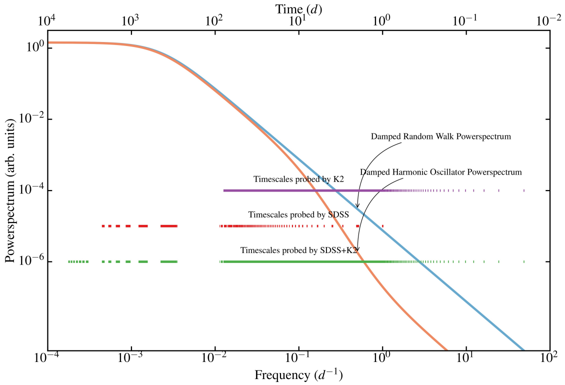
# C-ARMA(2,1) model of Zw 229-15
# Which is the real light curve?



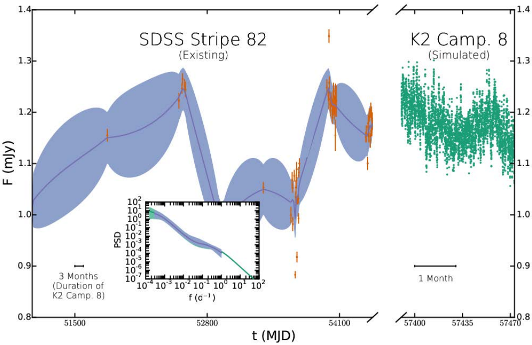
# Work in Progress
# K2 campaigns



# Work in Progress
# Power of SDSS+K2

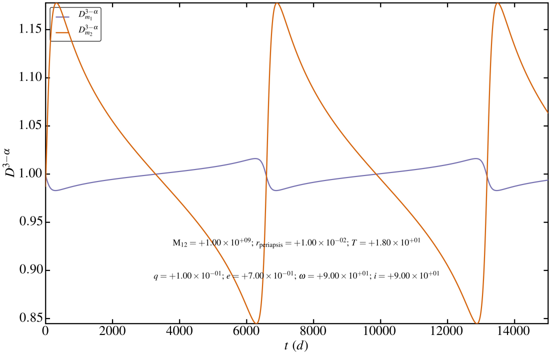


# Work in Progress
# K2 observations of Stripe 82 QSOs



# Work in Progress
# Beaming from binary SMBHs

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




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

# Work in Progress
# Beaming from binary SMBHs

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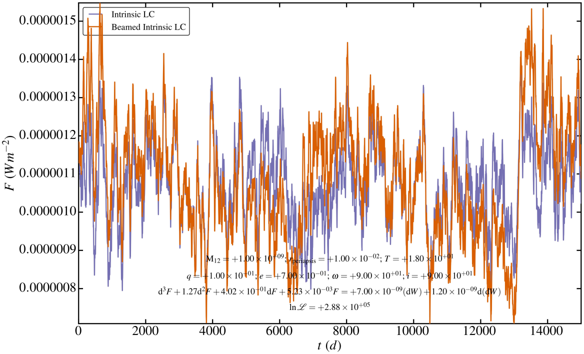


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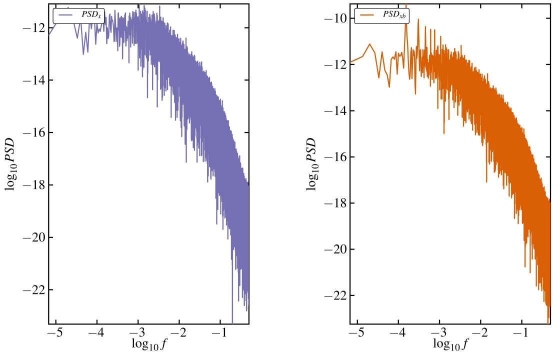
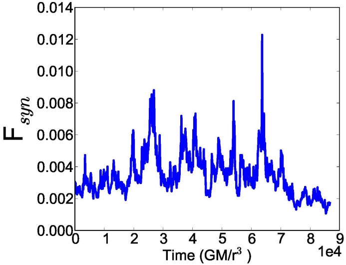



- Do C-ARMA techniques pick up these QPOs?
- Can we get the binary parameters from observations?

# 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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