An introduction to X-ray variability from black holes

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What do I hope to achieve?

Introduce some basic ideas that will be used a lot in the talks that follow

But the scope of this talk is rather limited…

Will focus on:

- XRBs and radio-quiet AGN (not ULXs)
- One-band only (no spectral-timing, interband correlations)
- detailed studies of individuals, small samples – not massive time domain surveys
- No time for “exceptions” like GRS 1915+105
- Timescales << typical postdoc contract

Fiducial timescales, frequencies

$$f_{lc} \sim 2\times10^5 \left(\frac{r}{r_g}\right)^{-1} \left(\frac{M}{M_\odot}\right)^{-1} \text{Hz} \qquad \left[\left(\frac{GM_\odot}{c^3}\right)^{-1} = 2\times10^5\right]$$

$$f_{dyn} \sim 2\times10^5 \left(\frac{r}{r_g}\right)^{-3/2} \left(\frac{M}{M_\odot}\right)^{-1} \text{Hz} \sim 2\pi f_{orb}$$

$$f_{therm} \sim f_{orb}\alpha$$

$$f_{visc} \sim f_{orb}\alpha\left(\frac{h}{r}\right)^2$$

Timescale	10 M_{sun}	10^6 M_{sun}
Light crossing	3×10^3 Hz (0.3 ms)	30 mHz (30 s)
Orbital	200 Hz (5 ms)	2 mHz (500 s)
Thermal	20 Hz (50 ms)	0.2 mHz (5 ks)
Viscous	0.2 Hz (5 s)	2×10^{-6} Hz (500 ks)

[assuming $\alpha \sim 0.1$, $h/r \sim 0.1$, $r/r_g \sim 6$]

could be much longer

Time series (aka light curves)

“Aperiodic”, “random”, “stochastic”

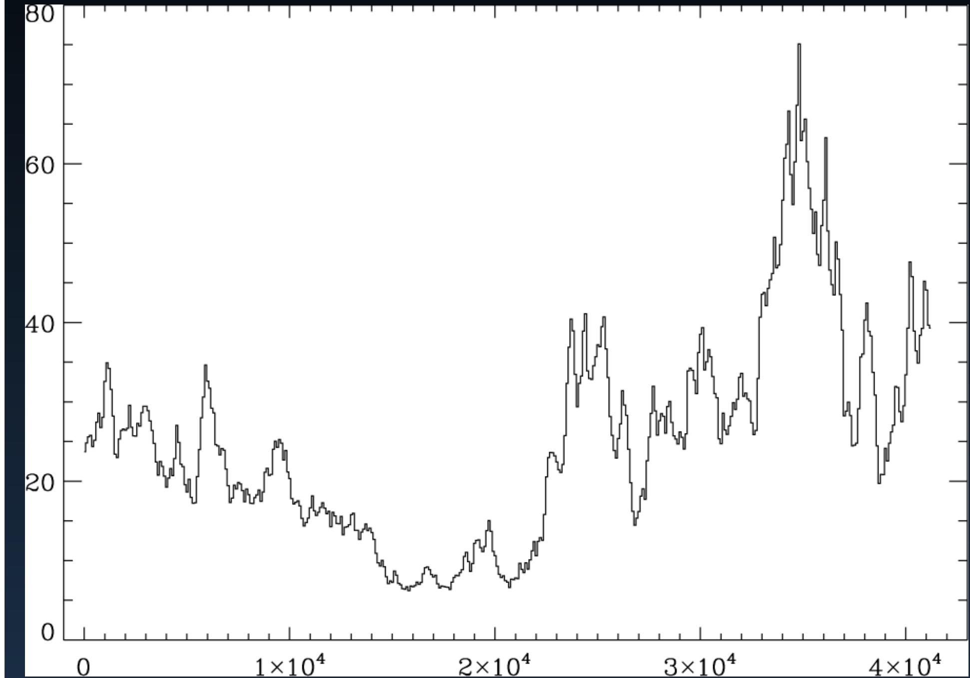
As we can fully describe a random variable in terms of its distribution, or moments (mean, variance, skew, …)

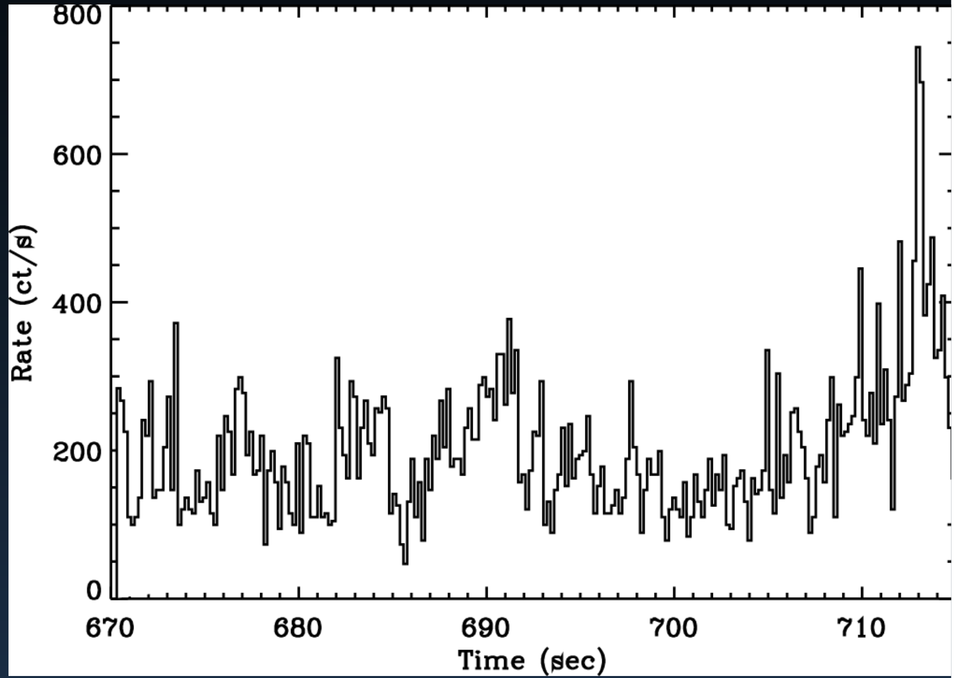
So we can describe a random time series in terms of its “distribution”: mean, auto-correlation function (ACF), higher-order moments

ACF and power spectrum are Fourier pairs

Power spectrum: distribution of variance, as function of frequency (~1/timescale)

Modern X-ray light curves

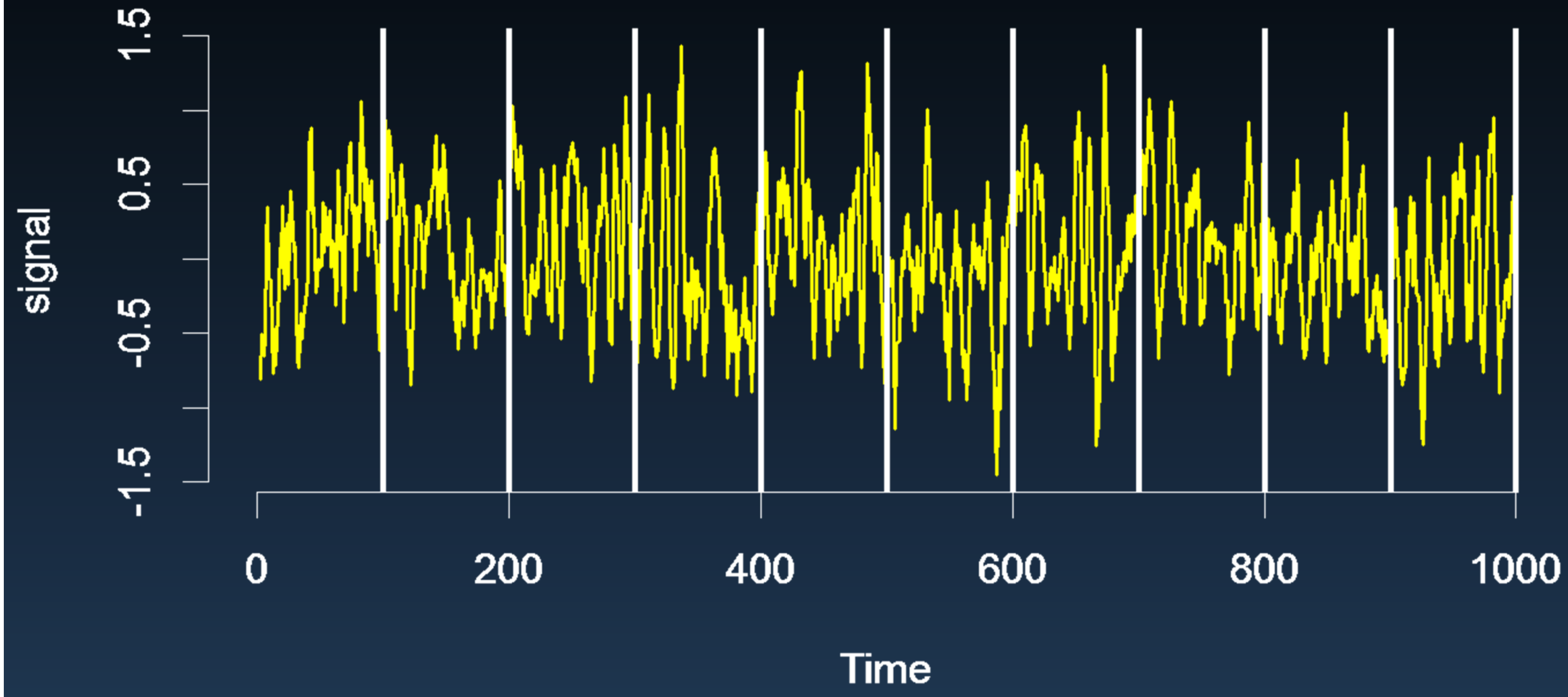




AGN (NGC 4051)
with XMM (0.2-10 keV)
0.5 day of data, with 50s resolution

XRB (GX 339-4)
with XMM (0.2-10 keV)
0.5 s of data, with ~0.2s resolution

Standard recipe



The most popular spectral estimate (in astronomy, at least) is the averaged periodogram: raw periodograms from each of M non-overlapping intervals are averaged. ‘Barlett’s method’ after M. S. Bartlett (1948, *Nature,* 161, 686-687)

Standard recipe:
Power spectrum analysis

observed = signal + noise
(not quite right!)

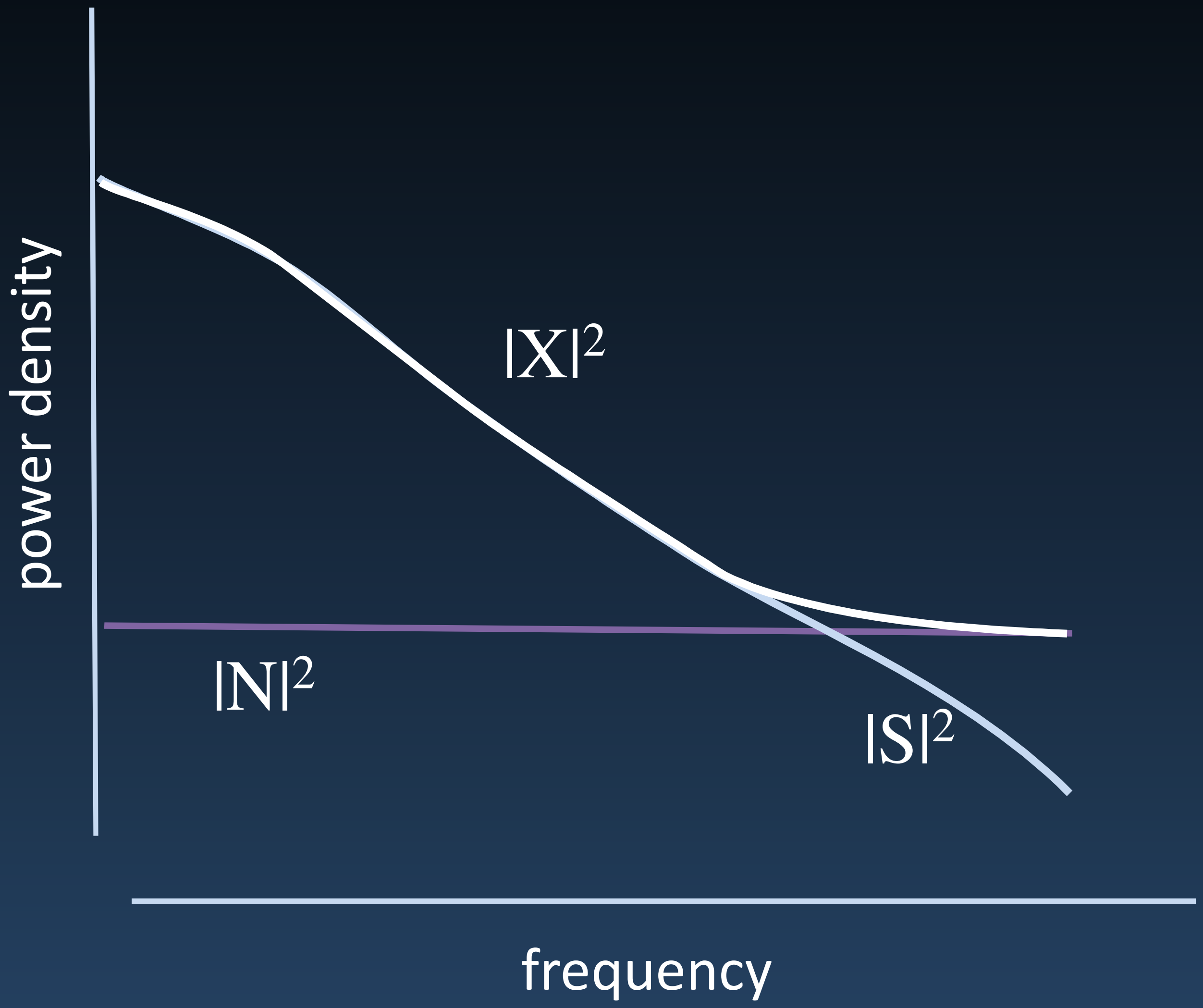
$$x = s + n$$

Fourier transforms
$$X = S + N$$

Periodogram
$$|X|^2 = |S|^2 + |N|^2 + \text{cross} - \text{terms}$$

Spectrum
$$P(f) = \left\langle |S|^2 \right\rangle = \left\langle |X|^2 \right\rangle - \left\langle |N|^2 \right\rangle$$

Standard recipe:
Power spectrum analysis



A message from Captain Data:

"More lives have been lost looking at the raw periodogram than by any other action involving time series!"

(J. Tukey 1980; quoted by D. Brillinger, 2002)

what we get (periodogram) → I_j

what we want → $P(f_j)$

chi-sq variable → χ_2^2

$$I_j \sim P(f_j)\chi_2^2 / 2$$

large scatter (~100%) and asymmetric distribution to each periodogram point.
And this is only true in the large N limit…

A message from Captain Data:

"More lives have been lost looking at the raw periodogram than by any other action involving time series!"

(J. Tukey 1980; quoted by D. Brillinger, 2002)

Fejer kernel

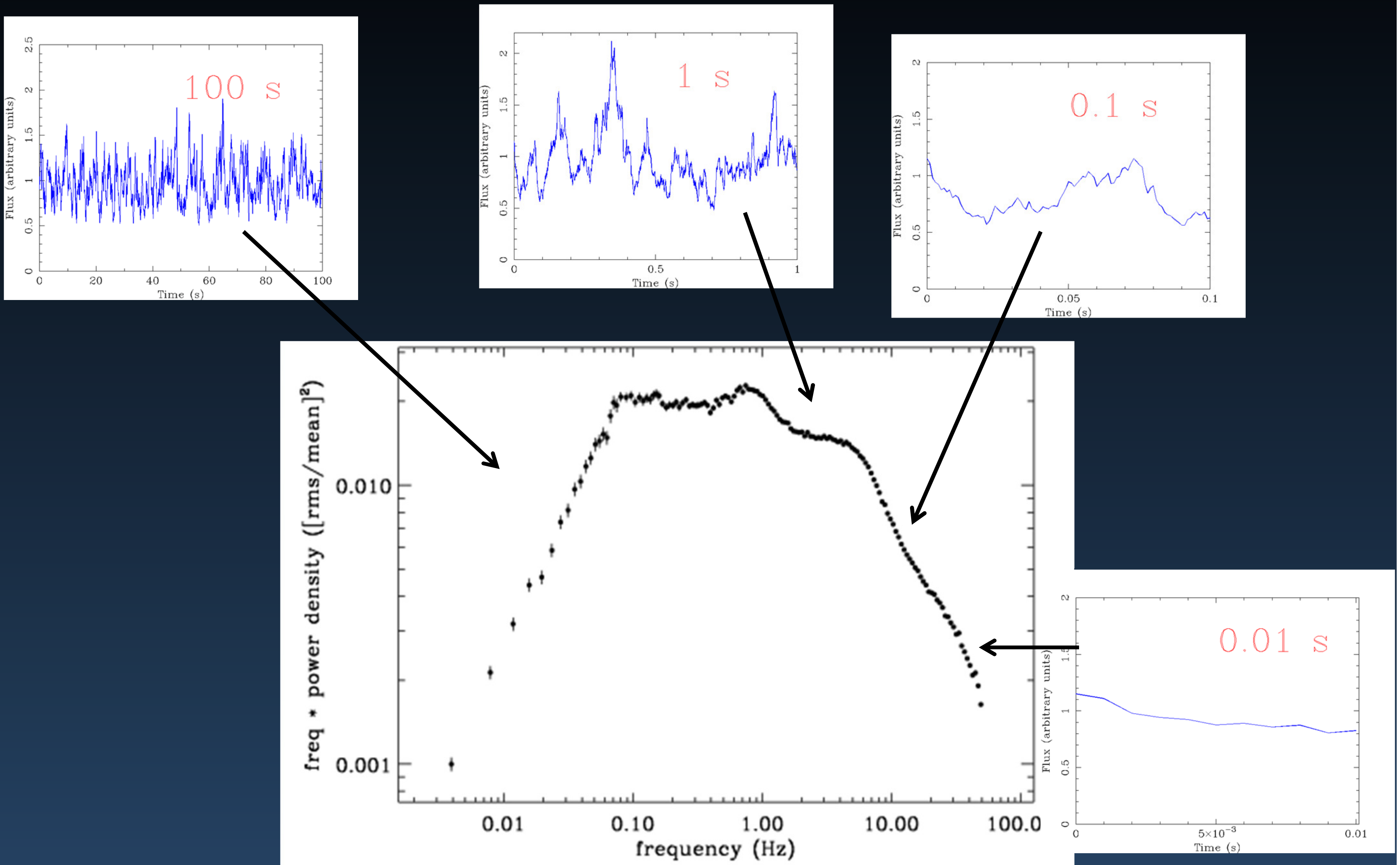
what we get (on average)

what we want

$$E[I_j] = \int_{-f(Nyq)}^{+f(Nyq)} F(f_j - f')P(f')\,\mathrm{d}f' = P(f) - bias[f]$$

even when we can "beat down" the intrinsic fluctuations in the periodogram, biases – in the form of ***leakage*** and ***aliasing*** – can be difficult to overcome. Especially true when N not **really** large, and variability is still "red"

Example power spectrum



power spectral features (zoology)

Broad-band noise (the “continuum”)

Previously modelled using piece-wise power laws

“soft state” power spectra often cut-off power law

Nowak (2000) and others showed Lorentzians work (for “hard state” power spectra)

See talks by L. Heil, A. Ingram (next)

Quasi-periodic oscillations (QPOs) are “peaked noise” (not periods) – bewildering phenomenology (but getting simpler?)

See S. Motta’s, Rapisarda’s and Steven’s talks (next)

In AGN?

See W. Alston’s talk (next)

X-ray binary power spectra

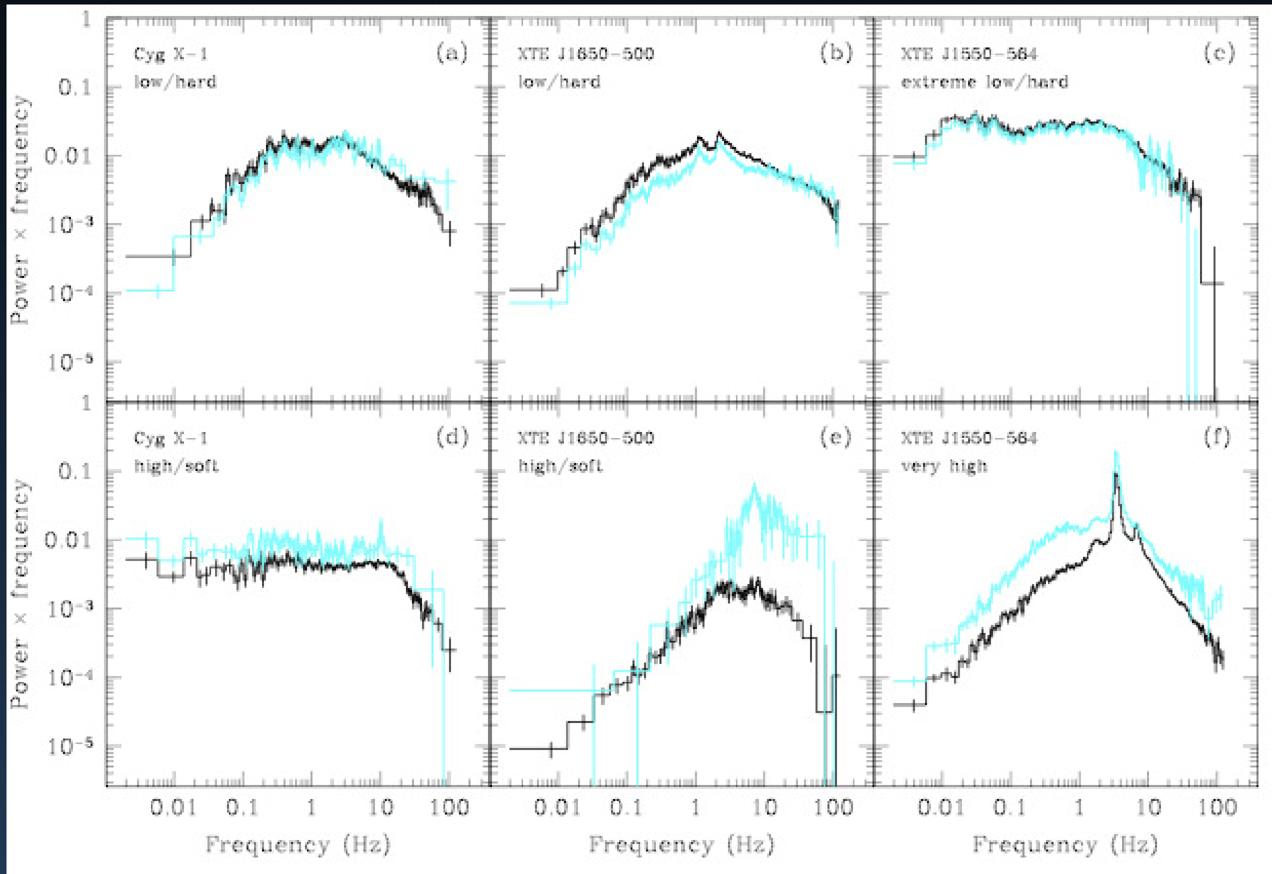
Usually dominated by "red noise"

Very broad range of frequencies

Broken power-law(s)

Or sum of broad Lorentzians

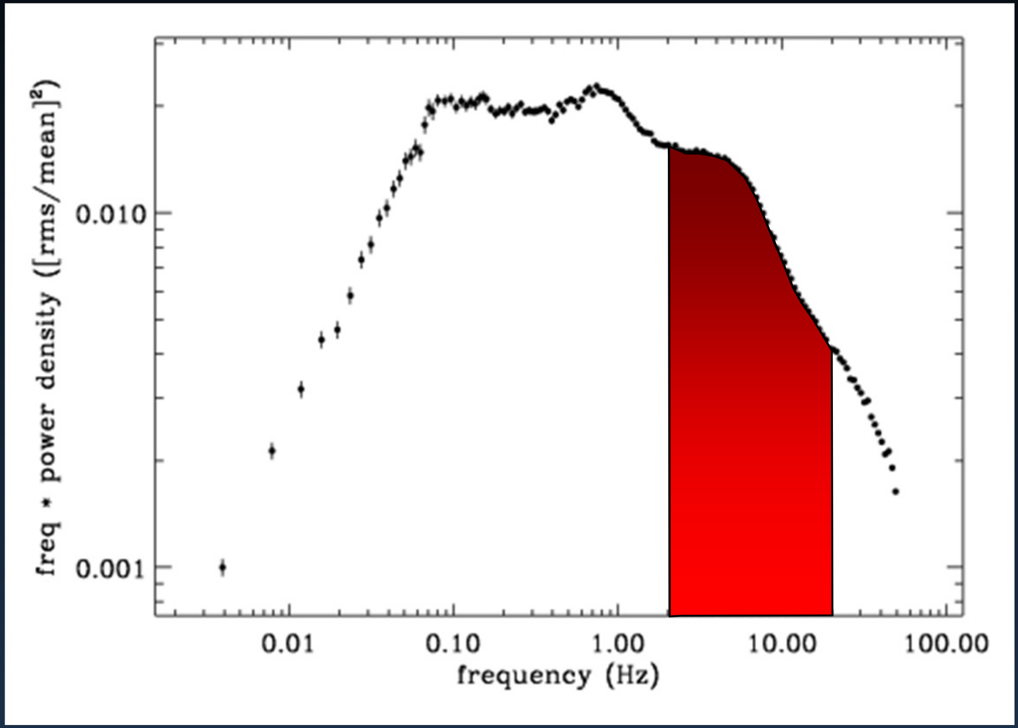
QPOs (width: $f/\Delta f > 2$)



Done & Gierlinski (2005)

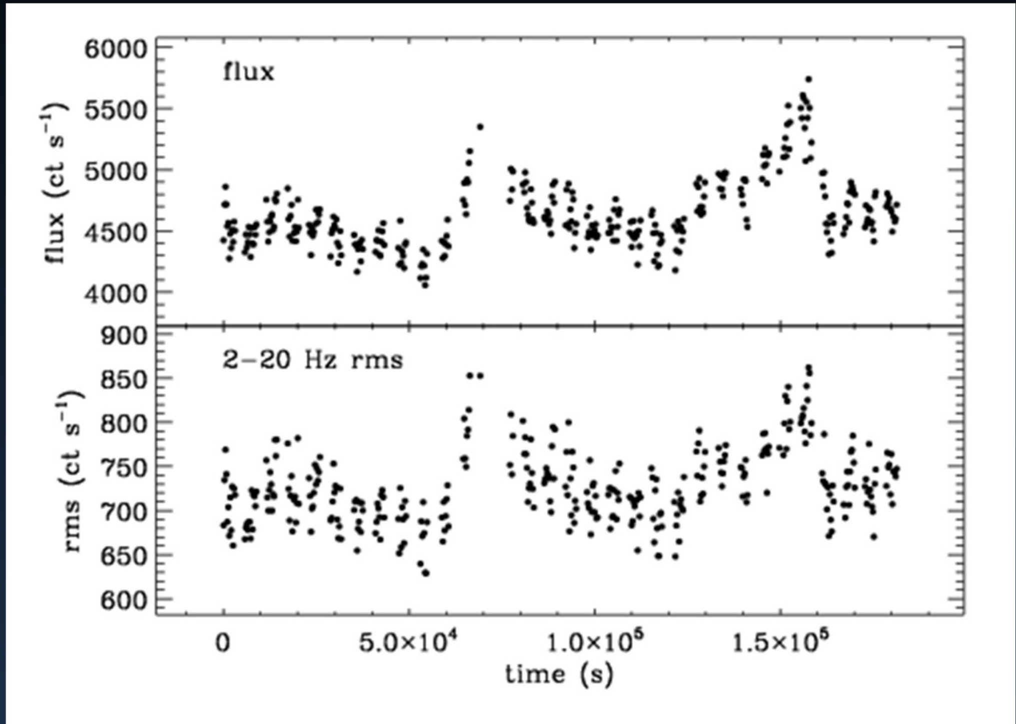
reviews by van der Klis (1989, 2006), Remillard & McClintock (2004, 2006)

Estimating rms



Variability dominated by broad-band noise (= aperiodic, stochastic, random)
Power spectrum contains all useful information *iff* stationary, Gaussian process
$\Rightarrow$ mean and variance (rms) do not change with time
We can integrate 2-20 Hz in many short data segments ($n\Delta t \geq 0.5$ s) and see…

rms-flux relation I

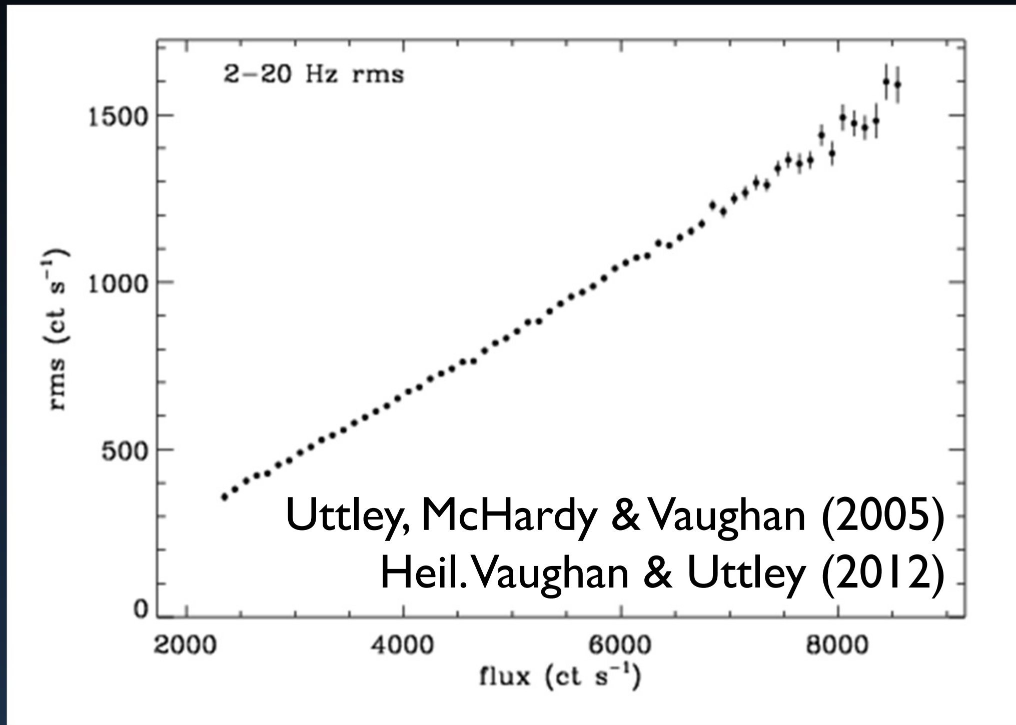


Average X-ray count rate (flux) over ΔT=256 sec segments (=65536Δt)

Calculate 2-20 Hz rms for each segment from periodogram

Compare time series of <flux> with rms

rms-flux relation II



Calculate <flux> and rms using $\Delta T=1$ sec segments

Average rms in flux bins to measure <rms> against <flux>

Use <rms> to reduce intrinsic scatter on rms

Strong linear relationship

In *all* accretion discs...?

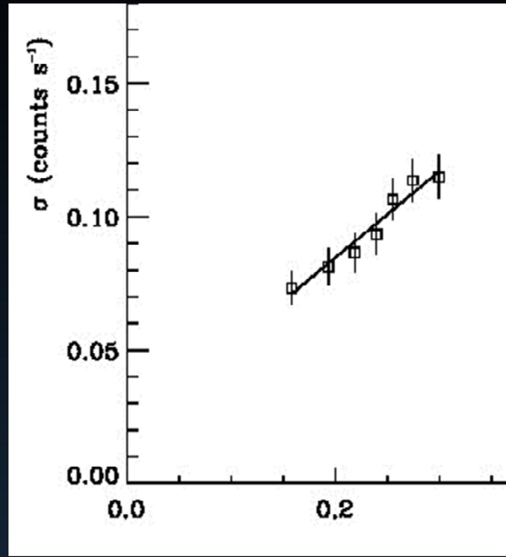
Optical fast variability of XRBs (Gandhi 2009)

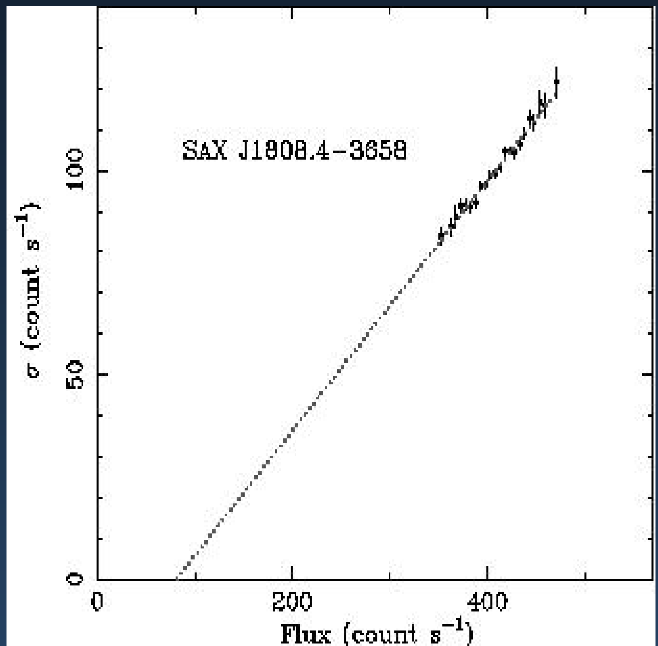
2 ULXs (Heil & Vaughan 2009)
[+Hernandez-Garcia, Vaughan et al. 2015]

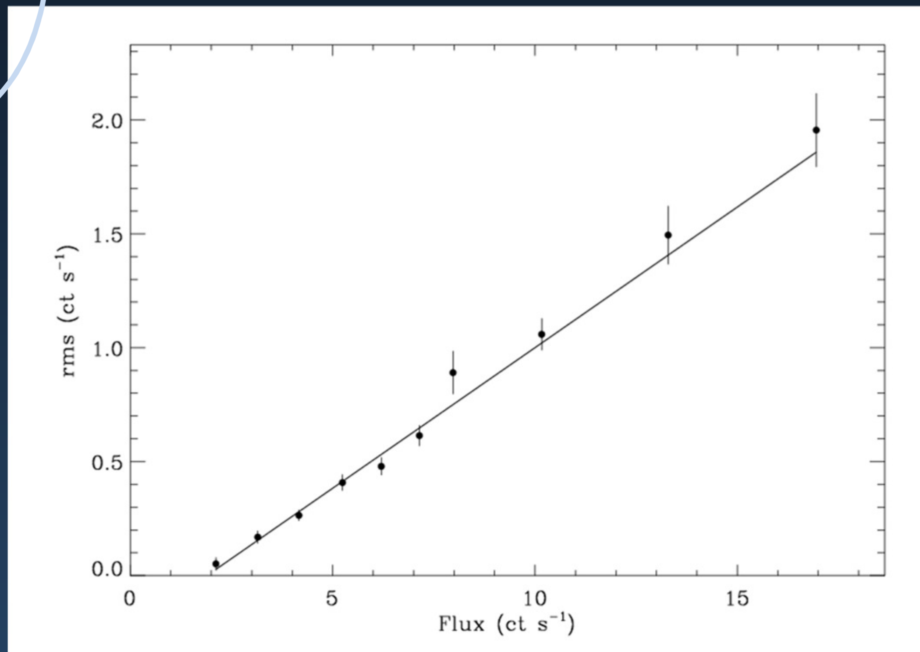
many Seyfert 1s (Vaughan et al. 2011)

neutron star XRBs (Uttley & McHardy 2001)

Also CVs (see Scaringi et al. 2014, 2015)



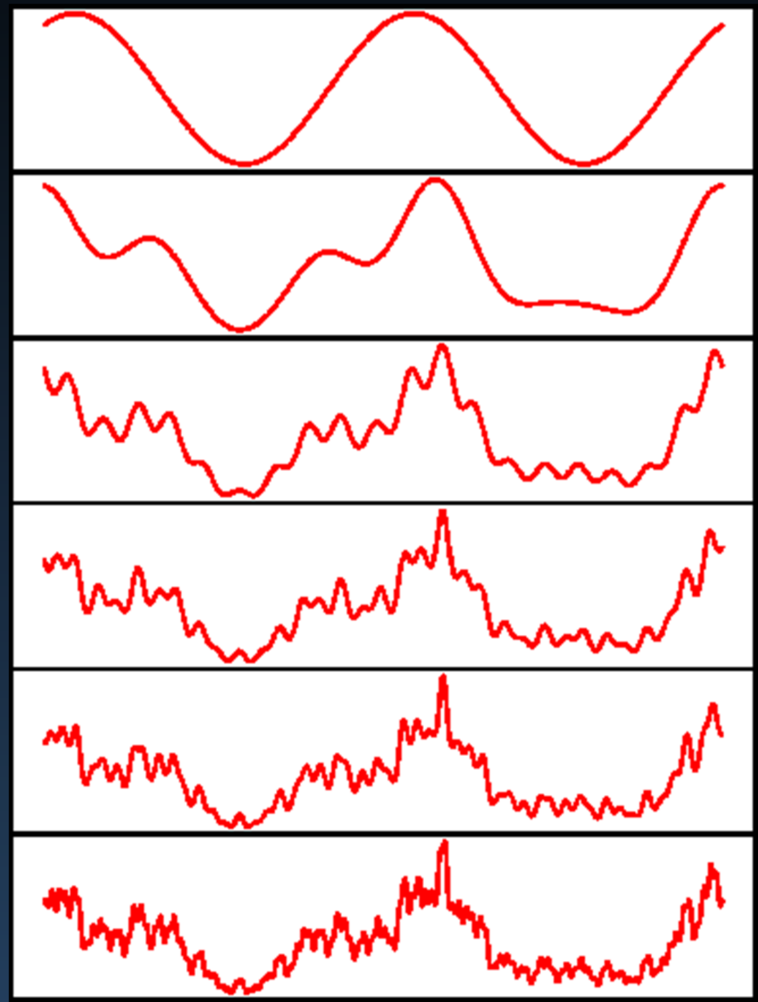




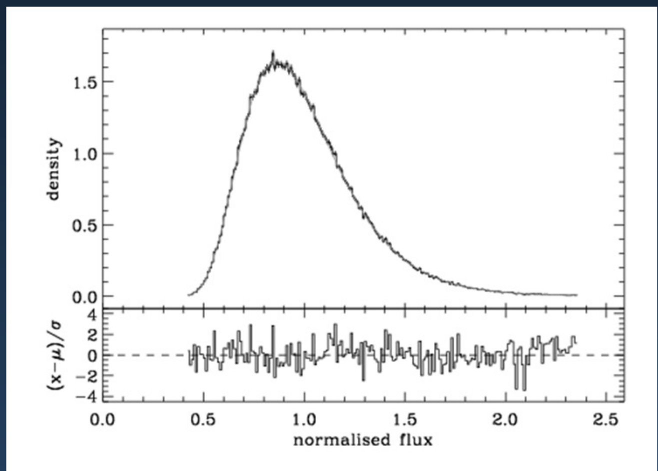
what does rms-flux mean?

"amplitude modulation":

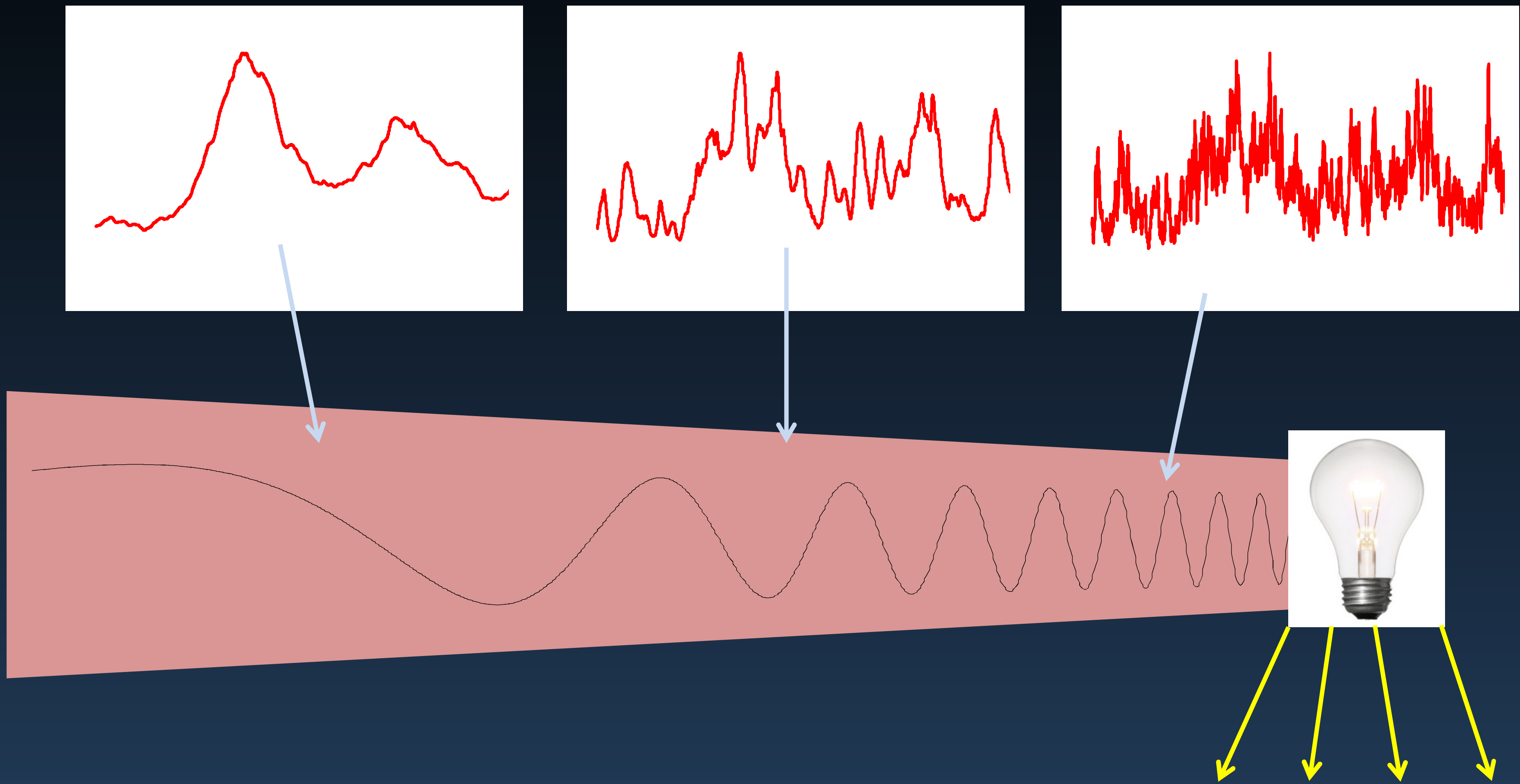
multiplicative coupling of variations on ***all*** timescales



The multiplicative analogue of a Gaussian (normal) stationary process is a *lognormal* stationary process.



What causes the variability?



(Lyubarskii 1997; Churazov et al. 2001; Kotov et al. 2001; King et al. 2004; Arevalo & Uttley 2006; Cowperthwaite & Reynolds 2014)

See talk by A. Ingram (next)

Other models are available

Are the F_x variations intrinsic (i.e. ~L_x)?

Or is L_x ~ constant and F_x varies due to extrinsic factors (e.g. line of sight absorption)

An important question!

Variable absorption does sometimes cause variability in AGN (see yesterday’s talks)

X-rays are “harder when fainter” (Seyfert 1s) – makes sense if absorption

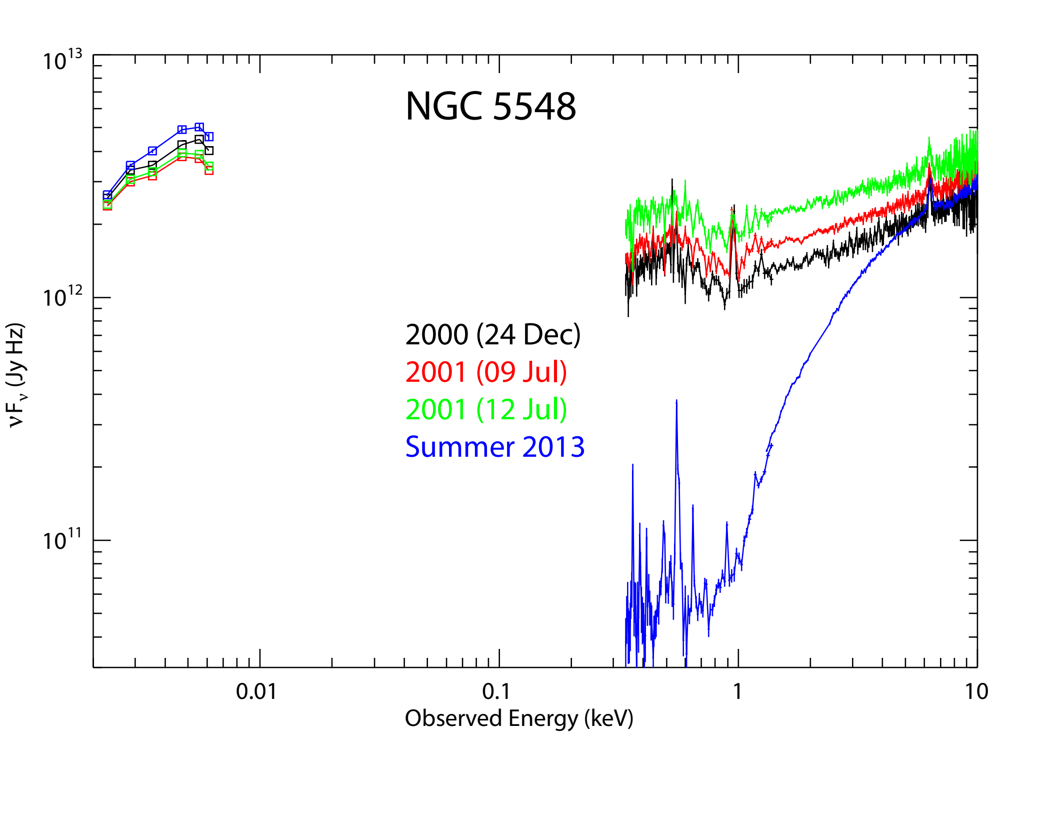
Can it all be “just absorption”? (see session VIII)

Absorption variability

Not the general solution. Needs to explain:

- broad-band noise power spectrum (in common with XRBs, CVs)
  (see also the AGN-XRB scaling results: McHardy et al. 2006 etc.)
- rms-flux relation (in common with XRBs, CVs)
- rev. mapping (yesterday's talks) assumes point-like central source (and that works ok)
- X-ray / opt correlations

Much simpler if L_x is variable, and absorption (sometimes) varies in front of that.



Mehdipour et al. (2015)

Looking ahead

- rapid, recent progress in X-ray "spectral-timing" (session VII, VIII). Likely to be more advances in methods and models
- need to cope better with uneven sampling (AGN people especially)
- better coordination of studies across wavebands (e.g. optical/IR vs. soft/hard X-rays) – for both XRBs and AGN
- surprises: e.g. the ultra-pulsar (session IX)
- ASTROSAT (2015+?)