

AGN Variability on Short Timescales: What does Kepler tell us about AGN Variability?

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Accretion Physics

Broadband Variability

Kepler

Kepler Light Curves

Rest Frame Light Curves

Structure Function Analysis

Modeling Stochastic Light Curves

Structure Function Analysis

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Exact MLE

Generalized PSD Models

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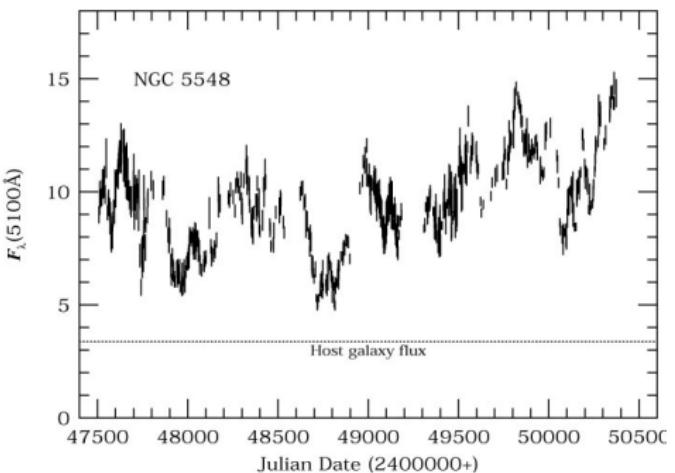
Summary

AGN Vary: Why?

AGN Variability

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Light curve of NGC 5548 (Peterson et al. 1999)

- ▶ ~ 90 % vary (Sesar et al. 2007)
- ▶ Pan-spectral: shorter $\lambda \Rightarrow$ stronger
- ▶ Stochastic! (Peterson 1997)
- ▶ Continuum variability \Rightarrow MHD driven instabilities

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What can we learn from Kepler?

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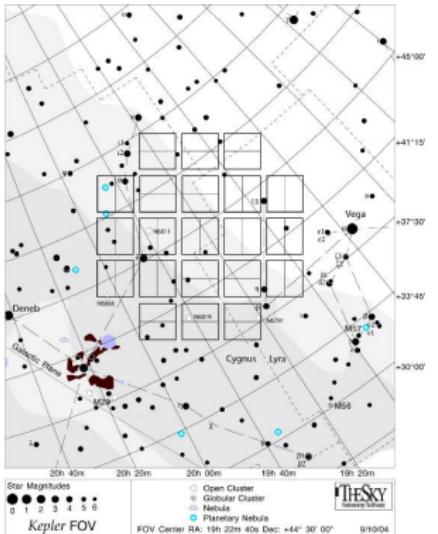
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Summary



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

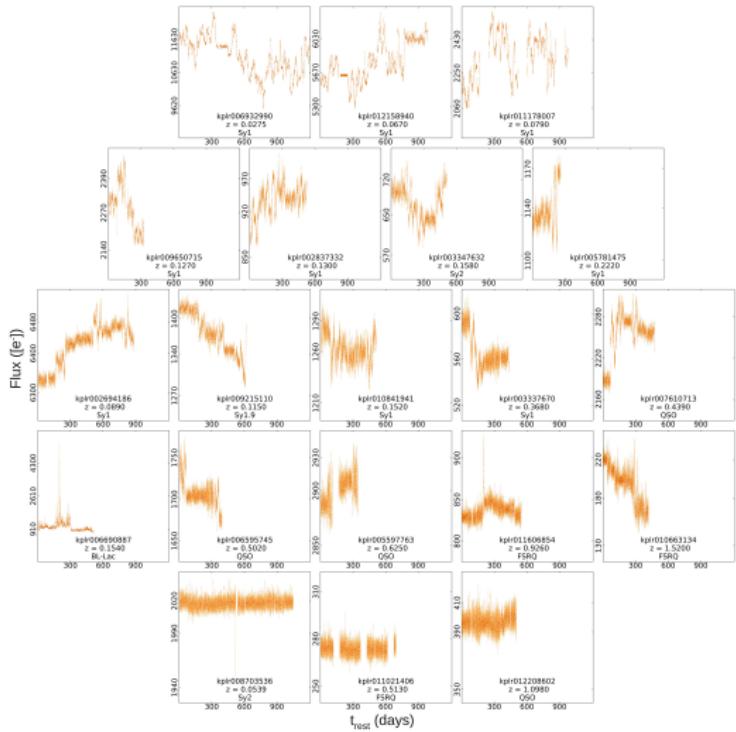
(Mushotzky et al. 2011; Edelson & Malkan 2012; Carini & Ryle 2012; Wehrle et al. 2013)

Kepler FoV (From NASA).

AGN Sample

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

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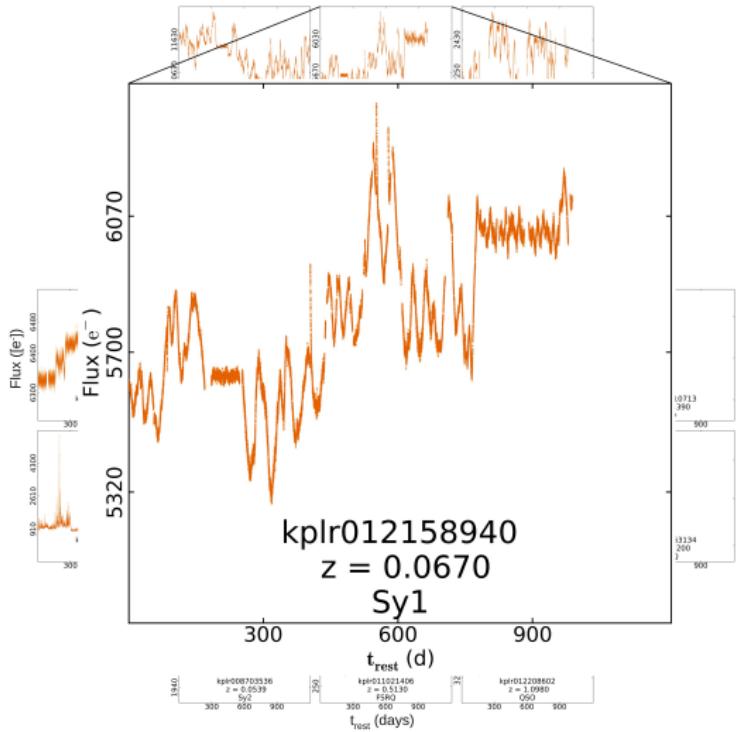
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AGN Sample

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- ▶ Seyfert 1
- ▶ $\delta t_{rest} \sim 27.5$ min
- ▶ $N \sim 50k$
- ▶ Stationary?

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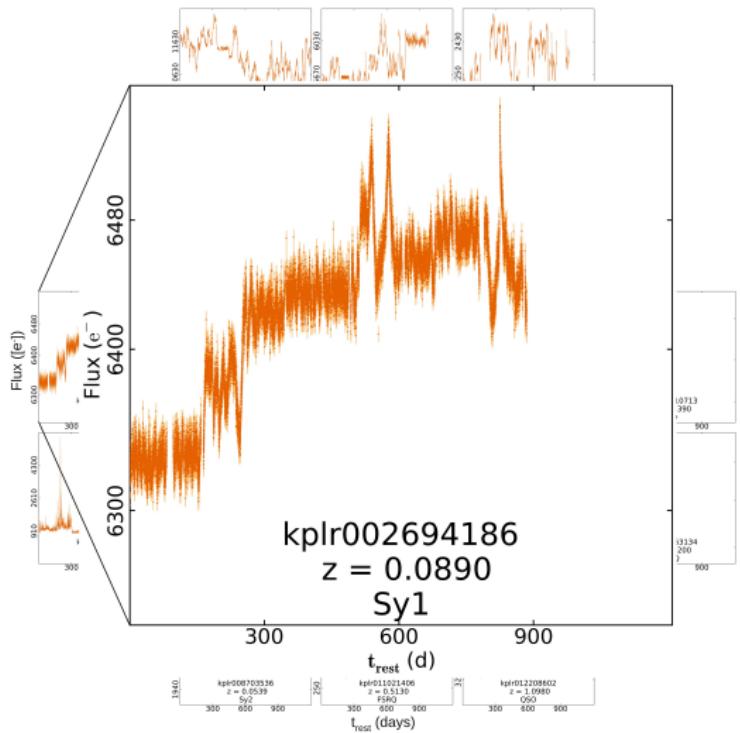
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- ▶ Seyfert 1
- ▶ $\delta t_{rest} \sim 27.0$ min
- ▶ $N \sim 44k$
- ▶ QPO?

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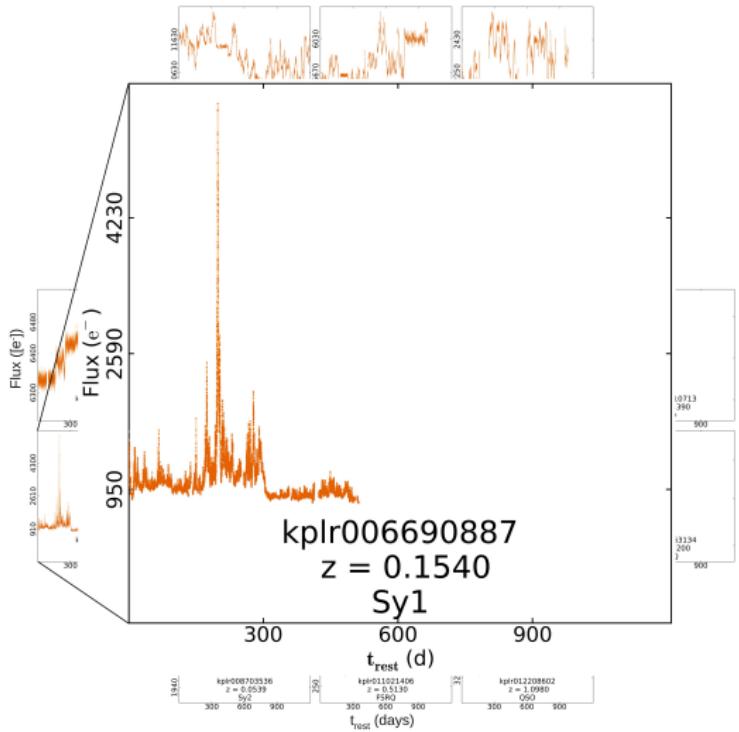
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AGN Sample

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- ▶ BL Lacertae object
- ▶ $\delta t_{rest} \sim 25.5$ min
- ▶ $N \sim 28k$
- ▶ Flares!

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Random Walks

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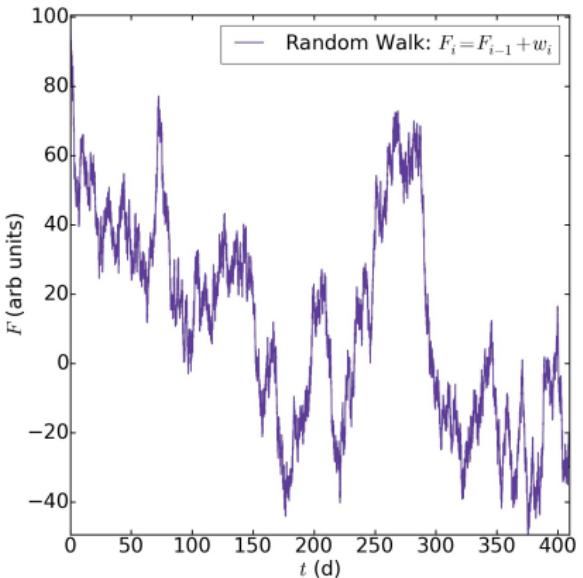
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Summary



- ▶ 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

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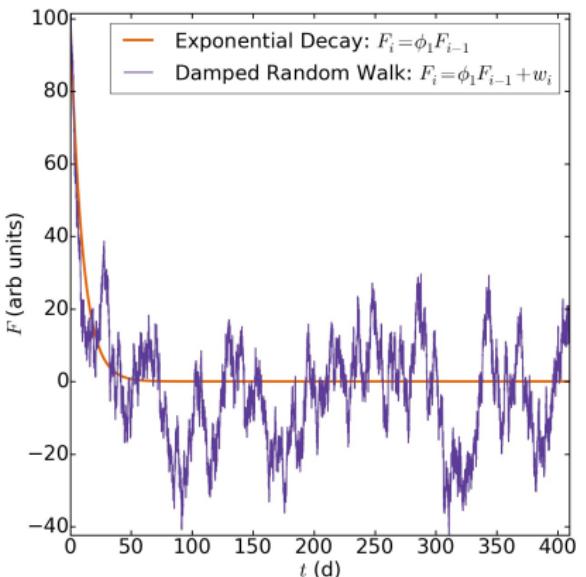
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Summary



- ▶ 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

$$\tau = 1 \text{ d.}$$

The Damped Random Walk

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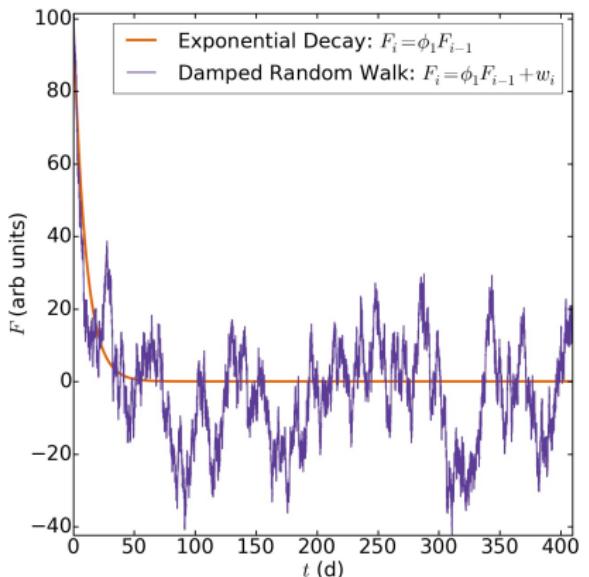
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Summary



$$\tau = 1 \text{ d}$$

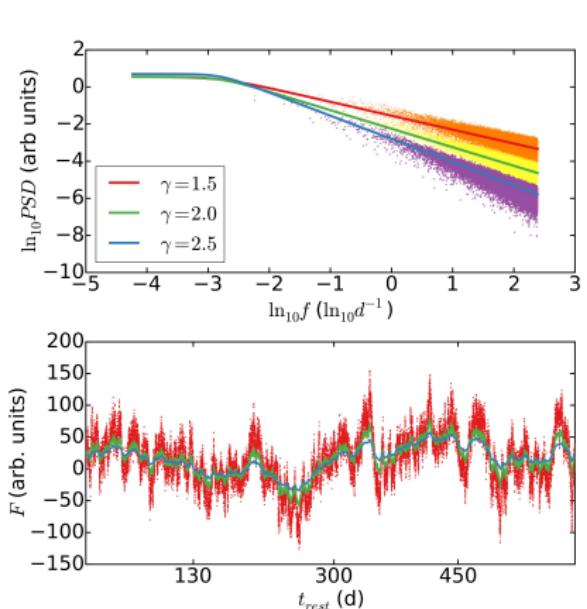
PSD of the Damped Random Walk

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$\tau = 100$ d



- ▶ $PSD \propto \frac{1}{f^2}$ on short timescales
- ▶ $PSD \propto \frac{1}{f^\gamma} \Rightarrow \sigma_{\alpha-fluc} \propto r^\gamma$ (Lyubarskii 1997; Cowperthwaite & Reynolds 2014)
- ▶ DRW: $\gamma = 2$ i.e. it is fixed - is this true?
- ▶ Generalize: $PSD \propto \frac{1}{f^\gamma}$ (McHardy et al. 2004)
- ▶ Test with Kepler data

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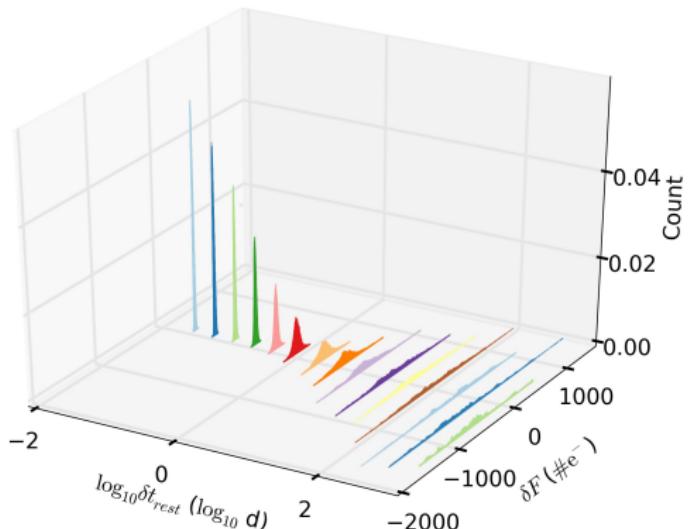
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Summary



- ▶ $\delta F = F(t + \delta t) - F(t)$
- ▶ $SF(\delta t) = \langle |\delta F|^2 \rangle_t$
- ▶ In insensitive to edge-effects, aliasing etc...

How does variance of δF vary with δt ?

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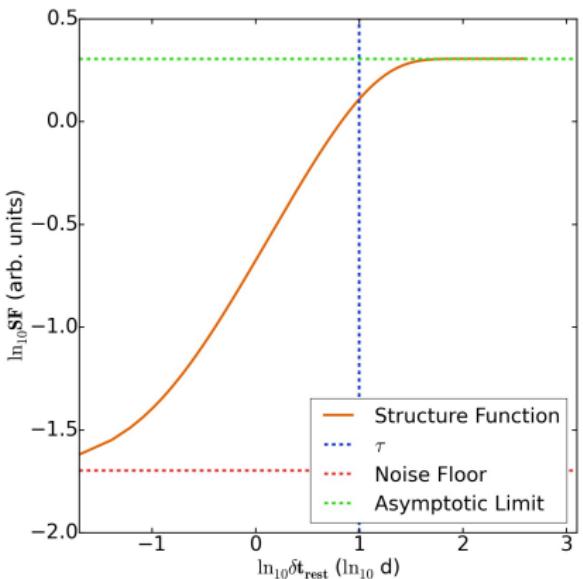
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Summary



- ▶ Short δt : ‘Noise floor’
- ▶ Slope $\sim \gamma$
- ▶ Long δt : Turnover
- ▶ Spurious breaks & features (Emmanoulopoulos et al. 2010)

Features in the Structure Function

Monte-Carlo Simulations

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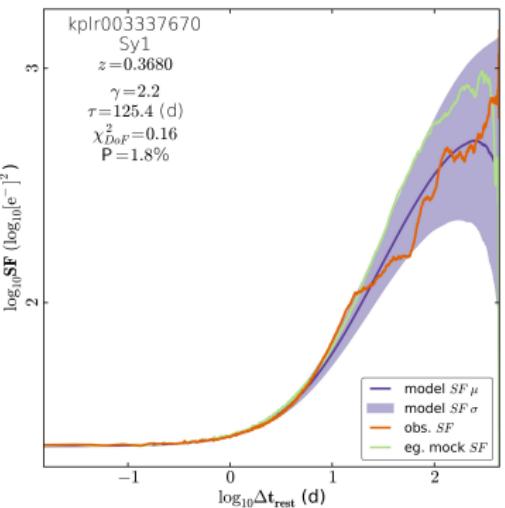
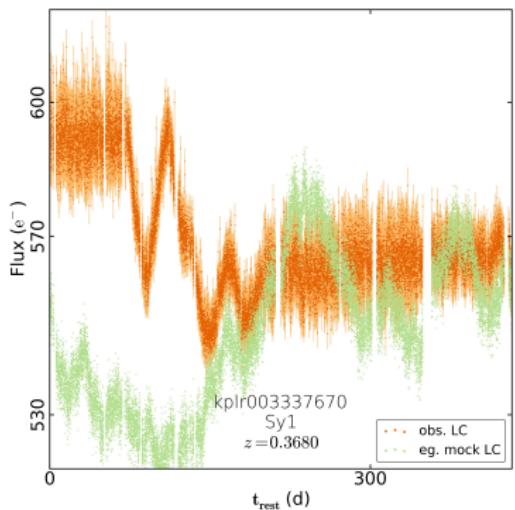
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Summary



- ▶ Best-fit Parameters: $\gamma = 2.2$ & $\tau = 125.4$ d
 - ▶ Maybe DRW ($\gamma_{DRW} \equiv 2$)!
- ▶ Best-fit PSD model accepted at $\sim 98\%$ level

Monte-Carlo Simulations

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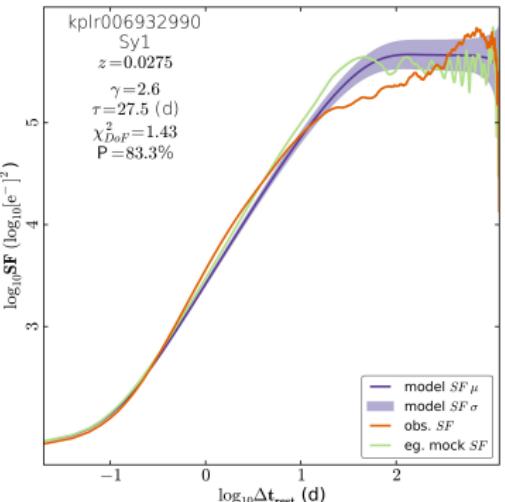
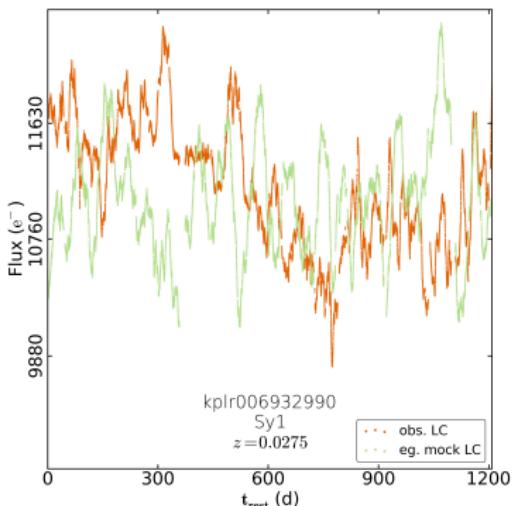
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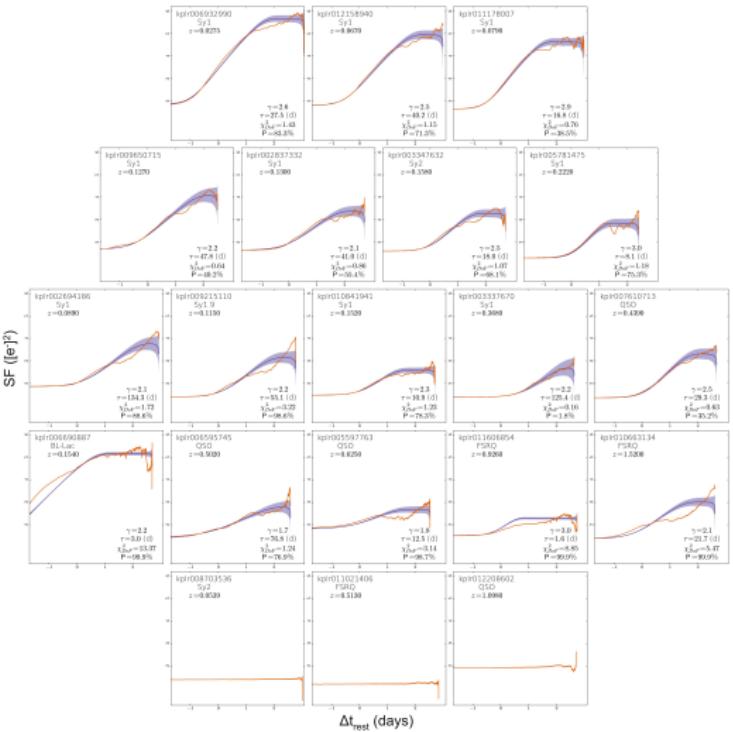


- ▶ Best-fit Parameters: $\gamma = 2.6$ & $\tau = 27.5$ d
- ▶ Not consistent with DRW ($\gamma_{DRW} \equiv 2$)
- ▶ Best-fit PSD model rejected at $\sim 83\%$ level

Structure Function Fits

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- Not all AGN \sim DRW
- Variability Onset Timescales ~ 150 -2000 min.
- PSD too simple?
- Kasliwal et al. (2015)

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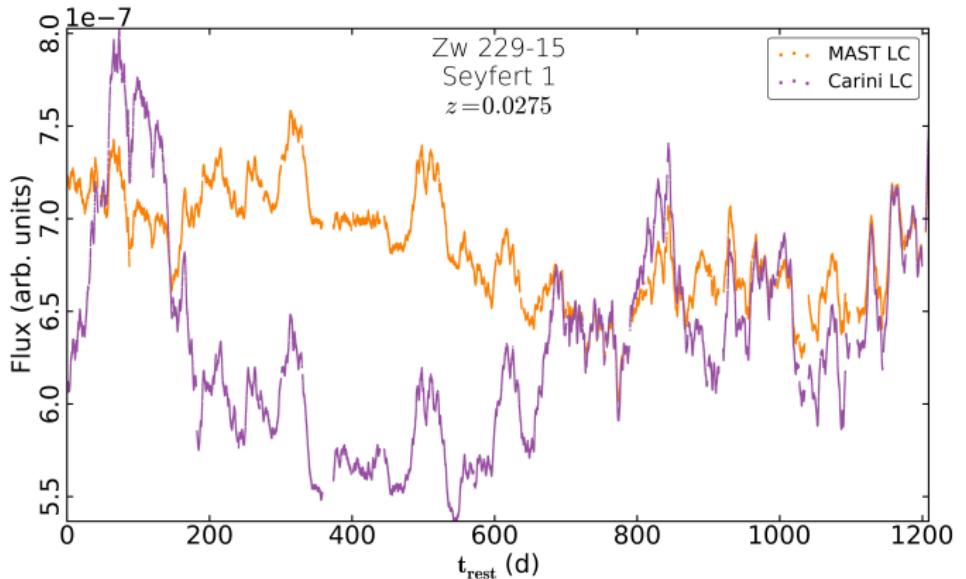
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Which Light Curve?

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- ▶ Carini LC - ground-based observations
- ▶ Is γ_{Carini} closer to $\gamma_{DRW} = 2$?

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SF Analysis of Carini LC

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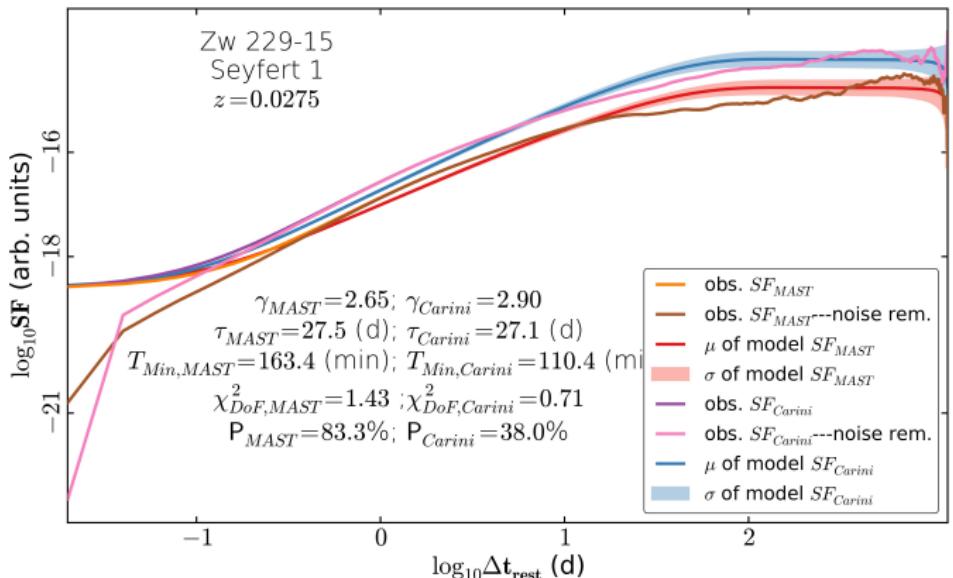
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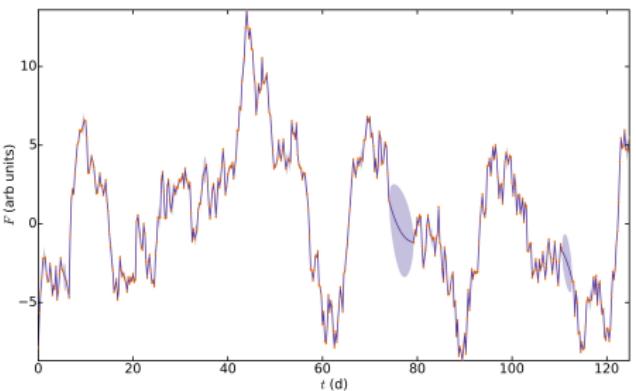
- Carini LC not consistent with DRW (steeper PSD).
- Kasliwal 2015b (*in prep*)

C-ARMA Stochastic Processes

AGN Variability

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$$\frac{d^2Y}{dt^2} + \frac{1}{4} \frac{dY}{dt} + \frac{1}{10} Y = \left(\frac{dW}{dt} \right) + 2 \frac{d}{dt} \left(\frac{dW}{dt} \right)$$

- ▶ n^{th} -order Stochastic-DE: C-ARMA process (Brockwell 2014; Kelly et al. 2014; Edelson et al. 2014)
- ▶ PSD: rational function - arbitrarily complex
- ▶ Kalman filter

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Summary

- ▶ Homogenous equation + unit impulse (Green's Function):

$$\frac{d^2G}{dt^2} + \frac{1}{4} \frac{dG}{dt} + \frac{1}{10} G = \delta(0)$$

- ▶ How does the system respond to a unit impulse?
- ▶ Thermal dissipation, rotation, viscous shear etc...
- ▶ Driving process (u):
- ▶ $u = \left(\frac{dW}{dt}\right) + 2\frac{d}{dt}\left(\frac{dW}{dt}\right)$
- ▶ MHD processes generating 'hot-spots'

C-ARMA Modelling of Carini Zw229-15

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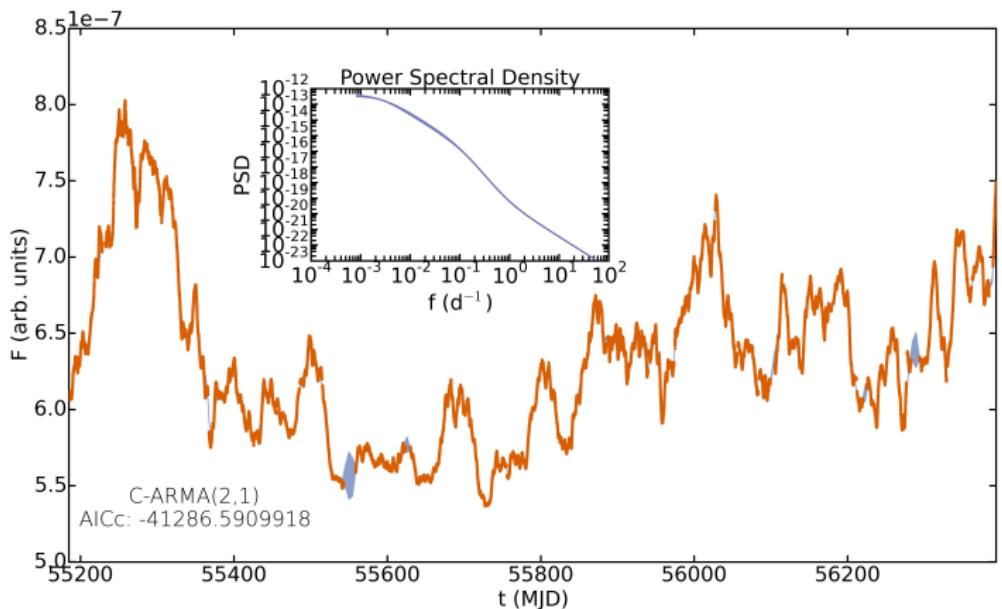
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- Best fit by C-ARMA(2,1) model: 2nd order SDE

Conclusions

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Summary

- ▶ Kepler AGN light curves show:
 - ▶ Wide variety of behavior
 - ▶ QPOs
 - ▶ Flares
- ▶ PSD slope using Monte-Carlo
- ▶ Not all AGN \sim DRW
- ▶ Use C-ARMA models + Kalman filter

Future Work: S82 + K2

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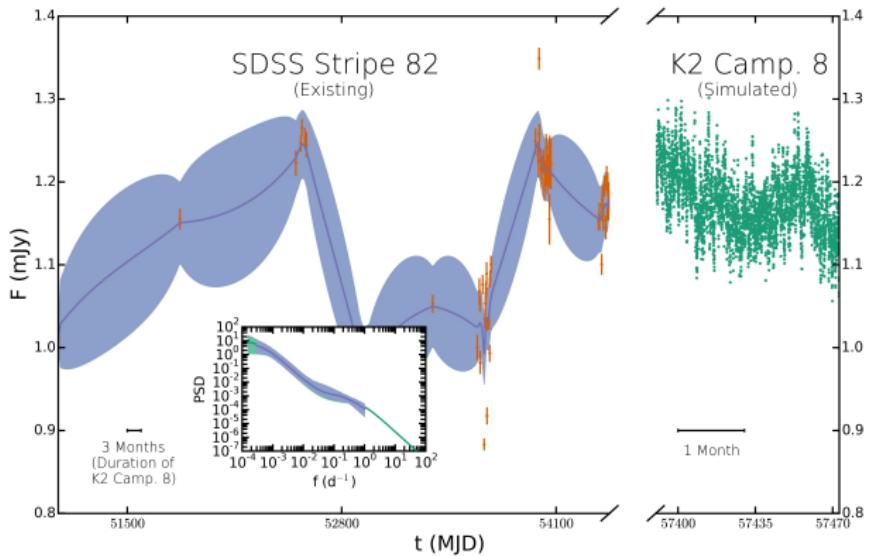
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Future Work

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- ▶ Advisor: Michael S. Vogeley
- ▶ Co-Advisor: Gordon T. Richards

References

[Data Quality](#)

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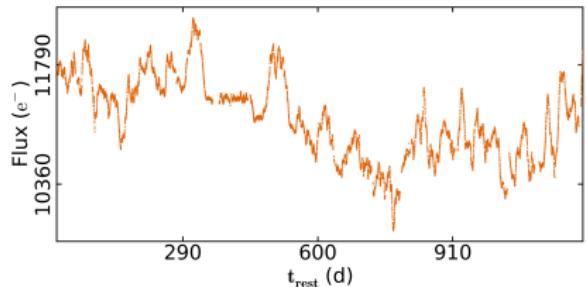
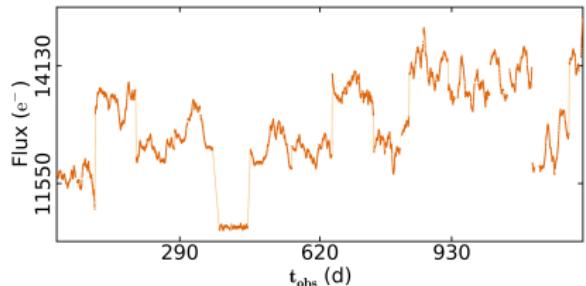
Data Quality Issues

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References

Data Quality



- ▶ Inter-Quarter Offsets
- ▶ Removed by end-matching means (100 data-points).
- ▶ Rolling Band Noise