Global Signals in Time-Series Data

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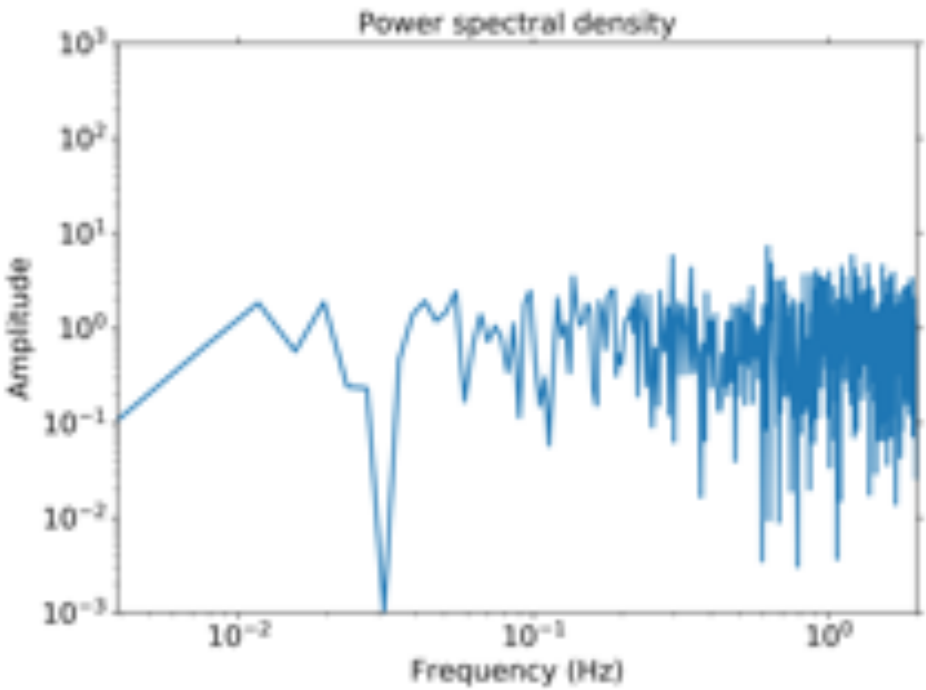
Image: NASA/JPL-Caltech

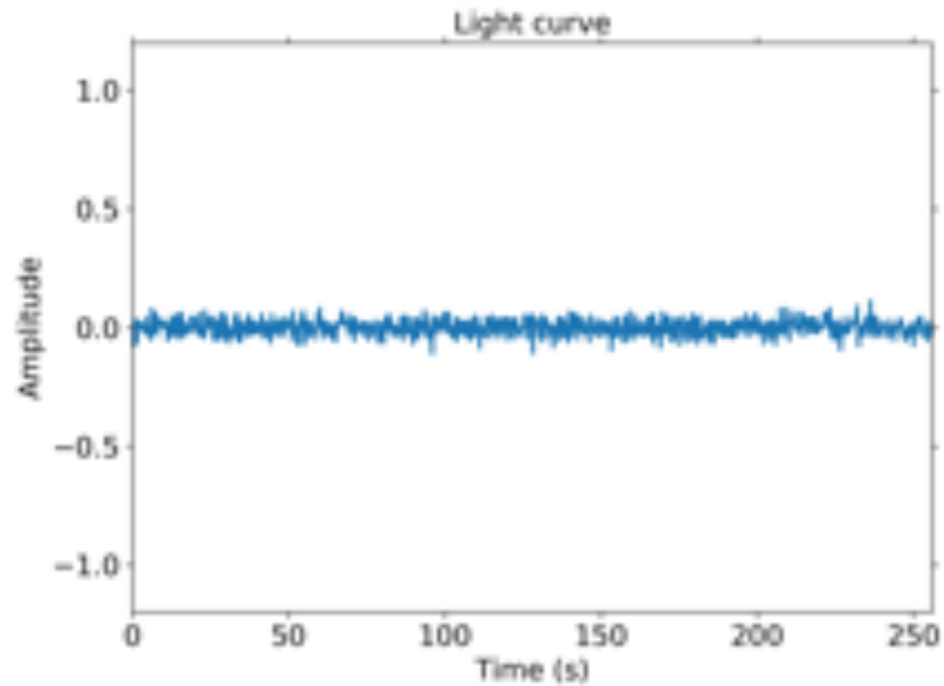
Outline

- Poisson noise, flicker noise, red noise
- Red noise pretending to be a cool signal
- Broadband/band-limited noise
- AGN reverberation
- Light echoes
- Orbital modulation
- Multi-wavelength jet physics
- Grab-bag of time domain science
- Things to worry about: deadtime and pile-up

Poisson noise (a form of "white noise")

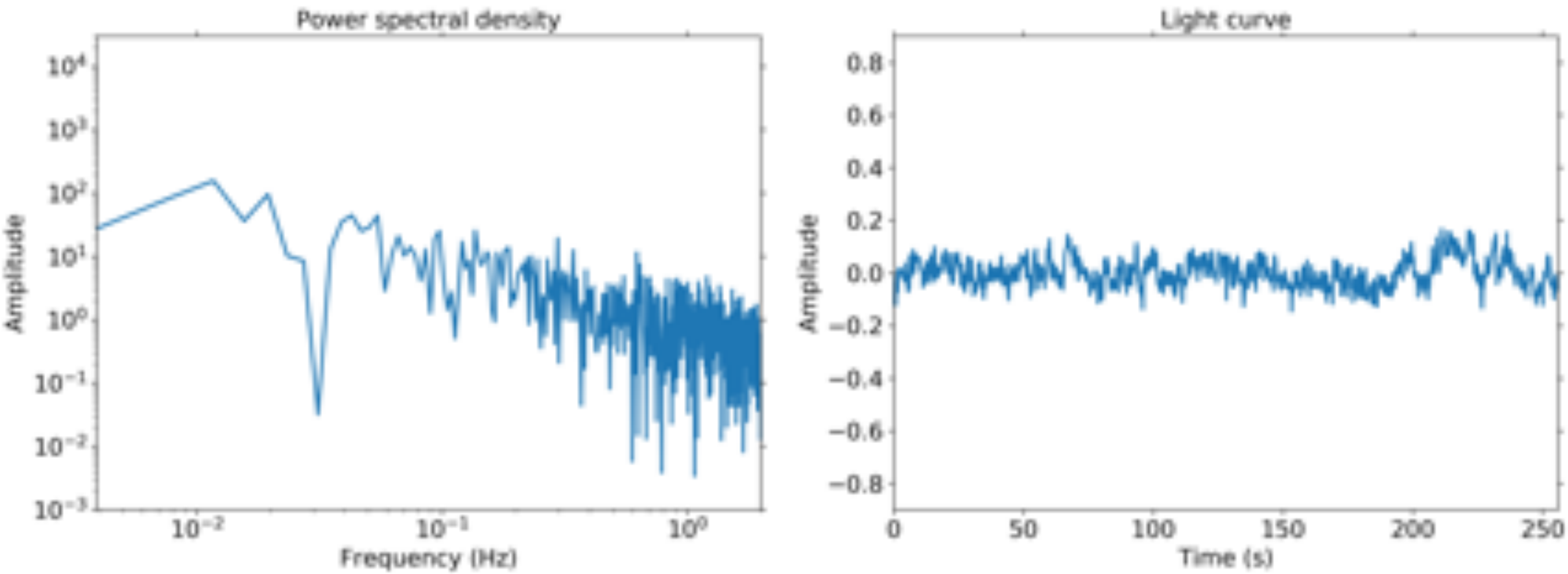
- In power spectra: $P \sim \nu^{\alpha}$, $\alpha = 0$
- Not correlated on any timescale





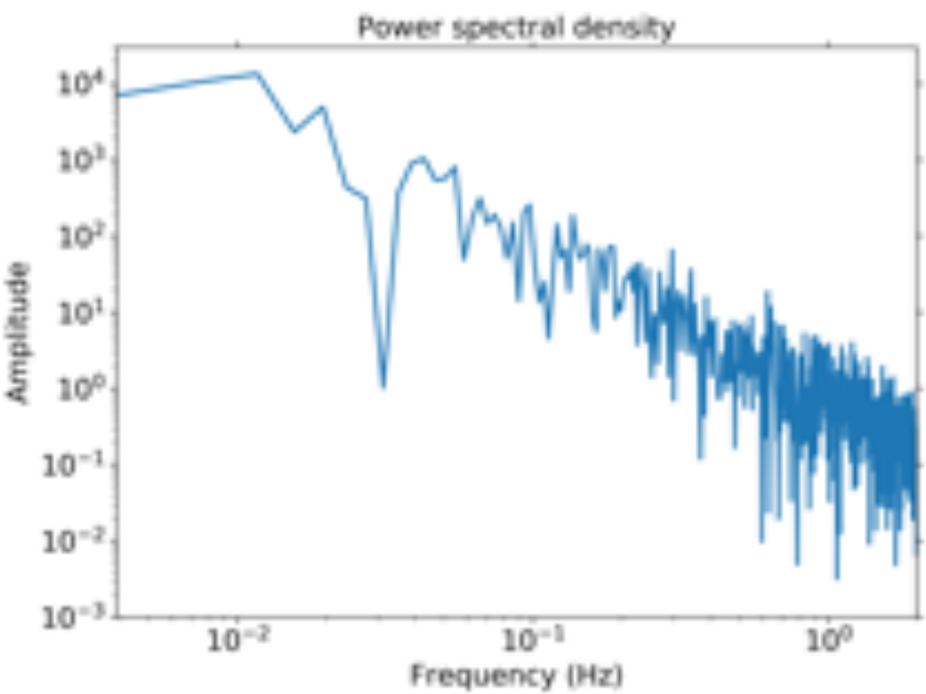
Flicker noise

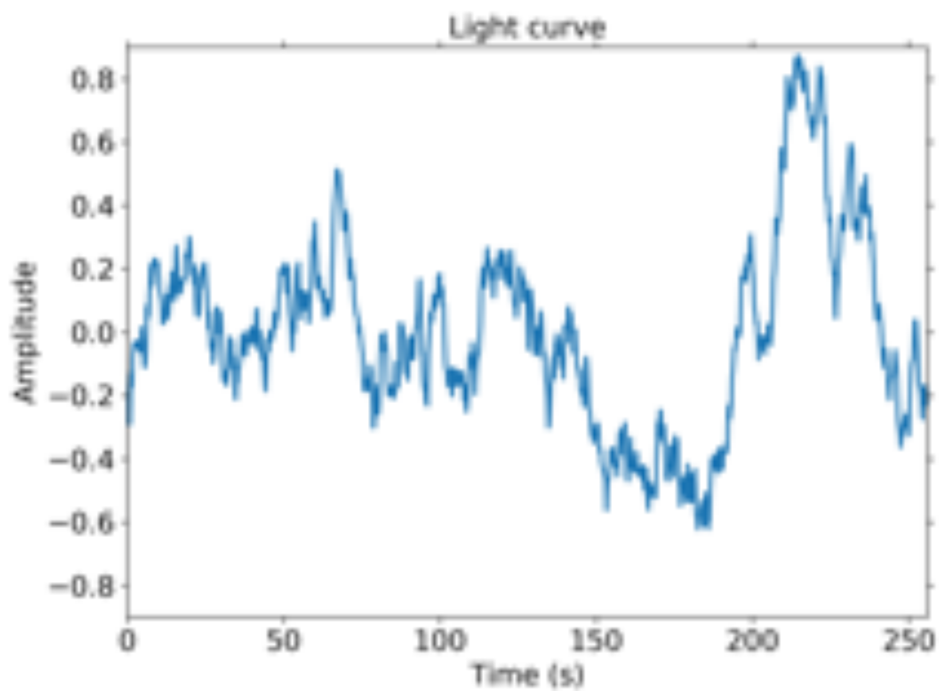
- In power spectra: P~ν^{α}, α=-1
- Correlated on medium-short timescales (short "memory")



Red noise (random walk)

- In power spectra: P~ν^{α}, α=-2
- Correlated on long timescales (long "memory")
- Ornstein-Uhlenbeck: ~red noise + friction: tends towards a mean value over long time



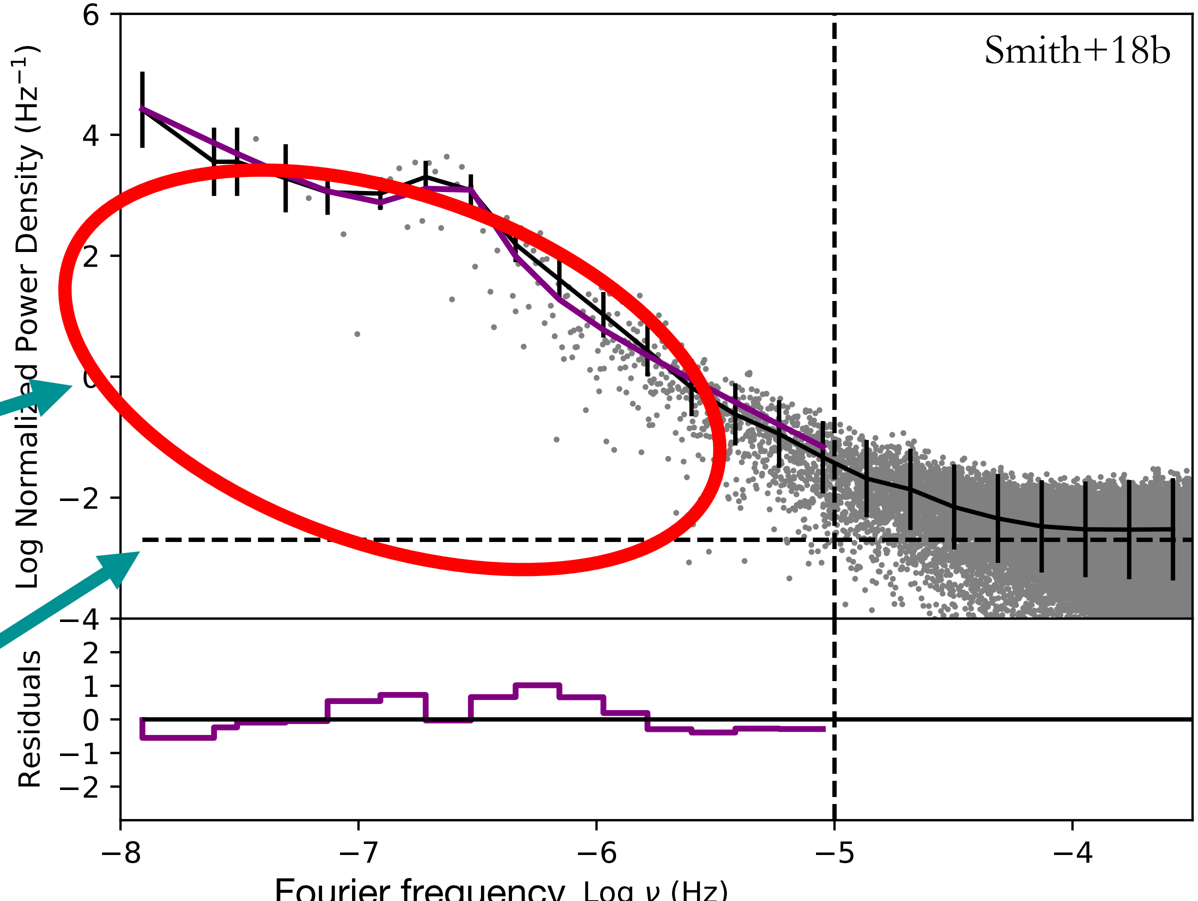


Beware of red noise!

- Cannot apply standard peak-finding algorithms, since those assume white noise (see Vaughan & Uttley '06)
- Bigger issue for SMBHs than stellar BHs due to timescales

Red noise

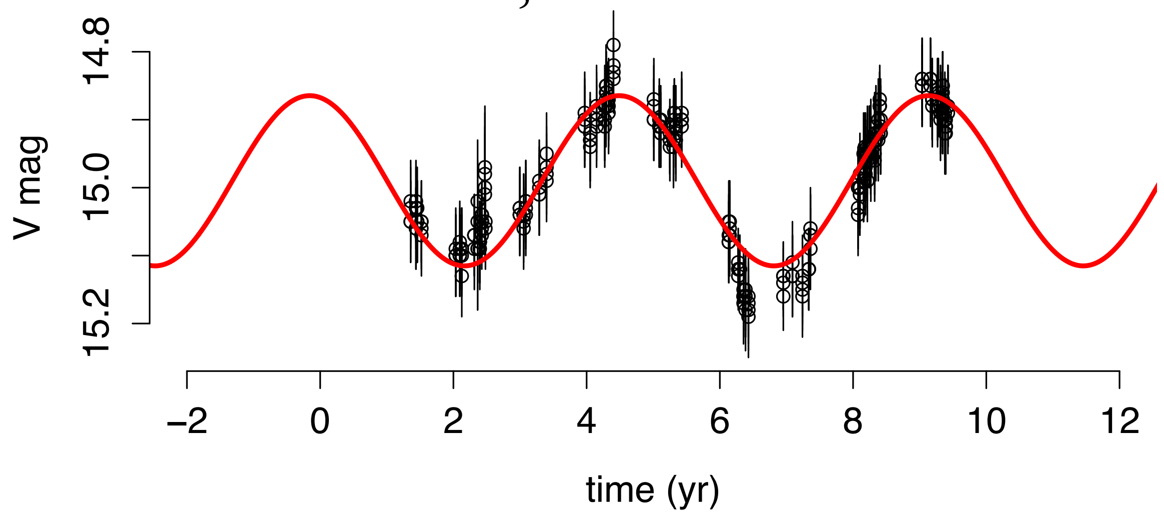
White/Poisson noise



Red noise vs signals

Data looks periodic!

PG 1302-102, CRTS data



Vaughan+16 (figure); Liu+18

Red noise vs signals

Data looks periodic!

Uneven sampling, gappy data, only 1.5 cycles

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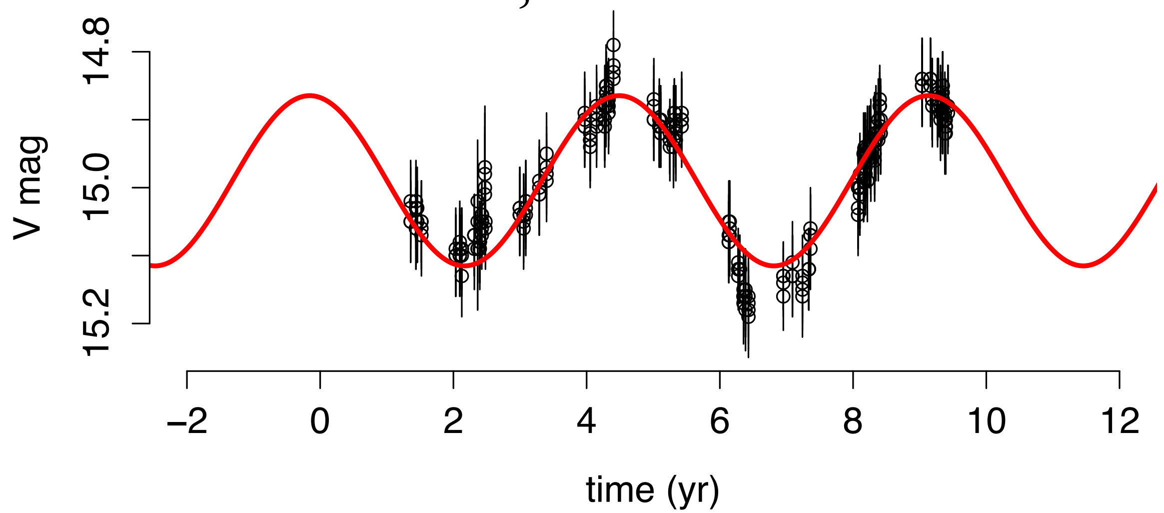

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(but it isn't)

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Sampling a random red noise process in same way can look like a "periodic" signal

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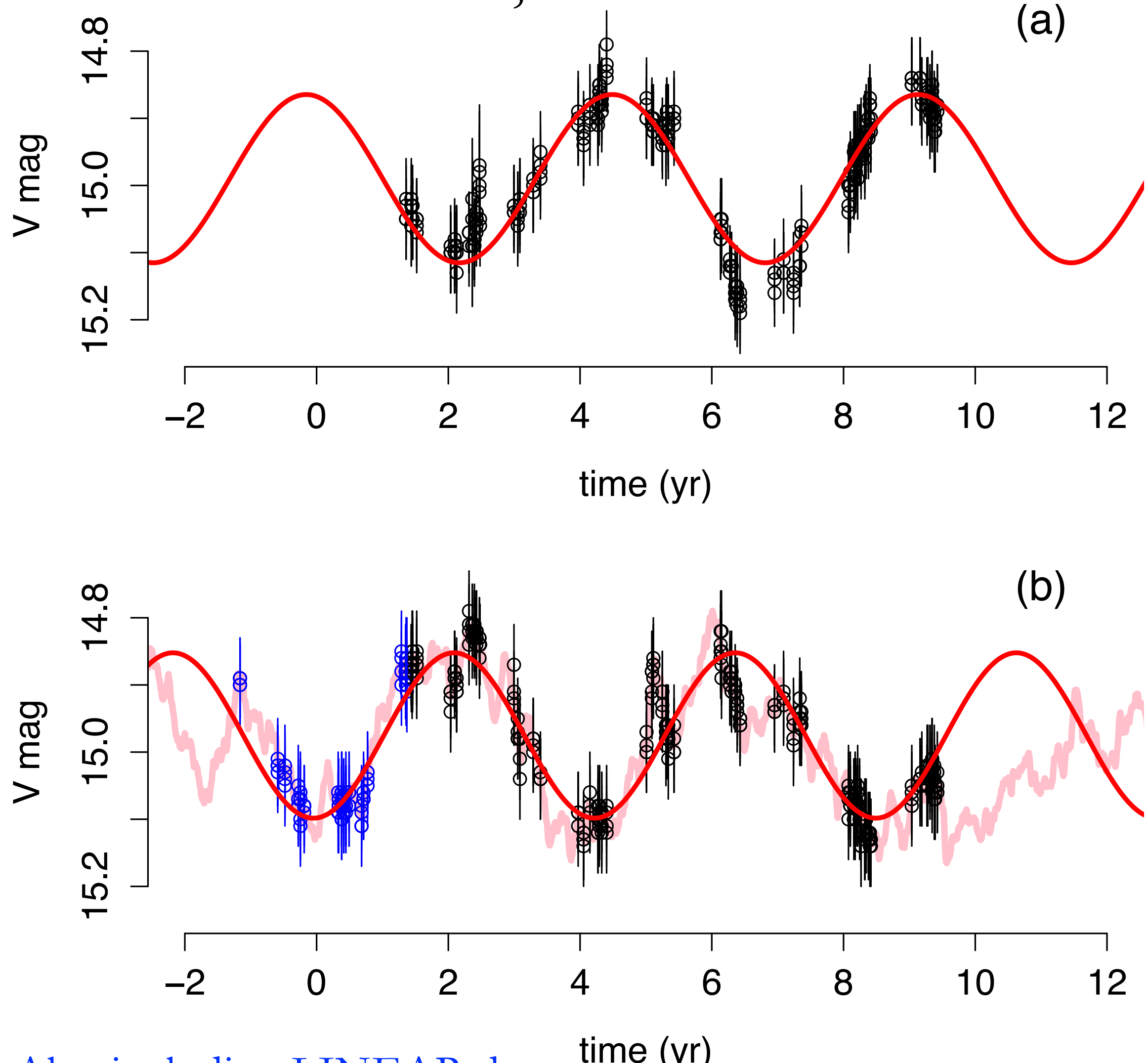


Also including LINEAR data

Vaughan+16 (figure); Liu+18

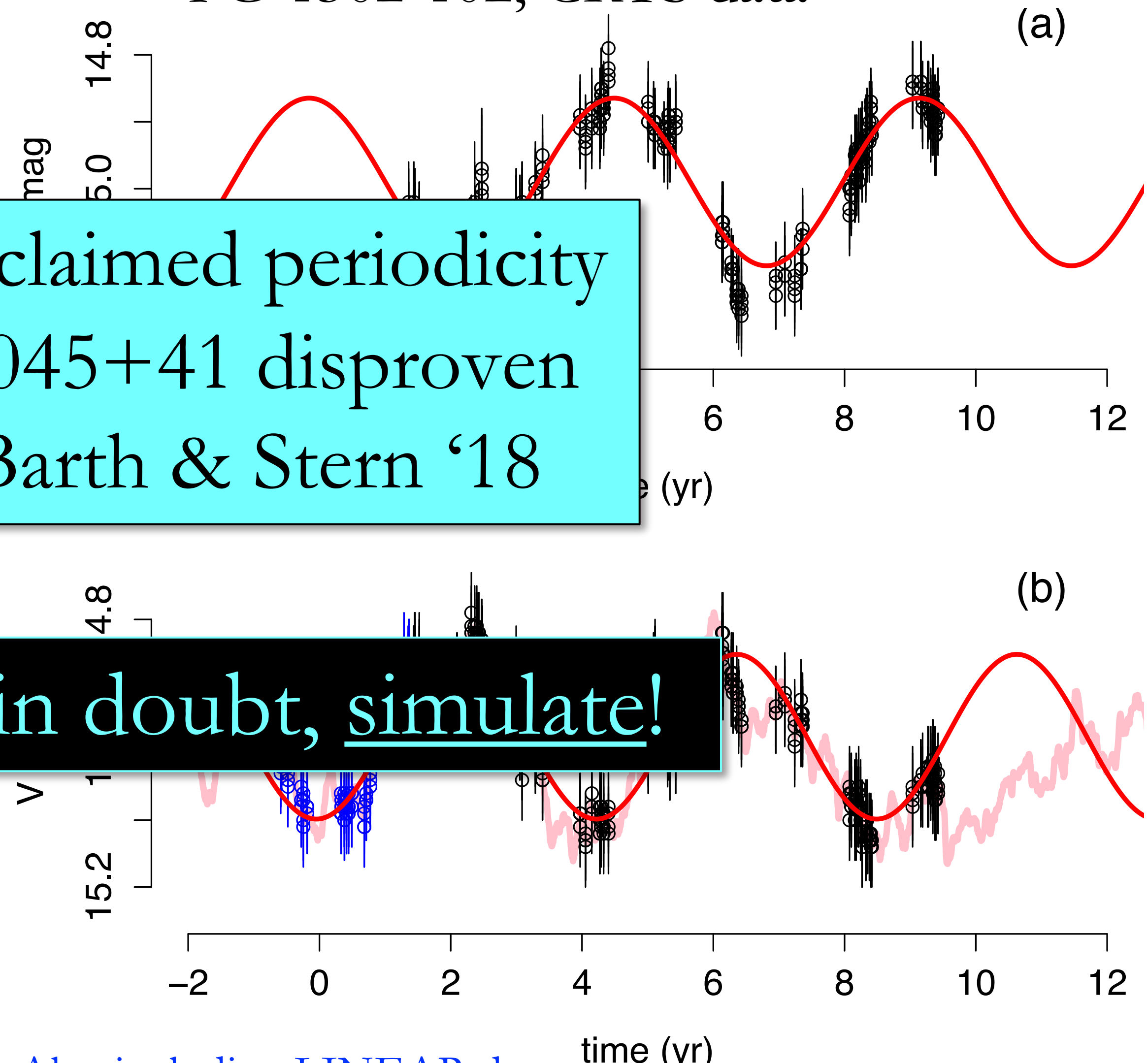
Red noise vs signals

Data looks periodic!
(but it isn't)

Uneven sampling, gappy data, only a few cycles

Sampling a random red noise process the same way can look like a "periodic" signal

PG 1302-102, CRTS data



Also: claimed periodicity in J0045+41 disproven by Barth & Stern '18

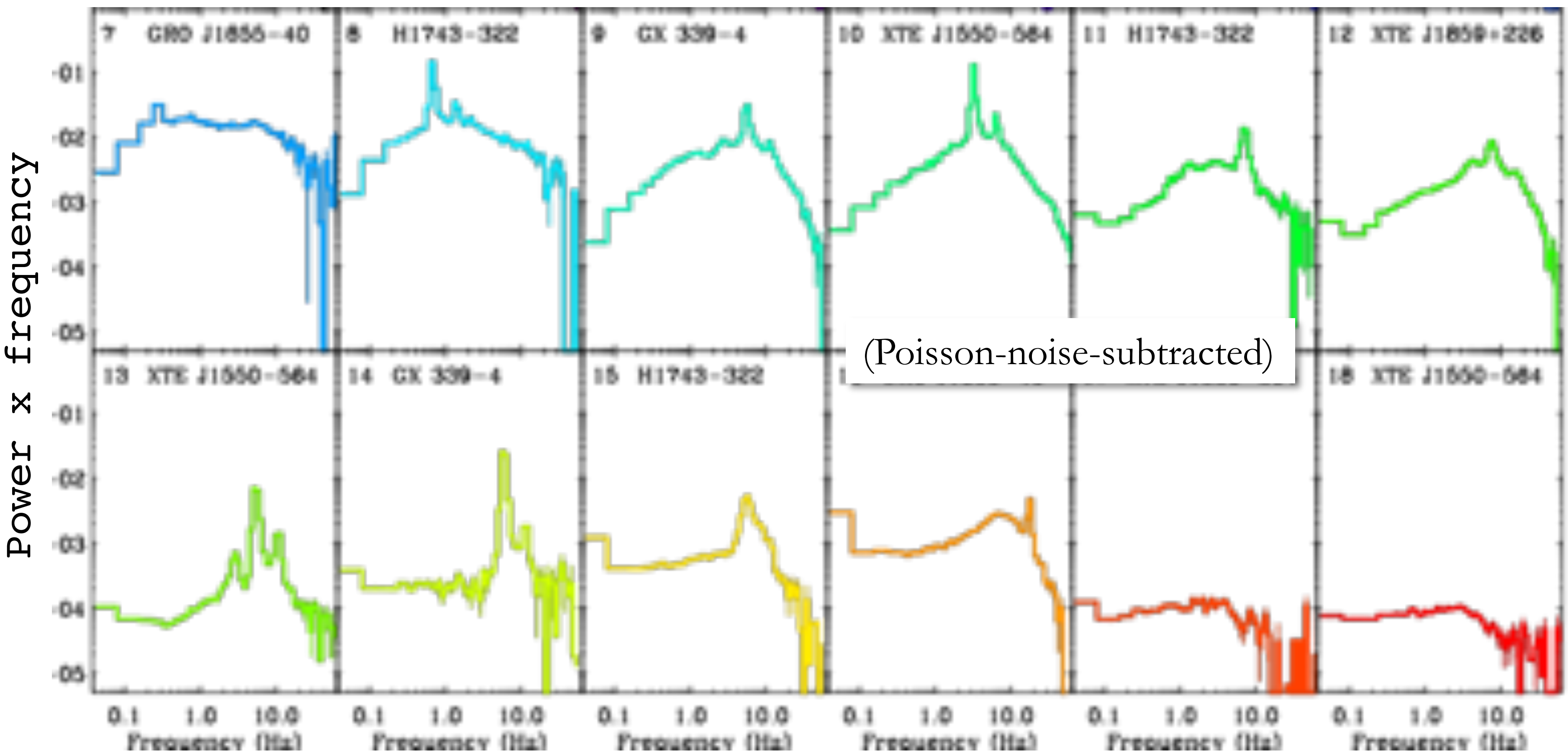
When in doubt, simulate!

Also including LINEAR data

Vaughan+16 (figure); Liu+18

Broadband/band-limited noise

- Accretion-induced variability
- Across mass scales: protostars to AGN!



Heil+15b

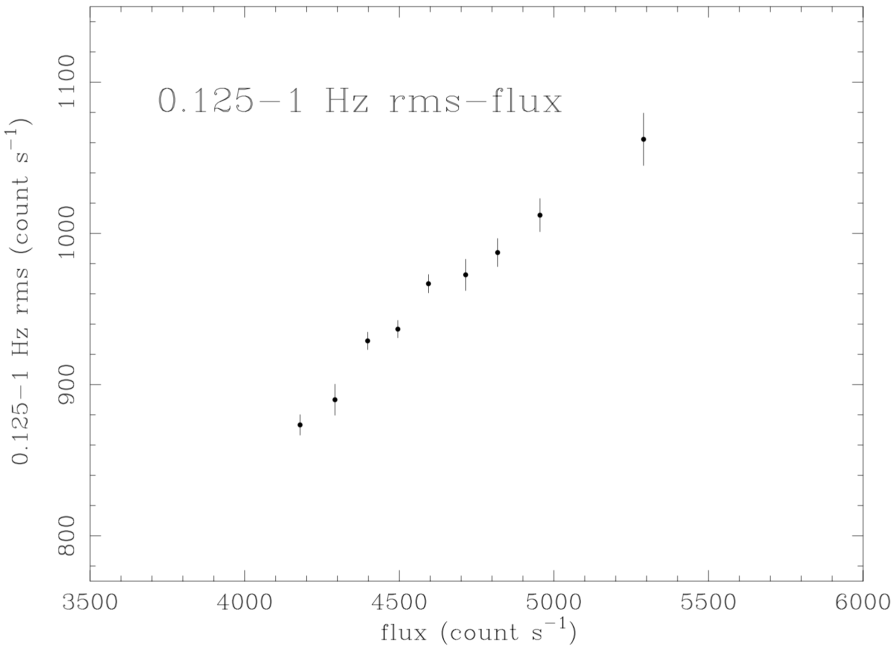
Rms-flux relation

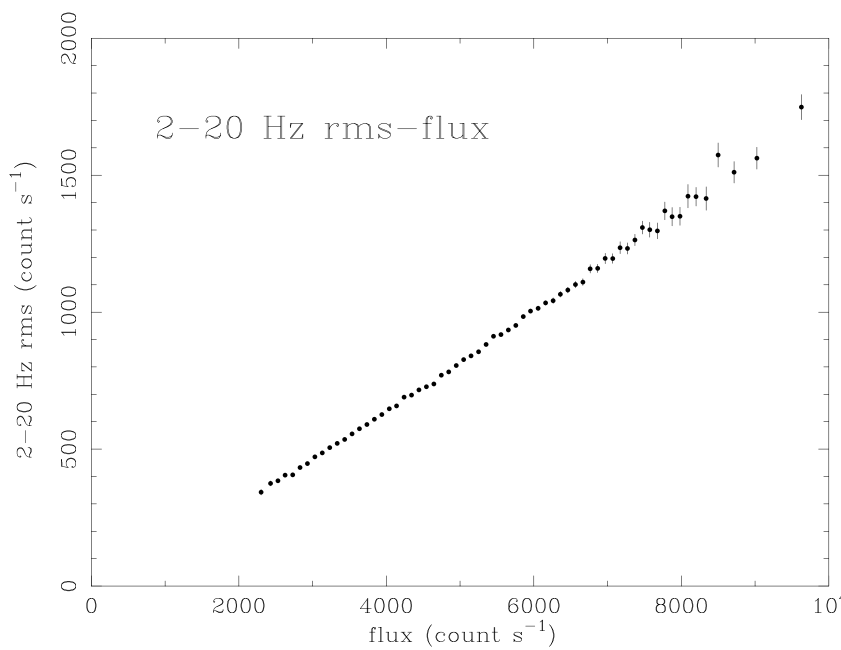
$$\mathrm{rms} = \sqrt{\sum_{\nu_1}^{\nu_2} \langle P(\nu_i) \rangle \Delta\nu}$$ (use Poisson-noise-subtracted power!!)

for a frequency range ν_1 to ν_2

- Positive linear relation in accreting sources! Slope changes with observed spectrum

Wide-range analysis and thorough explanation: Heil+12
Applied to AGN: Vaughan+11





Uttley+McHardy01; Uttley+05

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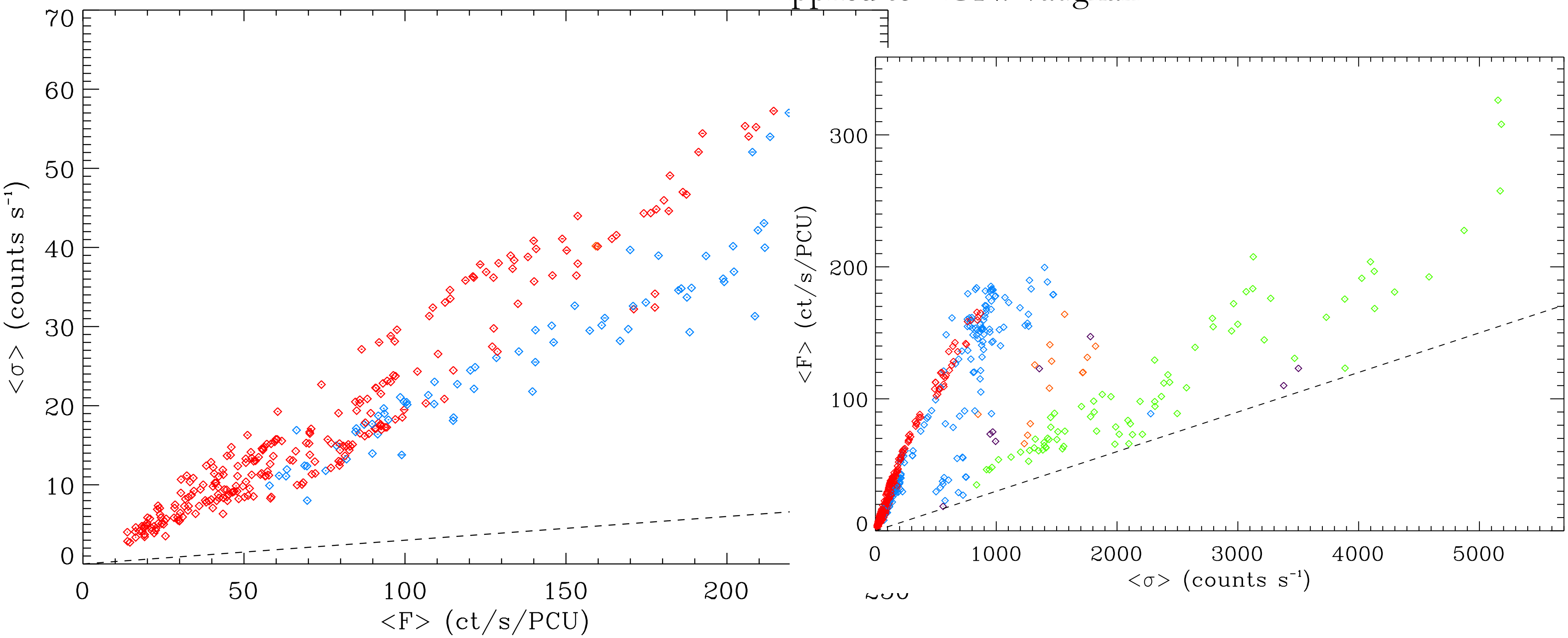

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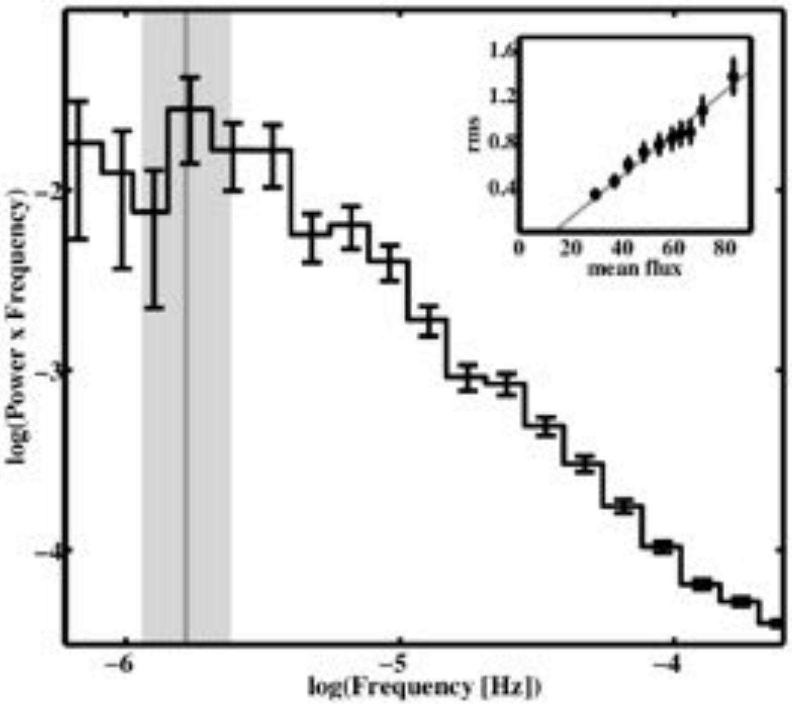
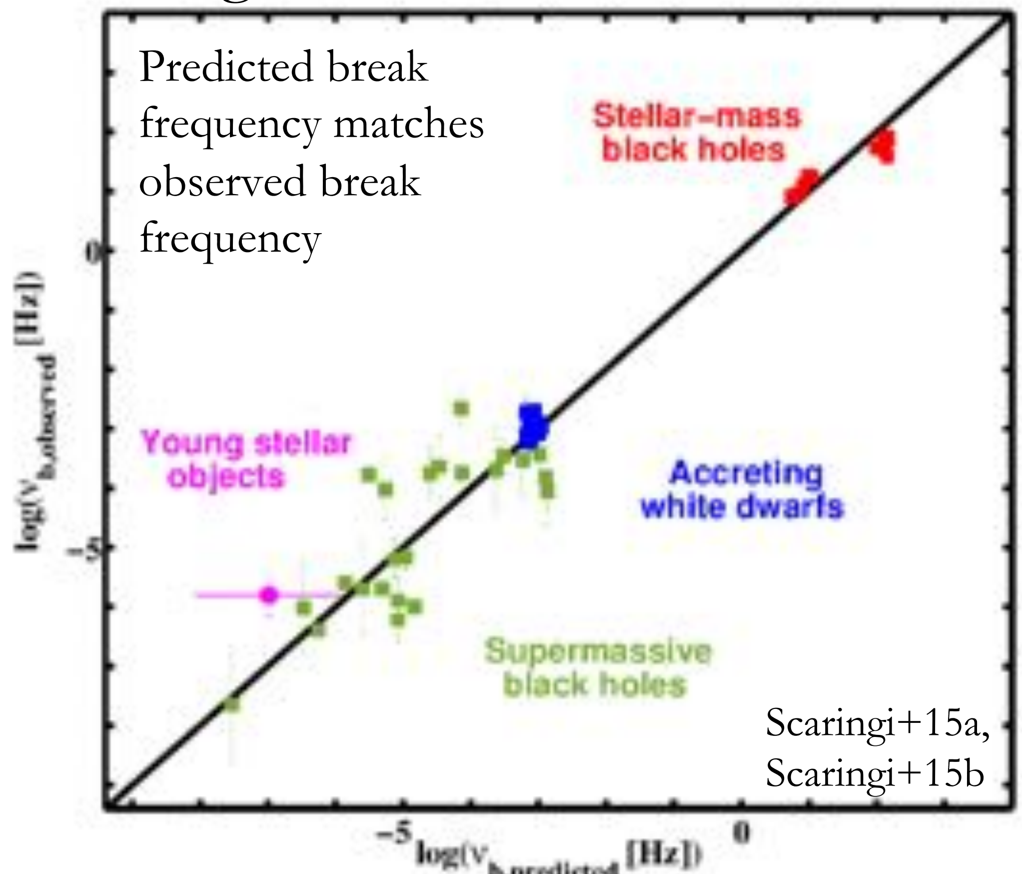
Young Stellar Object
(accreting protostar)



Predicted break frequency matches observed break frequency

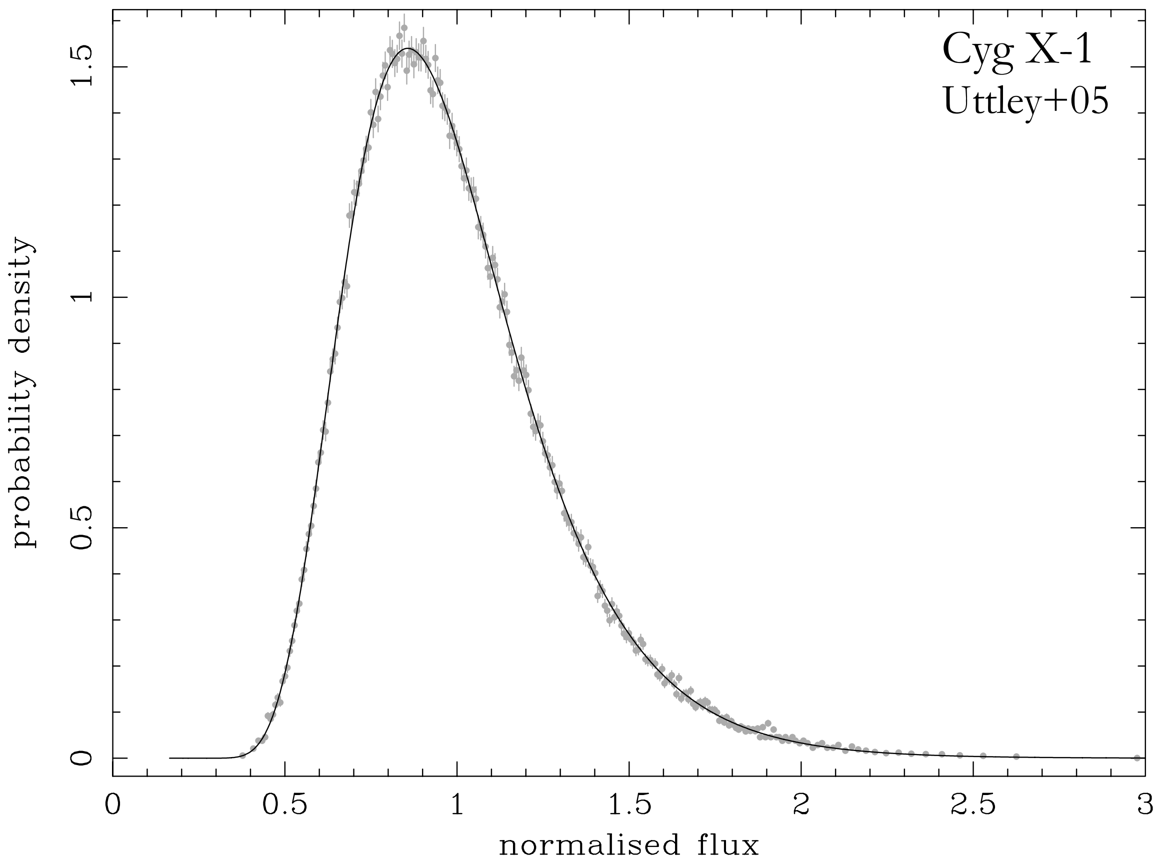


Scaringi+15a, Scaringi+15b

Uttley+McHardy01; Uttley+05

Log-normal flux distribution

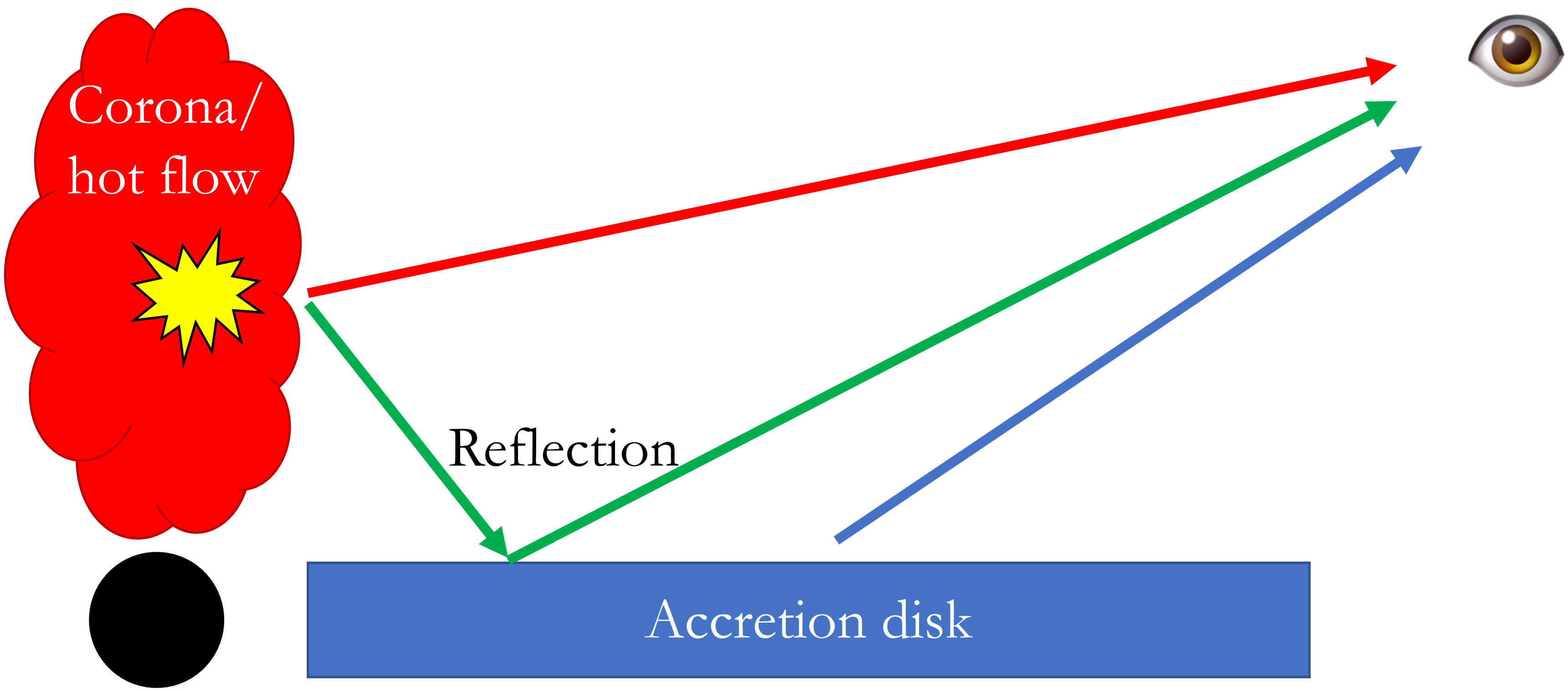
- For small equal-length segments, plot flux histogram
- Log-normal: positive skewness



Also seen in:

- NIR observations of Sgr A* (an SMBH; Witzel+18)
- Optical observations of Sco X-1 (a neutron star; Scaringi+15a)
- Cataclysmic variables (white dwarfs; Scaringi+14)

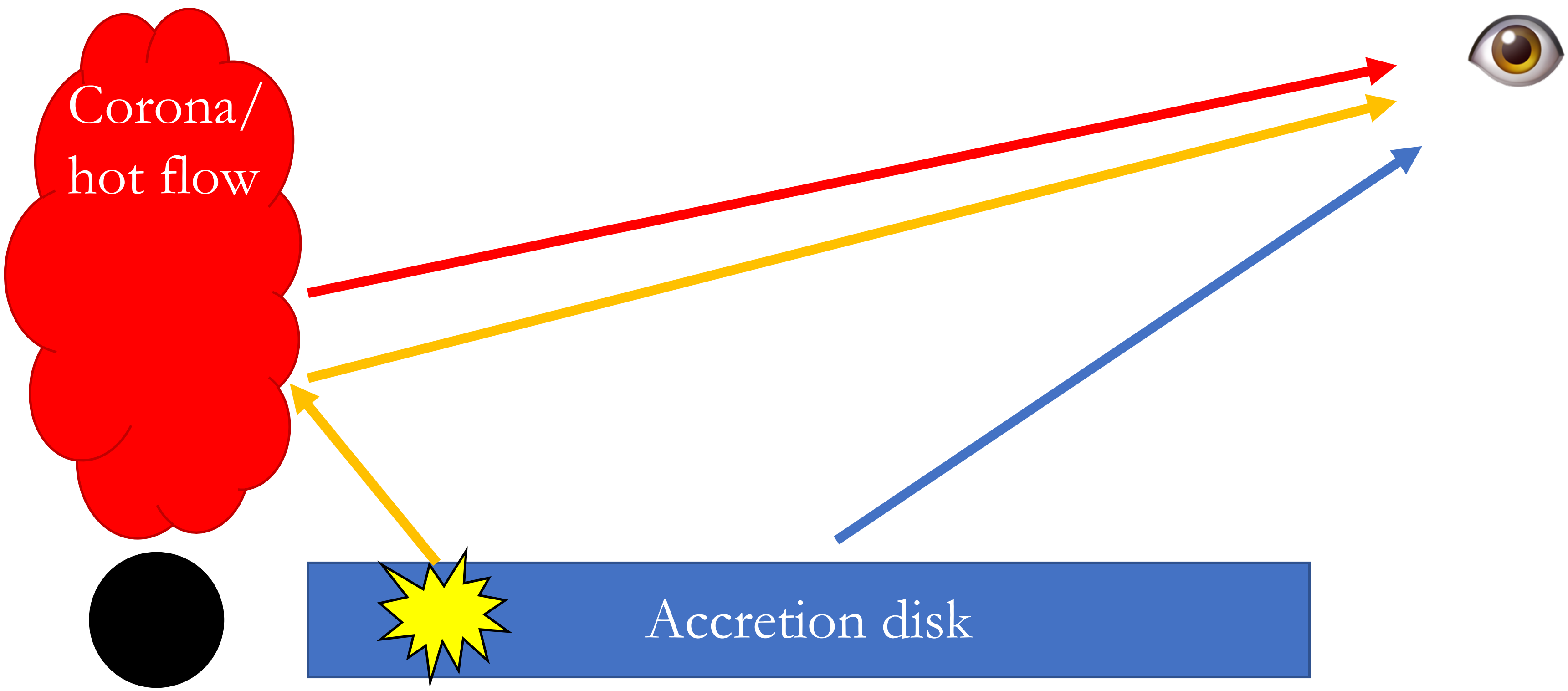
AGN reverberation



Reverberation mapping: looking for "self" similarities between simultaneous light curves of different energies with cross spectral data products

Blandford+McKee82; Uttley+14 review; see work by, e.g., Barth, Cackett, Fabian, Kara, Reynolds, Wilkins, Zoghbi

AGN reverberation



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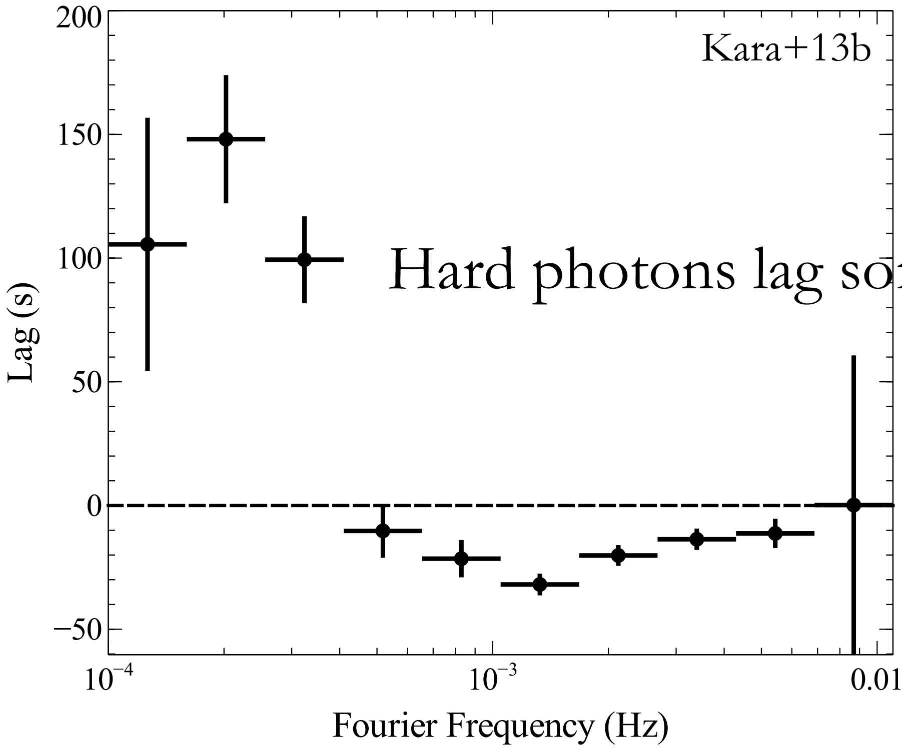
AGN reverberation

- 1H0707-495 (NLS1)
- 1.3Ms of XMM data



Hard photons lag soft photons

Soft photons lag hard photons

AGN reverberation

- 1H0707-495 (NLS1)
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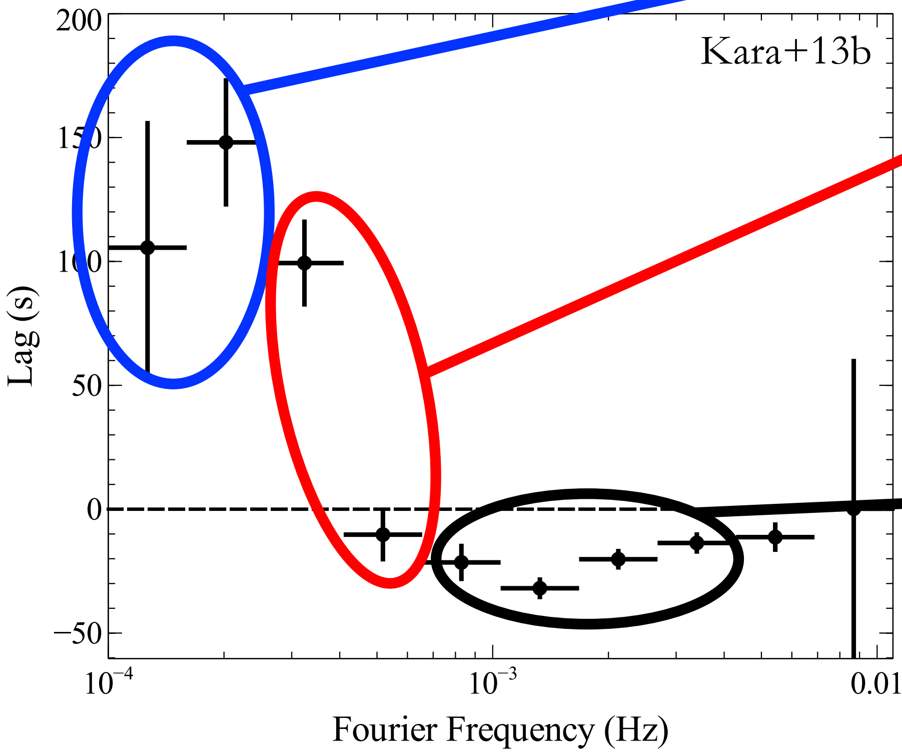
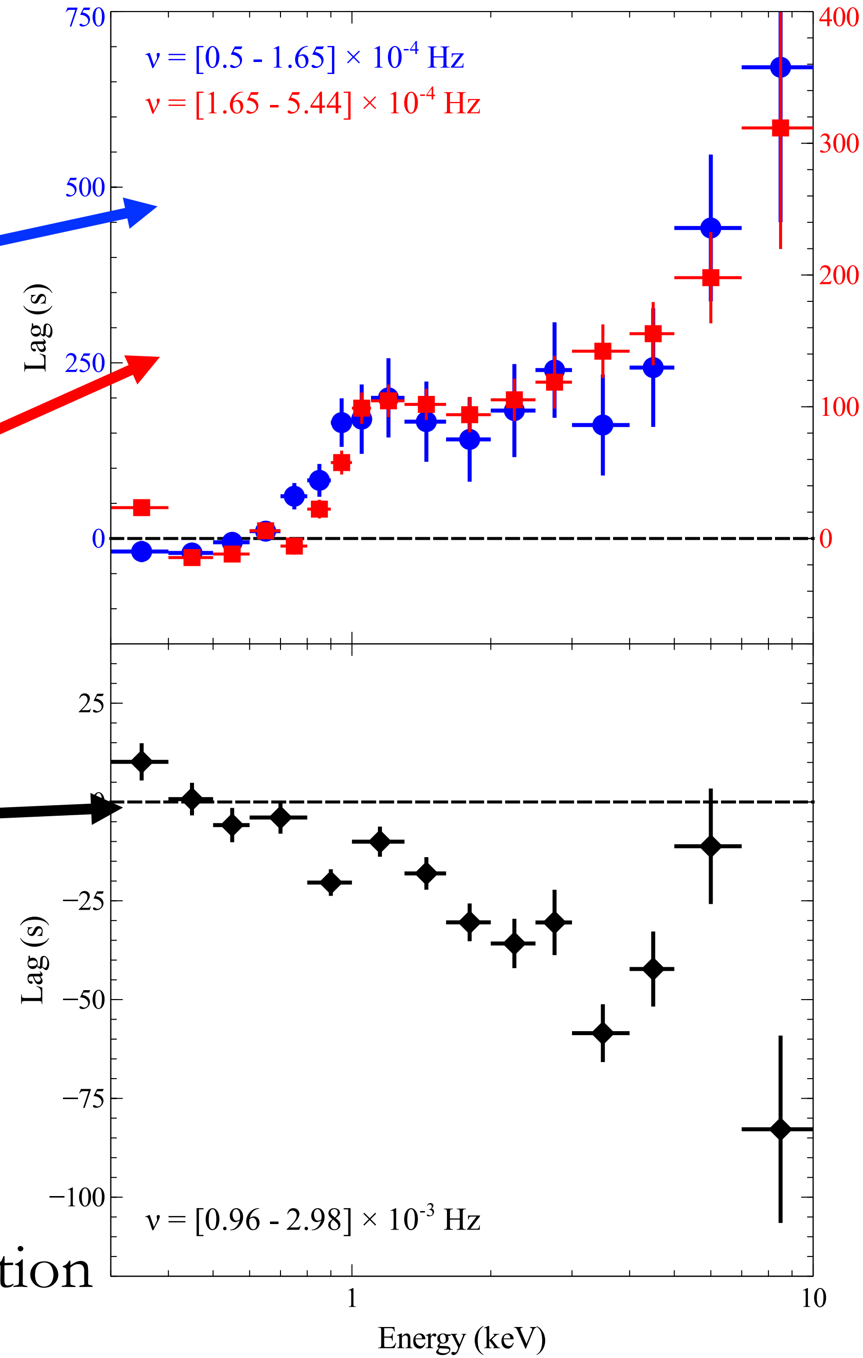
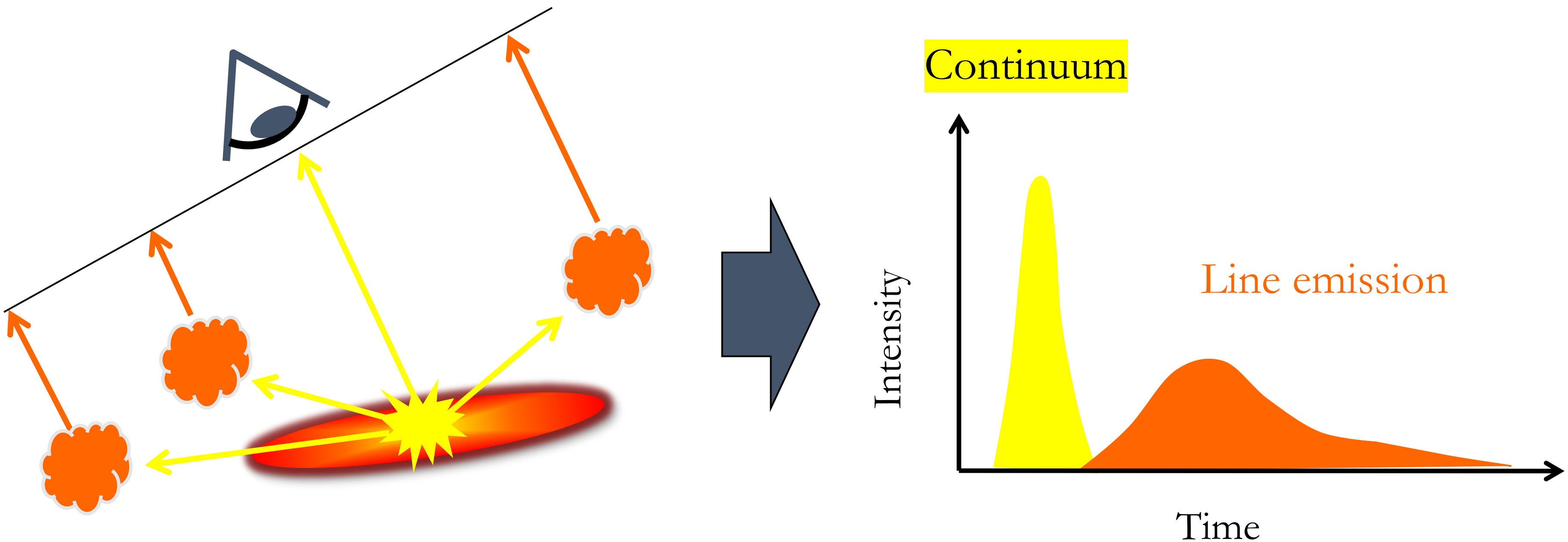




- Hard lags: Comptonization of accretion fluctuations in disk
- Soft lags: light travel delay of reflection

AGN reverberation modeling

- Impulse response function or transfer function



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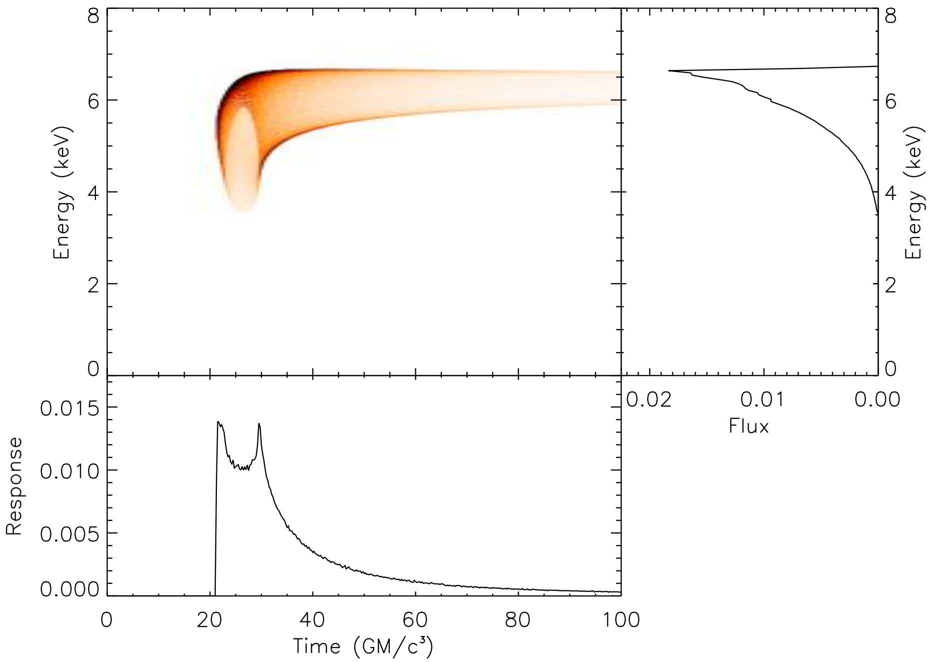
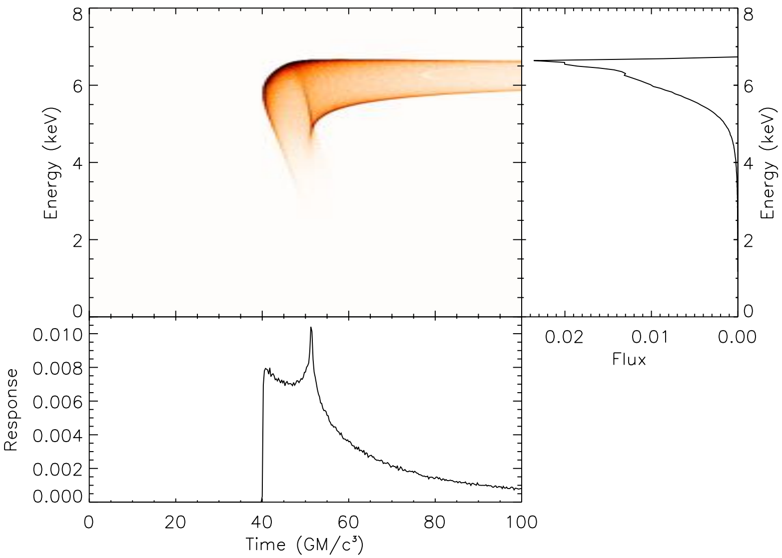
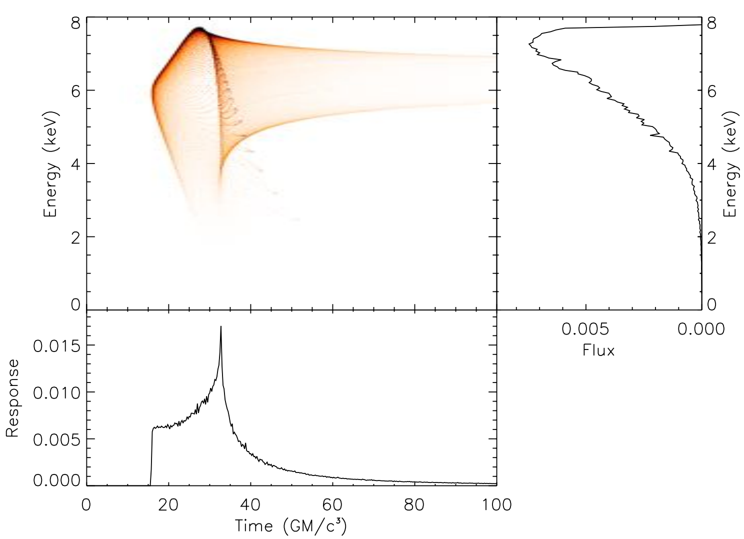
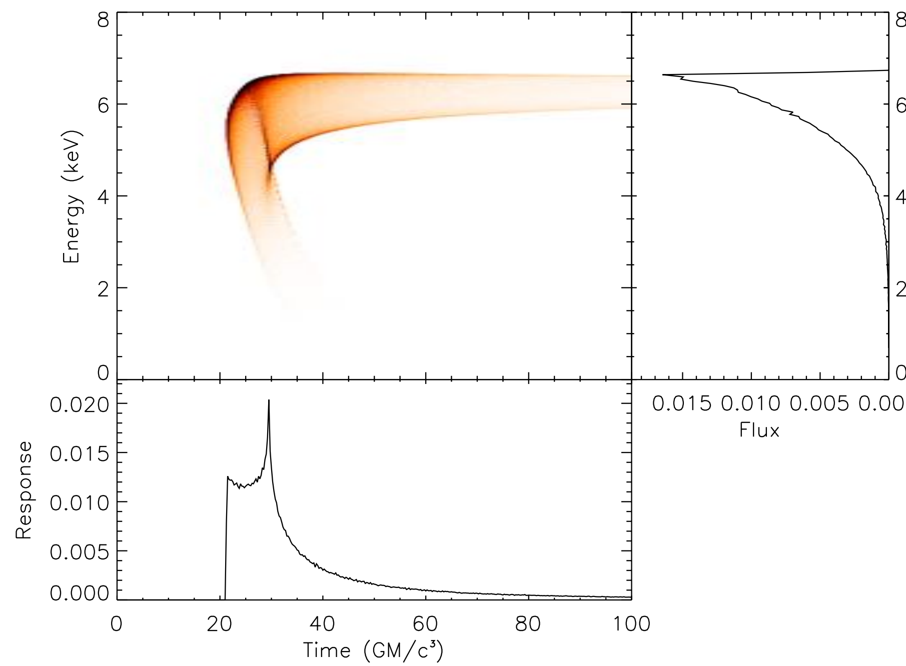
AGN reverberation m









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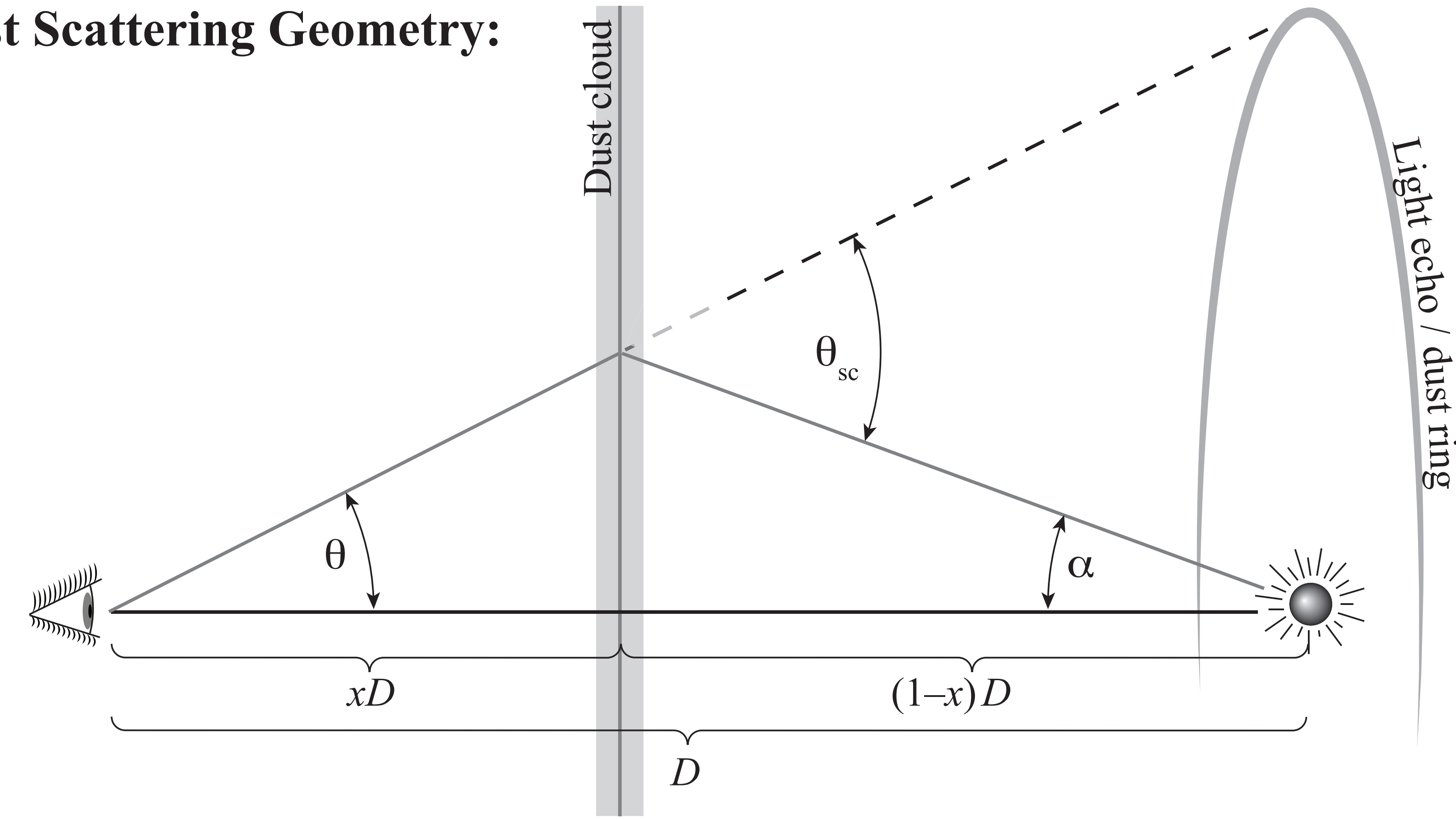
Light echoes

- Bright impulse or flare, light is scattered by dust

Dust Scattering Geometry:



Heinz+16

Light echoes

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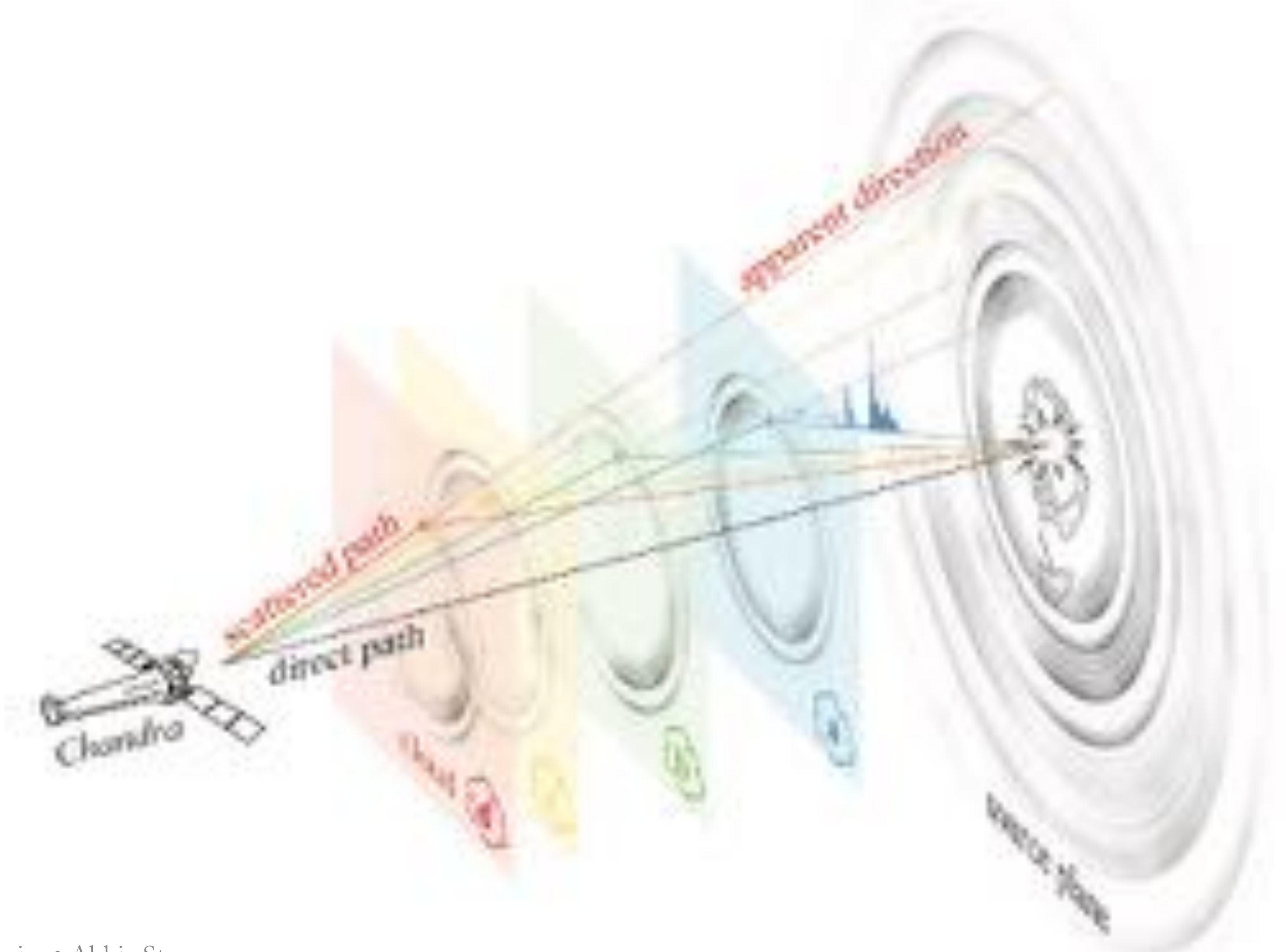

Heinz+15

Light echoes

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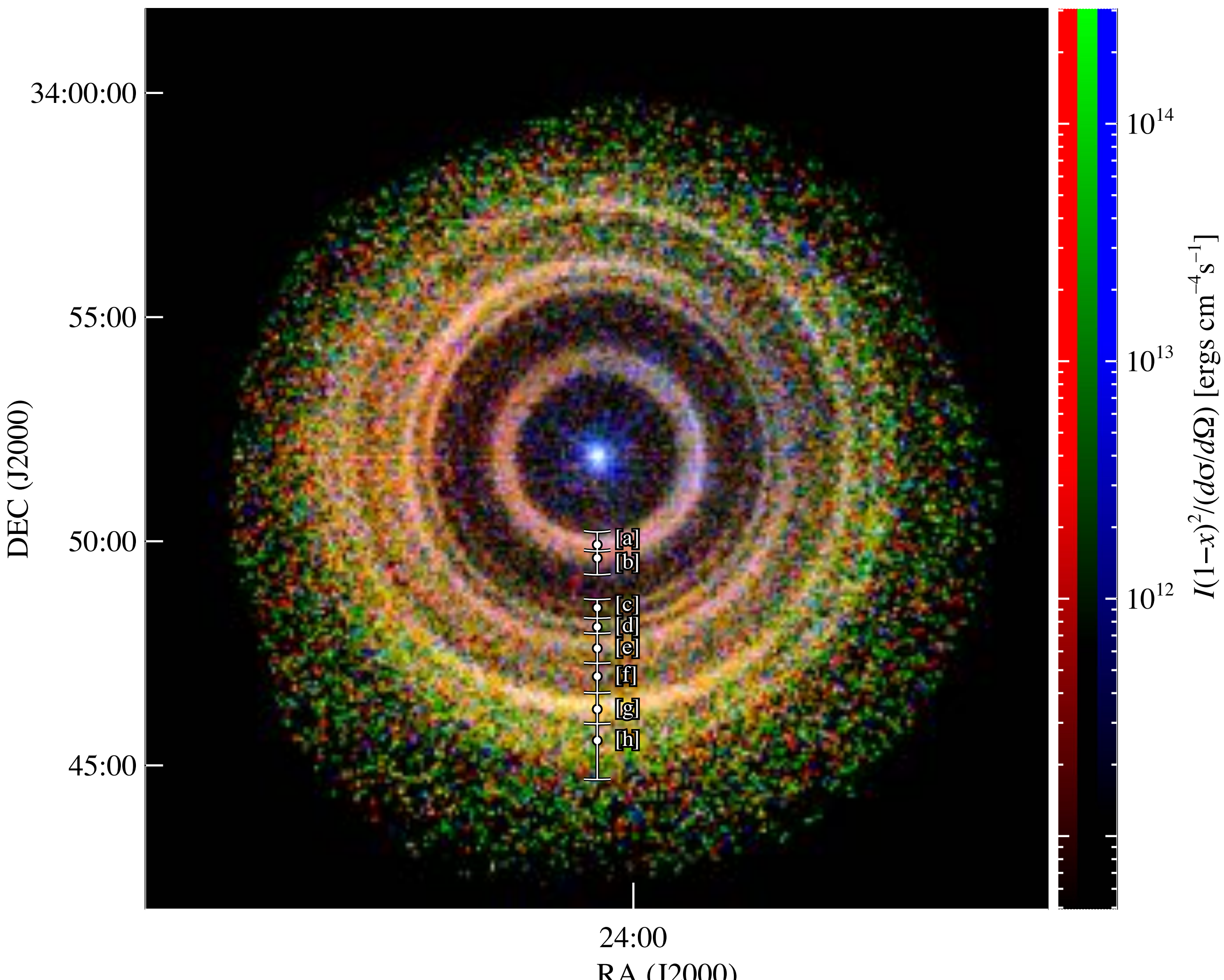

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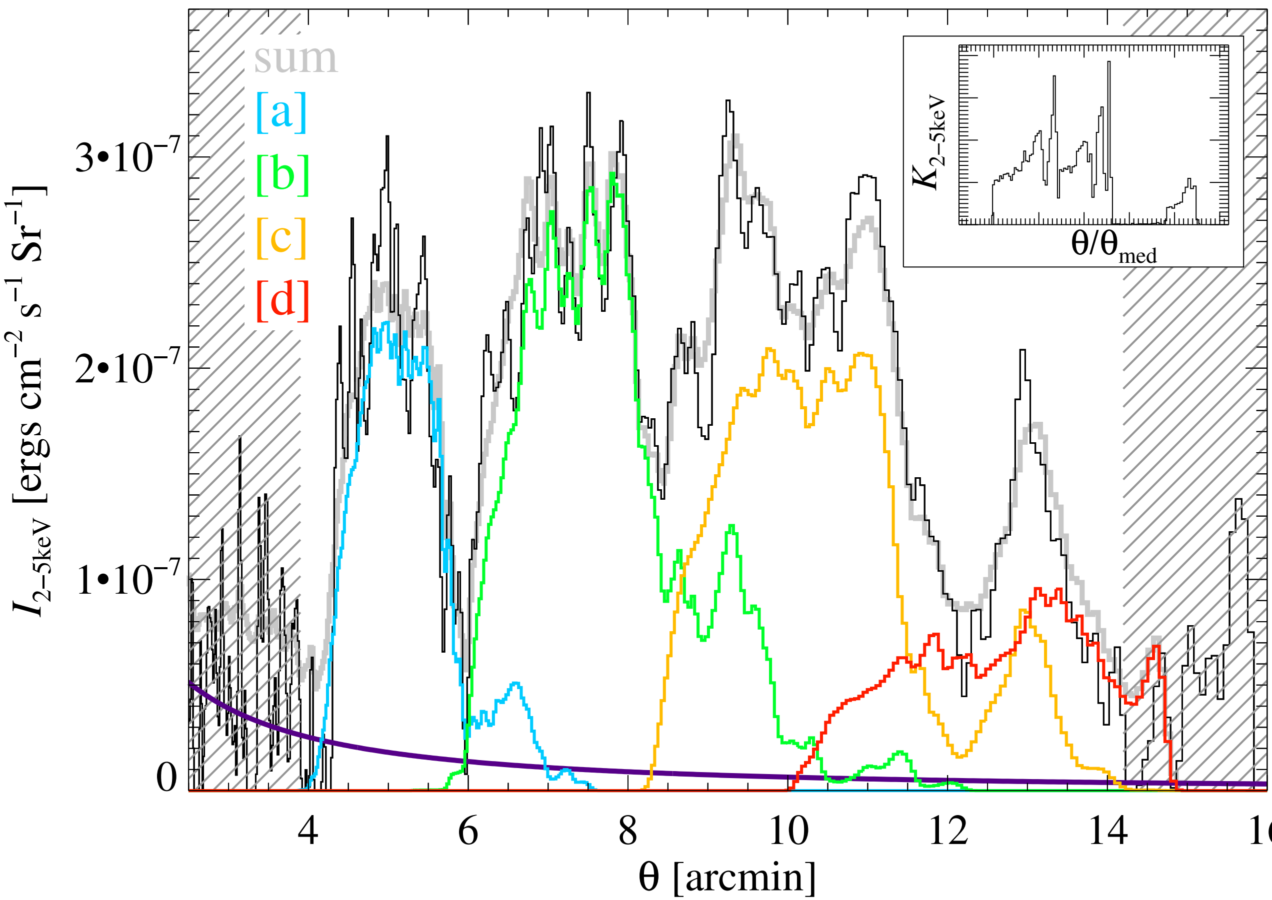

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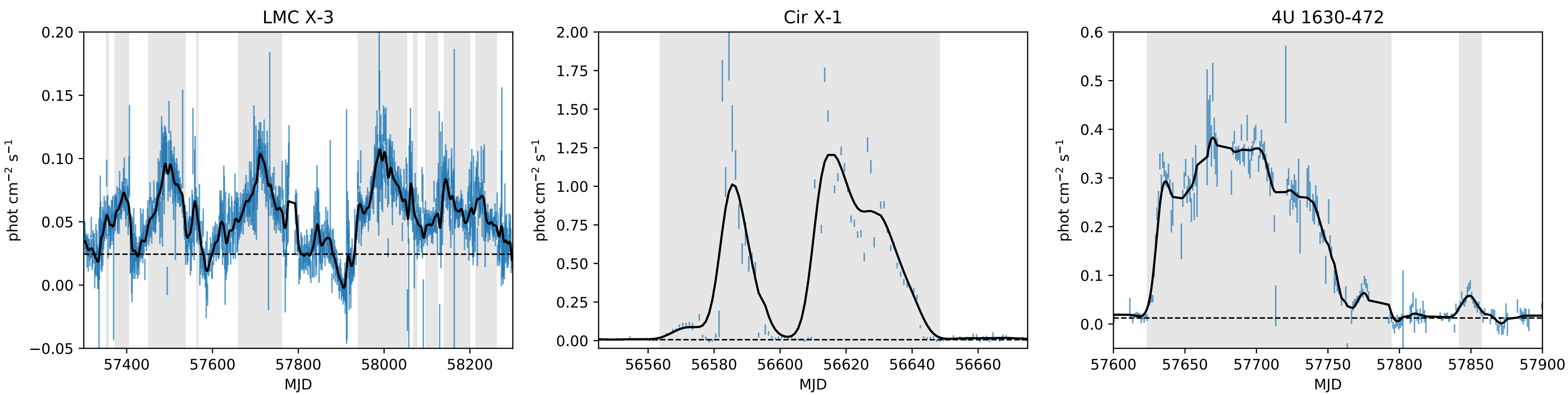


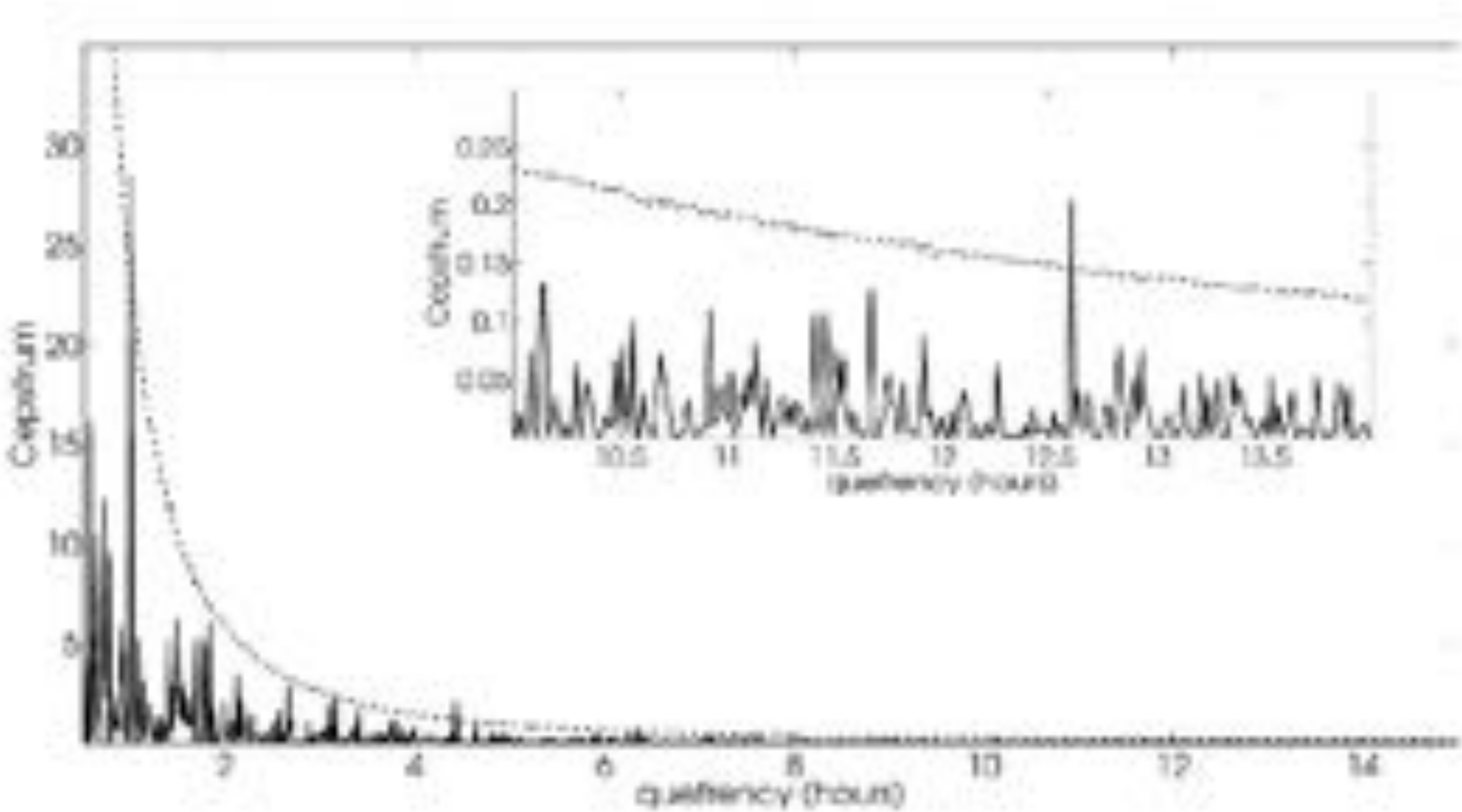
- Dust-echo tomography – map precise distance and composition of dust in ISM

Corrales+19

Light echoes

- Cepstrum ("echogram"): Fourier technique to look for light echoes in a single light curve

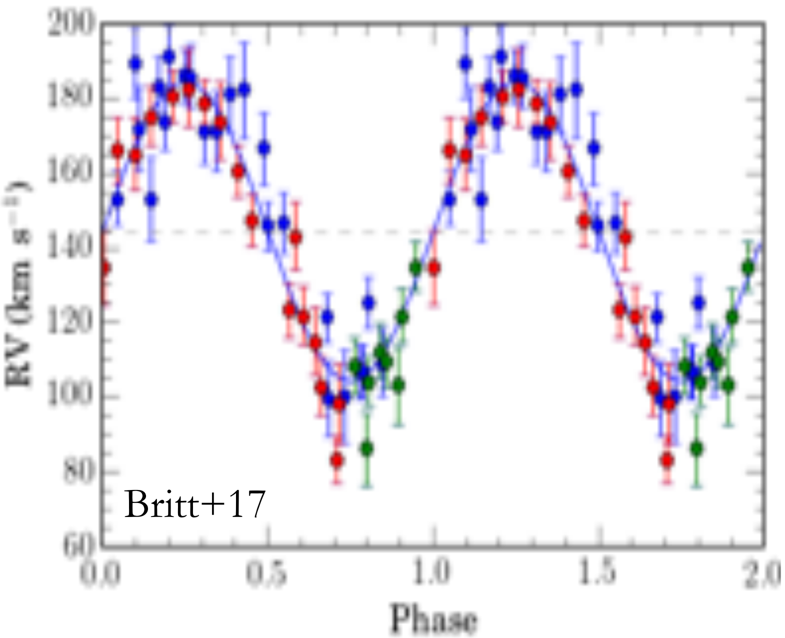
$$\text{Cep} = \text{IFT}(\log(\text{FT}(\text{signal}))$$

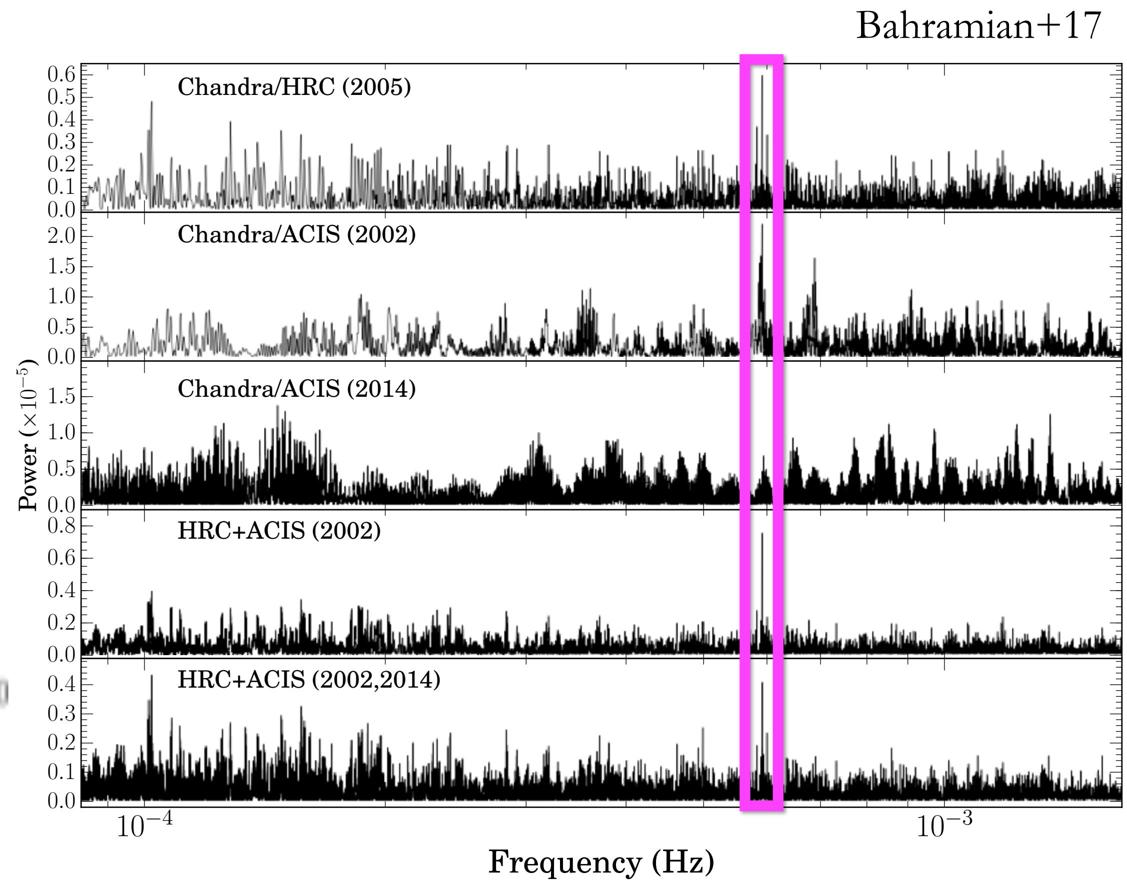


Scaringi+15a

Also used in analyzing sunspots, earthquake tremors, human speech

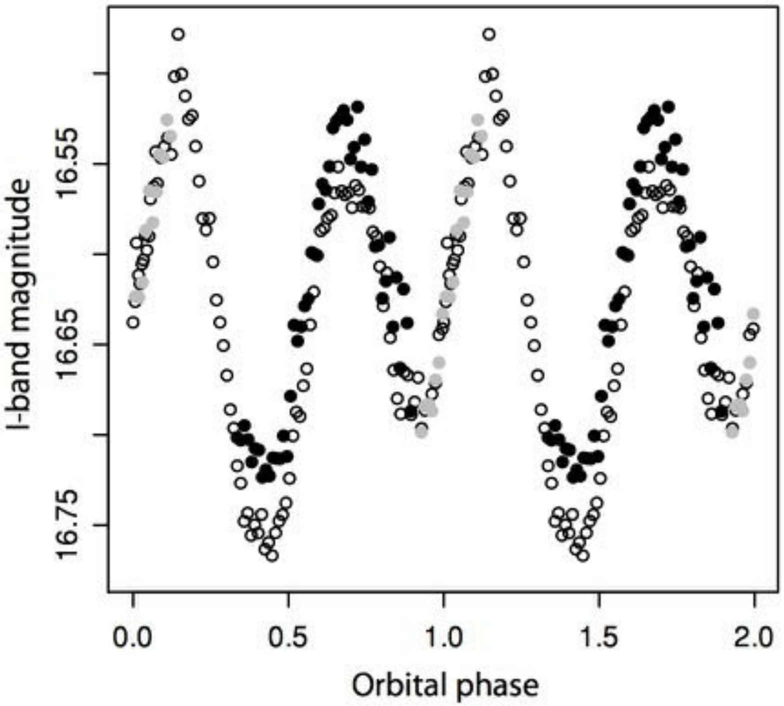
Orbital binary motion in X-ray binaries





- Optical radial velocity measurements of companion star
- Power spectra of multiple epochs, multiple instruments, 10-60ks exposures

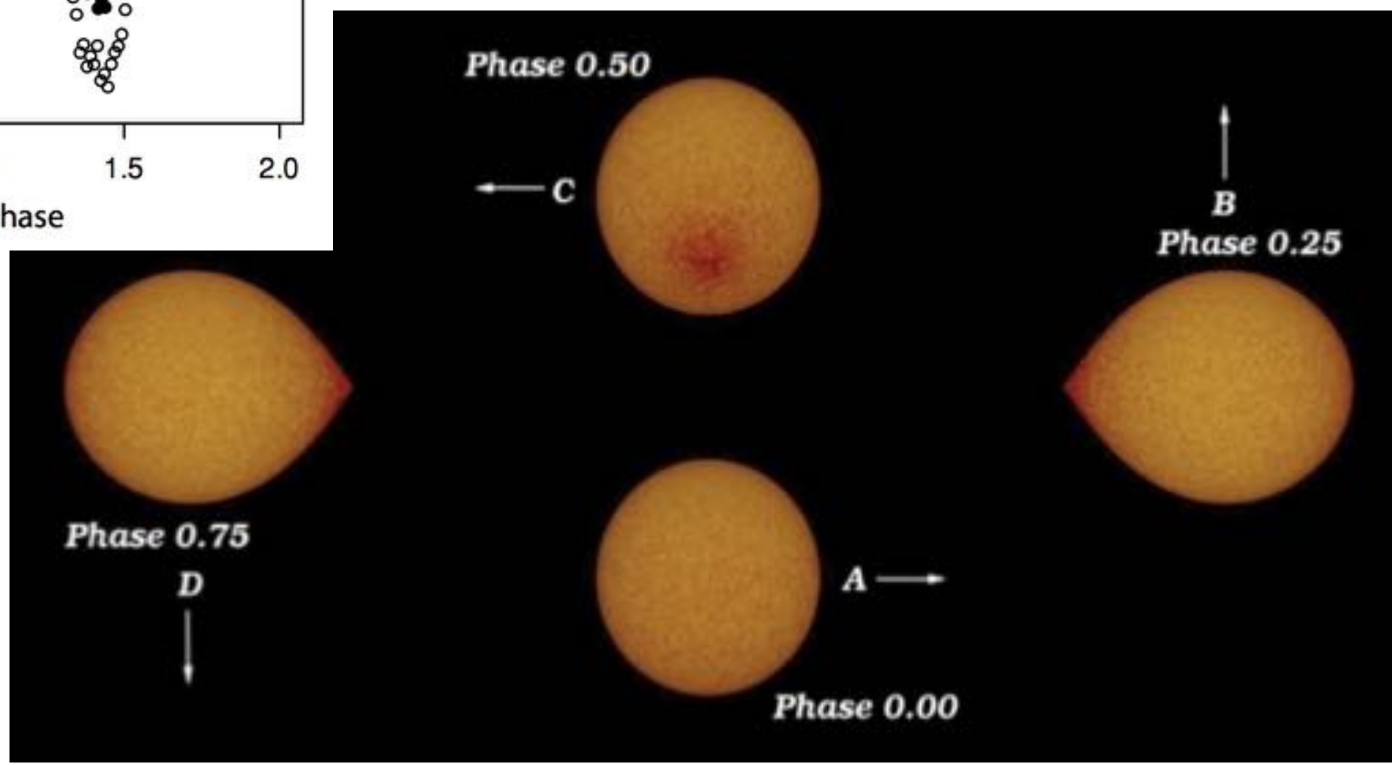
Ellipsoidal modulations



Cantrell+10

- Companion star in close orbit with a compact object
- Double-peaked light curve in one orbital period

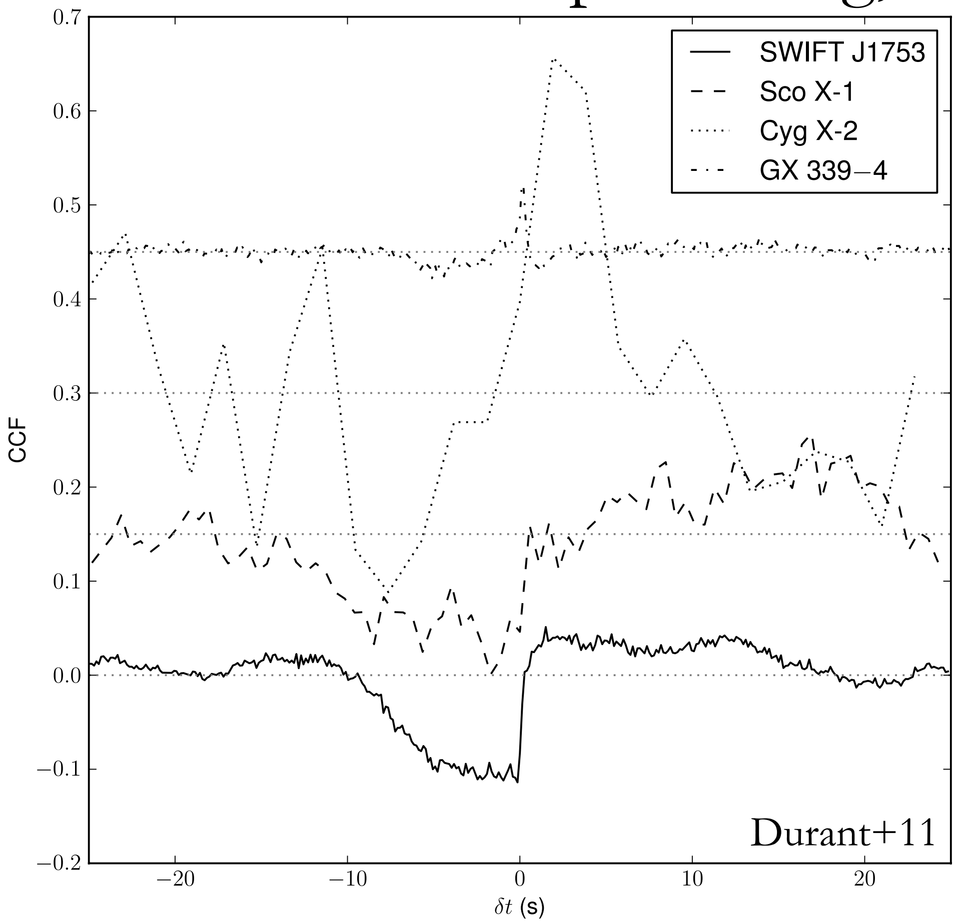
Seward+Charles10



Analyzed with time-domain photometry

Auto- and cross-correlation

- Correlate a light curve with itself or other light curves (same signal in a different energy band)
- Reverberation/reprocessing, accretion-ejection relation



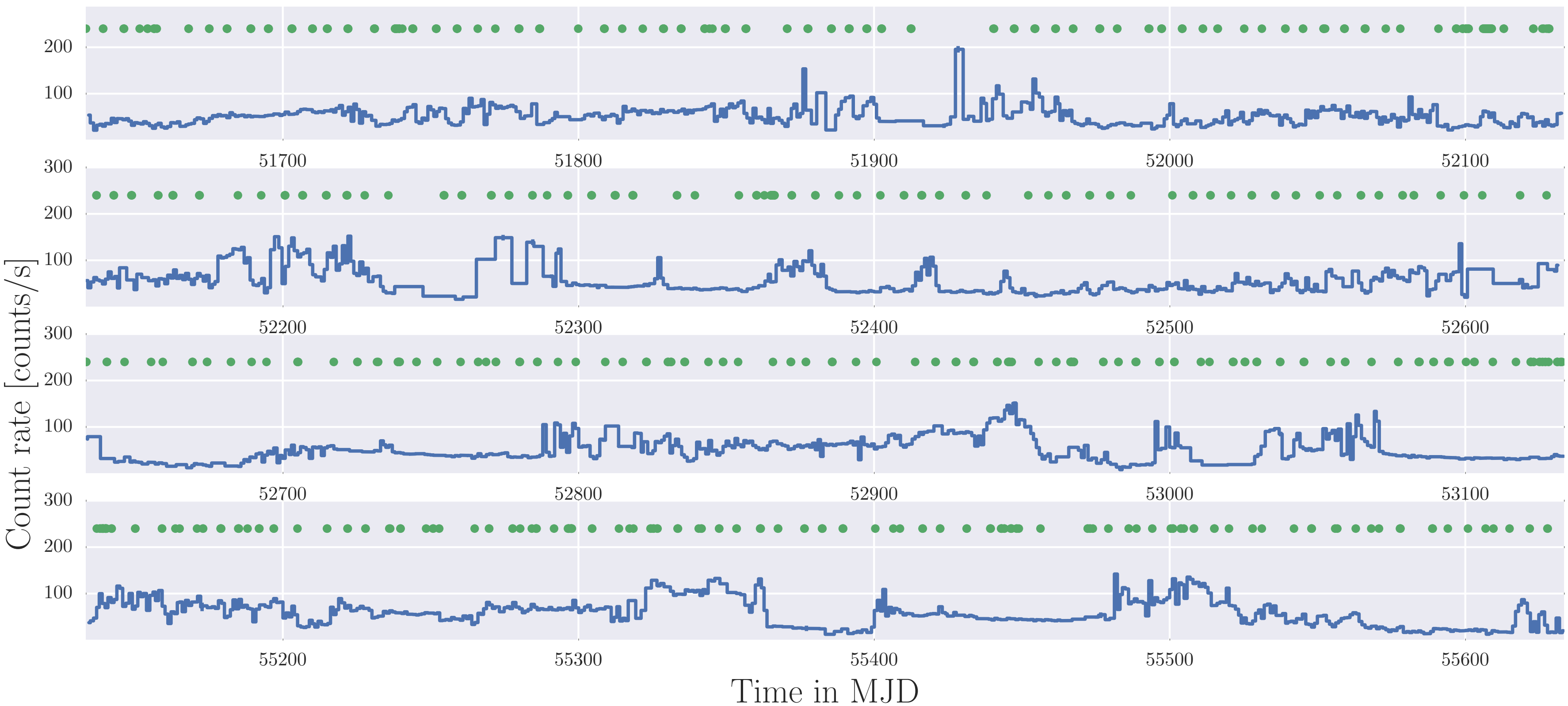
WARNING: Errors are correlated between time bins! Need to use covariance matrix or bootstrapping

see e.g. Emmanoulopoulous+10

See Edelson+Krolik88; see also papers by e.g. Casares, Gandhi, Hynes, Plotkin, Shahbaz, Veledina

Machine learning for BH variability

- GRS 1915+105: microquasar with 14 distinct variability states



Adapted from Huppenkothen+17

Machine learning for BH variability

- GRS 1915+105: microquasar with 14 distinct variability states
- How are the different variability patterns related?
  - Machine learning!

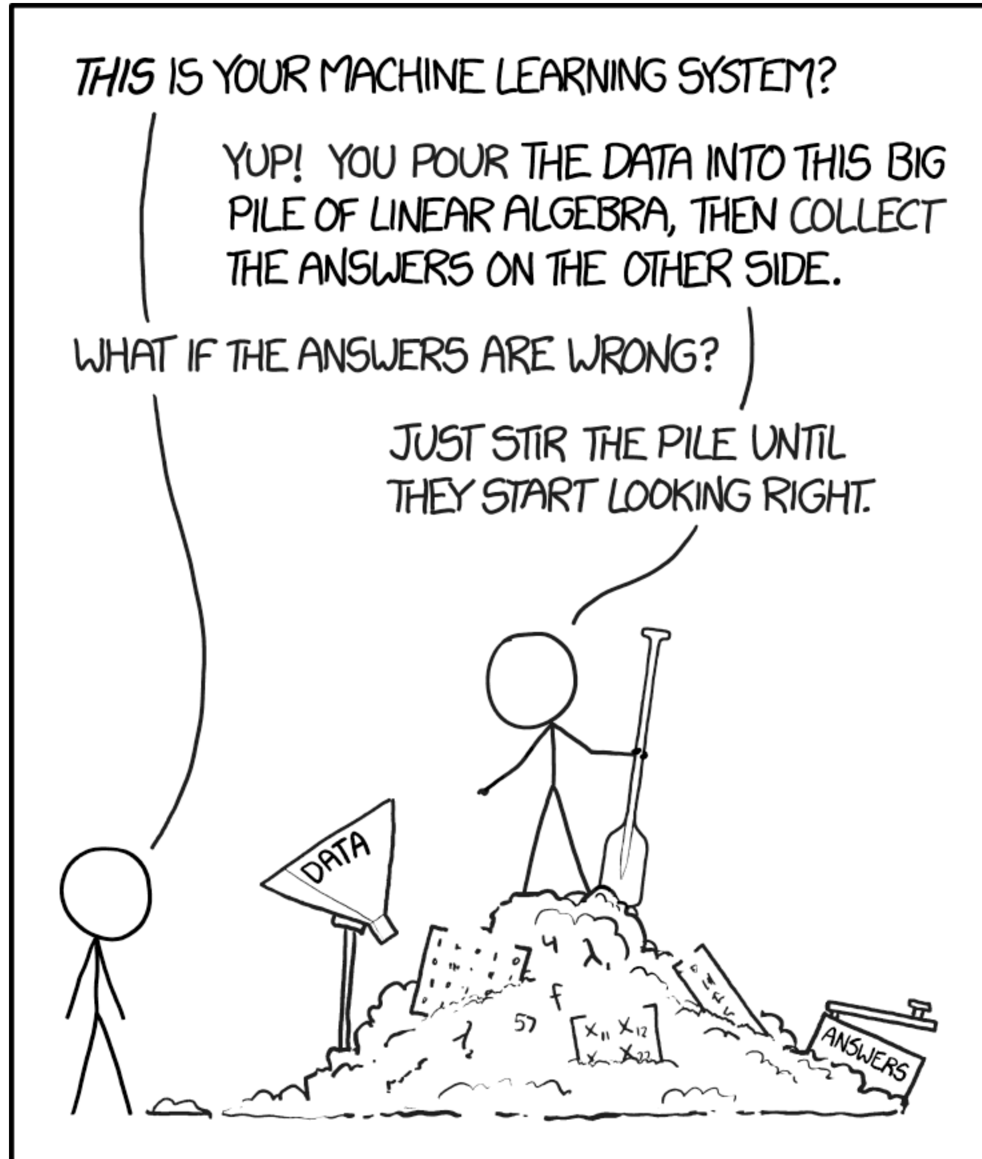


Image: XKCD; h/t D. Huppenkothen

Machine learning for BH variability

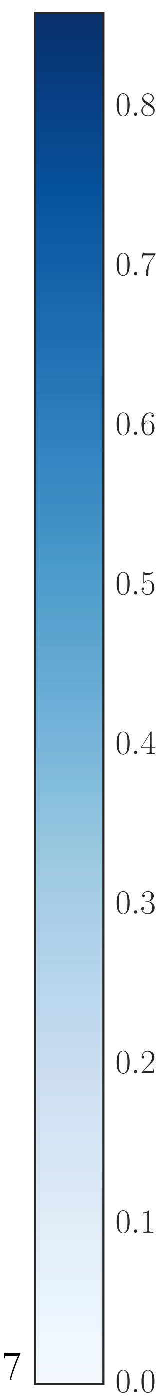
States correlate with themselves (if in state χ, 85.9% of the time it stays in state χ)

Some states are more prone to transition to other states

Some states never transition to other states

Transition Matrix

Initial state \ Final state	α	β	χ	δ	η	γ	κ	λ	μ	ν	ω	ϕ	ρ	θ
α	0.478	0.225	0.130	0.000	0.007	0.007	0.014	0.000	0.022	0.036	0.000	0.022	0.022	0.036
β	0.013	0.729	0.090	0.016	0.002	0.007	0.011	0.004	0.022	0.021	0.003	0.016	0.021	0.044
χ	0.008	0.030	0.859	0.012	0.002	0.007	0.009	0.002	0.007	0.016	0.002	0.016	0.014	0.016
δ	0.000	0.037	0.099	0.737	0.002	0.023	0.009	0.007	0.012	0.018	0.002	0.025	0.021	0.007
η	0.014	0.014	0.068	0.000	0.753	0.000	0.014	0.014	0.000	0.027	0.014	0.014	0.055	0.014
γ	0.000	0.040	0.092	0.026	0.000	0.736	0.015	0.004	0.026	0.007	0.007	0.011	0.022	0.015
κ	0.006	0.038	0.076	0.009	0.000	0.006	0.700	0.035	0.067	0.009	0.003	0.012	0.015	0.026
λ	0.010	0.050	0.109	0.040	0.000	0.020	0.109	0.554	0.059	0.000	0.030	0.010	0.000	0.010
μ	0.005	0.108	0.073	0.011	0.000	0.022	0.024	0.030	0.667	0.005	0.000	0.019	0.024	0.013
ν	0.033	0.052	0.225	0.016	0.003	0.007	0.016	0.003	0.010	0.562	0.007	0.013	0.020	0.033
ω	0.010	0.020	0.099	0.030	0.020	0.020	0.030	0.020	0.000	0.010	0.663	0.059	0.020	0.000
ϕ	0.003	0.035	0.103	0.012	0.001	0.001	0.007	0.001	0.009	0.003	0.003	0.795	0.018	0.009
ρ	0.003	0.054	0.075	0.010	0.003	0.008	0.013	0.002	0.020	0.013	0.008	0.011	0.759	0.020
θ	0.006	0.088	0.076	0.010	0.001	0.007	0.003	0.000	0.006	0.016	0.007	0.017	0.014	0.748



Huppenkothen+17

Other cool time-domain science

- Asteroid rotation curves
- Eclipsing stellar binaries
- Flares and starspots; coronal mass ejections and sunspots
- Heartbeat stars
- Recurrent novae in white dwarfs
- Fast radio bursts
- Tidal disruption events
- Proper motion/parallax
- ...and more!

Things to sometimes worry about

- Deadtime occurs with X-ray detectors if your (bright) source is emitting photons faster than your detector can handle. Once some chip of the detector has detected a photon, it can't detect another photon until it reads out its existing photon detection through the electronics. It's called 'deadtime' because the detector is effectively dead for that brief readout period.
    - Measurable as deviation from expected Poisson noise power-law at high frequencies in the power spectrum
    - Accumulates over an observation; for a few ks observation, could have several seconds of deadtime to adjust the exposure time by
- Pile-up is a sibling of deadtime that affects spectra

Summary

- A lot of cool science happens in the time domain
- <u>Techniques</u>: power spectra, lags, cepstrum, auto/cross -correlation and -covariance, radial velocity of spectral lines, time-domain spectroscopy, photometry, imaging
- Understand assumptions of models, techniques; question your own assumptions about data, process
- It's possible to get over-excited about the signal processing literature; keep the physics/science in mind when considering analysis routes
- When in doubt, simulate!
- Thesis introductions are great to read for an overview of topics/ techniques

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