Timing and Spectral Variability in Black Holes

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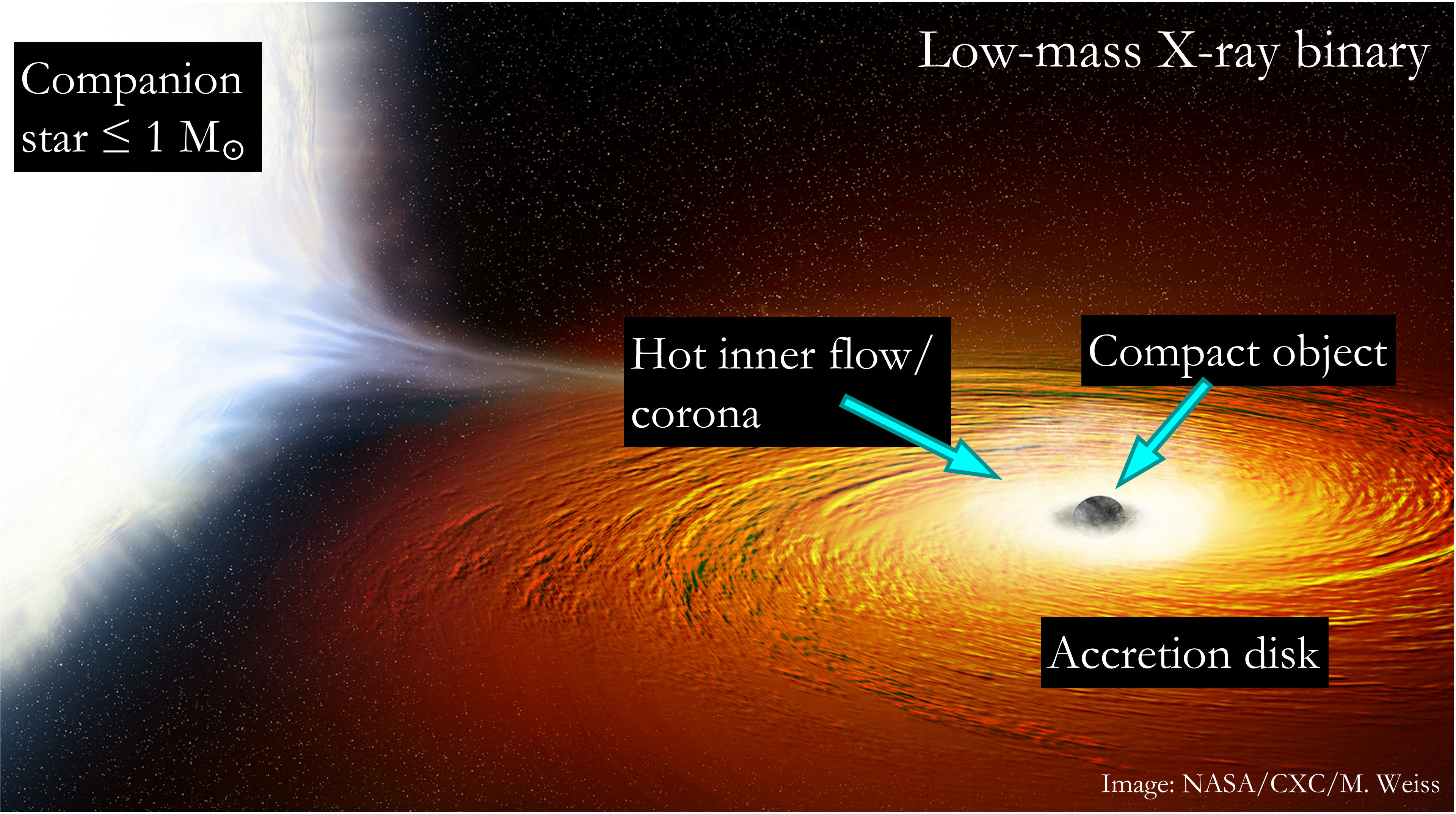
Outline

- Variability in stellar-mass black holes
- Spectral-timing analysis (incl. machine learning)
- Red noise vs. interesting signals
- Stingray: open-source spectral-timing software
- *STROBE-X*: next-gen. broadband X-ray observatory

Variability in stellar-mass BHs

- Many are transient: outburst over months/year



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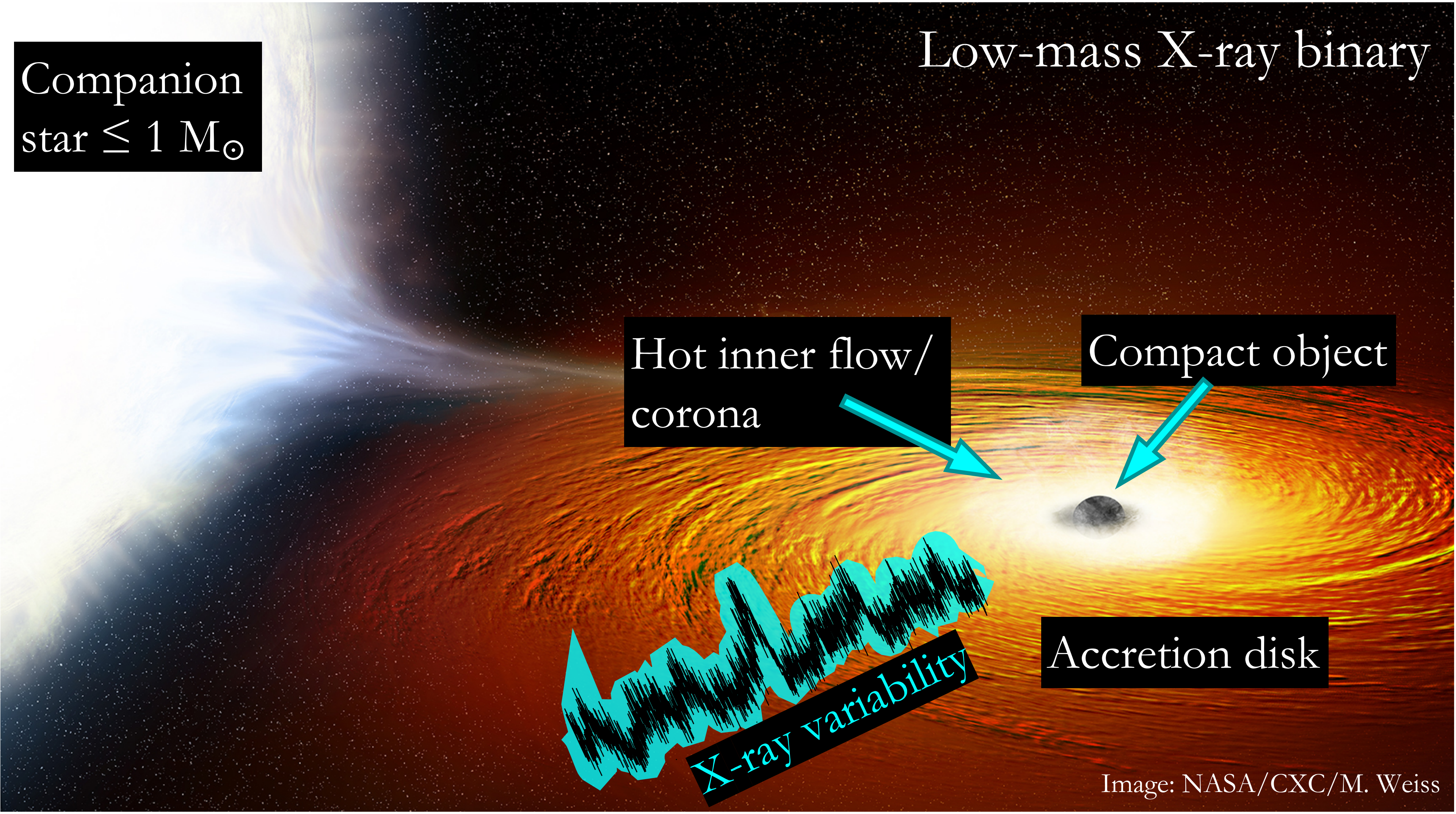
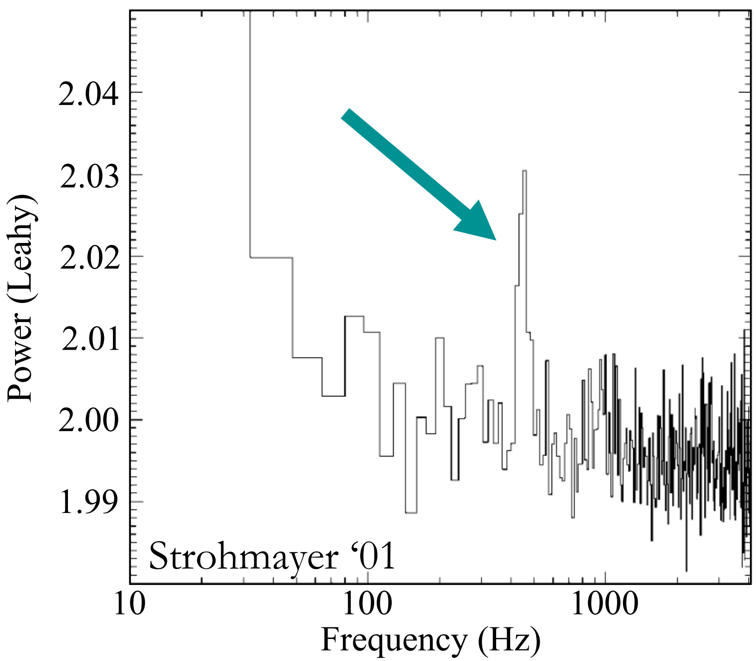


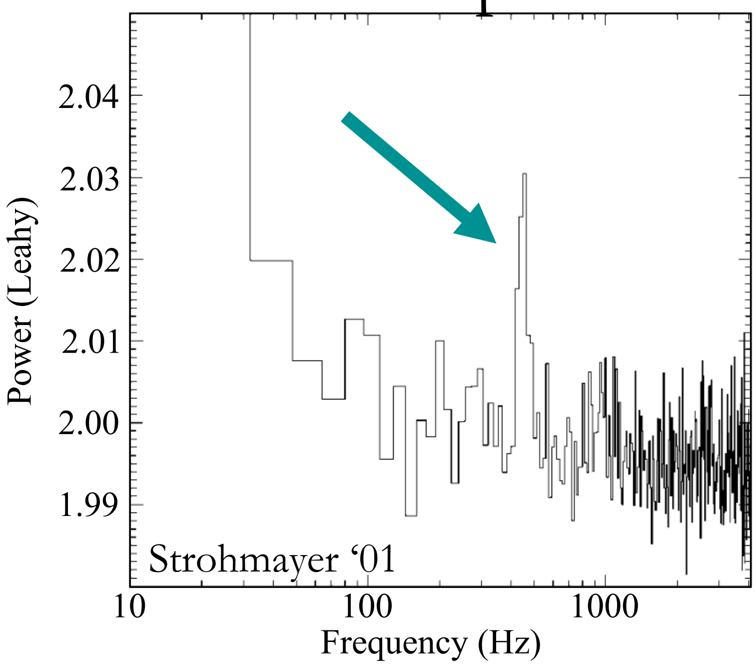
Variability in stellar-mass BHs

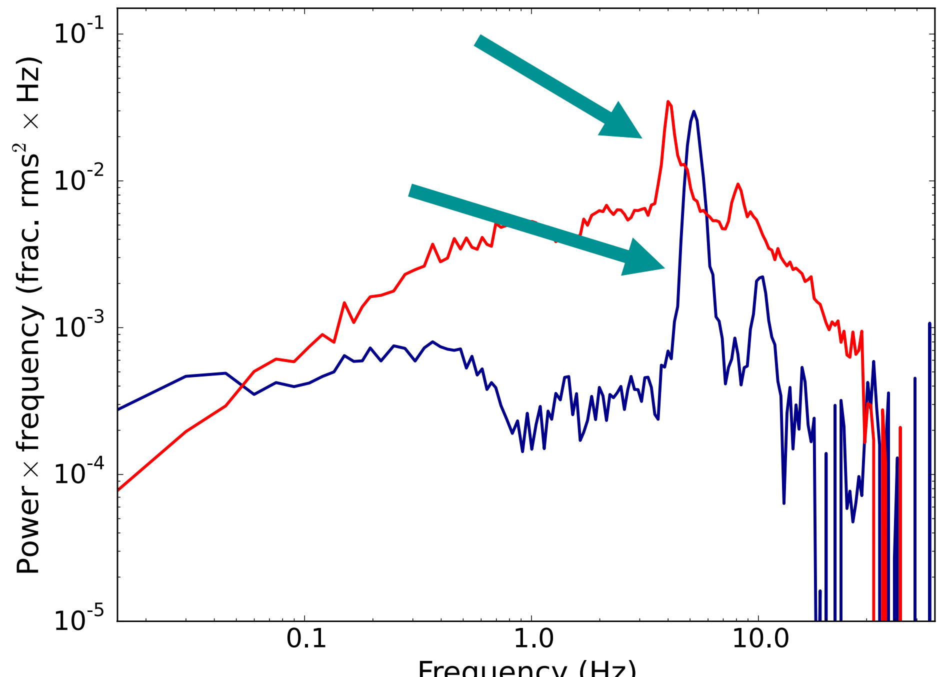
- Quasi-periodic oscillations (QPOs)
  - High-frequency: 100's Hz
    - Hot blobs in Keplerian orbit at inner disk edge?



Variability in stellar-mass BHs

- Quasi-periodic oscillations (QPOs)
  - High-frequency: 100's Hz
    - Hot blobs in Keplerian orbit at inner disk edge?
  - Low-frequency: ~0.1-10's Hz
    - Precession of corona/hot flow? Magnetic warps in disk? Comptonized disk fluctuations?





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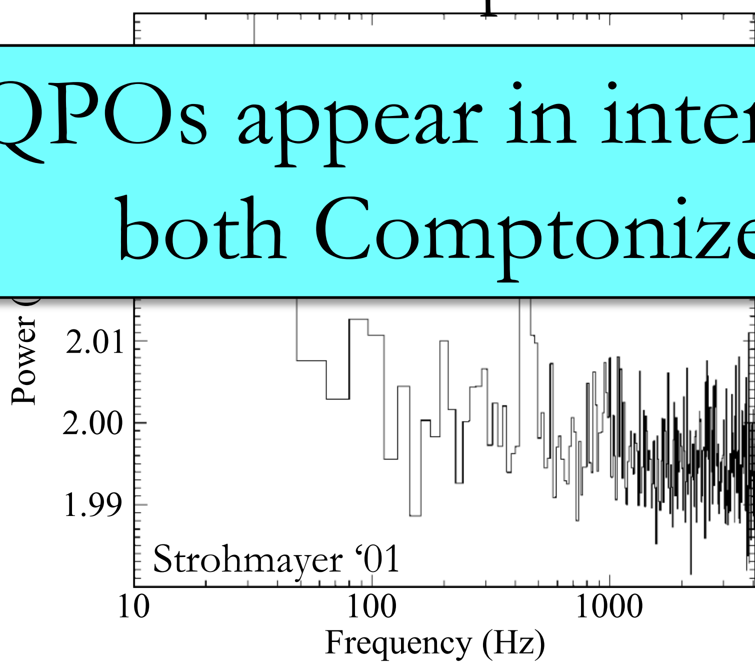
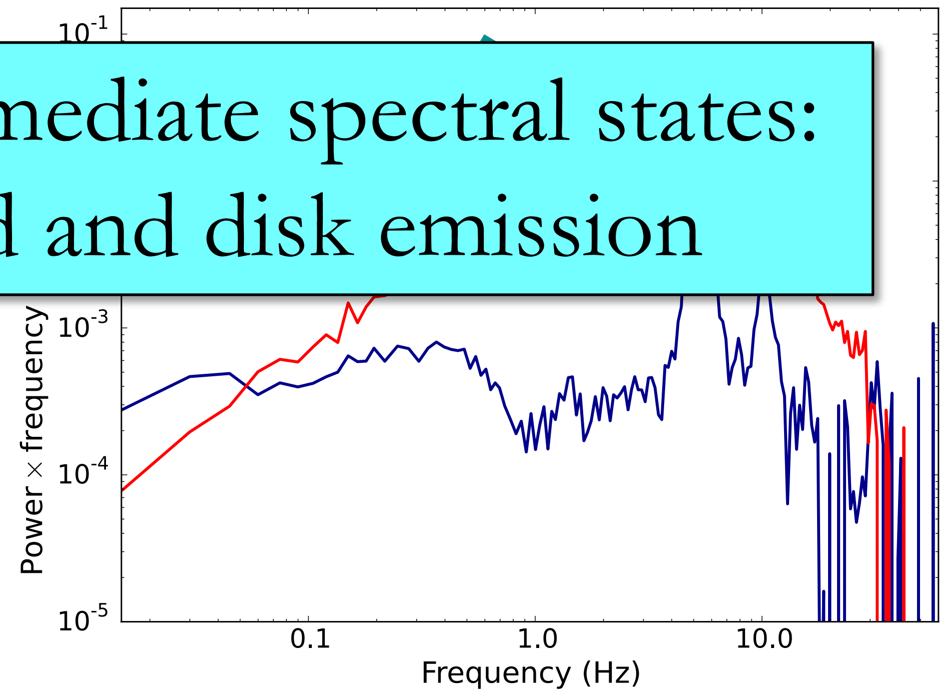
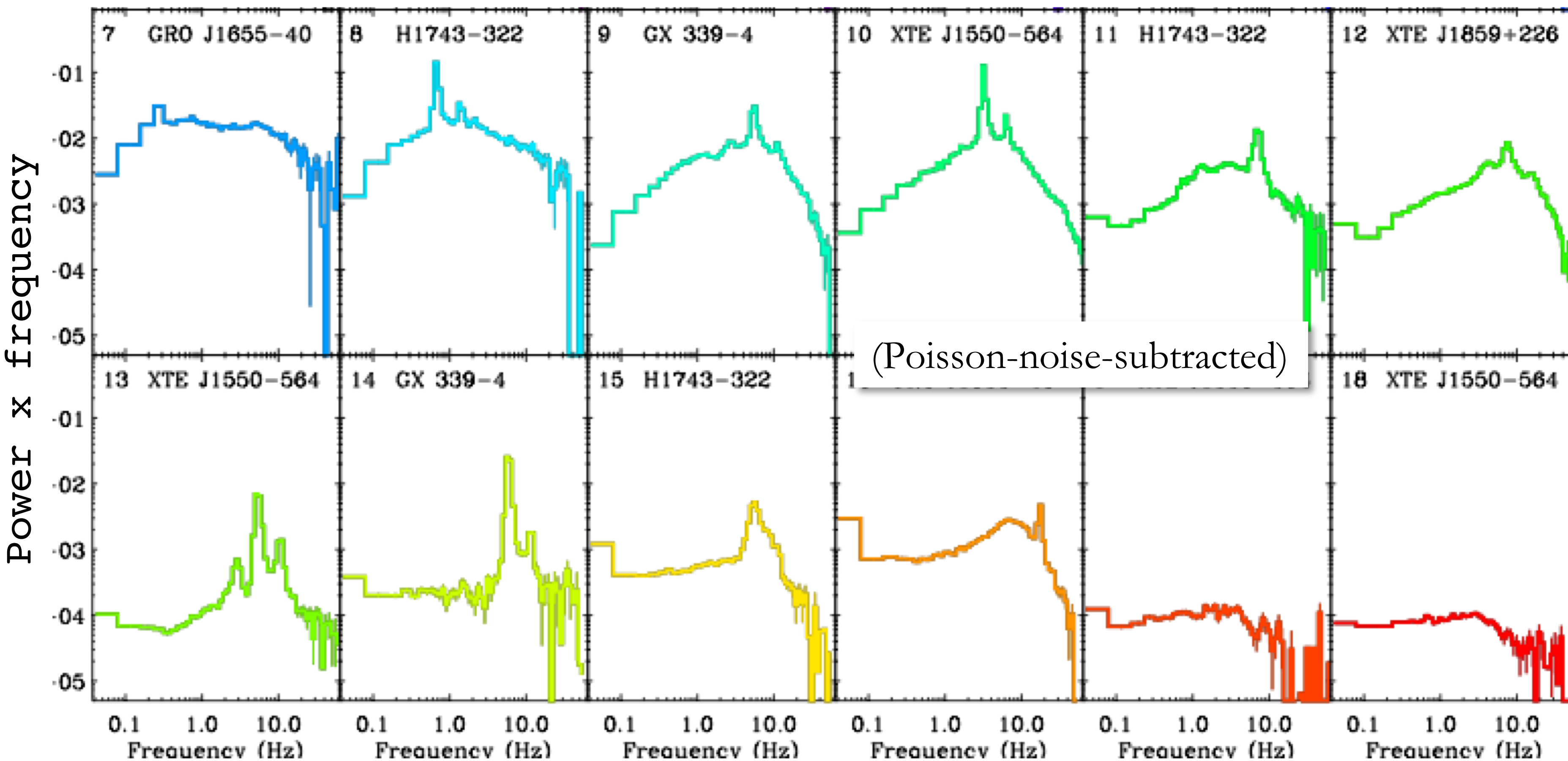




QPOs appear in intermediate spectral states: both Comptonized and disk emission

Variability in stellar-mass BHs

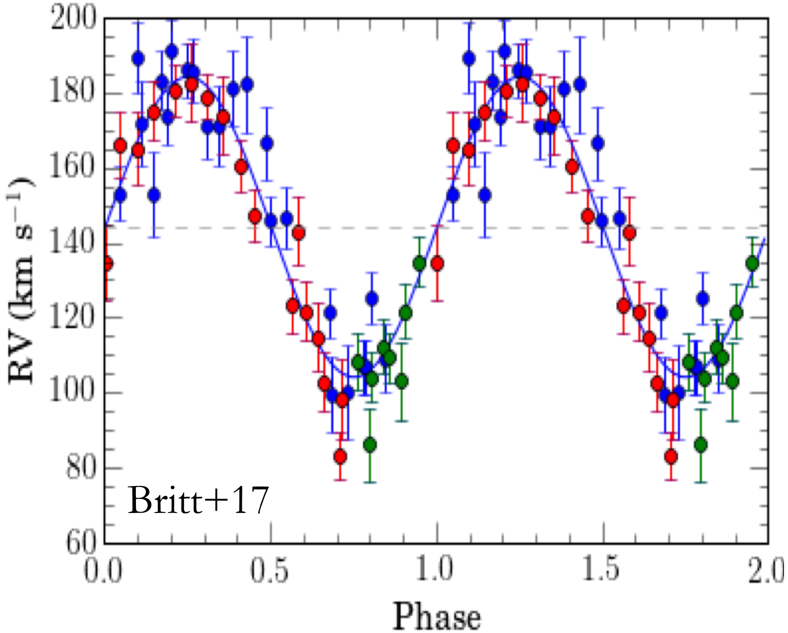
- Broadband noise (band-limited noise): $\lesssim 1$ Hz
  - Propagating fluctuations in accretion disk?

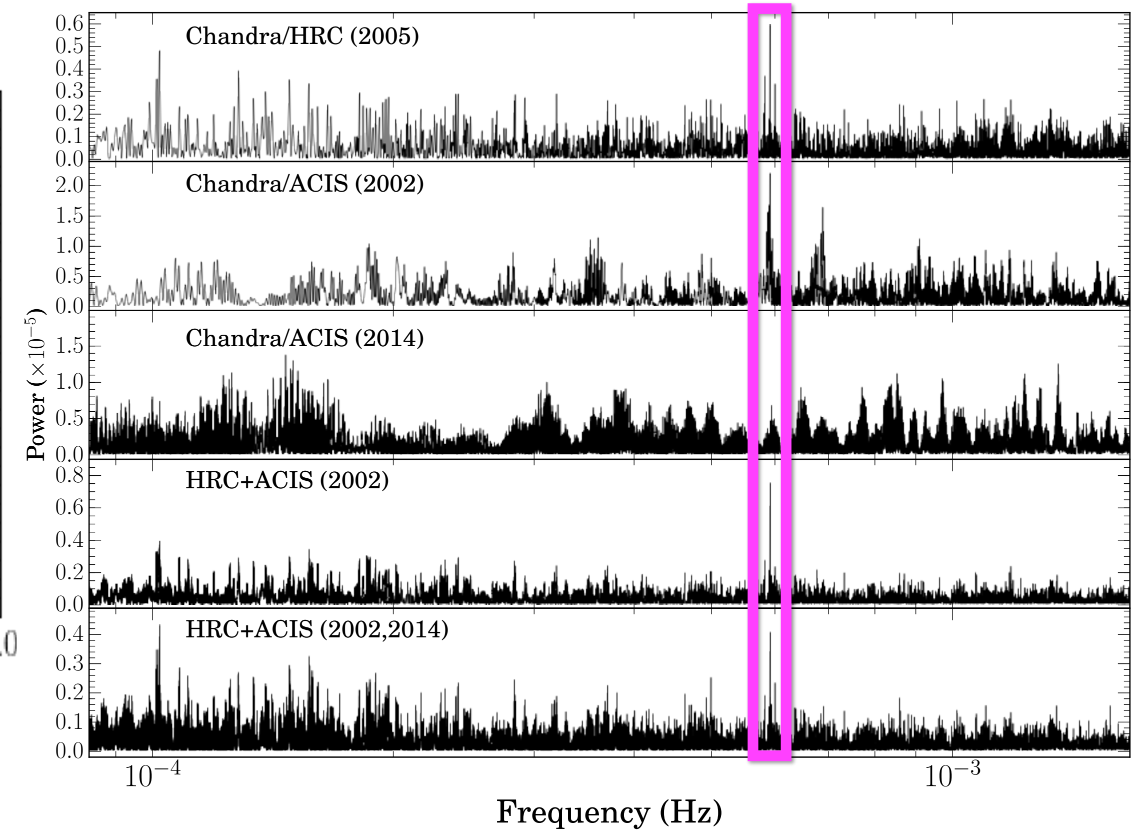


Heil+15b

Variability in stellar-mass BHs

- Orbital binary motion: period > 10 min

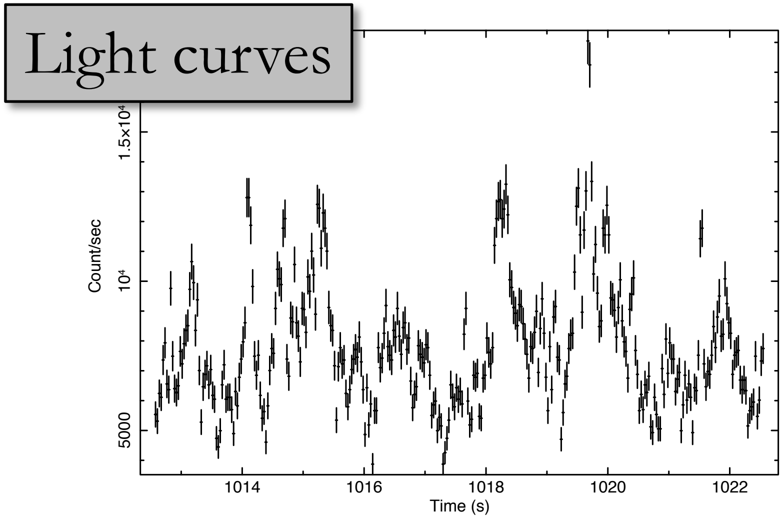


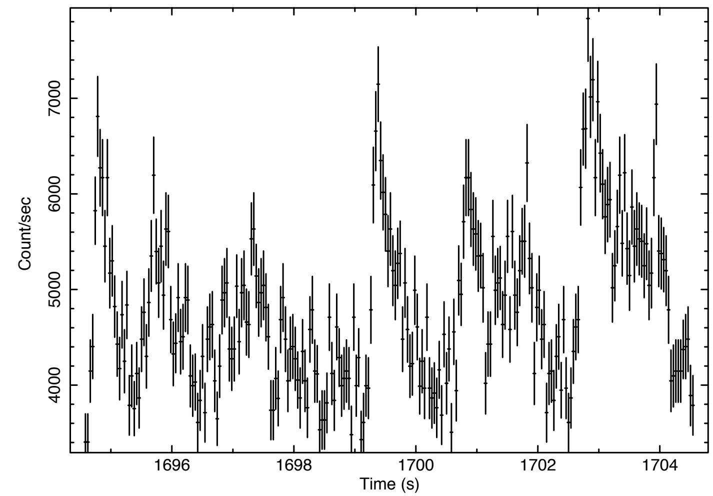


- Optical radial velocity measurements of companion star

- Power spectra of multiple epochs, multiple instruments, 10-60ks exposures

BH variability is hard to see by eye!



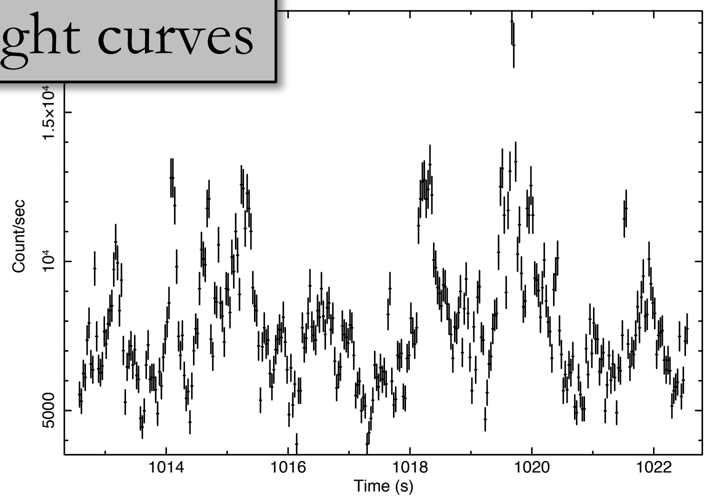


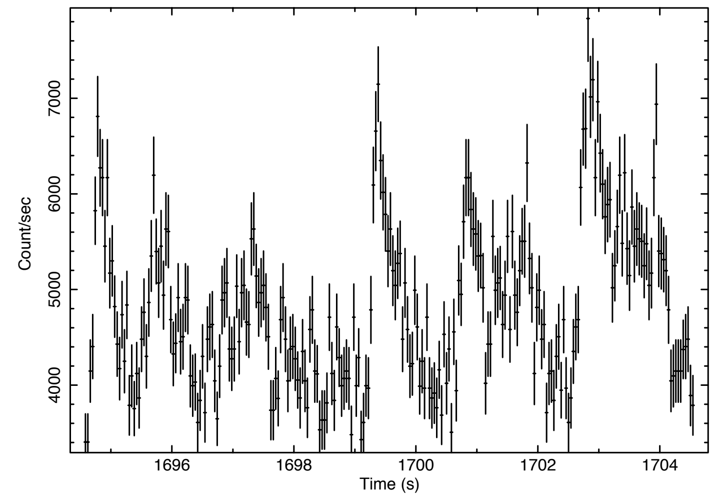
BH variability is hard to see by eye!

Noise: Cygnus X-1

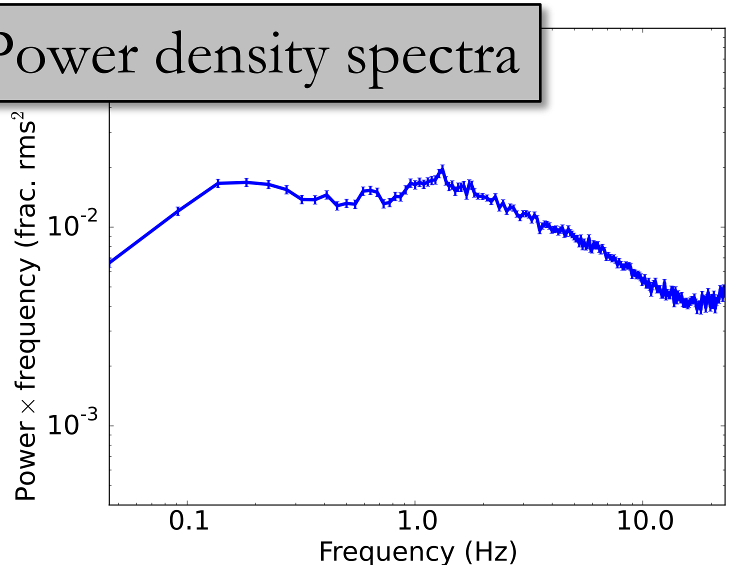
Signal: GRS 1915+105

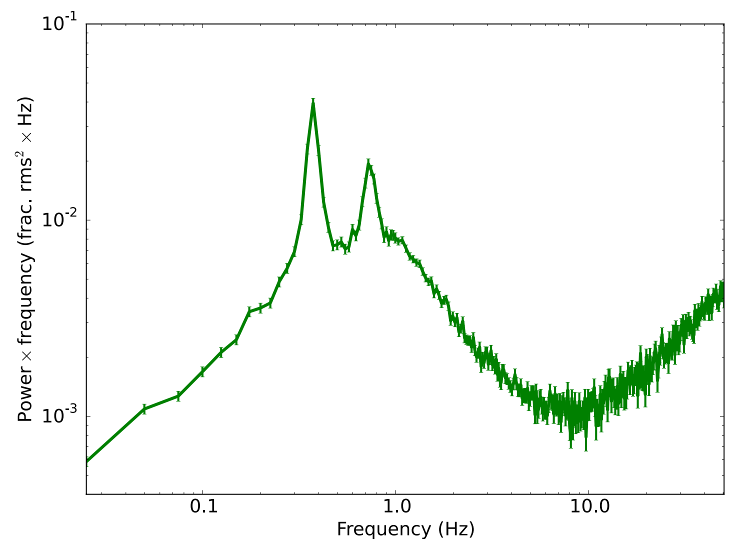
Light curves





Power density spectra





The timing toolbox

- Power spectra/periodograms
- Bispectra, bicoherence
- Coherence

See Uttley+14 for a review of techniques

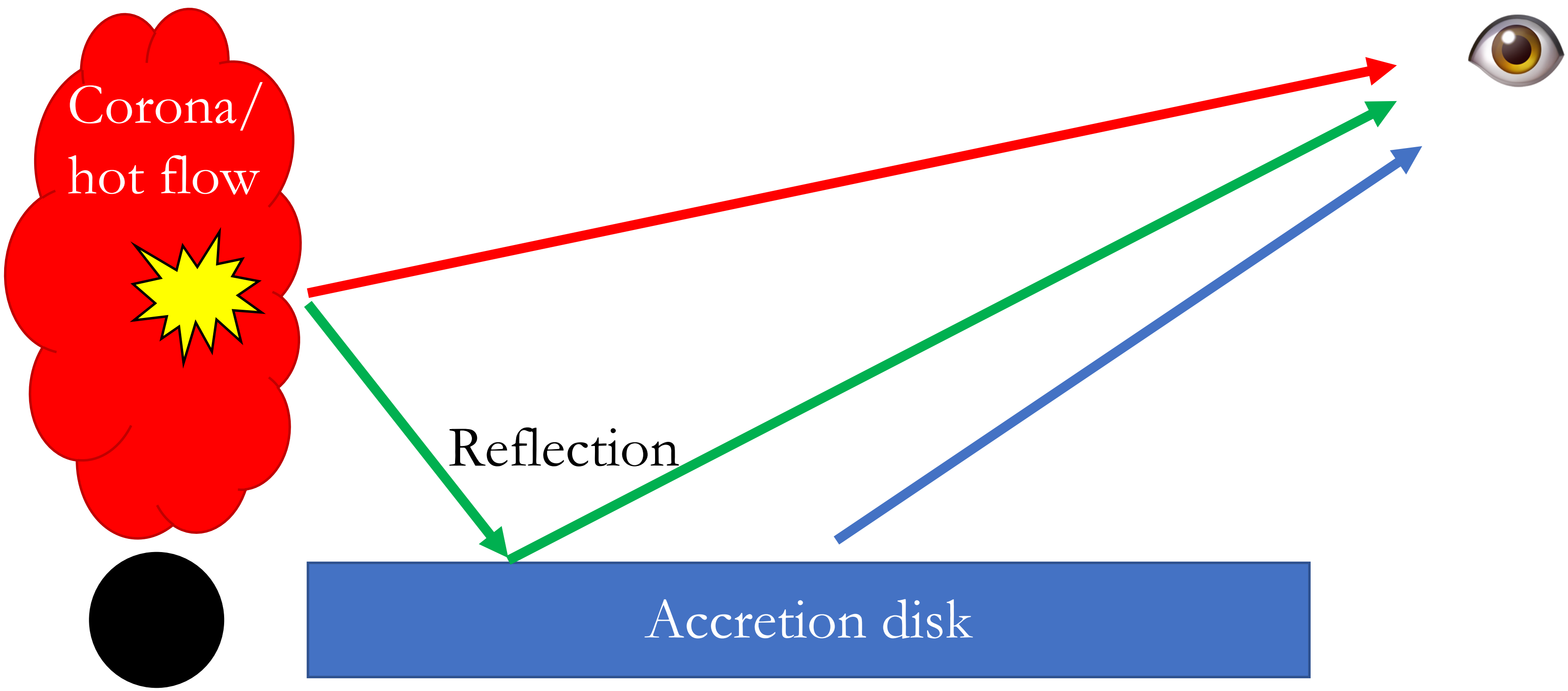
The spectral-timing toolbox

- Power spectra/periodograms
- Bispectra, bicoherence
- Coherence
- rms and covariance spectra
- Cross spectra, cospectra
- Energy- and frequency-dependent time lags
- Cross-correlation
- Phase-resolved spectroscopy

} Fourier techniques

See Uttley+14 for a review of techniques

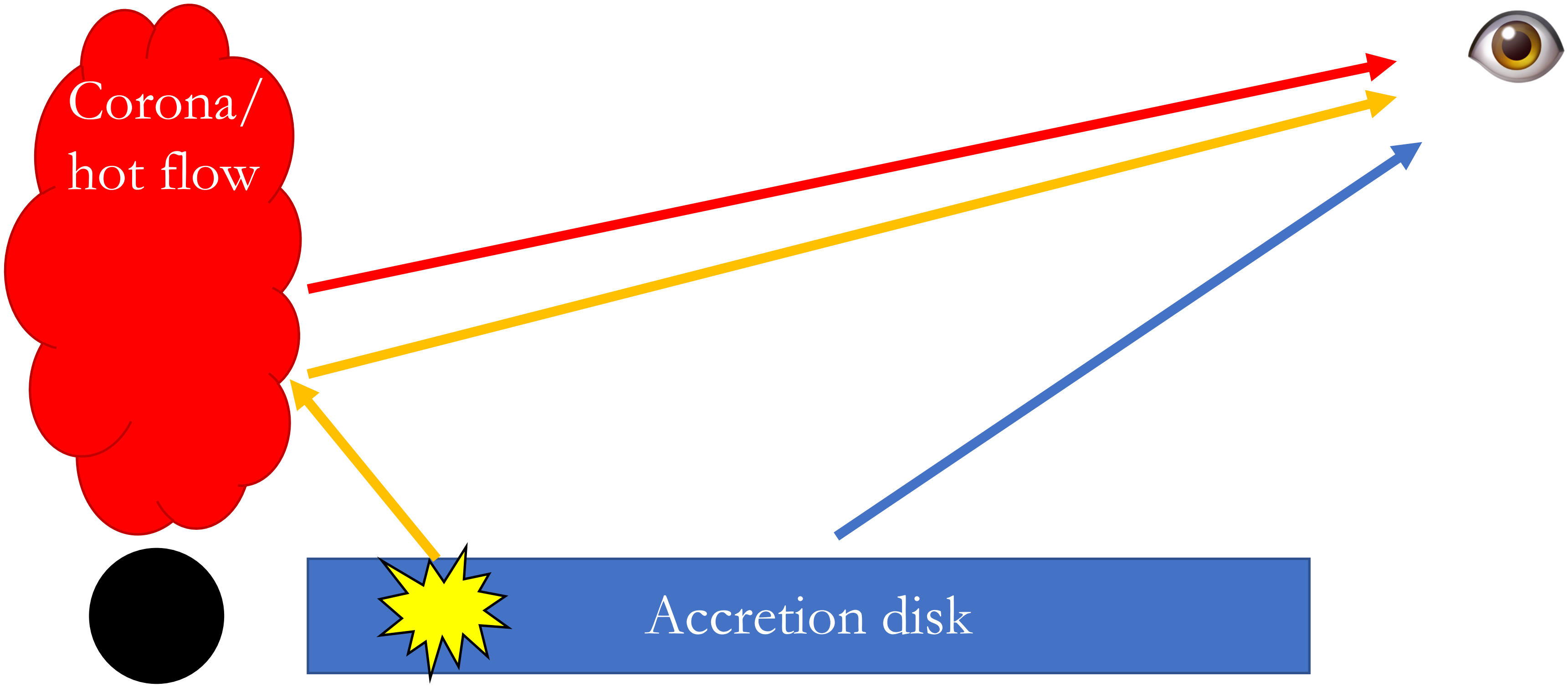
AGN reverberation



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

See work by, e.g., Cackett, Fabian, Kara, Uttley, Wilkins, Zoghbi

AGN reverberation



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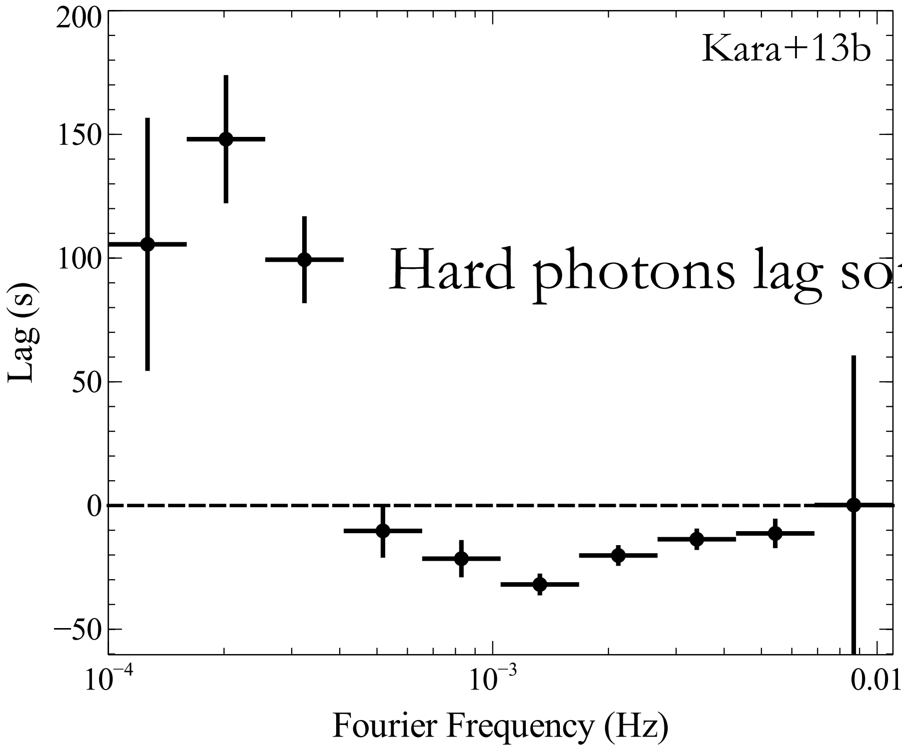
AGN reverberation

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



Hard photons lag soft photons

Soft photons lag hard photons

AGN reverberation

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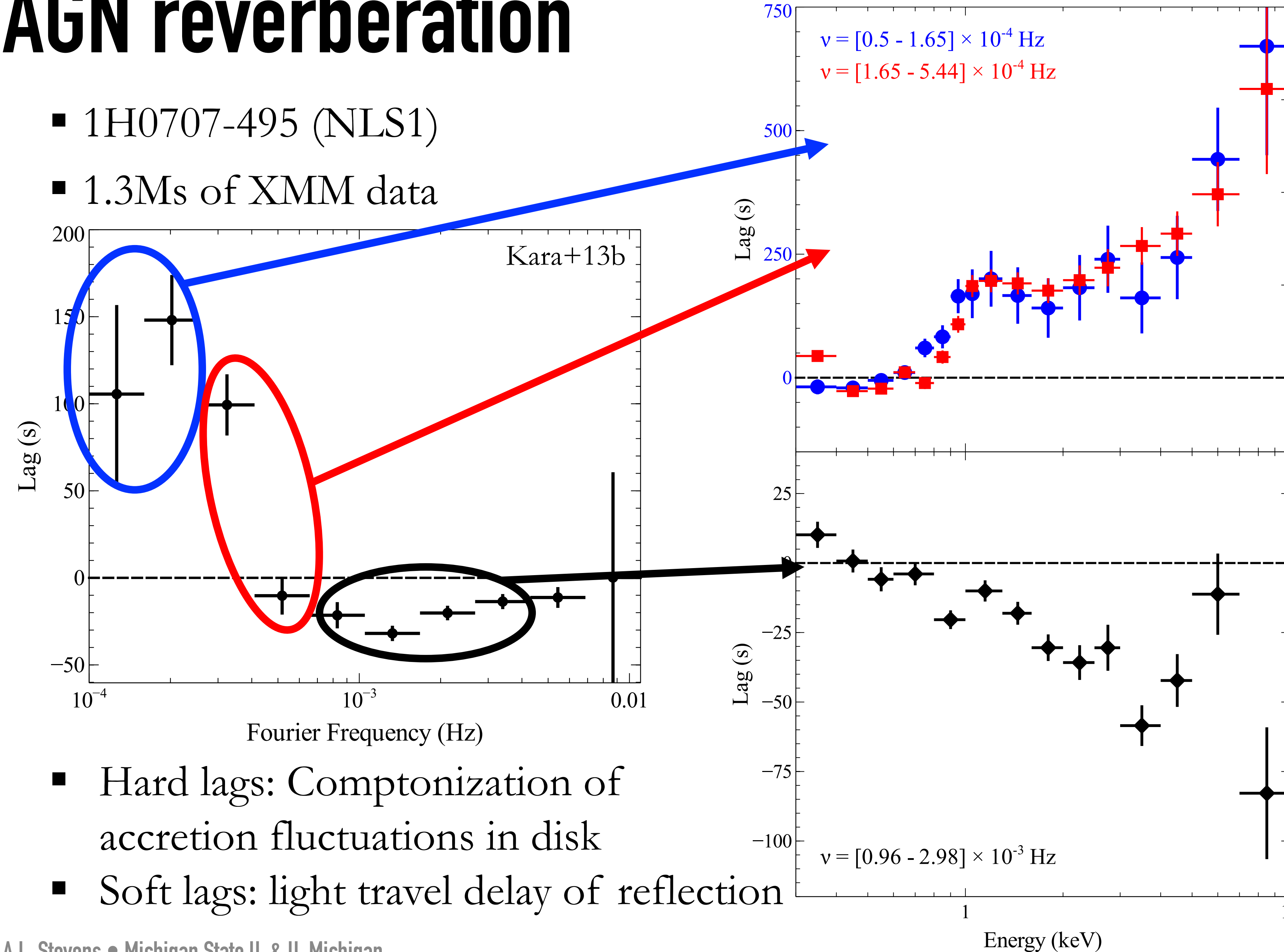
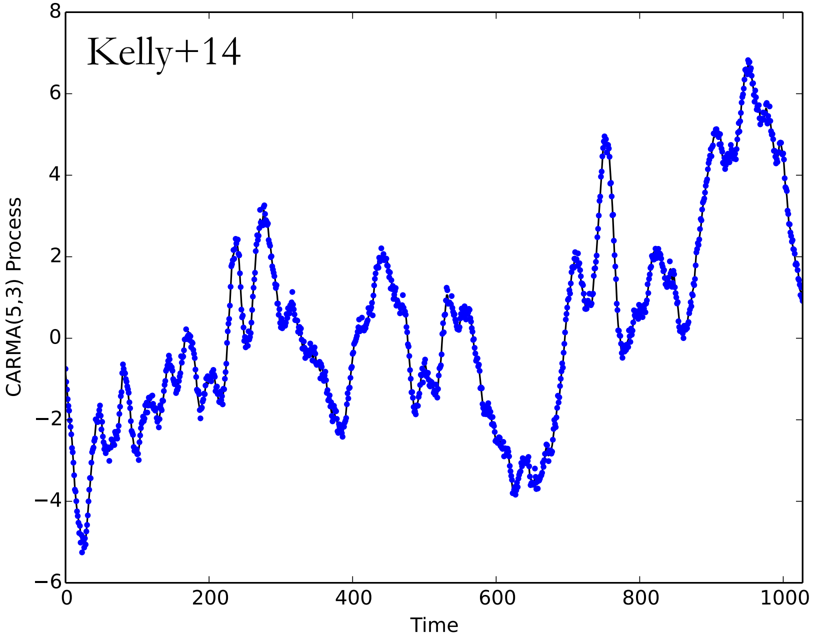
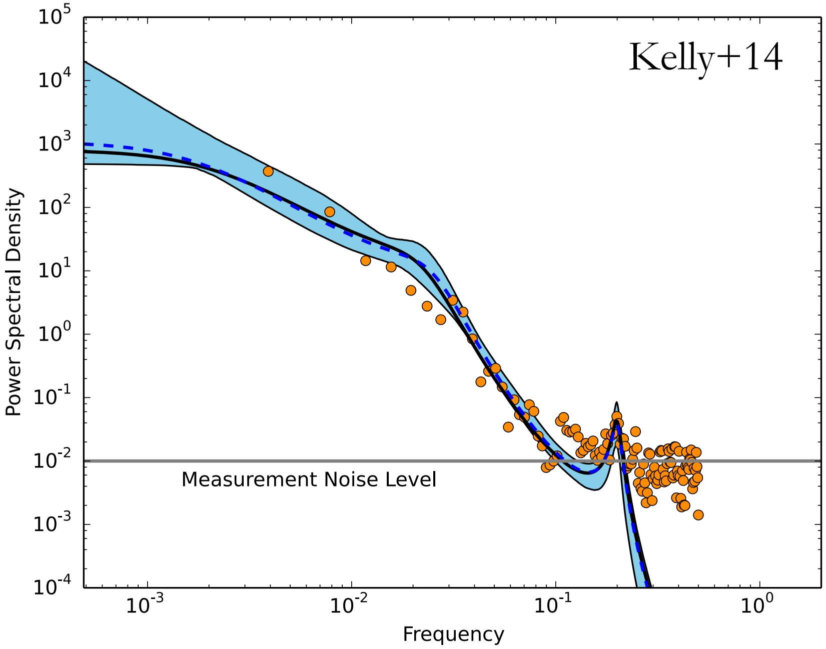


- Hard lags: Comptonization of accretion fluctuations in disk
- Soft lags: light travel delay of reflection

Gaussian processes (recap from yesterday)

- Modeling the light curve in the time domain

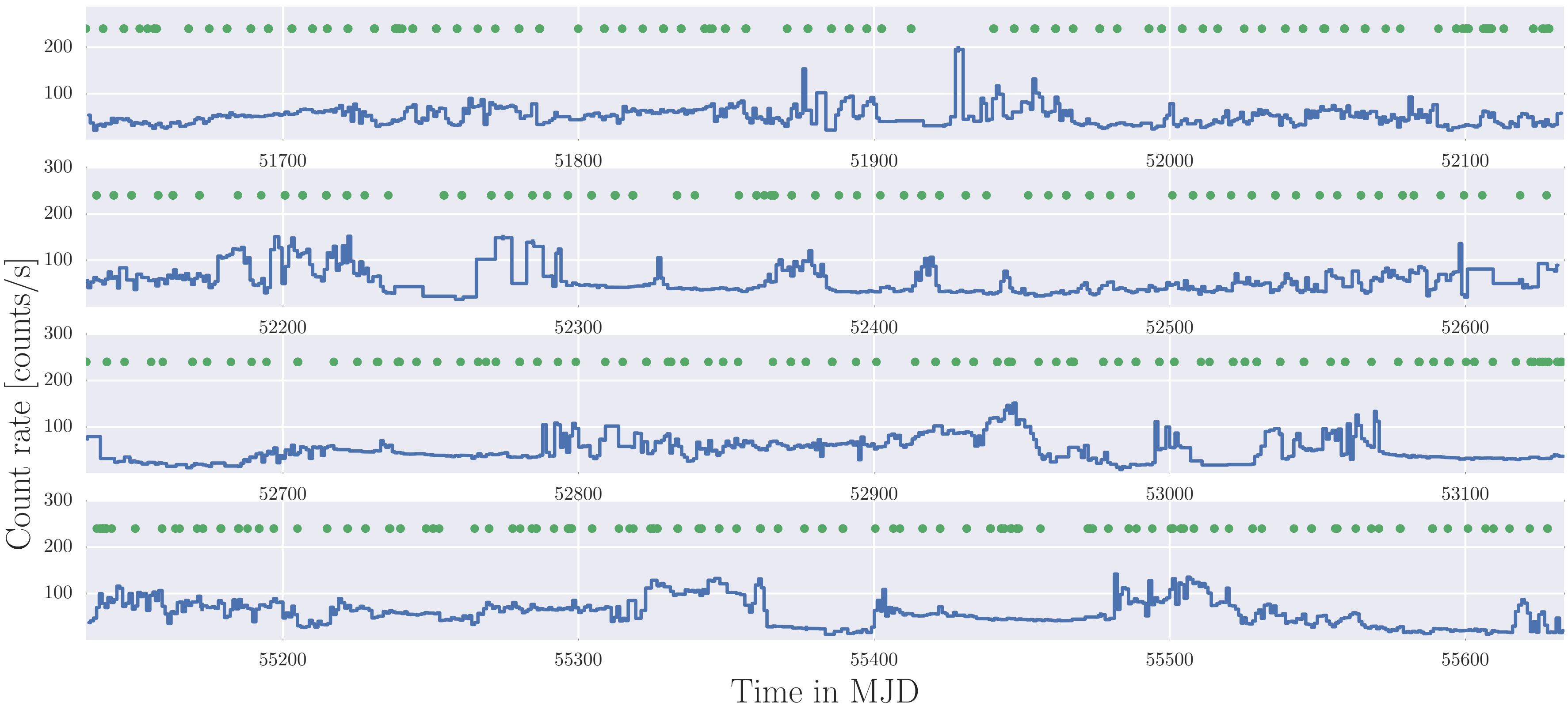




- CARMA models (Kelly+14)
- Celerite (Foreman-Mackey+17)
- ARIMA models (Zhang+18)

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!

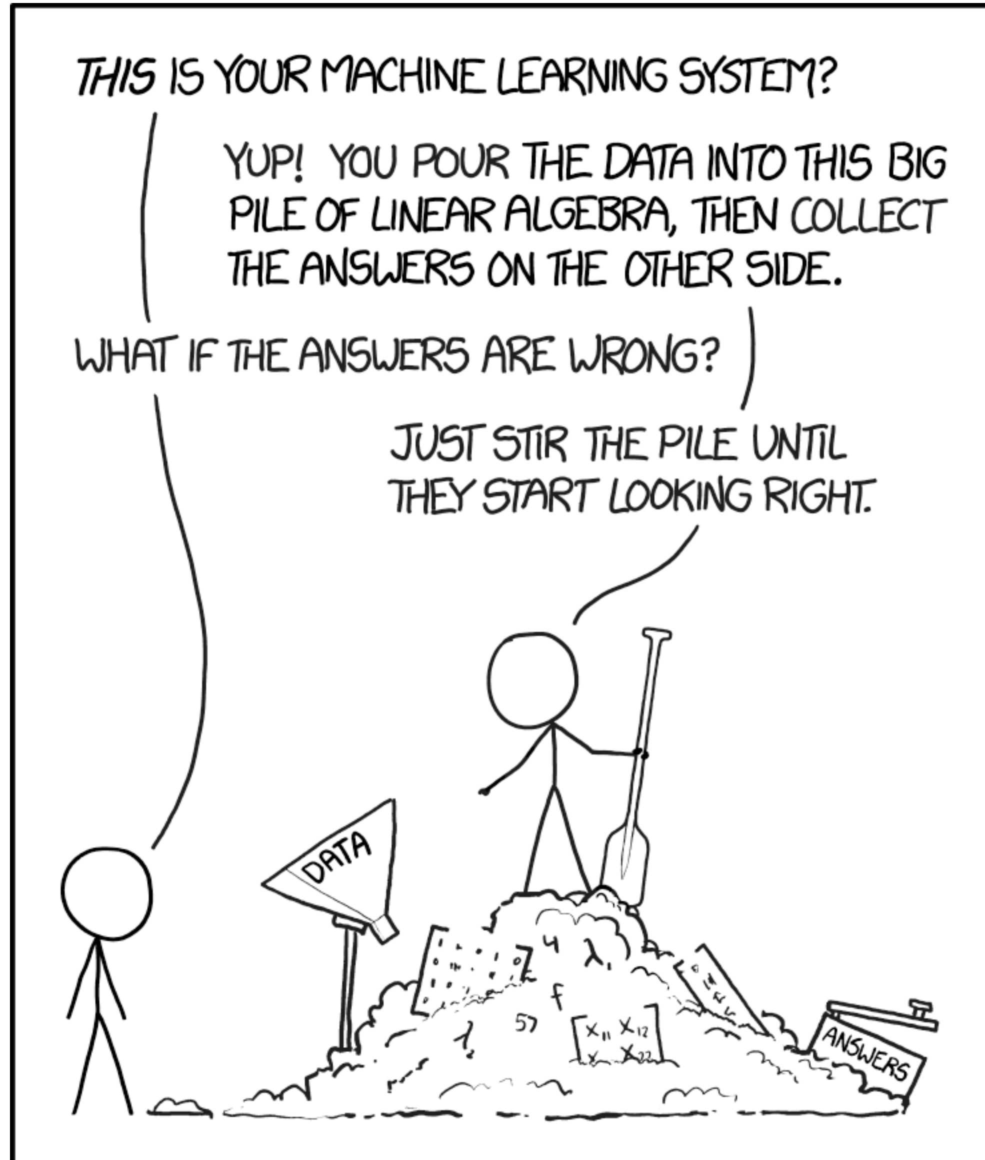


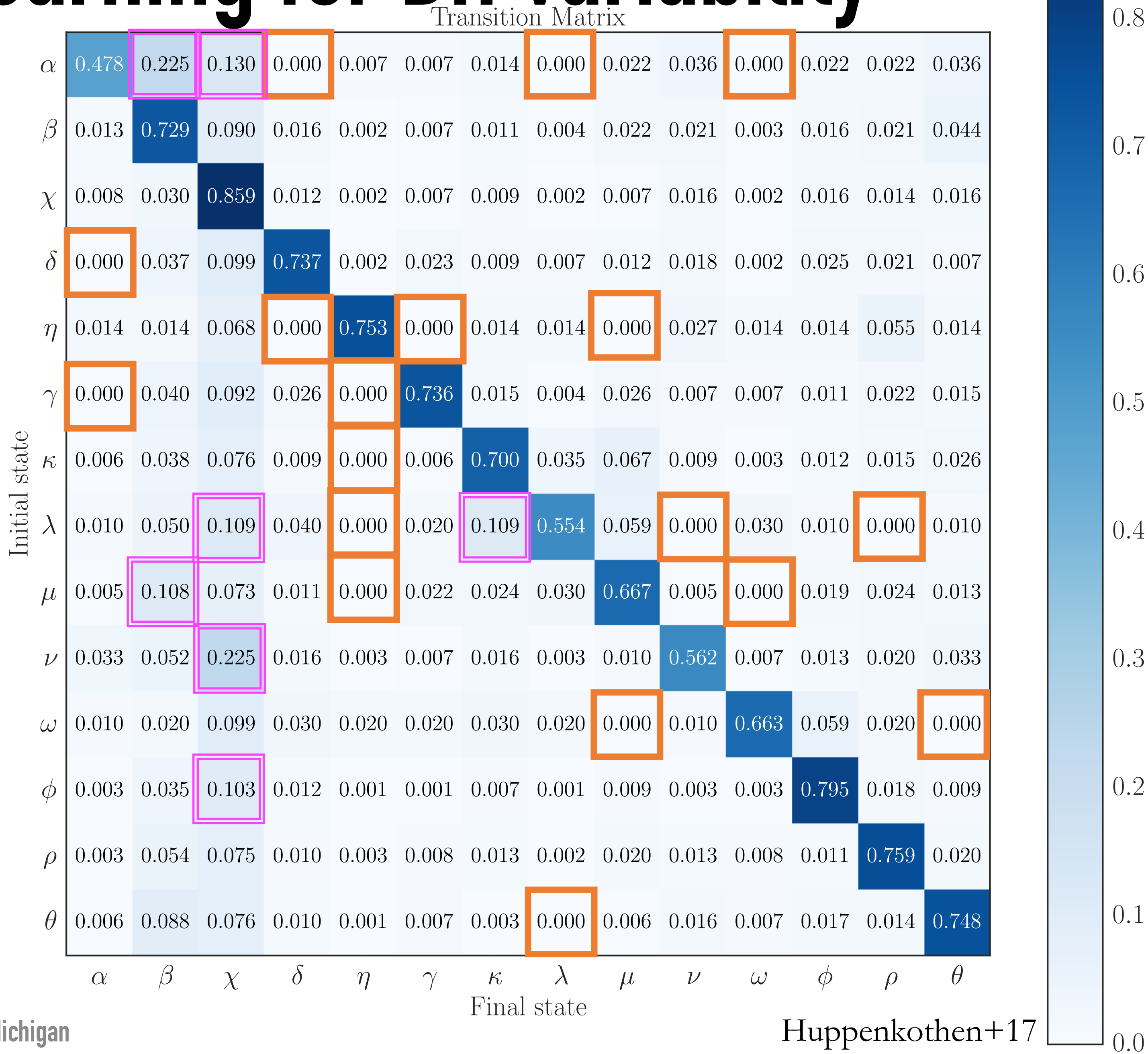
Image: XKCD; h/t D. Huppenkothen

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



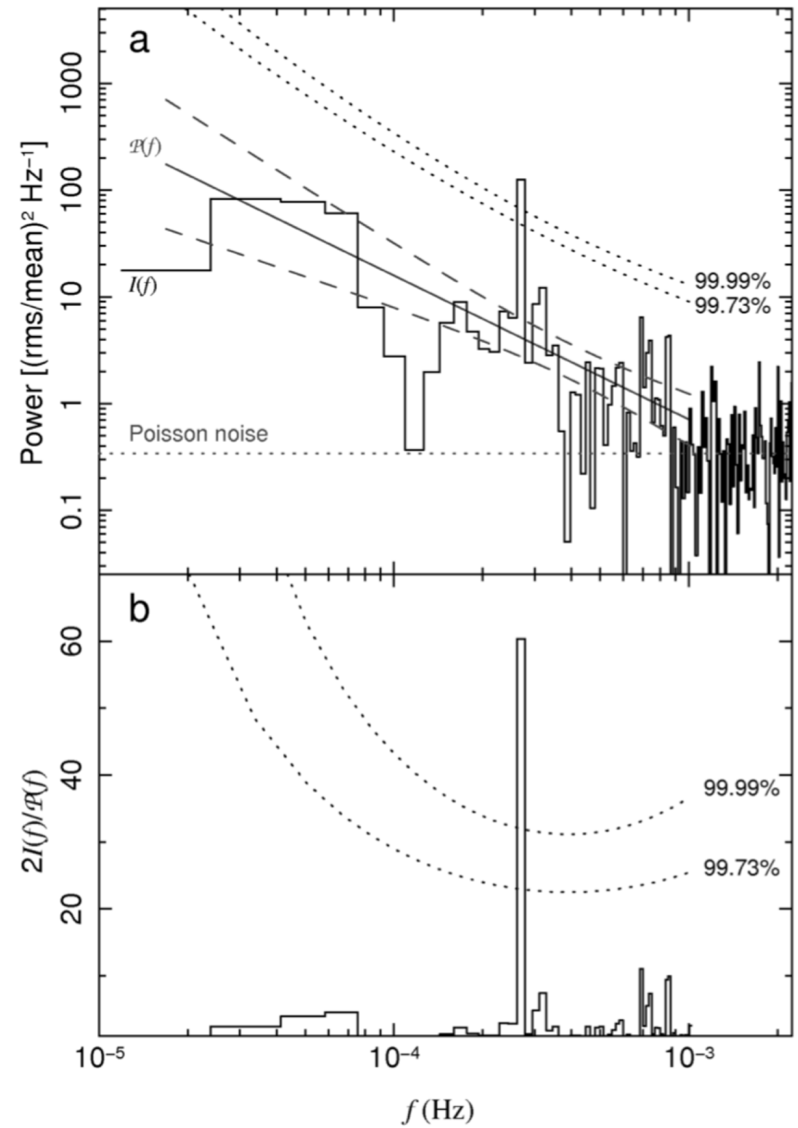
Initial \ Final	α	β	χ	δ	η	γ	κ	λ	μ	ν	ω	ϕ	ρ	θ
α	0.478	0.225	0.130	0.000	0.007	0.007	0.014	0.000	0.022	0.036	0.000	0.022	0.022	0.036
β	0.013	0.729	0.090	0.016	0.002	0.007	0.011	0.004	0.022	0.021	0.003	0.016	0.021	0.044
χ	0.008	0.030	0.859	0.012	0.002	0.007	0.009	0.002	0.007	0.016	0.002	0.016	0.014	0.016
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

~1 hr periodicity in RE J1034+396

- NLS1, 91 ks in 2007 with XMM-Newton
- Saw 16 ‘cycles’ (periods) in one uninterrupted observation!
- Evenly-sampled time bins
- Signal attributed to high-freq. QPO
  - If at innermost stable circular orbit, M_{BH}~7x10^6-1x10^7 M$_\odot$

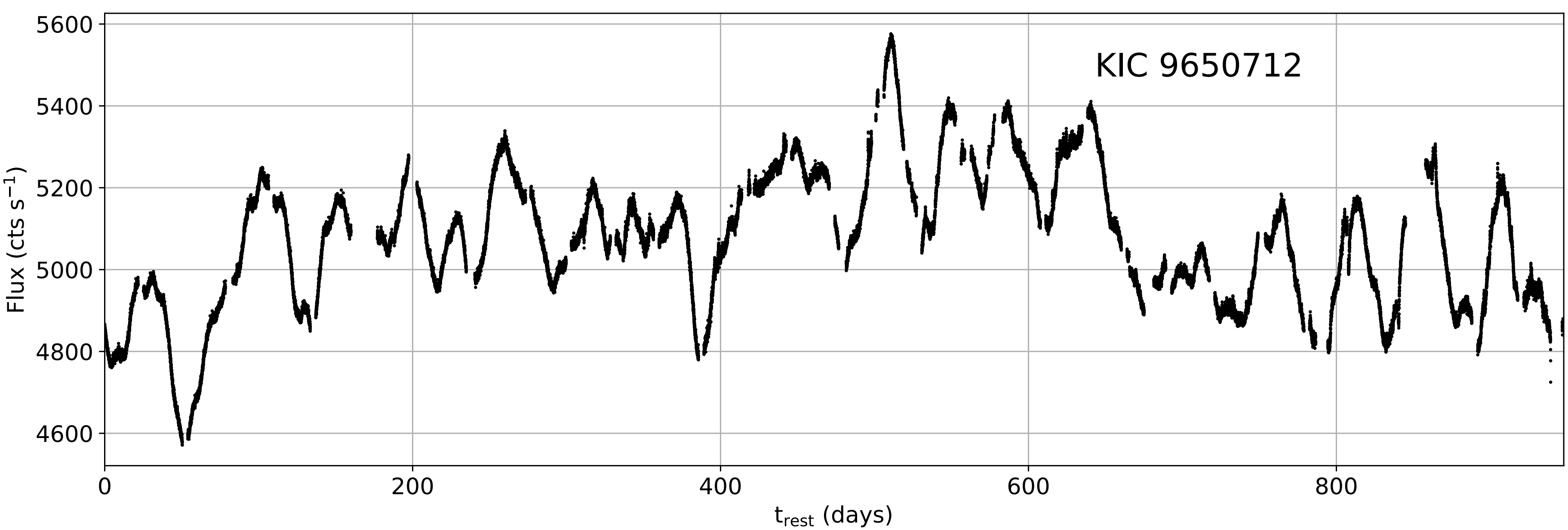
Gierlinski+08
Alston+14



44 day low-freq. QPO in KIC 9650712

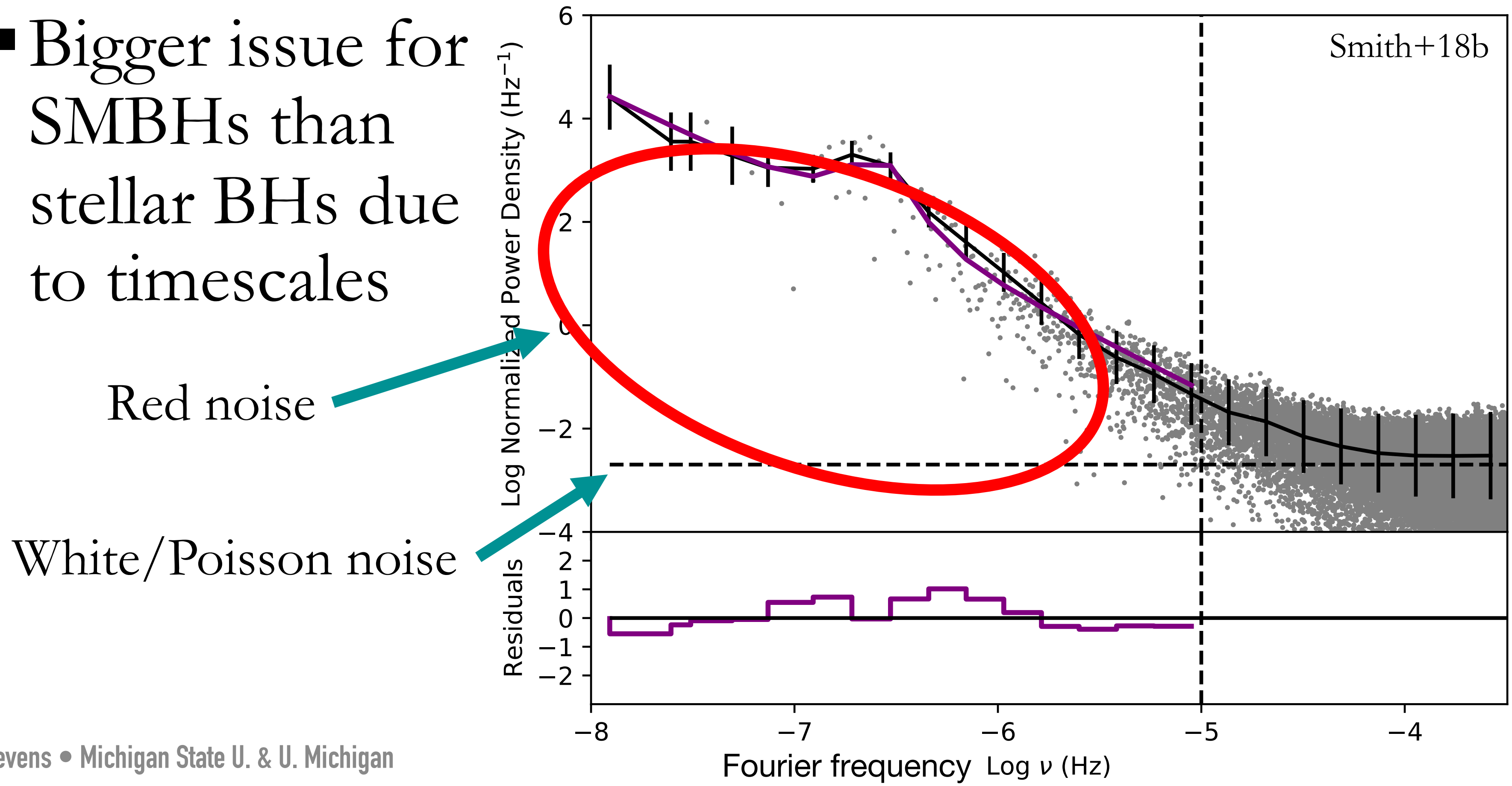
- NLS1 in original Kepler field
- 30 minute cadence over 3.5 years: ~30 cycles
- Tested periodicity via simulations (Uttley+02) and Lomb-Scargle periodogram

Smith+18b



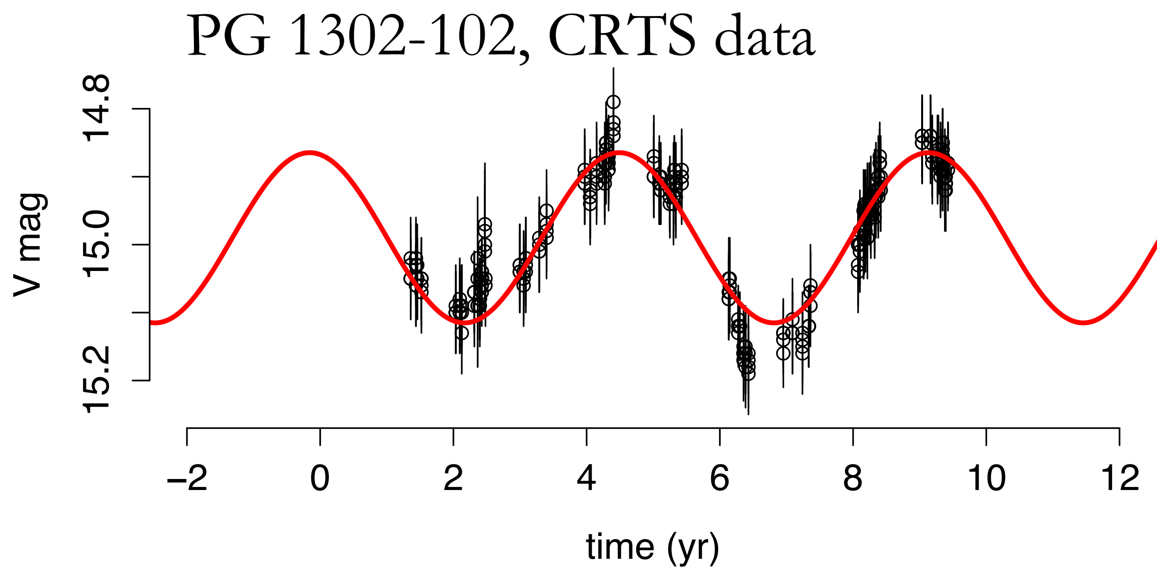
Beware of red noise!

- Red noise: steep power spectrum at low frequencies
- 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 vs signals

Data looks periodic!

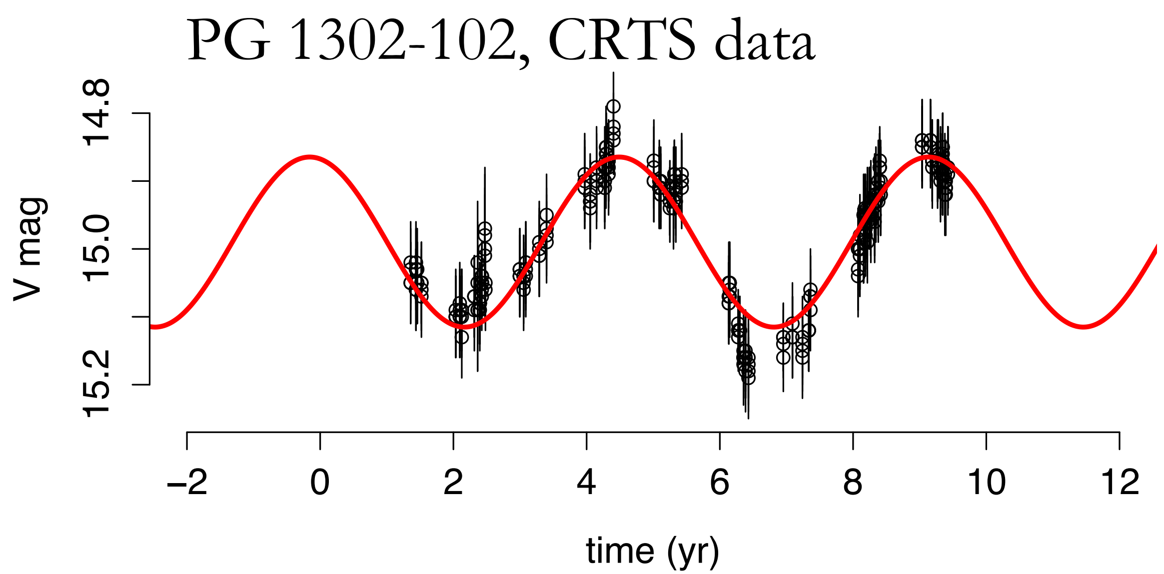


Vaughan+16 (figure); Liu+18

Red noise vs signals

Data looks periodic!

Uneven sampling, gappy data, only 1.5 cycles



Vaughan+16 (figure); Liu+18

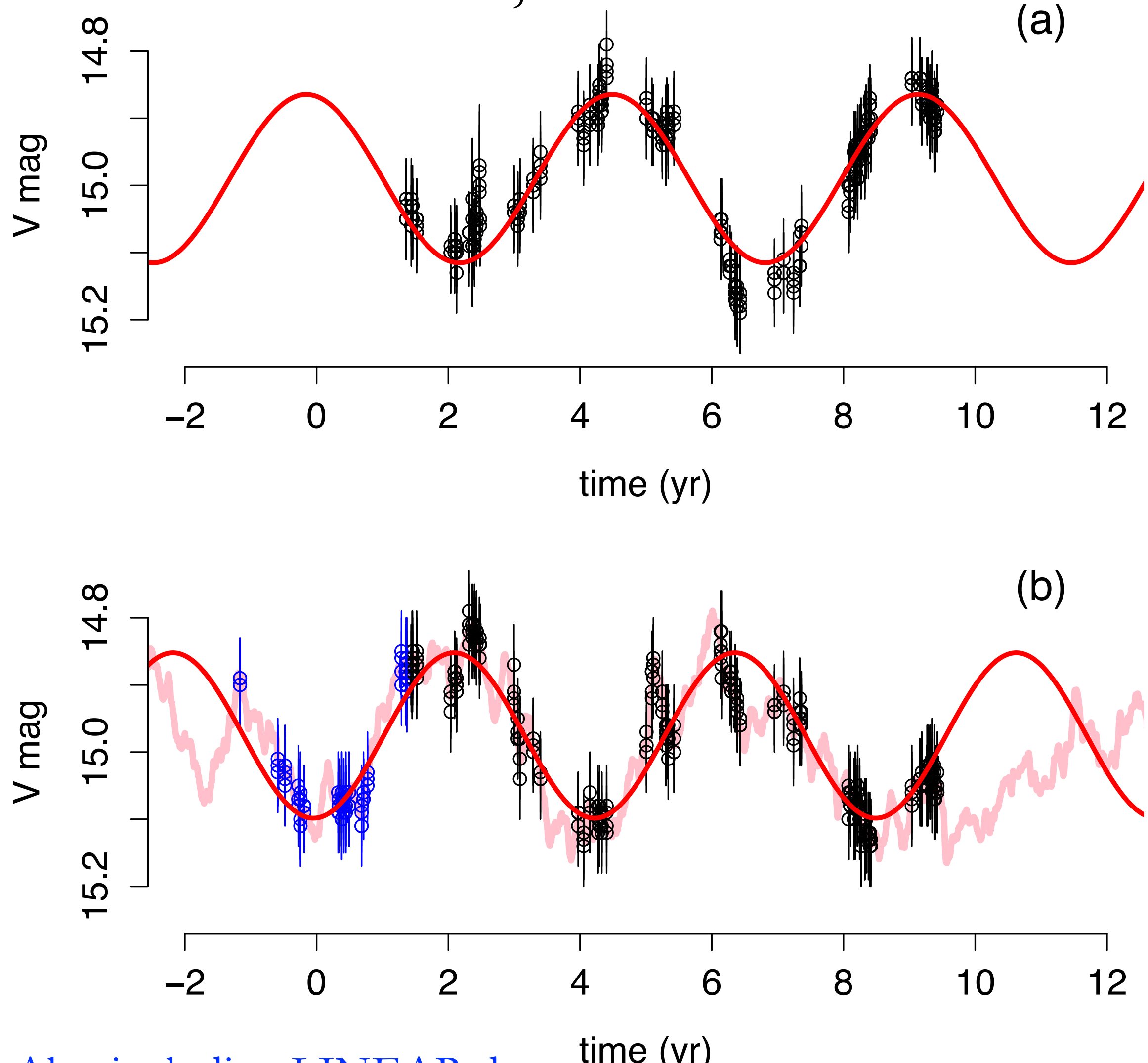
Red noise vs signals

Data looks periodic!
(but it isn't)

Uneven sampling, gappy data, only 1.5 cycles

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

PG 1302-102, CRTS data



Also including LINEAR data

Vaughan+16 (figure); Liu+18

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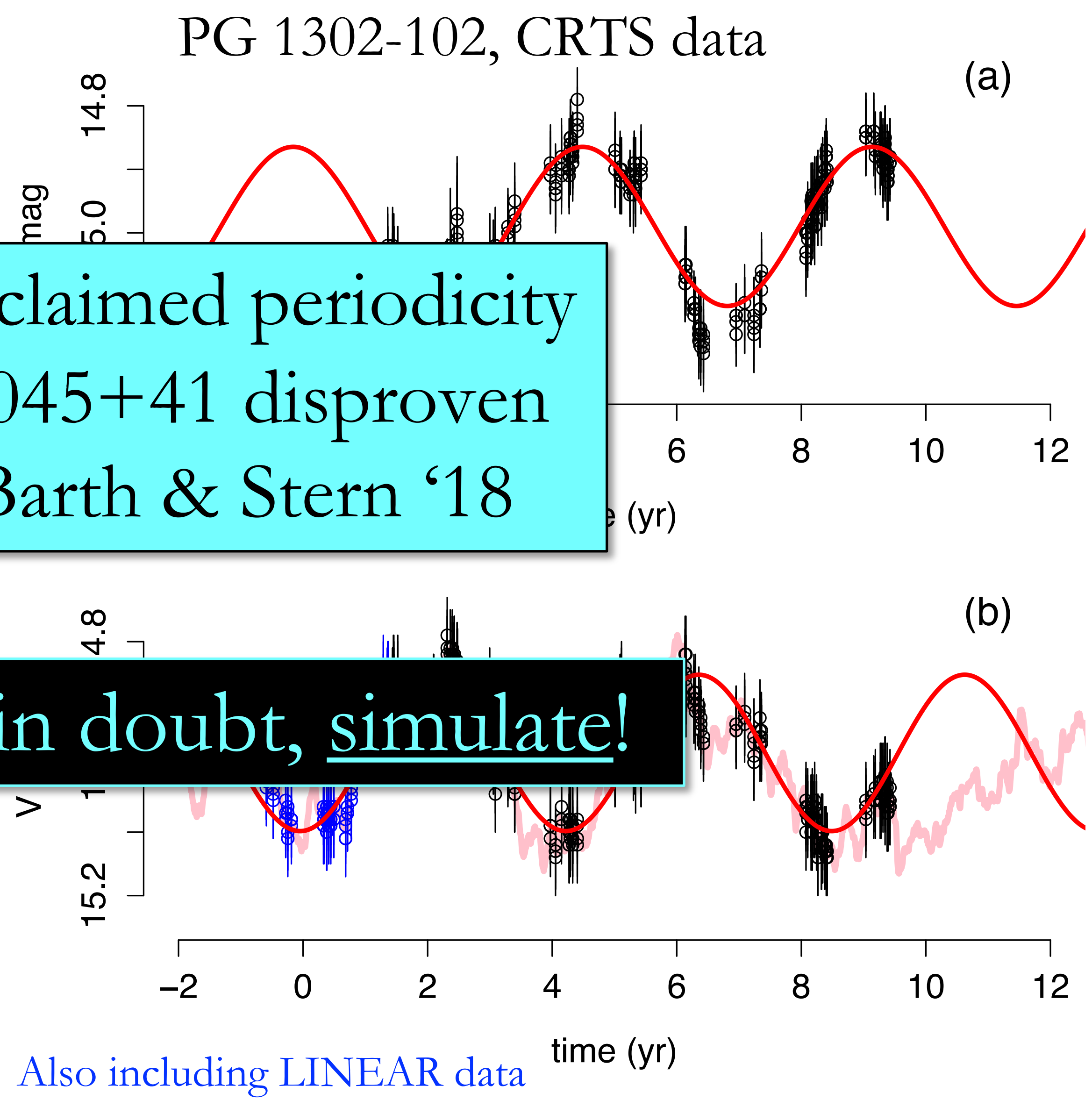


Also: claimed periodicity in J0045+41 disproven by Barth & Stern '18

When in doubt, simulate!

Vaughan+16 (figure); Liu+18

Stingray: spectral–timing software

- Open-source, community-driven and -developed, python, Astropy-affiliated package
- Stingray: Python library of analysis tools
- HENDRICS: shell scripting interface
- DAVE: graphical user interface
- Tutorials in Jupyter(/iPython) notebooks
- github.com/StingraySoftware

- Leads: D. Huppenkothen, M. Bachetti, A.L. Stevens, S. Migliari, P. Balm
- Google Summer of Code students: S. Sharma ('18); O. Hammad and H. Rashid ('17); U. Khan, H. Mishra, and D. Sodhi ('16)
- Other major contributors: E. Martinez Ribeiro, R. Valles

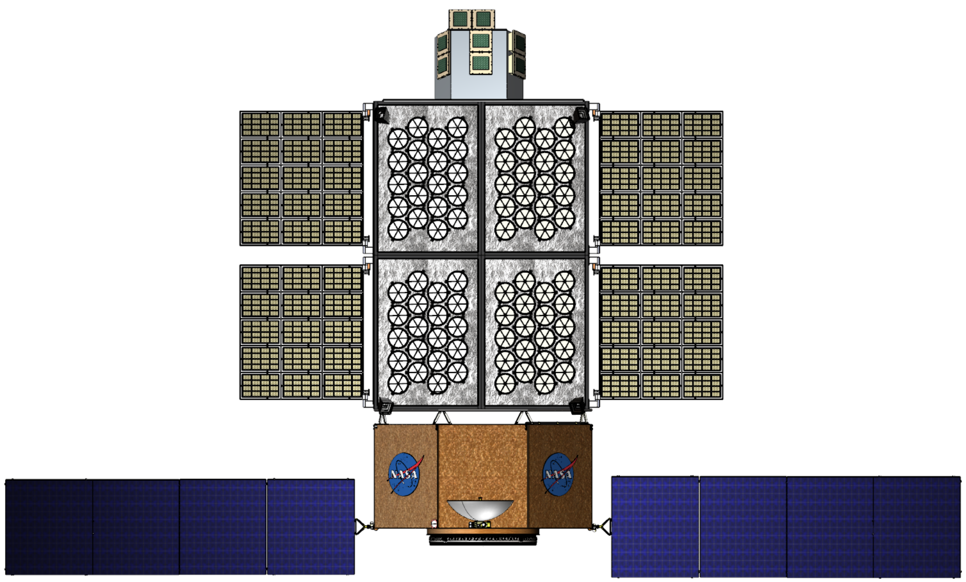
Google Summer of Code

Stingray: spectral-timing software

- Library of time series analysis methods
  - Power spectra, cross spectra, bispectra
  - Lag-frequency & lag-energy spectra
  - Rms & covariance spectra
  - Coherence, cross-correlation
  - Handles GTIs, pulsar & QPO searches
  - Phase-resolved spectroscopy of QPOs
- Simulator, modeling
- Well-tested on X-ray timing data (RXTE, NuSTAR, XMM, some NICER); also used by a few people for radio timing

STROBE-X instrument concept

- Flexible, high-throughput X-ray observatory with large area
- Science drivers: spin distribution of BHs, X-ray reverberation, disk-jet connection, LIGO EM counterparts, GRBs, TDEs, etc!



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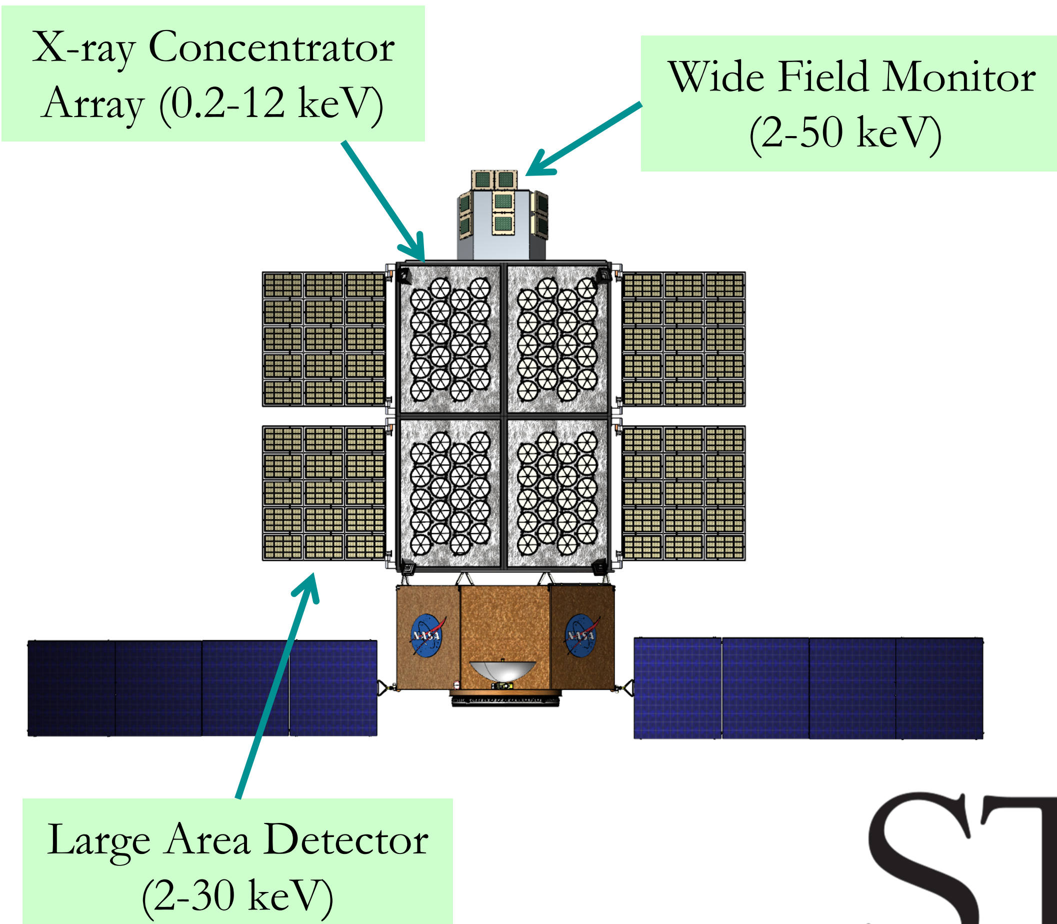

STROBE-X

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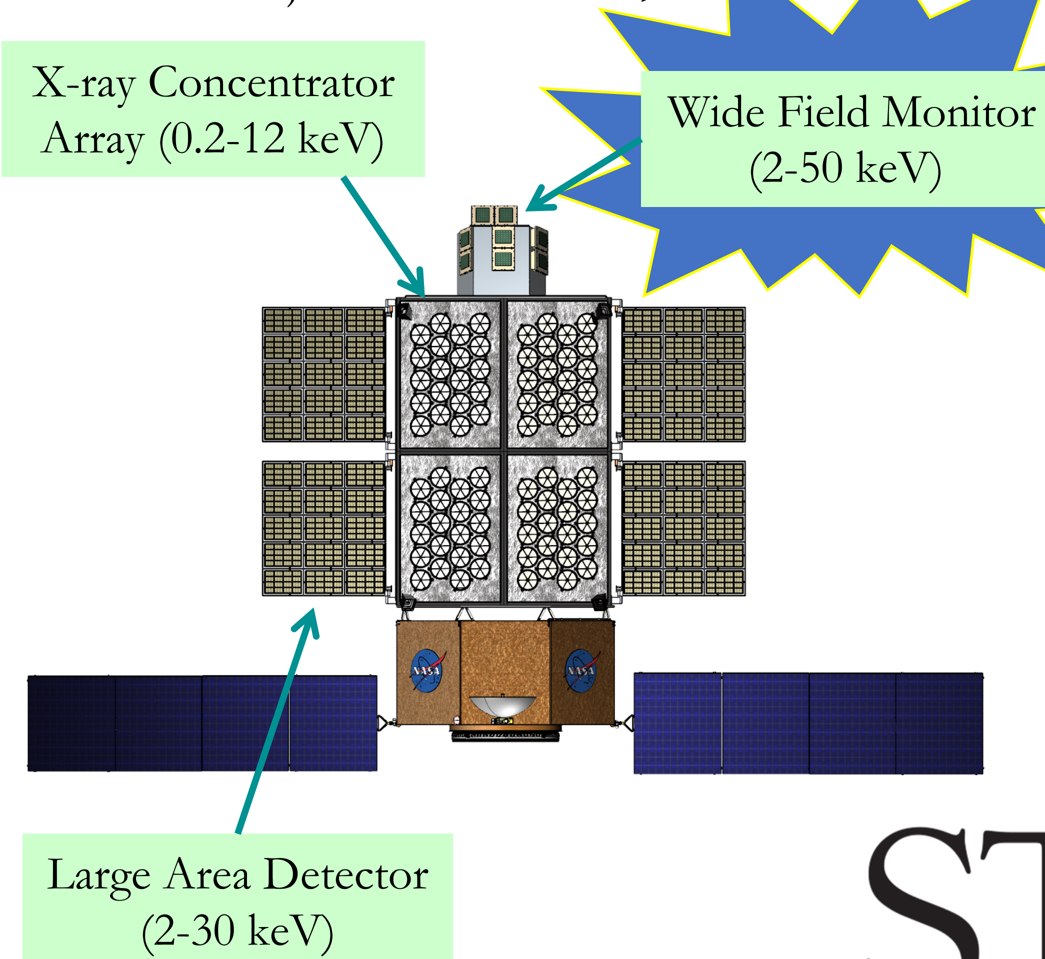

- 4 SSD camera pairs
- 70°x70° FOV per pair
- 4.12 sr sky coverage
- 300 eV energy resolution
- 1 arcmin position accuracy

STROBE-X

Resources

- Understand assumptions of models, techniques; question your own assumptions about data, process
- Periodicities and simulations: Vaughan & Uttley '06; Vaughan+16; Liu, Gezari, & Miller '18; Barth & Stern '18
- Timing and spectral-timing: Vaughan '13; Uttley+14
- When in doubt, simulate!
- Spectral-timing software: StingraySoftware.github.io
- STROBE-X: see Ray+18 in SPIE
- See also talks this morning & Thursday morning

GitHub: abigailStev
Email: alstev@msu.edu
Twitter: @abigailStev

STROBE-X instrument parameters

Large Area Detector (LAD)	
Number of Modules	60
Eff. Area per Module (cm^2)	850
Effective Area (cm^2 @ 10 keV)	**51,000**
Energy Range	**2–30 keV**
Detector	SDD (segmented large-area)
Power per Module (W)	10
Instrument Power (W)	600
Background Rate (mcrab)	10
Background Rate (c/s)	1,480
Energy Resolution	**200 – 300 eV FWHM**
Collimator	1° FWHM
Time Resolution	10 μs
Count Rate on Crab (2-30 keV)	148,020
Telem Rate on 100 mcrab (kbps)	355

X-ray Concentrator Array (XRCA)	
Number of XRC units	80
Eff. Area per XRCU	272
Effective Area (cm^2 @ 1.5 keV)	**21,760**
Energy Range	**0.2–12 keV**
Detector	SDD (single pixel)
Instrument Power (W)	140
Diffuse Background (c/s)	2.2
Radiation Background (c/s)	0.1
Background Rate (c/s)	2.2
Energy Resolution	**85 – 175 eV FWHM**
Collimator	4 arcmin FWHM
Time Resolution	100 ns
Count Rate on Crab (0.2-10 keV)	147,920
Telem Rate on 100 mcrab (kbps)	947

Wide-Field Monitor (WFM)	
# of Camera Pairs	4
FOV/Camera Pair	70° × 70° FWHM
Eff. Area/Camera Pair	**364 cm^2**
Optics	1.5-D coded mask
Energy Range	**2-50 keV**
Energy Resolution	**300 eV FWHM**
Detector	SDD (1.5D)
Instrument Power (W)	92
Sensitivity (1 s)	**600 mcrab**
Sensitivity (1 day)	**2 mcrab**
Sky Coverage (sr)	**4.12**
Angular Resolution	4.3 arcmin
Position Accuracy	**1 arcmin**
Telemetry Rate (kpbs)	340