Stochastic Model for Quasar Variability

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Outline

- Quasars
    - structure, emission, variability
- Data characteristic
- Observed variability
- Stochastic modeling
- Conclusions and future

Quasars

1040 NATURE March 16, 1963 Vol. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

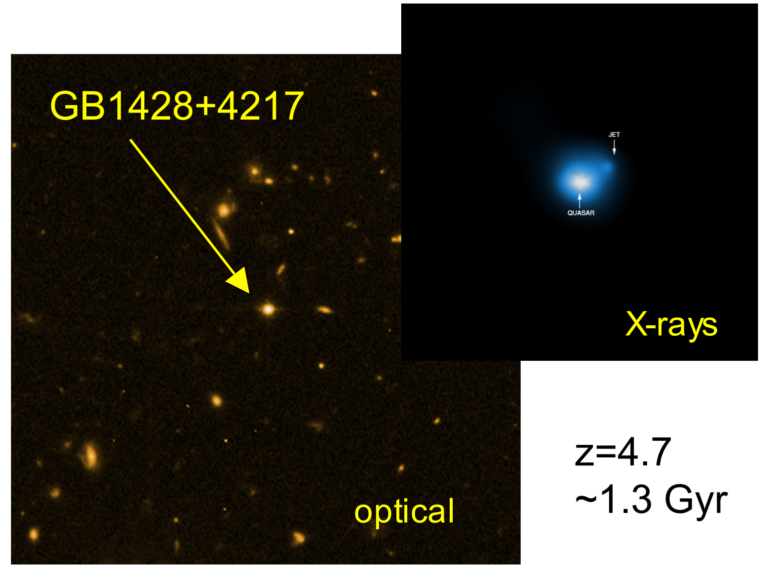
THE only objects seen on a 200-in. plate near the positions of the components of the radio source *3C* 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A. 12h 26m 33·35s ±0·04s, Decl. +2° 19′ 42·0″ ±0·5″ (1950), or 1″ east of component *B* of the radio source. The end of the jet is 1″ east of component *A*. The close correlation between the radio structure and the star with the jet is suggestive and intriguing.

Table 1. Wave-lengths and Identifications

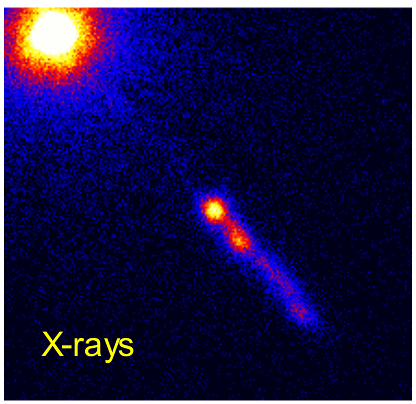
λ	$\lambda/1{\cdot}158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hε
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

Oke in a following article, and by the spectrum of another star-like object associated with the radio source *3C* 48 discussed by Greenstein and Matthews in another communication.

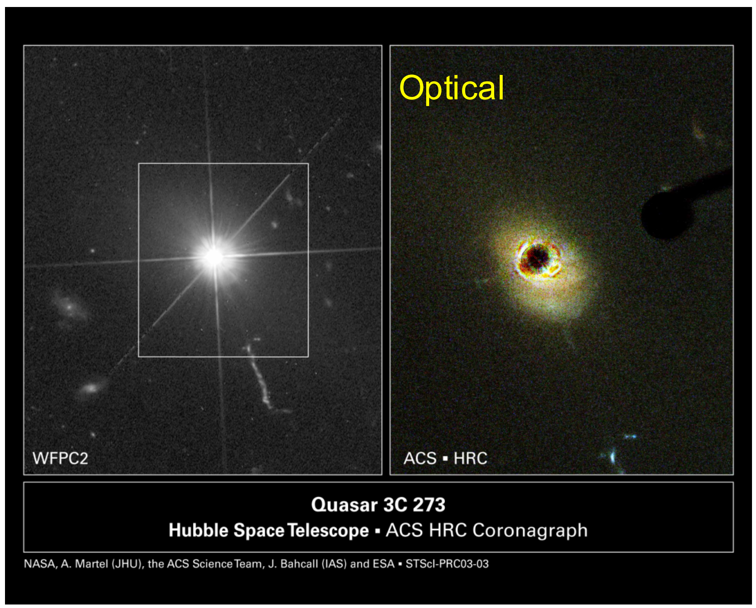
The unprecedented identification of the spectrum of an



z=4.7
~1.3 Gyr



Chandra X-ray Observatory

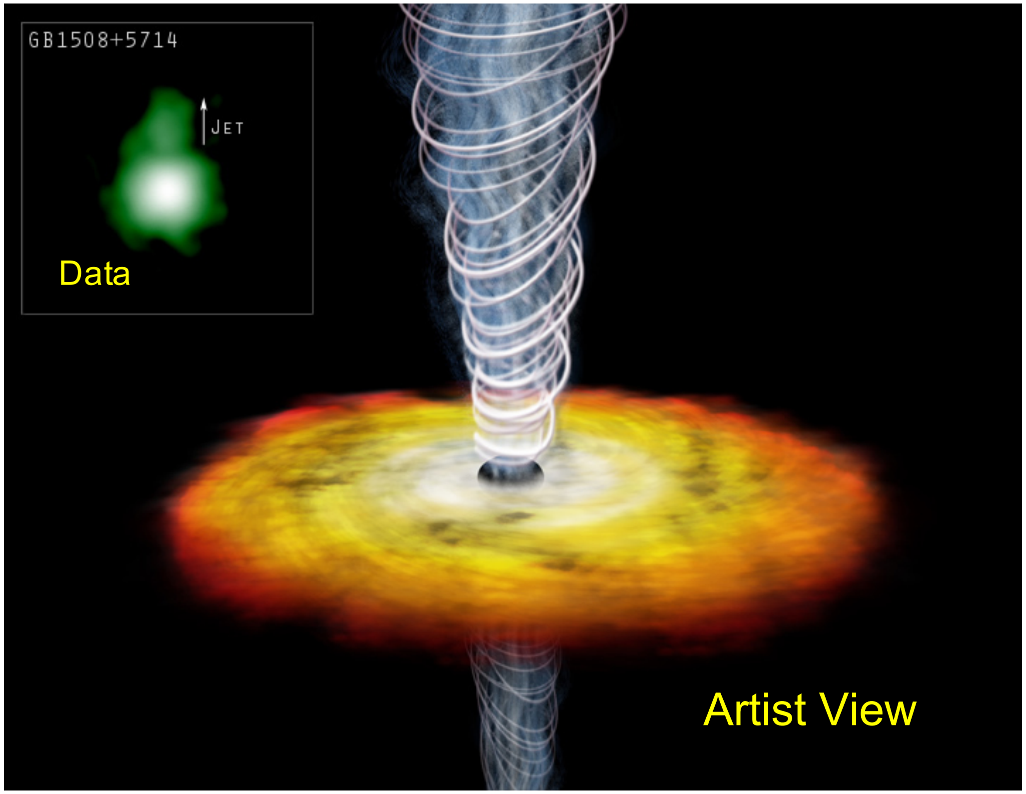


Redshift - a shift of emission lines in the spectrum gives the distance
Quasars are detected at high distances
The most distance know today is at z=7.1 (0.763 Gyr after BB, now 13.67 Gyr)

Quasar Structure

- Accretion Disk
- Hot corona
- Torus
- Clouds
- Relativistic Jet

All contribute to the emission



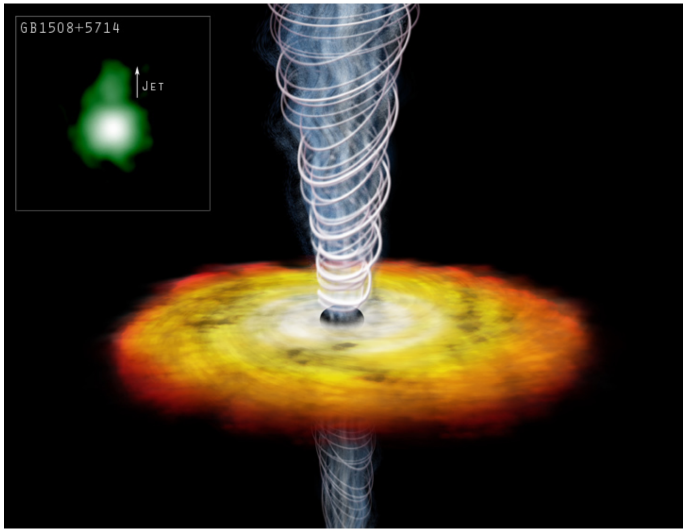
Black Hole gravity is fundamental to the quasar power

Why study variability?

- The primary emission is not resolved!
- The variability allows us to “look inside” the unresolved region:
  - constrain the emission region size
  - learn about energetics of the system
  - understand the physics, e.g. viscosity constraints, connection between different emission sites

Origin of Variability

- On the line of site
  - Occultation events - clouds, torus, wind
  - Microlensing
- Intrinsic to the quasar
  - Optical emission
    - » Continuum - Accretion flow
    - » Emission lines - BLR
  - X-rays
    - » Corona, hot plasma
    - » Outflow (also in radio, γ-rays)
    - » Reflection



Variability Timescales

- Light crossing time at the characteristic radius 100 r_s

$$t_{lc} = 1.1\ M_8\ R_{100rs}\ \text{days}$$

- Orbital time

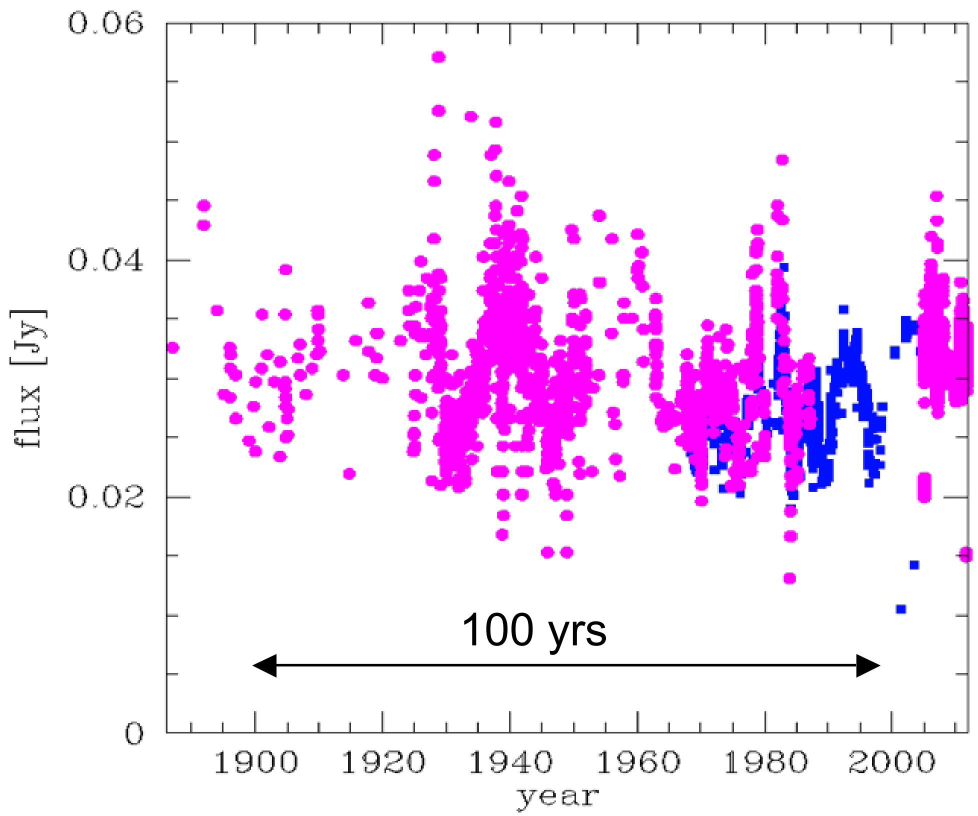
$$t_{orb} = 104\ M_8\ (R_{100rs})^{3/2}\ \text{days}$$

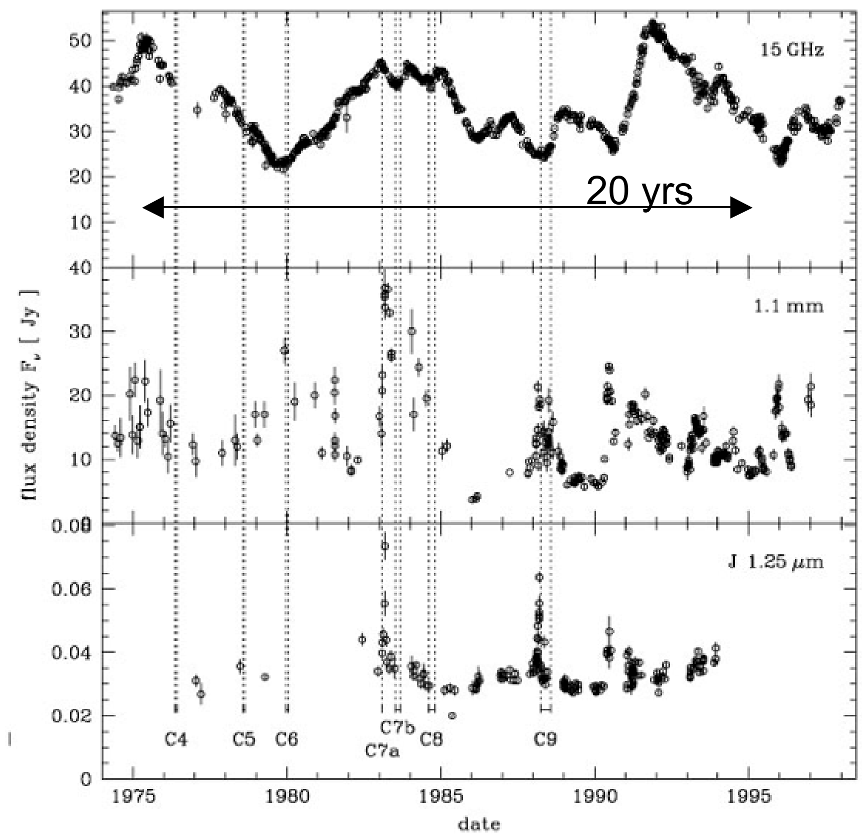
- Thermal (note the viscosity dependence) time

$$t_{th} = 4.6\ (\alpha_{0.01})^{-1}\ M_8\ (R_{100rs})^{3/2}\ \text{years}$$

$R_{100rs} = R\ /100r_S$ - characteristic radius $r_s = 2\ GM_{bh}/c^2$
$M_8 = M_{bh}\ /1e8M_{sun}$ - black hole mass

Long-term Quasar Variability





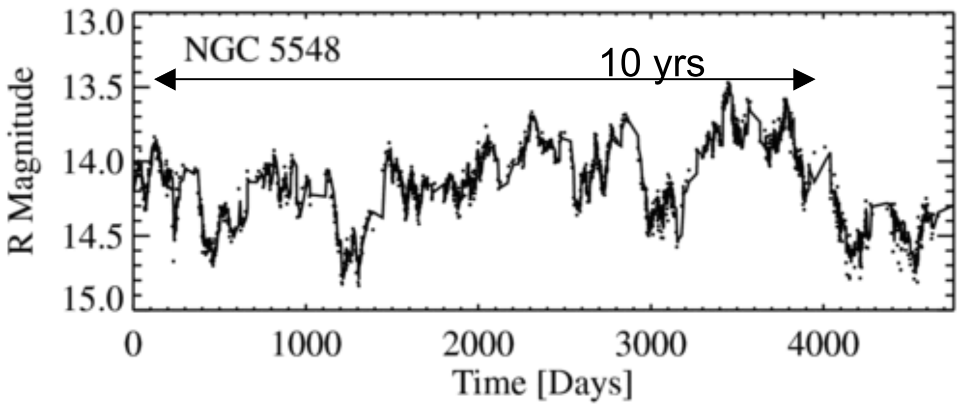
3C 273 Optical Variations
>100 years

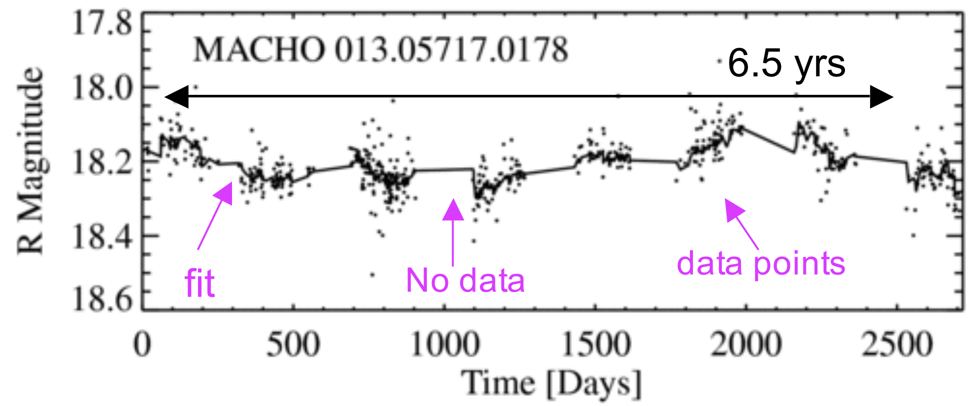
Radio Outbursts

Outbursts in radio typically every 8.1 year (Zhang 2010)
Outbursts are accompanied by ejections of superluminal blobs

http://ned.ipac.caltech.edu/level5/March02/Courvoisier/Cour6_2.html

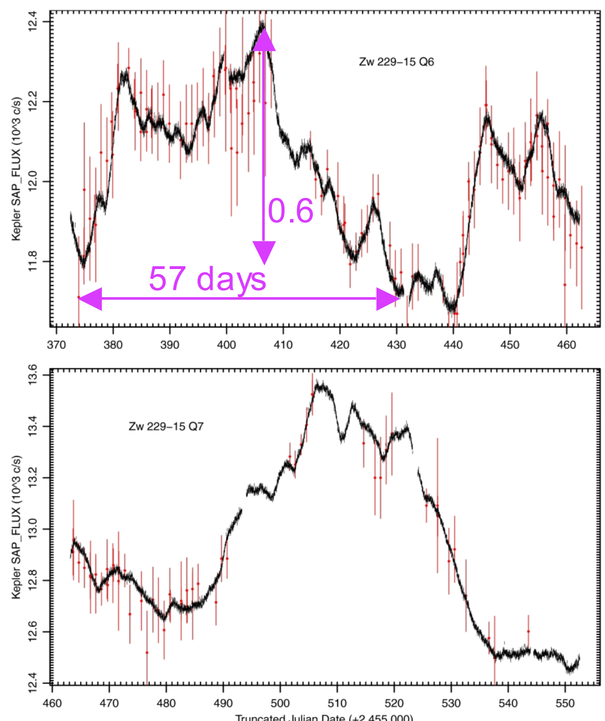
Short-term Quasar Variability





Kelly, Bechtold & Siemiginowska 2009

Kepler Flux



Mushotzky et a 2011

~90 days

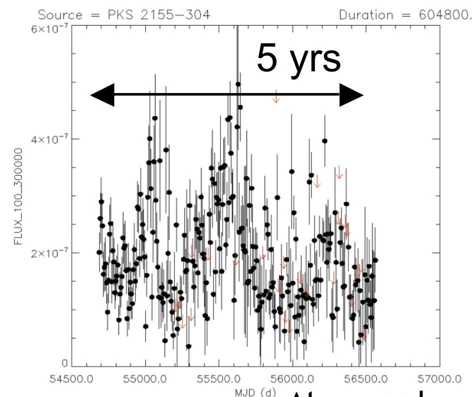
- Good optical data covering a few years
  MACHO, OGLE, AGN Watch, PanSTARRS
- Continuum variations on long and short times
- Relatively small amplitude (10-20%)
- No periodic variations

The best sampled optical light curves (every 30 min) from *Kepler* - only a few AGN known
Probe orbital timescales to thermal timescales

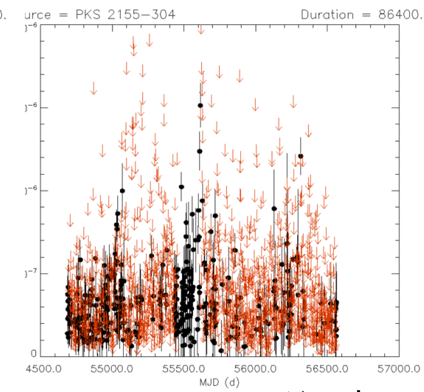
X-ray and γ-ray Variability

- Variations on all the observed timescales
- Difference in time-bins and coverage
- Flares?
- Origin in a jet or hot corona

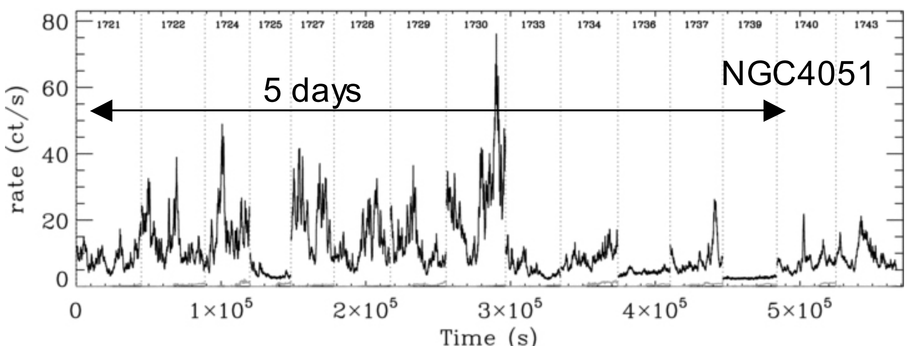
PKS 2155-304



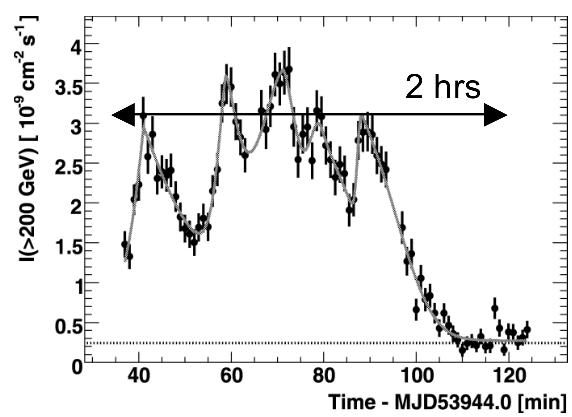
Fermi γ-rays



XMM-Newton X-rays

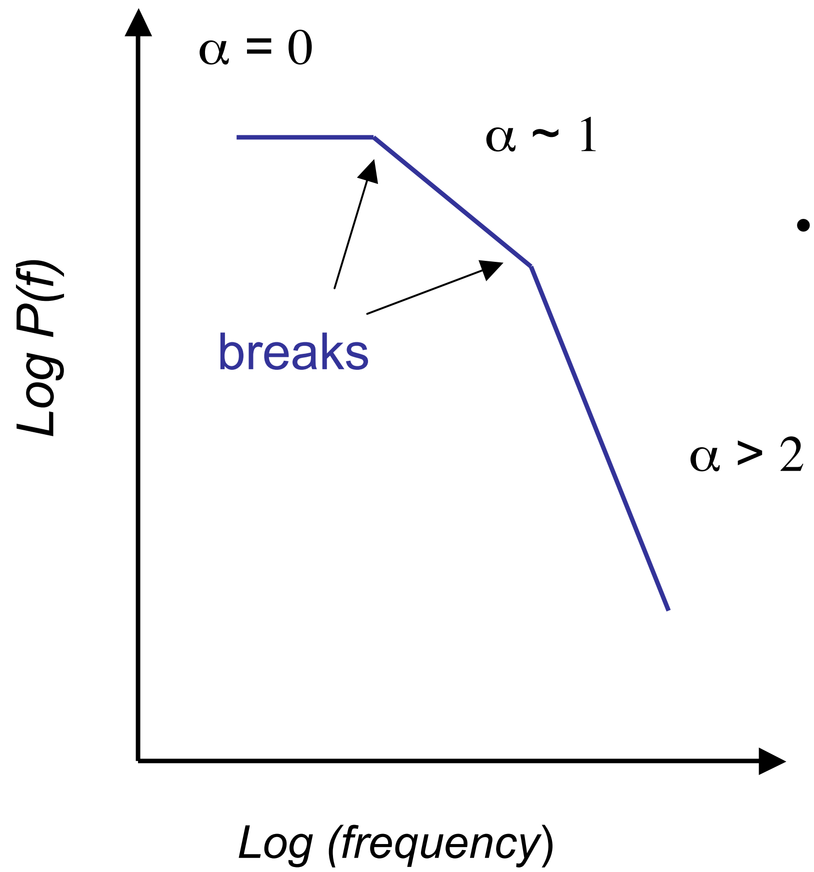


Vaughan et al. 2011



Aharonian et al 2007

Modeling Variability: PSD



- PSD modeling:
  - Non-parametric
  - good for quantifying the variability (e.g. characteristic time-scales)
- But has several limitations:
  - limited in discriminating between physical models for variability.
  - Shape evolves with time, e.g. dramatic changes between different spectral states
  - Light curves have a finite duration time and often non-uniform sampling causing windowing effects
  - Power from low frequency can leak into high frequency (e.g. red noise leak) and from high frequency to low frequency (aliasing)
  - Periodicity in the optical data due to observational constraints by the Earth orbit etc.

see Uttley & McHardy 2001, Uttley et al. 2002, Vaughan et al. 2003, Uttley et al. 2005

Modeling Variability: Time-series

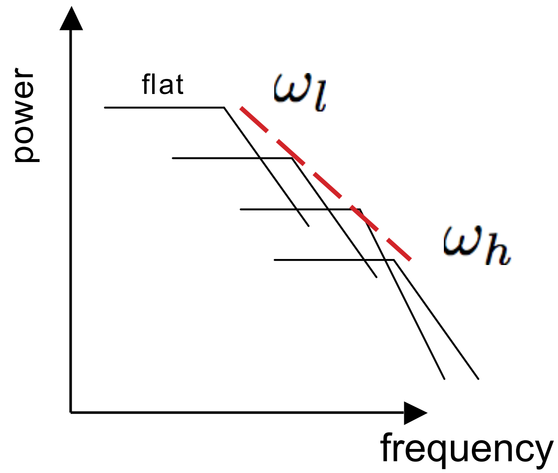
- Assume that the observed variations are generated by an underlying stochastic process - a parametric model
- Observations are different realizations (samples) from that process
- Main goal: determine the NATURE of the physical system responsible for that process.
- Modeling the data (light curves) directly is free of the windowing effects.
- Gives unbiased estimates of the characteristic timescales and variance of the process.
- Needs a parametric model for a light curve - use CAR (continuous auto-regression or OU) - characteristic frequency, rate of perturbations and the amplitude
- Link to the accretion disk equations: a perturbation in the accretion rate driving the changes in the emitted flux

Stochastic Model for Quasar Light curves

$$dX(t) = -\omega_0 (X(t) - \mu)dt + \zeta dW(t), \quad \omega_0 \zeta > 0$$

Stochastic process

White noise



Parameters: μ, ω_0, ζ

Mean value, characteristics frequency and the amplitude of the driving noise

Relaxation time

$$\tau = 1/\omega_0$$

$$Y_M(t) = \mu + \sum_{i=1}^{M} c_i X_i(t)$$

c_i mixing weights

Superposition

Disk Equations

Evolution of the Standard Disk

Surface density

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}(r^{1/2}\nu\Sigma)\right].$$

Accretion rate

$$\dot{M}(r,t) = 6\pi r^{1/2}\frac{\partial}{\partial r}(r^{1/2}\nu\Sigma).$$

$$x = r^{1/2}$$

Perturbation of $r^{1/2}\nu\Sigma$

$\Rightarrow u(x,t) = x\Delta(\nu\Sigma)$

$$\Delta\dot{M}(r,t) \propto \partial u(x,t)/\partial x.$$

Disk Evolution with a noise term

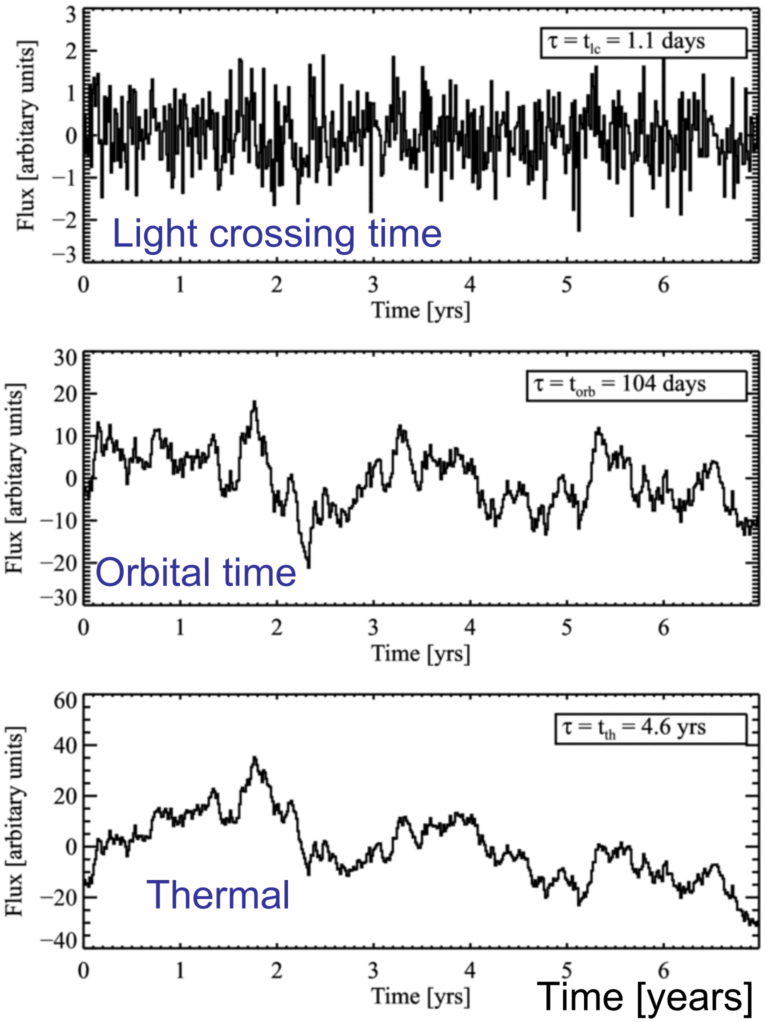
$$\frac{\partial u(x,t)}{\partial t} = \frac{3\nu(x)}{4}\frac{\partial^2 u(x,t)}{\partial x^2} + \frac{\partial W(x,t)}{\partial t}$$

$$\Delta\dot{M}(x,t) = 3\pi\frac{\partial u(x,t)}{\partial x}$$

$$u(x,0) = u_0(x)$$

$$u(0,t) = 0 = \frac{\partial u(x_{\max},t)}{\partial t}.$$

Simulating Optical Lightcurves



$M_{BH} = 10^8 M_{sun}$ and with different timescales
7 years, sampled every 5 days

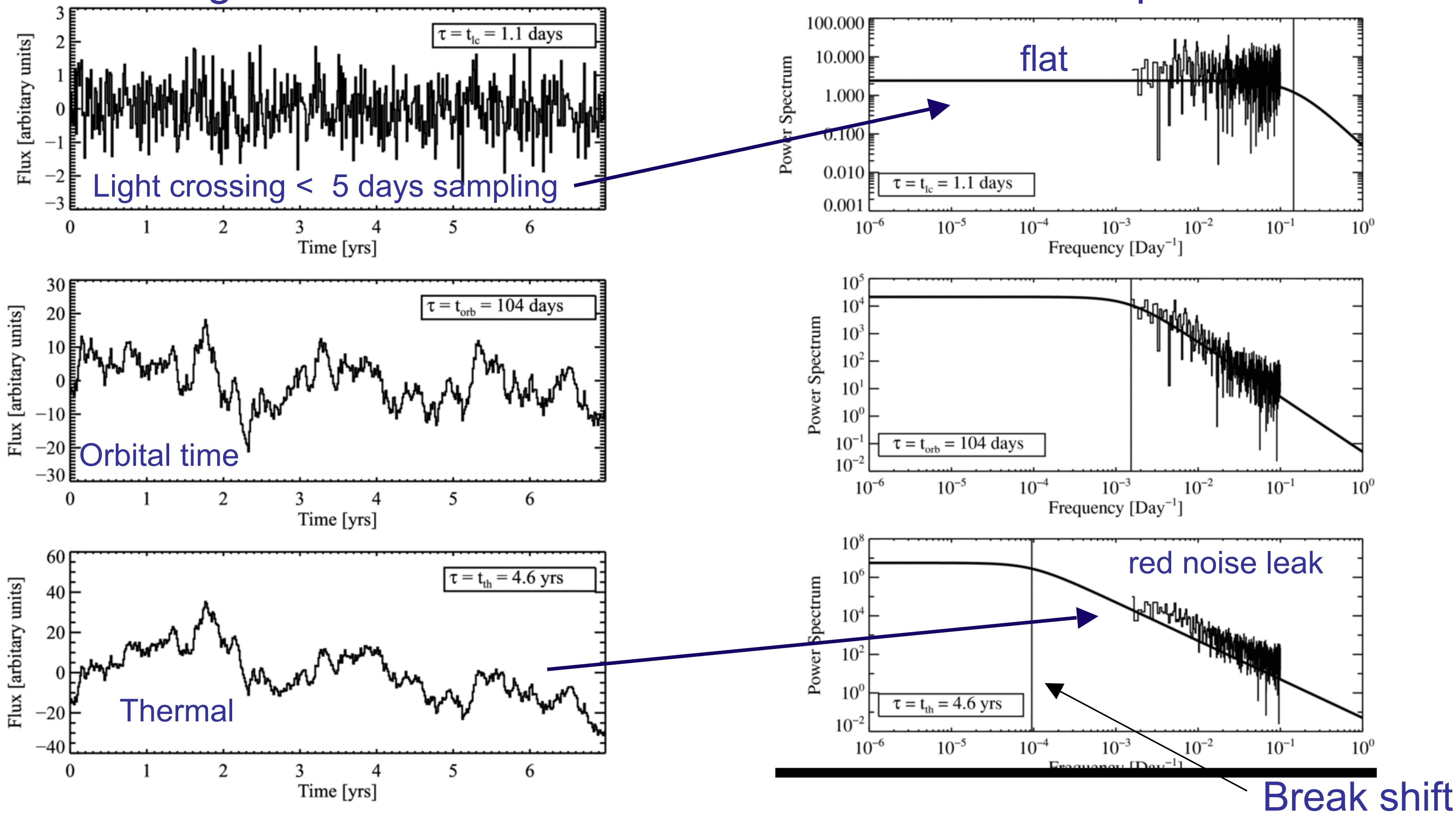
Kelly, Bechtold & Siemiginowska, 2009 ApJ 730 52

- Simple Stochastic process
- $P(f) \sim f^{-2}$ are consistent with damped random walk
- $P(f)$ - Break at the characteristic timescale of the process
- Possible link to physical parameters:

- Characteristic frequency, i.e. relaxation time of the process, might relate to the time required for diffusion to smooth out local accretion rate perturbations
- Amplitude of the driving noise, variability resulting from local turbulence or other perturbations to the magnetic field etc.

Simulating Optical Lightcurves

CAR Lightcurves — Power Spectrum

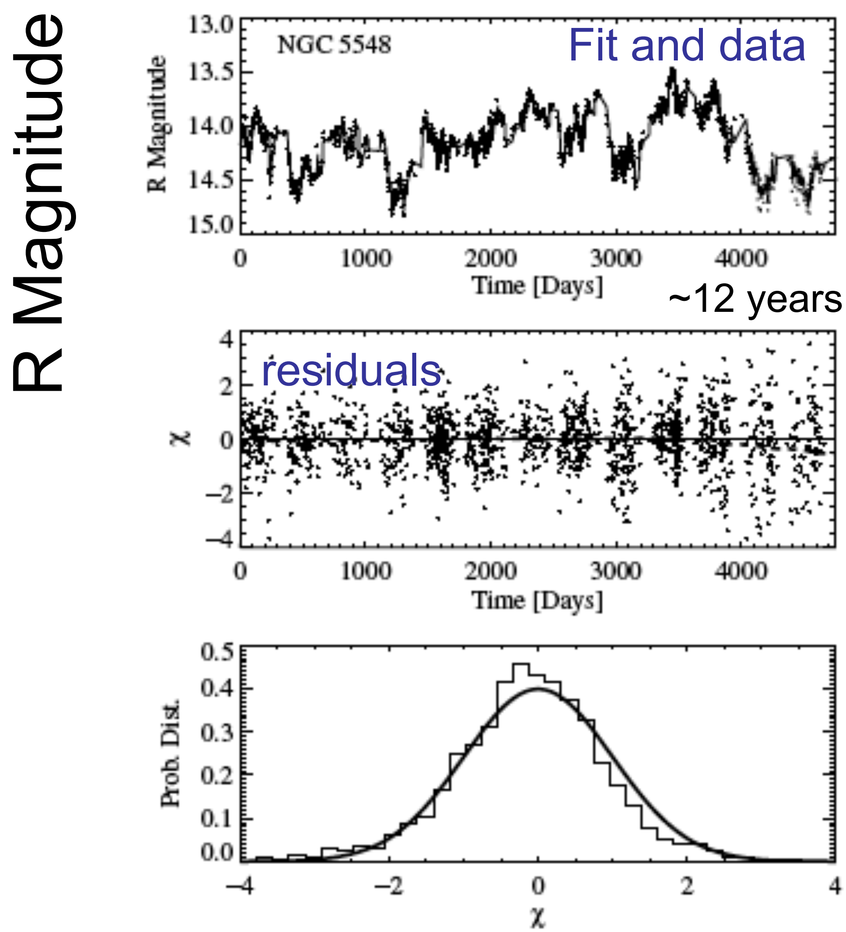


Kelly, Bechtold & Siemiginowska, 2009 ApJ 730 52

$M_{BH} = 10^8 M_{sun}$ and with different timescales
7 years, sampled every 5 days

Modeling Optical Light curves

NGC 5548



- 100 quasars with optical light curves
- Defined likelihood and performed MCMC analysis to model the observed light curves.
- Best fit light curve, characteristic timescales and variability parameters
- NGC 5548 fit with the characteristic timescale of 214 days

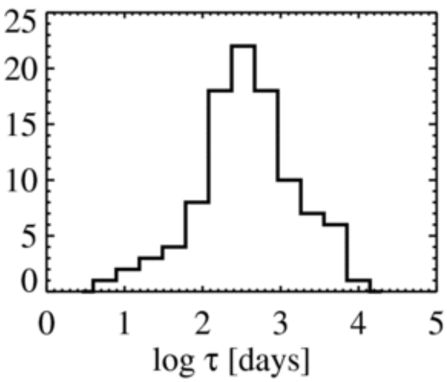
$$p(x_1, \ldots, x_n | b, \sigma, \tau) = \prod_{i=1}^{n} \left[2\pi\left(\Omega_i + \sigma_i^2\right)\right]^{-1/2} \times \exp\left\{-\frac{1}{2}\frac{\left(\hat{x}_i - x_i^*\right)^2}{\Omega_i + \sigma_i^2}\right\} \quad (6)$$

$$x_i^* = x_i - b\tau \quad (7)$$

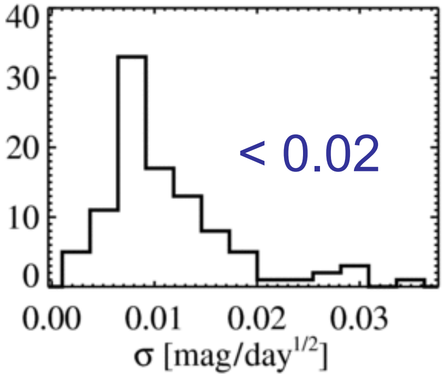
Modeling Optical Light curves

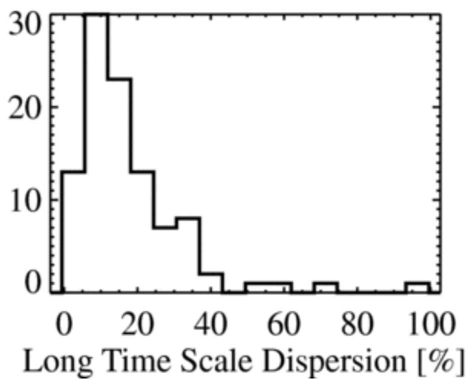
Sample of 100 quasars: MACHO, PG sample, AGN Watch

timescale $10\text{-}10^4$ days

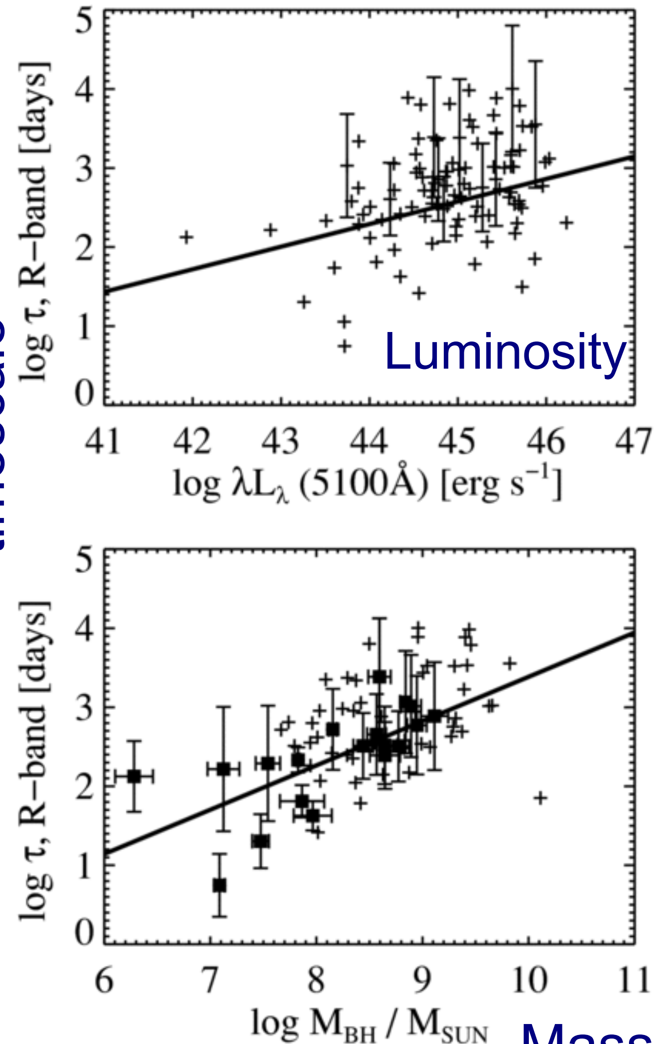


Short-term variations





timescale



Mass

Model Comparison: Deterministic v. Stochastic

6304 quasars
SDSS Stripe 82
20 models

Bayes Factors
for model comparison

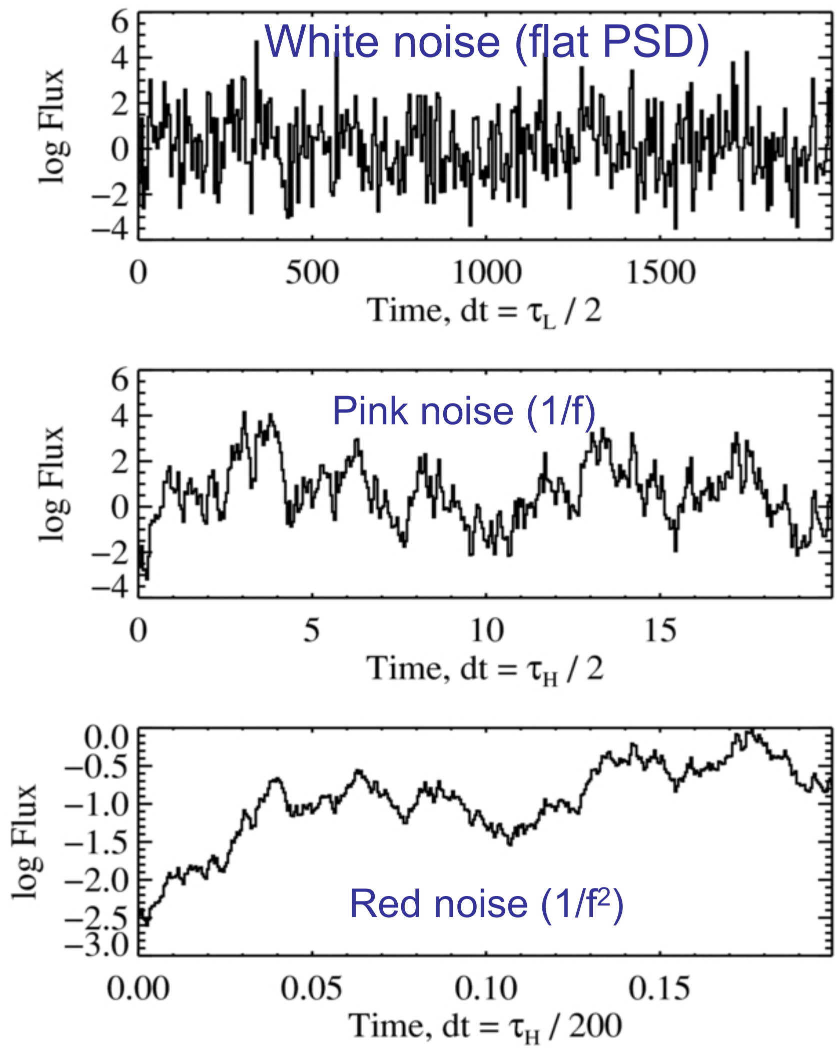
Results of evidence-based model comparison.

Model	Number of model parameters	No decisive evidence against it at 3σ	No decisive evidence against it at 5σ	No decisive evidence against it at 7σ	No decisive evidence against it at 10σ	Max evidence
Constant	1	0	0	0	0	0
Constant plus noise	2	59	64	73	94	4
Sinusoid (flat prior in P)	4	28	37	46	58	2
Sinusoid (flat prior in $\log P$)	4	20	23	29	39	2
Sinusoid (periodogram prior)	4	27	30	39	50	4
Two sinusoids (flat priors in P)	7	33	36	45	60	7
Sinusoid (flat prior in P) plus noise	5	467	583	721	921	149
Wiener process (random walk)	2	2205	2724	3230	3949	11
OU process (damped random walk)	3	6023	6069	6093	6131	5047
Gaussian CAR(2) process ($\varphi_1 = \varphi_2 = 0.1$)	2	0	0	0	1	0
Gaussian CAR(2) process ($\tau_1 = \tau_2$)	3	1	2	2	3	0
Gaussian CAR(2) process ($\tau_1 \neq \tau_2$)	4	5	5	5	5	5
Cauchy CAR(1) process ($\varphi = 1$)	2	81	108	172	361	36
Symmetric stable CAR(1) process ($\varphi = 1, \beta = 0$)	3	0	0	0	0	0
Stable CAR(1) process ($\varphi = 1$)	4	0	0	0	0	0
Gaussian CARMA(1, 1) process	4	0	0	0	0	0
Constant + Gaussian ARCH(1) process	3	236	268	306	355	69
Sinusoid + Gaussian ARCH(1) process	6	923	1208	1529	2096	155
Gaussian CAR(1)-ARCH(1) process	4	1884	2257	2639	3183	219
Gaussian CAR(1)-GARCH(1, 1) process	5	3542	3912	4285	4751	536
Gaussian CARMA(1, 1)-GARCH(1, 1) process	6	1533	2041	2593	3486	58

Notes.For each model under consideration we quote the number of model parameters, the number of QSO lightcurves where there is no decisive evidence against this model at a specified confidence level, and the number of QSO lightcurves where each model provides the highest evidence. The upper block of the table contains deterministic models. The middle block contains stochastic models with constant variance, while the lower block contains stochastic process with stochastic variance. (Periods of all sinusoids are between 1 and 10 000 days.) The last column adds up to the total of 6304 QSO lightcurves, the other columns do not.

Andrae, Kim D-W, Bailer-Jones, 2013, A&A, 554, A137

Simulating X-ray Light curves



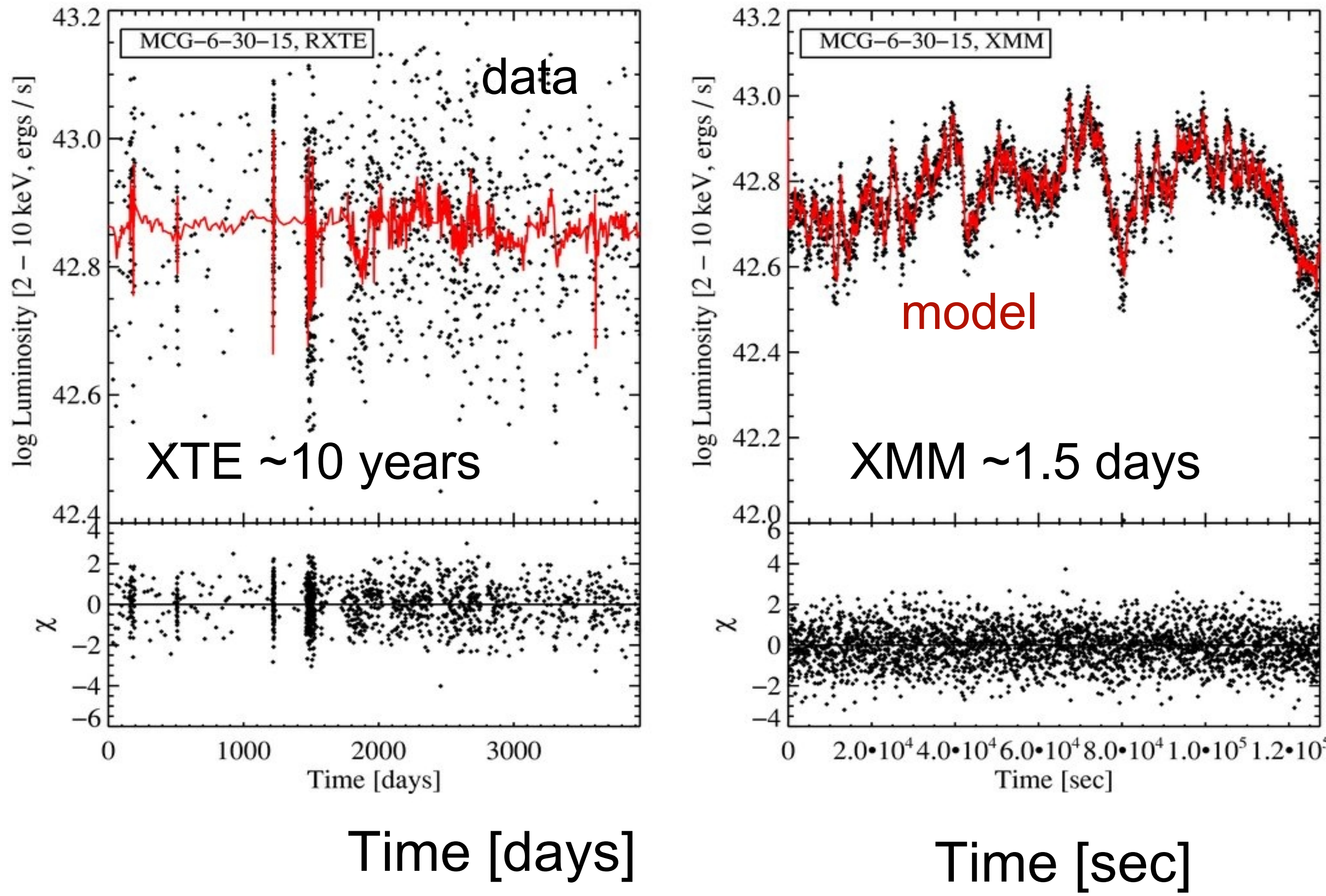
- X-rays from hot corona
- **Two breaks in PSD** =>
  two characteristic timescales
- **Linear Combination** of Stochastic processes
- Model light curves - Likelihood analysis

Observations probe different parts of the same process

Kelly, Sobolewska & Siemiginowska, 2011 ApJ 730 52

Modeling X-ray Variability

MCG-6-30-15



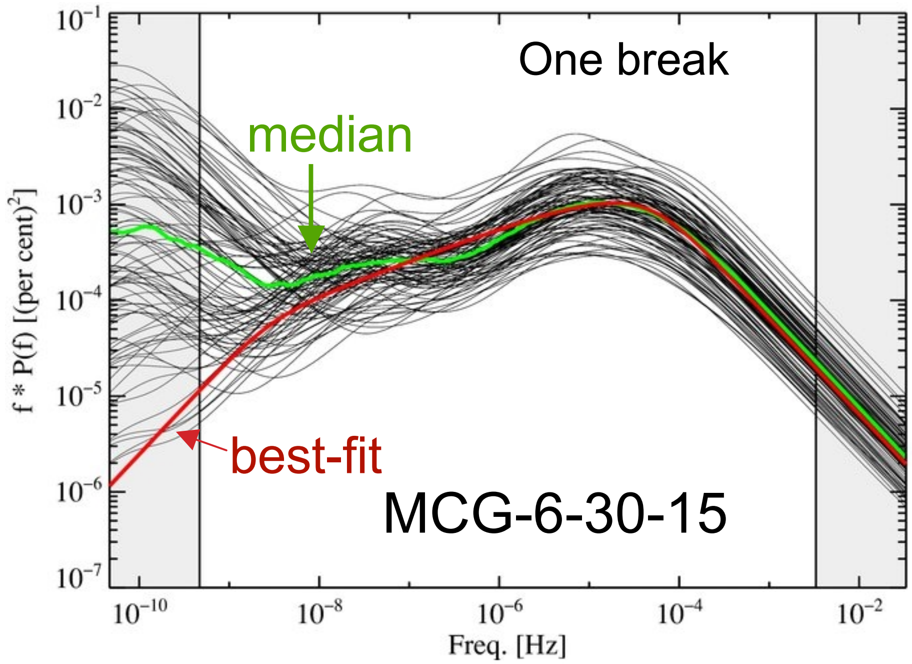
Time [days]

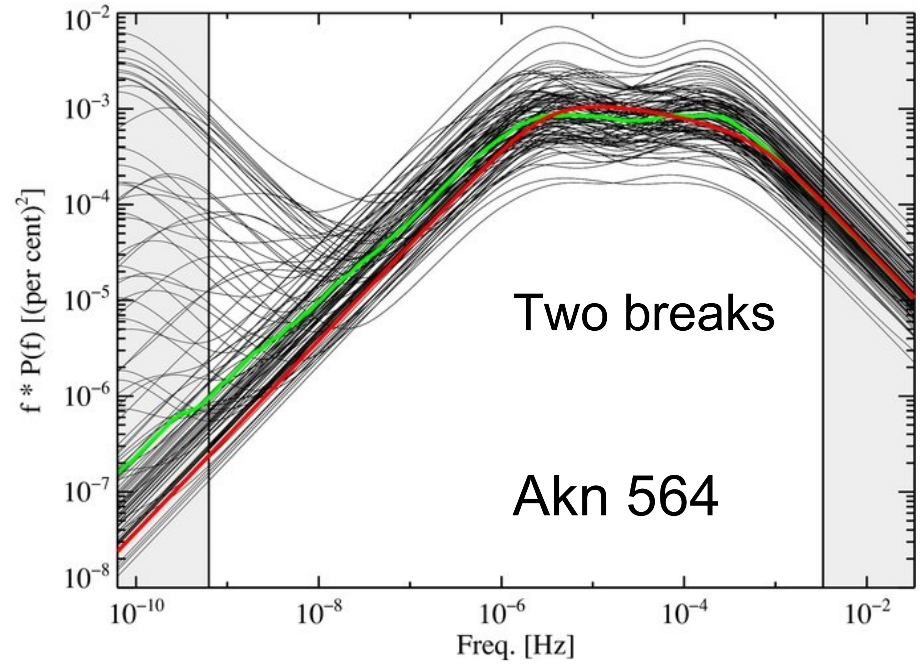
Time [sec]

Kelly, Sobolewska & Siemiginowska, 2011 ApJ 730 52

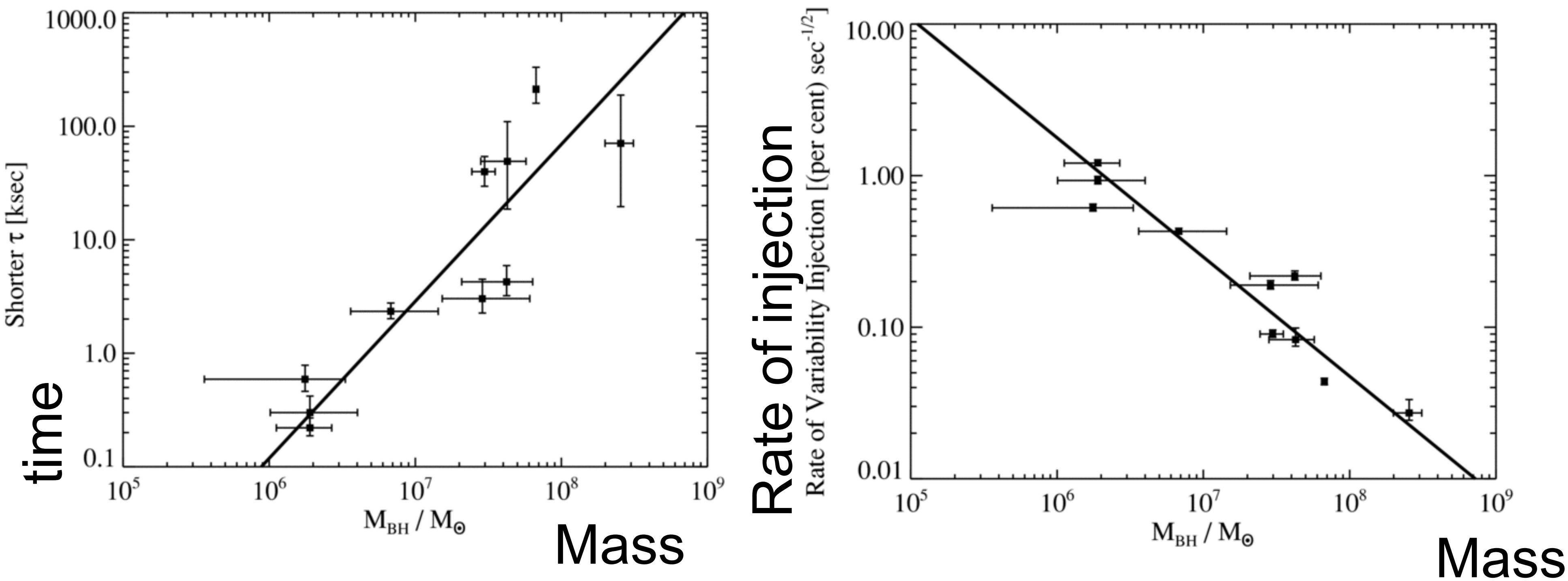
Modeling X-ray Variability

100 realizations of the PSD given the observed lightcurves





Modeling X-ray Light Curves

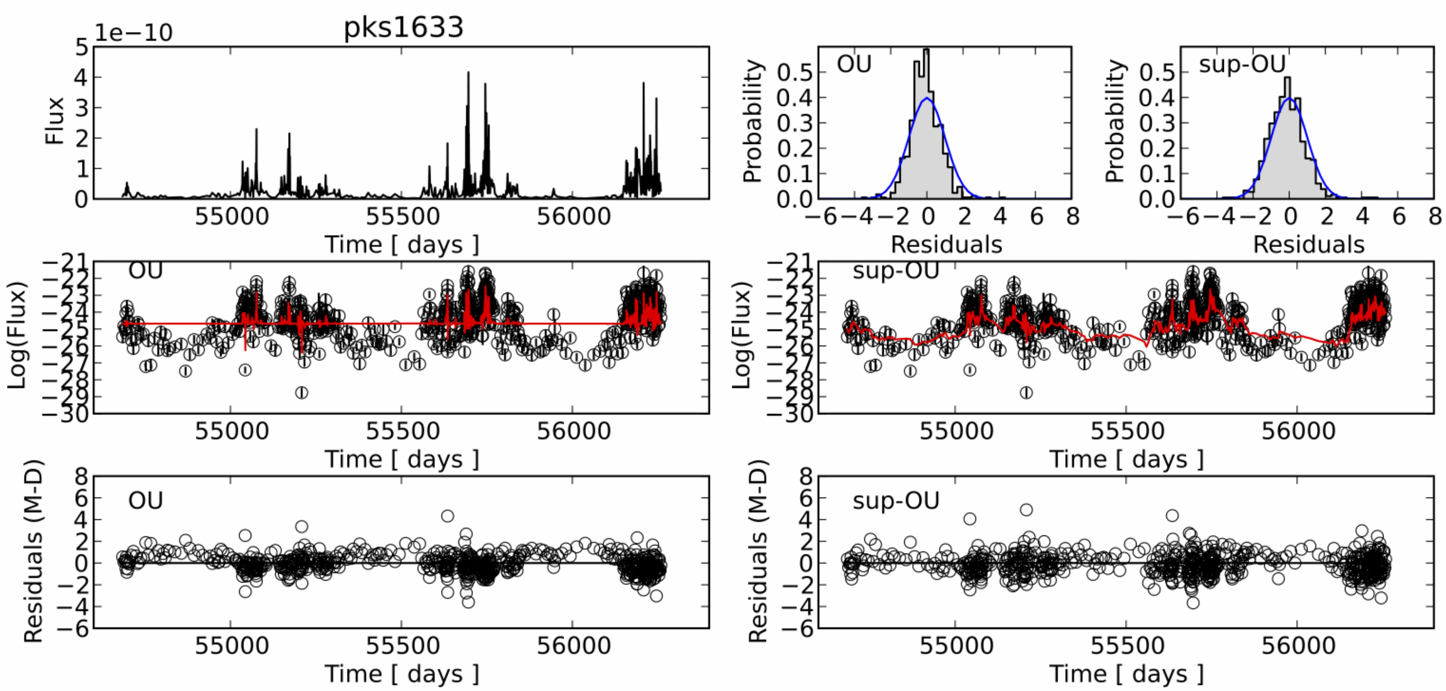


Best method to measure a black hole mass (see also Kelly et al 2013 for Poisson case)

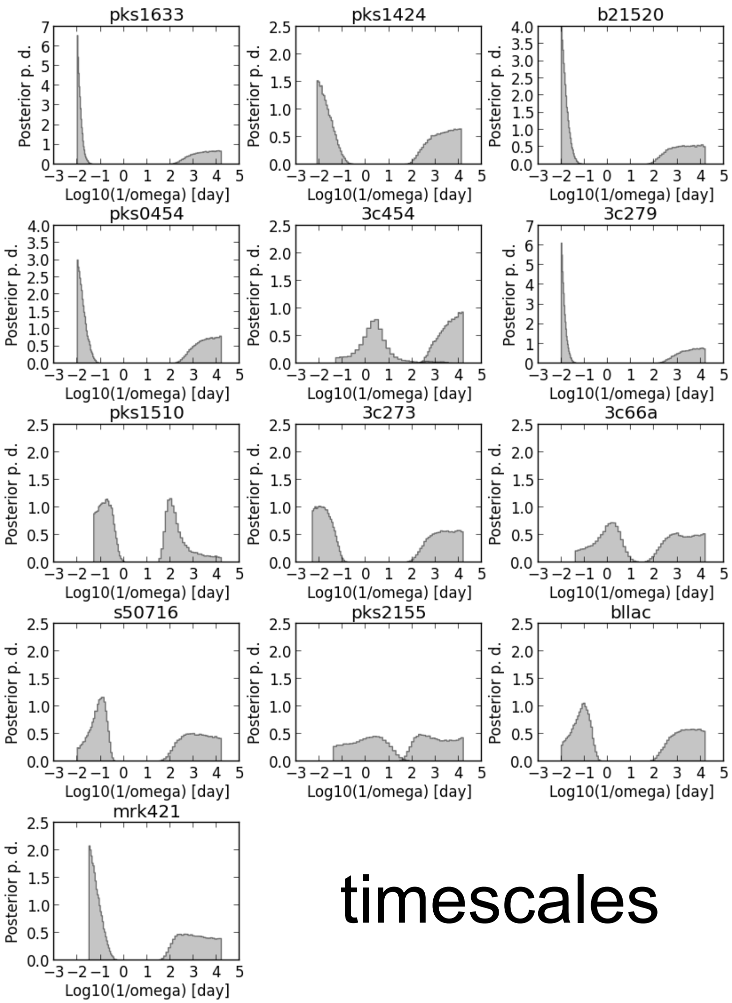
Modeling γ-ray Light Curves

Single OU process

Superposition

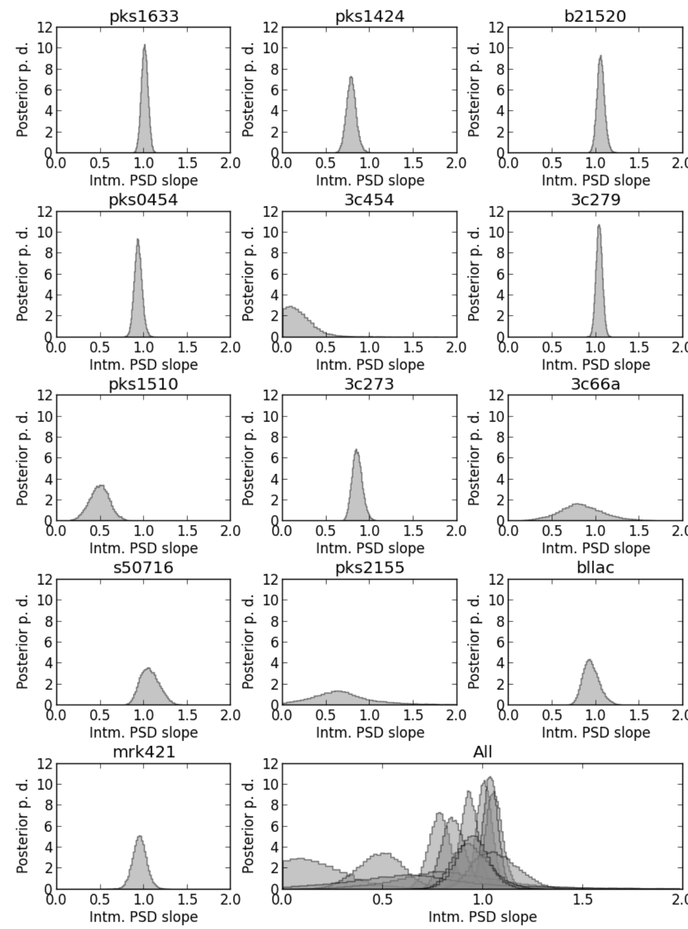


Modeling γ-ray Light Curves



timescales

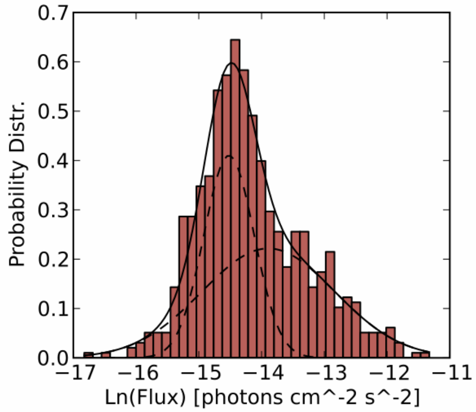
PSD slope



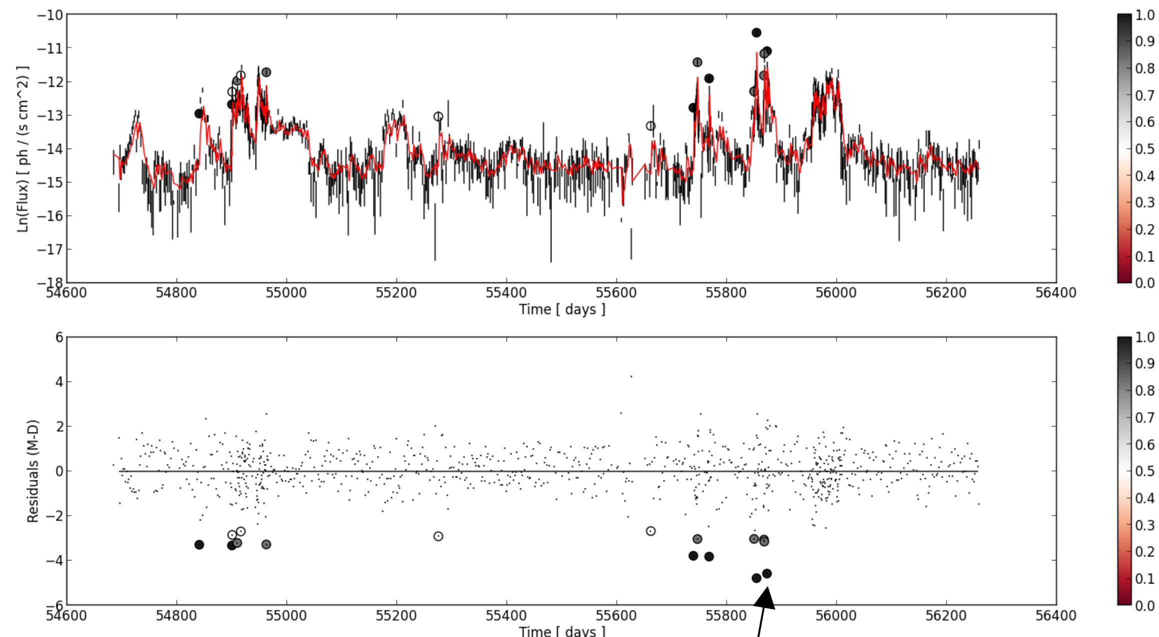
Modeling γ-ray Light Curves: Outliers

How can we separate the flares/outbursts from the continuous stochastic variations?

Flux

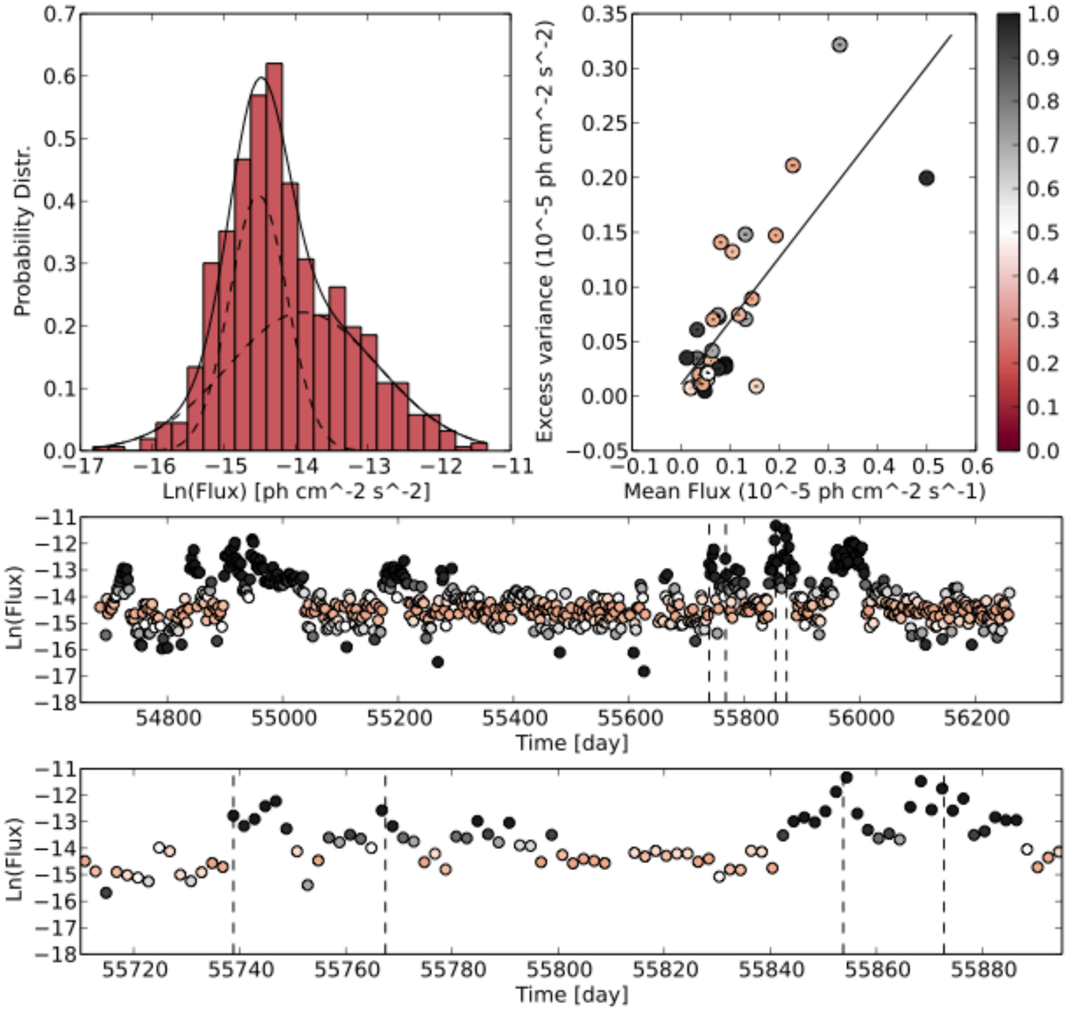


Bi-modal



outliers

Identifying Flares



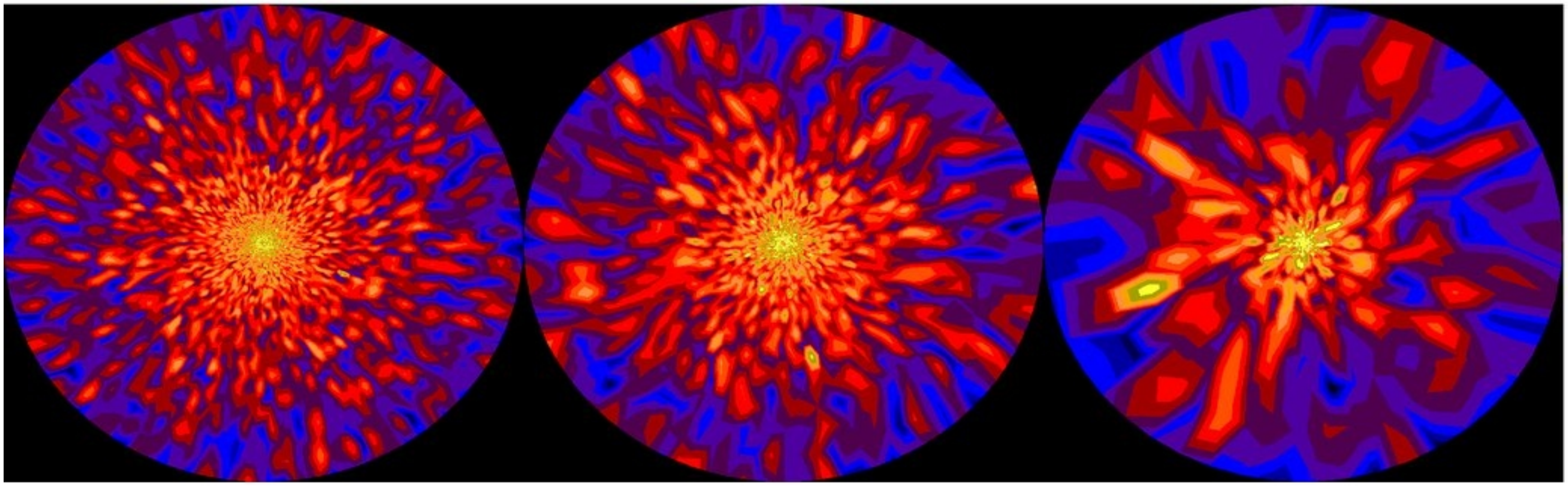
When does the flare begin?

Modeling Light Curves: Summary

- Variations consistent with the stochastic process -perturbations to the luminosity could be caused by magnetic turbulence.
- Perturbations smoothed on the timescales shorter than the orbital or thermal timescales
- Timescales correlates with M_{bh} and luminosity
- Significant anticorrelation between M_{bh} the amplitude of the driving noise => very good constraints on the mass.
- Both short and long-term observed light curves due to the same process.
- Origin of optical and X-ray variations partially shared.
- Mixed stochastic process describes the evolution of viscous, thermal and radiative perturbations

Stochastic View of the Accretion Disk

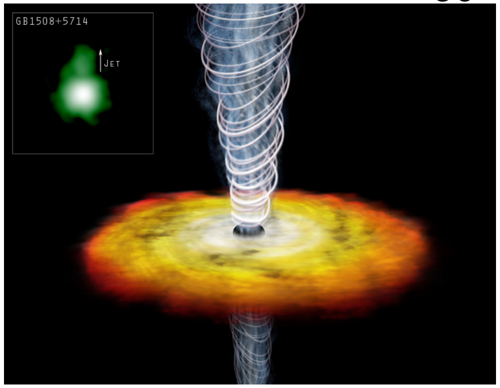
Dexter and Agol 2011 ApJ 727 L24



n=2200 n=550 n=140

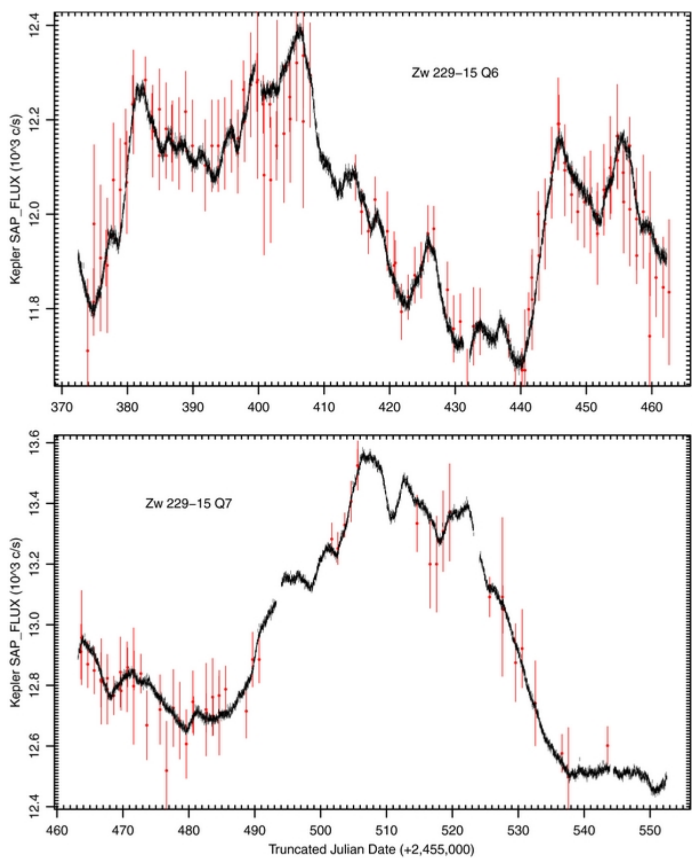
Temperature maps assuming that Temp(ϕ, r, $time$) follows a damped random walk in each independent zone n assuming the local temperature characteristic timescale of 200 days.

Outbursts, Flares and Shortest Timescales

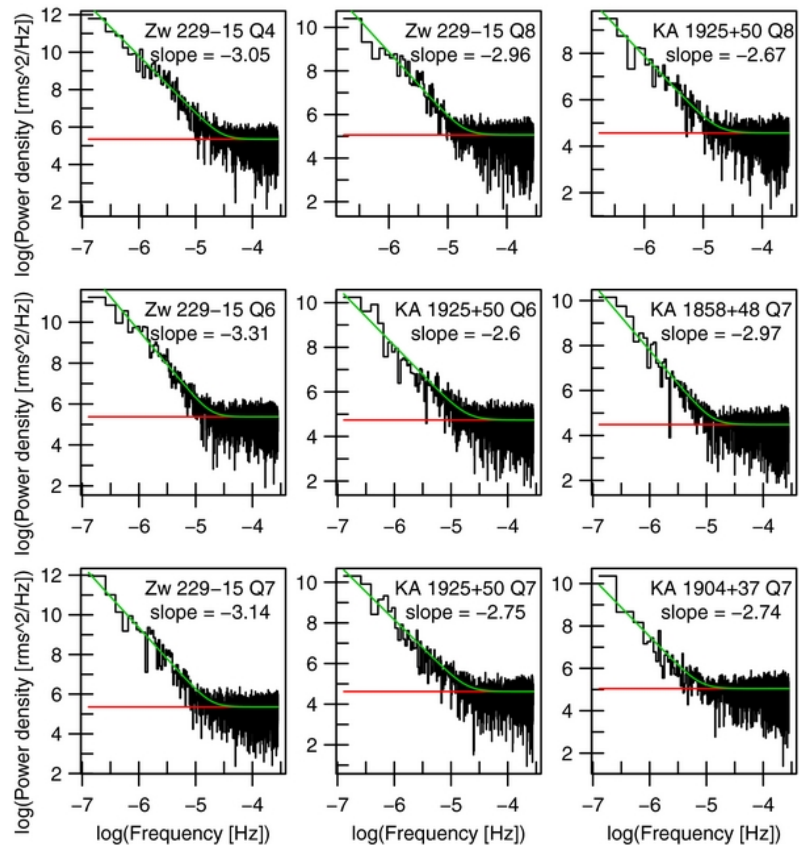


- Large amplitude, rapid rise and short durations events are not described by the stochastic random walk in linear regime - variability due to physical processes related to a relativistic jet?
- Best observational examples of rapid outbursts can be found in gamma-rays and TeV
- Optical variations in Kepler data - probe shortest dynamical timescales, these data are not consistent with the linear regime

Optical lightcurves from Kepler



slope < -2

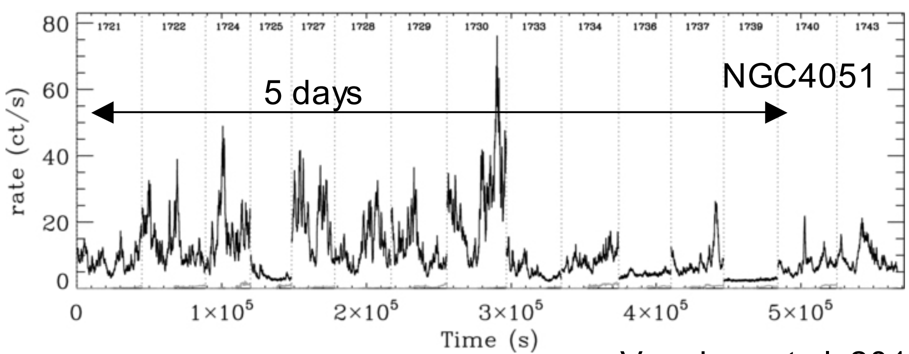


Future Projects

How to model the flares?

Non-linear models for Kepler light curves

XMM-Newton X-rays



Vaughan et al. 2011