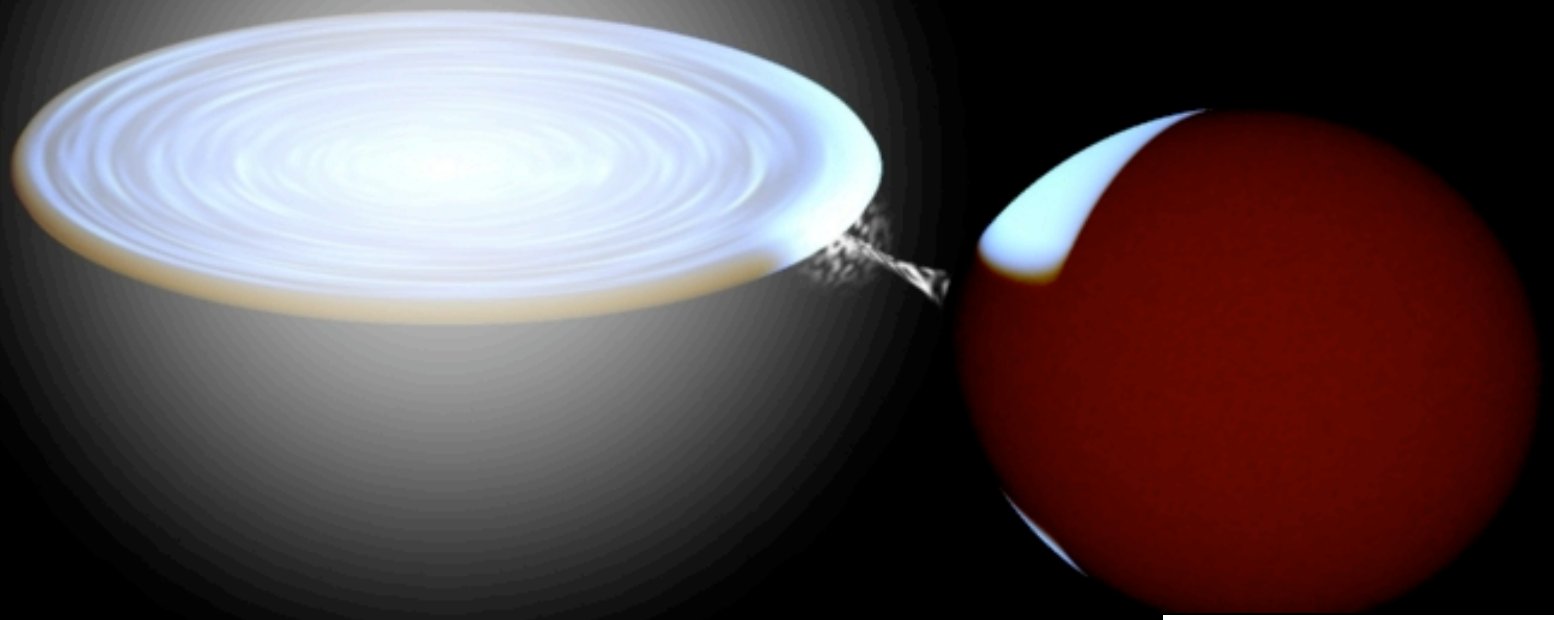
Accretion in Neutron Star/Black Hole Systems



Robert Hynes

Louisiana State University

LSU
LOUISIANA STATE UNIVERSITY

Lecture 5 Outline

Echo mapping

•

Other causes of X-ray/optical correlations

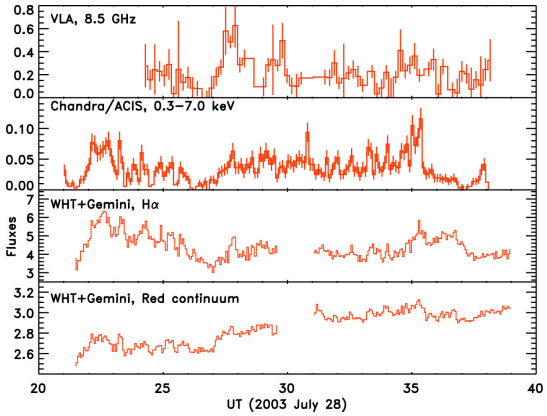
•

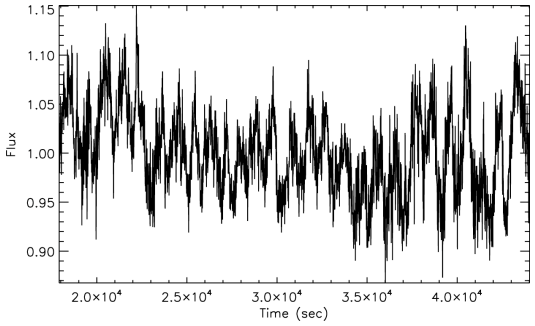
Quiescent Variability

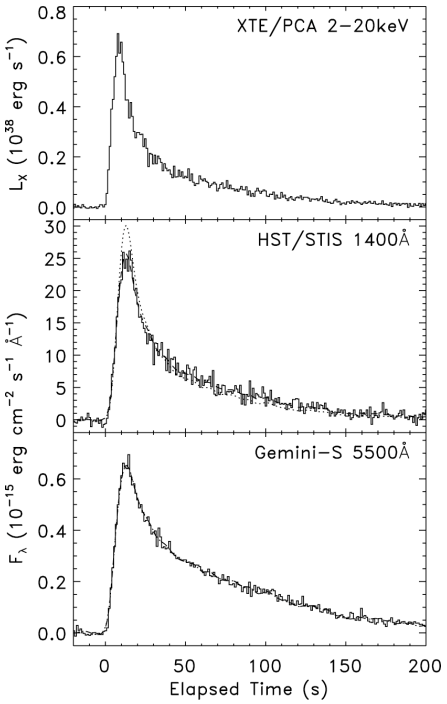
Rapid Multiwavelength Variability

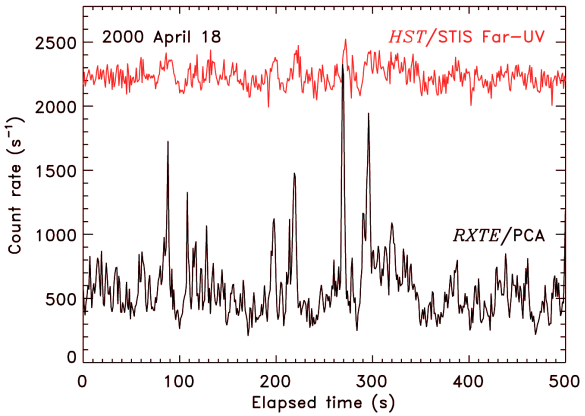
X-ray binaries vary on short timescales

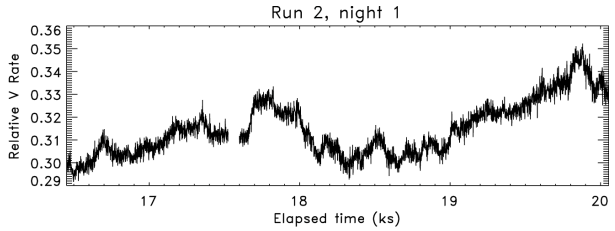
- Milliseconds, seconds, minutes, hours
- Luminous & quiescent states
- Black holes & neutron stars
- X-ray, optical, UV, IR, radio

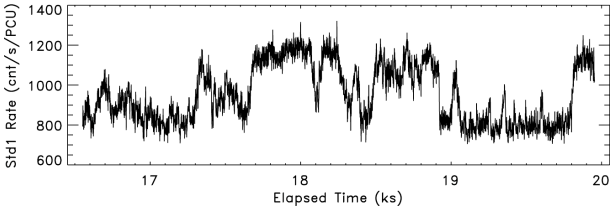








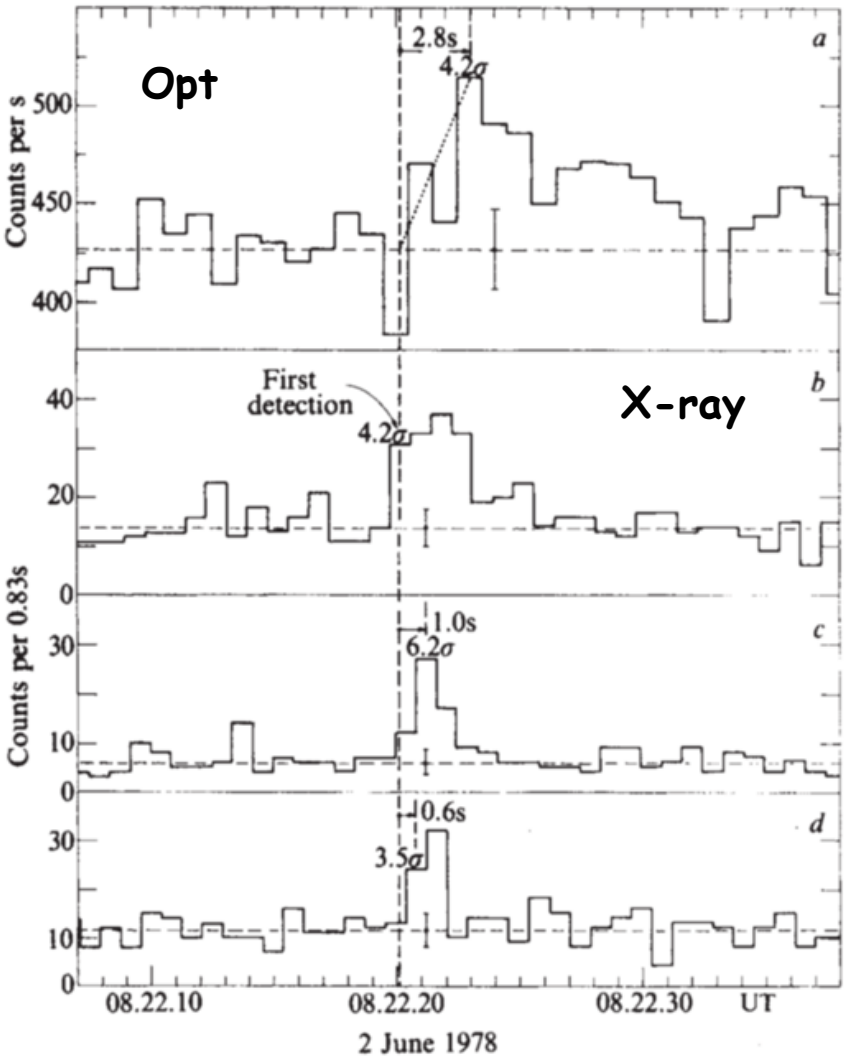




Type I X-ray Bursts in the Optical

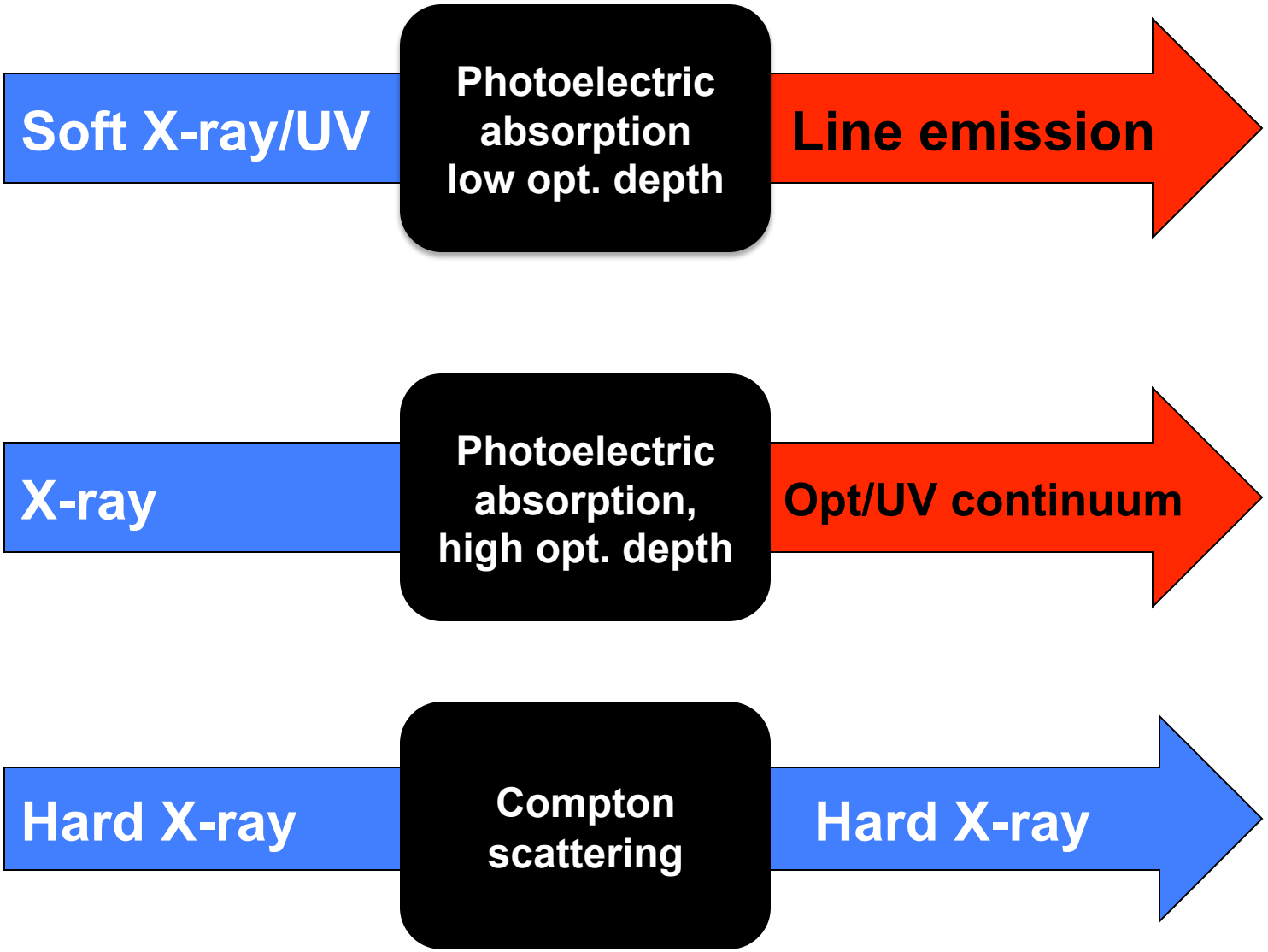
Optical bursts discovered 1978 in 4U1735-44

- Grindlay et al. (1978, Nat., 274, 568); McClintock et al. (1979, Nat., 279, 48)
- Also in Ser X-1 (Hackwell et al. 1979, ApJ, 233, L115)



From McClintock et al. (1979, Nat., 279, 48)

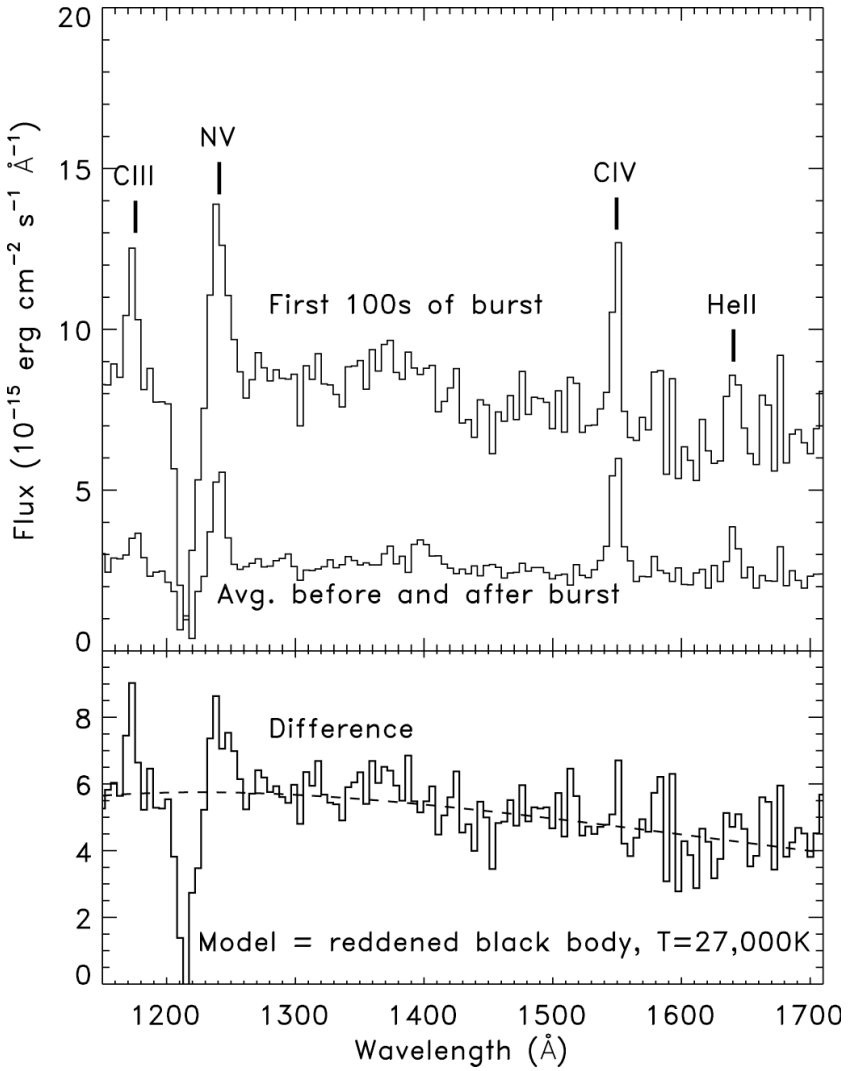
Reprocessing of Ultraviolet and X-rays



A Reprocessed Burst Spectrum in EXO 0748-676

HST TIMETAG far-UV spectra

- Burst spectrum is hot continuum
- NV, CIII lines also enhanced



From Hynes et al. (2006, ApJ, 648, 1156)

Echo-mapping in X-ray Binaries

Developed for Active Galactic Nuclei

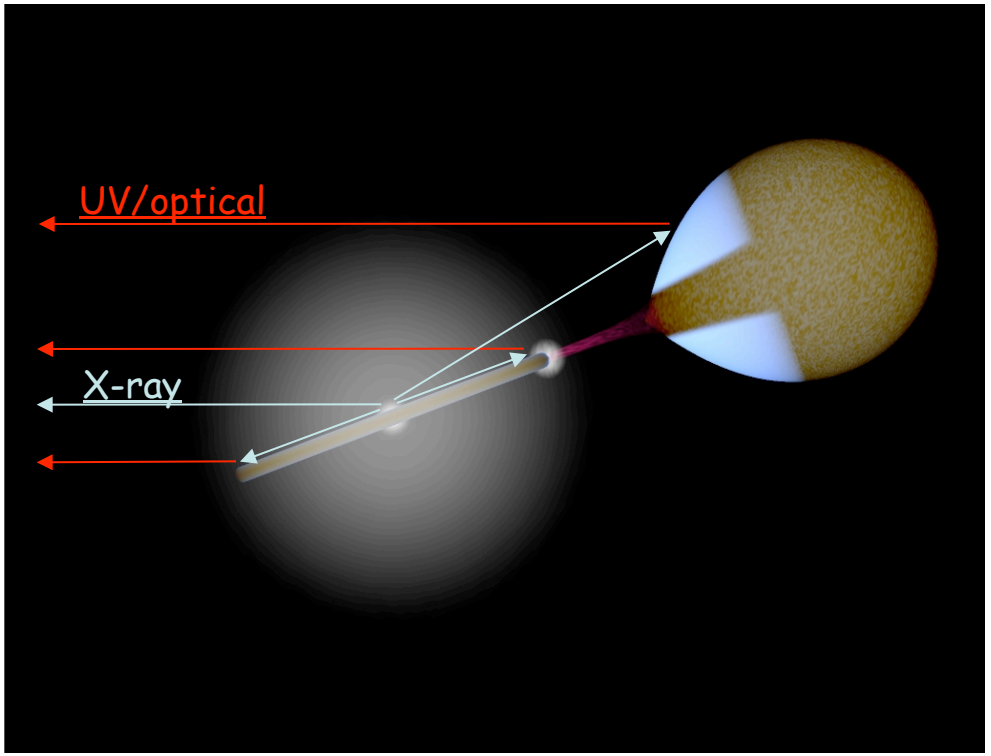
- Also known as reverberation mapping
- Blandford & McKee, (1982, ApJ, 255, 419)

The Method

- Analogous to radar – use light travel time delays of reprocessed radiation to measure spatial scales
- Derive lags in light-sec

Practical limitations

- Overlap between facilities
- High signal-to-noise and time-resolution needed



X-ray to Optical Transfer Functions

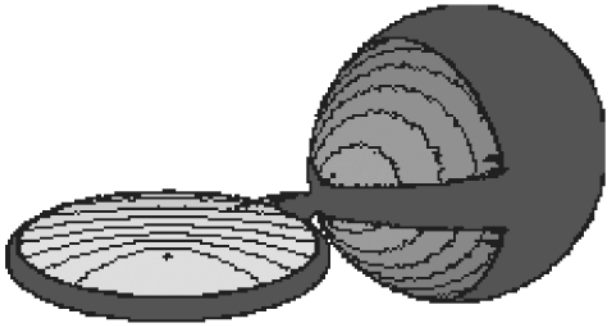
Optical lightcurve

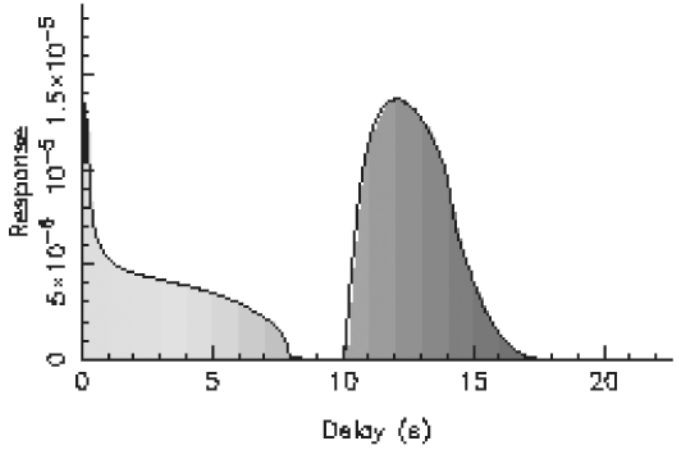
- **X-ray lightcurve convolved with TRANSFER FUNCTION (response)**

$$L_{opt}(t) = L_X * \Psi = \int L_X(t-\tau)\Psi(\tau)d\tau$$

Cross-correlation function

- **X-ray auto-correlation function convolved with response**
- **Essentially blurred transfer function**





From O'Brien et al. (2002, MNRAS, 334, 426)

Gaussian Transfer Functions

What do we actually see?

Optical lags X-ray

- Measure mean lag

Optical is smeared version of X-ray

- Measure smearing timescale
- Characterize with standard deviation of smearing

Define Gaussian transfer function

$$\Psi(\tau) = \Psi_0 \exp\left(-\frac{(\tau-\tau_0)^2}{2\Delta\tau^2}\right)$$

- Specify mean lag and smearing
- Equivalent to measuring first two moments of delay distribution

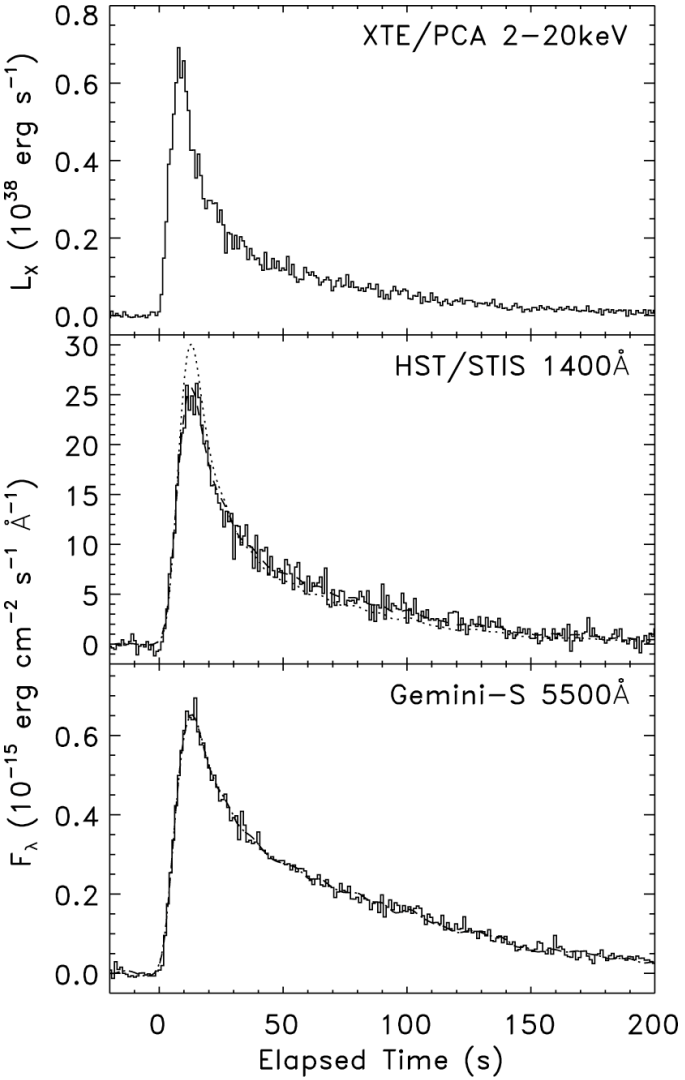
EXO 0748-676

Simultaneous X-ray, optical + UV

- Good wavelength leverage to constrain reprocessor temperature

Burst fitting

- $\tau \sim 4.1$s
- $\Delta\tau \sim 2.5$s
- Temperature increase from 18,500K to 35,000K
- Area ~ disk + companion area
- Multi-temperature reprocessor required



From Hynes et al. (2006, ApJ, 648, 1156)

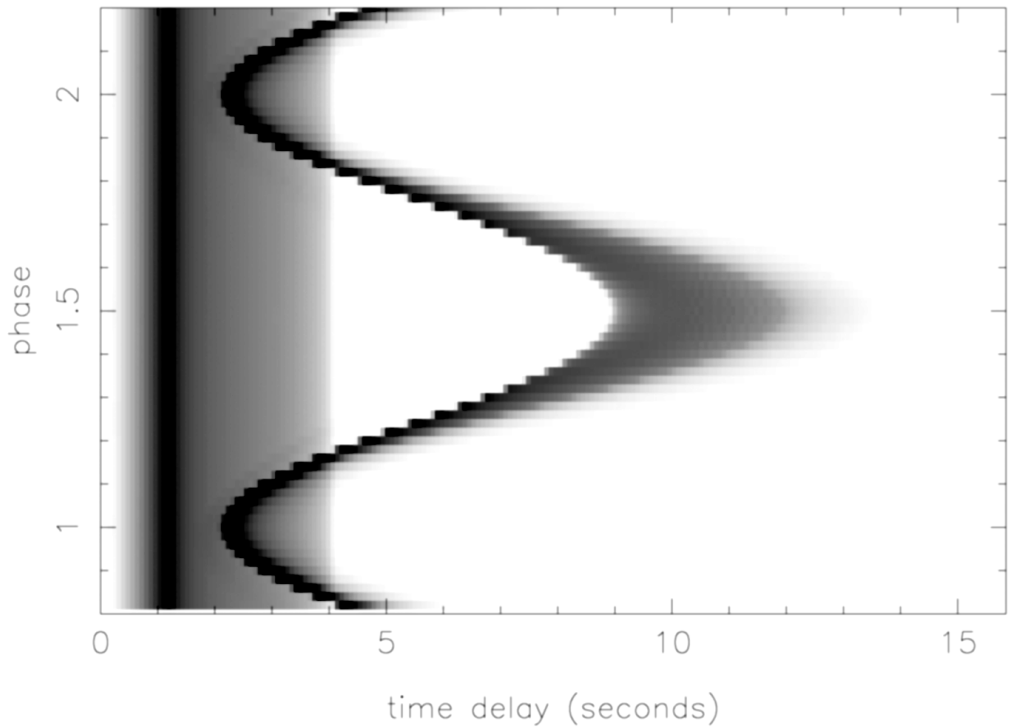
Echo Tomography

Phase dependence

- Non-axisymmetric reprocessor will change lag
- e.g. companion lag ~ a (1-sin i cos ϕ)

System parameters

- Can determine binary separation and inclination, independent of other uncertain parameters.

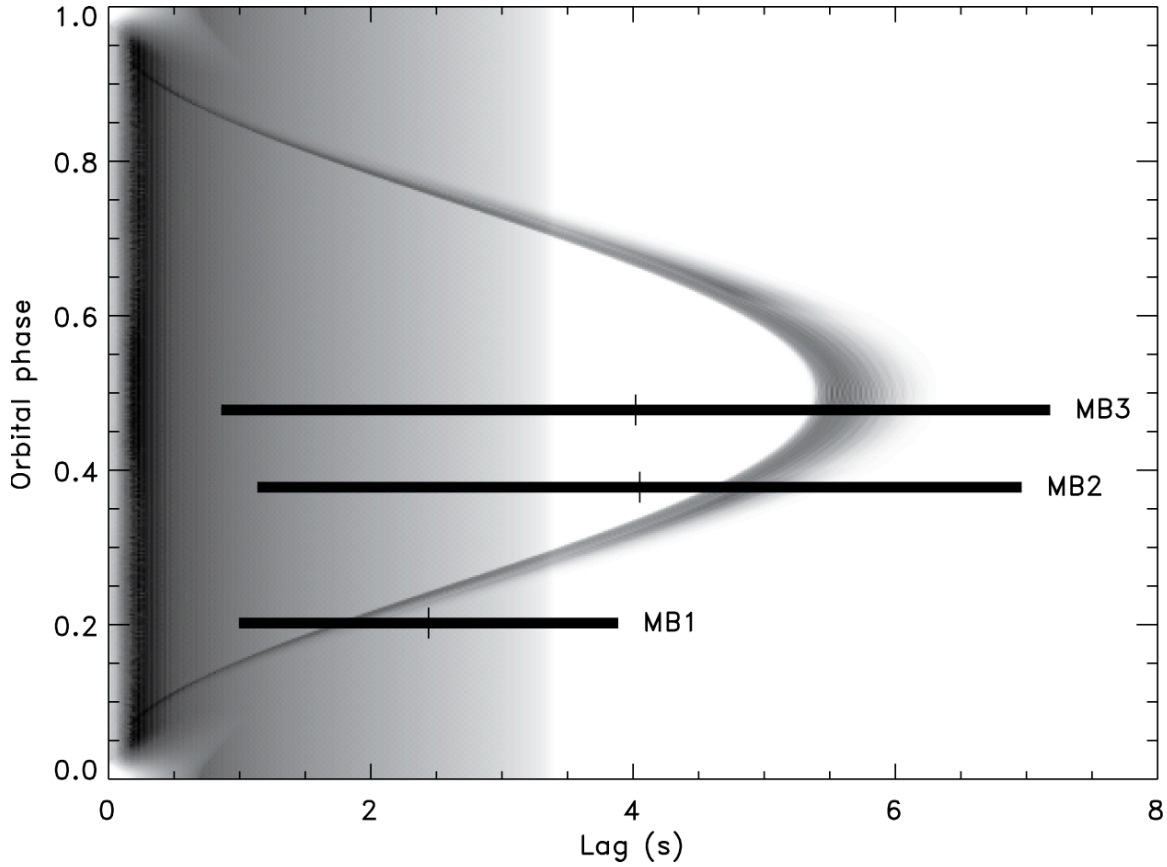


From O'Brien et al. (2002, MNRAS, 334, 426)

Burst Echo Tomography

Mean lag and smearing appear modulated on orbital period

- Broadly consistent with expectations for reprocessing by both disk and companion



From Hynes et al. (2006, ApJ, 648, 1156)

Emission Line Echo-Mapping of Sco X-1

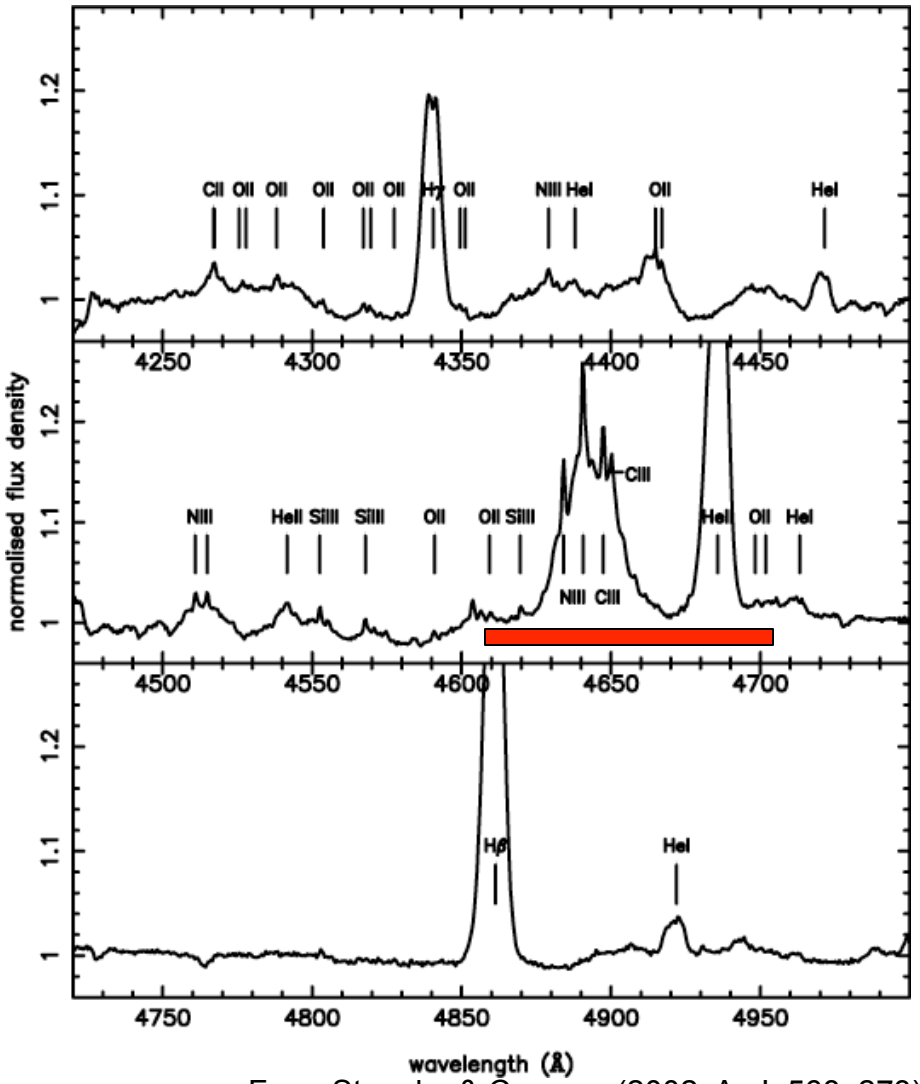
Use Bowen blend

- CIII/NIII lines near 4640Å
- Trace companion star (Lecture 4)

100Å interference filter

- Narrow Bowen lines
- Broad Bowen lines
- HeII
- ~90% continuum

See Munoz-Darias et al. (2007, MNRAS, 379, 1637)

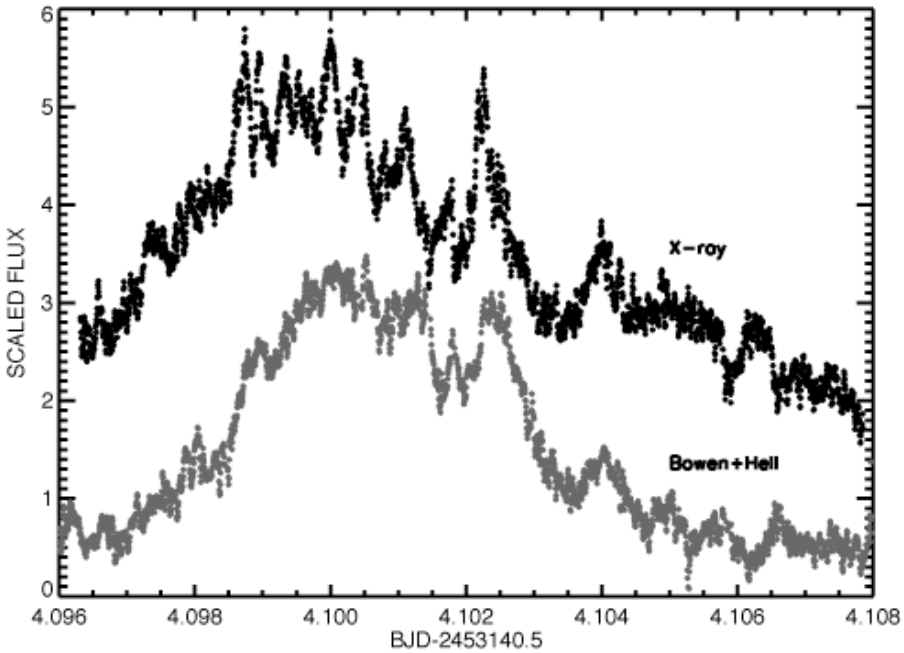


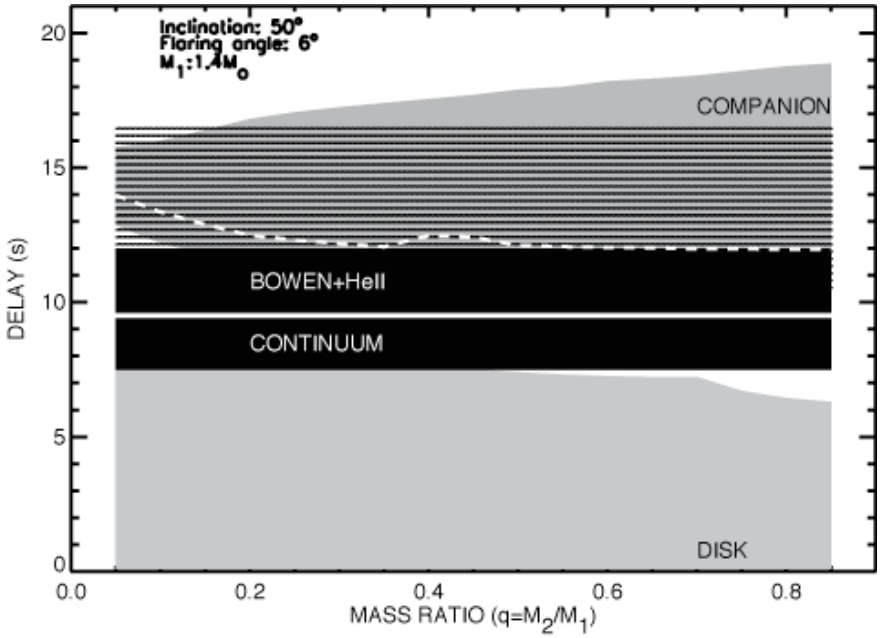
From Steeghs & Casares (2002, ApJ, 568, 273)

Bowen Line Echo-Mapping of Sco X-1

Dramatic correlations in flaring branch

- Continuum: 8.5 ± 5.5 s
- Line + continuum: 10.75 ± 6.25 s
- Line only: 13.5 ± 8.5 s



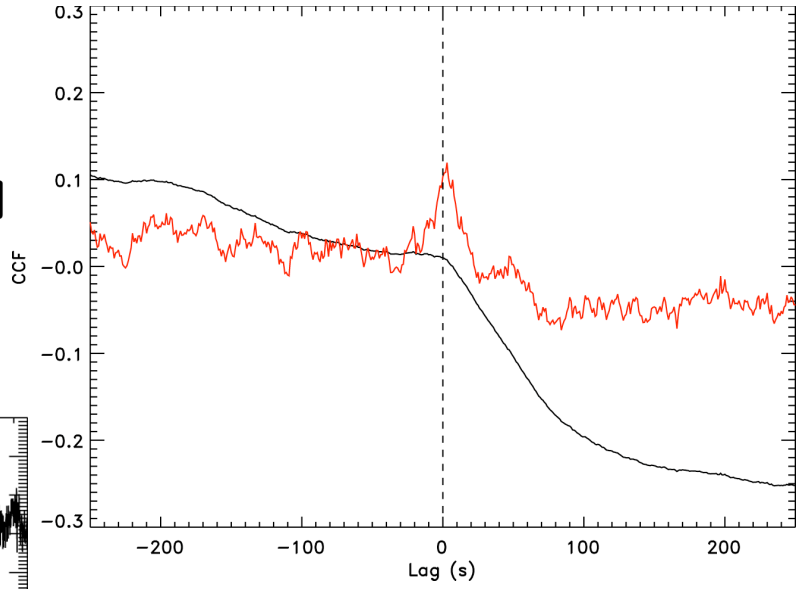


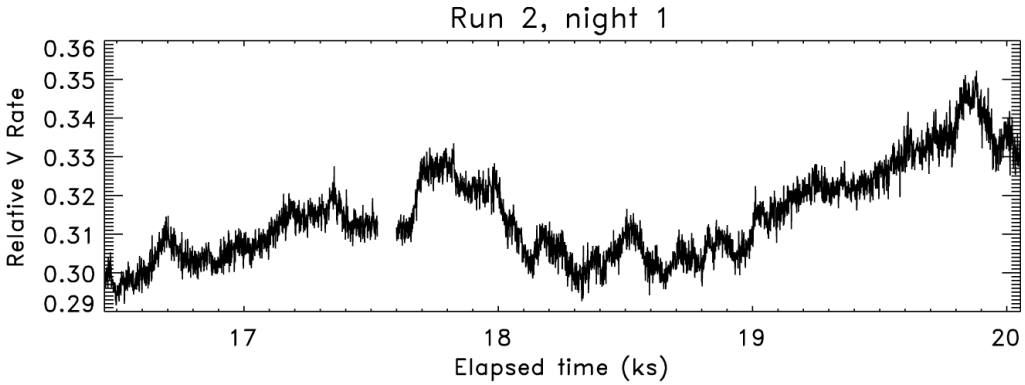
From Munoz-Darias et al. (2007, MNRAS, 379, 1637)

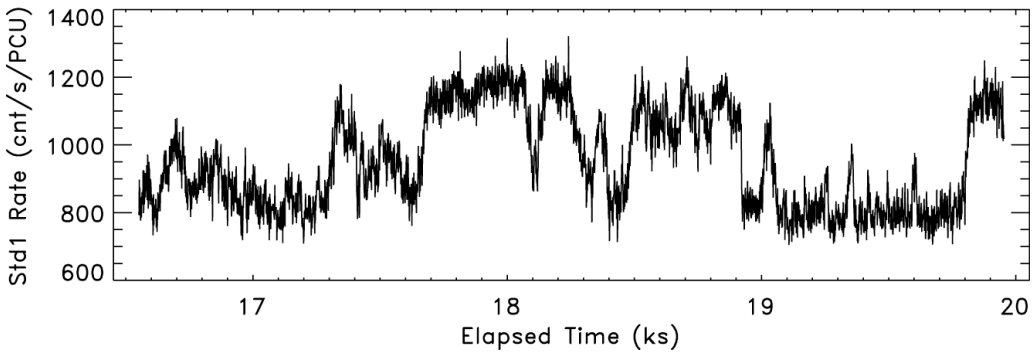
Flaring Branch Correlations in Cyg X-2

Largest amplitude X-ray variability

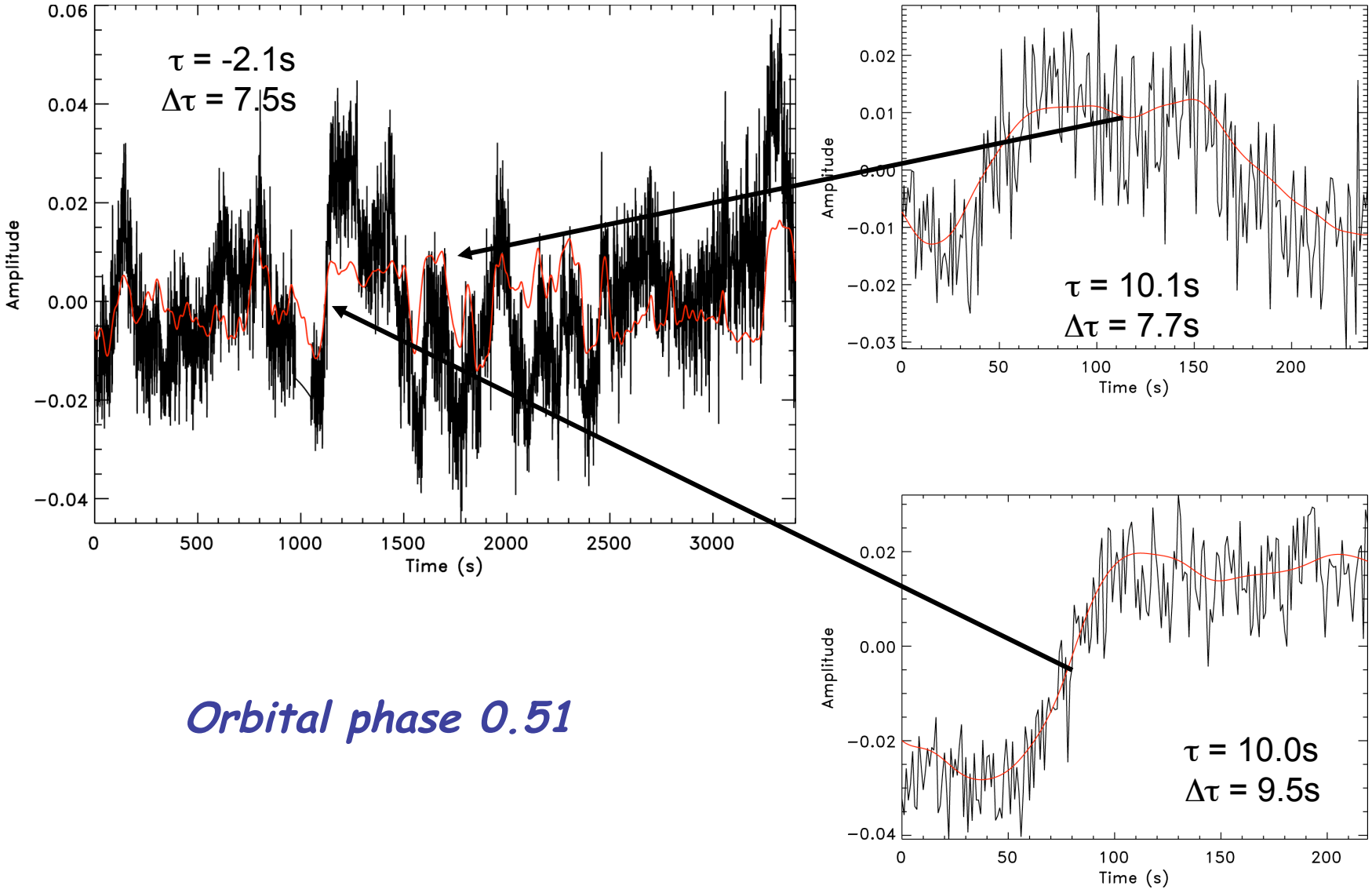
- Clearly correlated optical variations
- Relationship between X-ray and optical is complex nonetheless





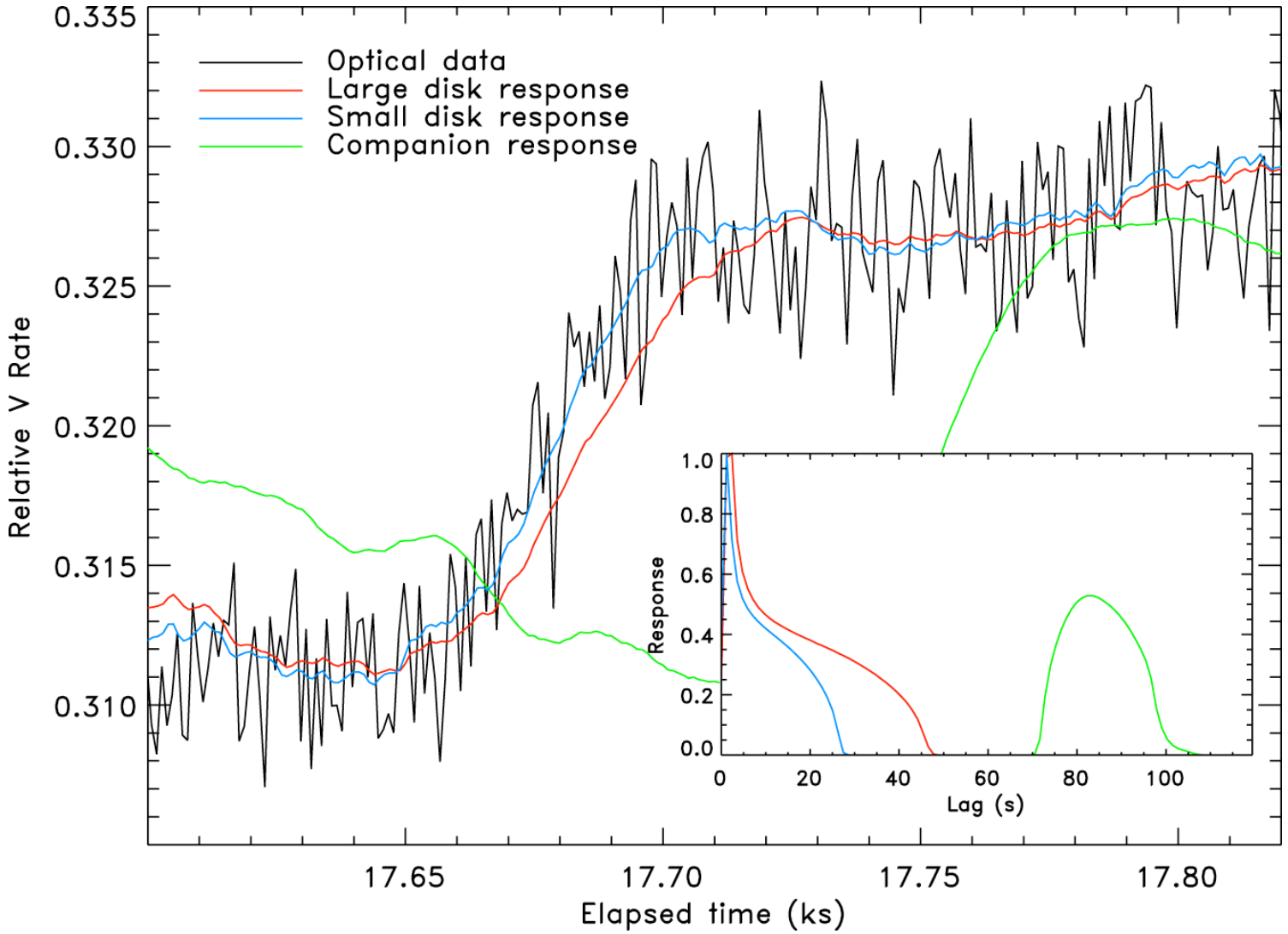


Gaussian Transfer Functions



Orbital phase 0.51

Model Transfer Functions

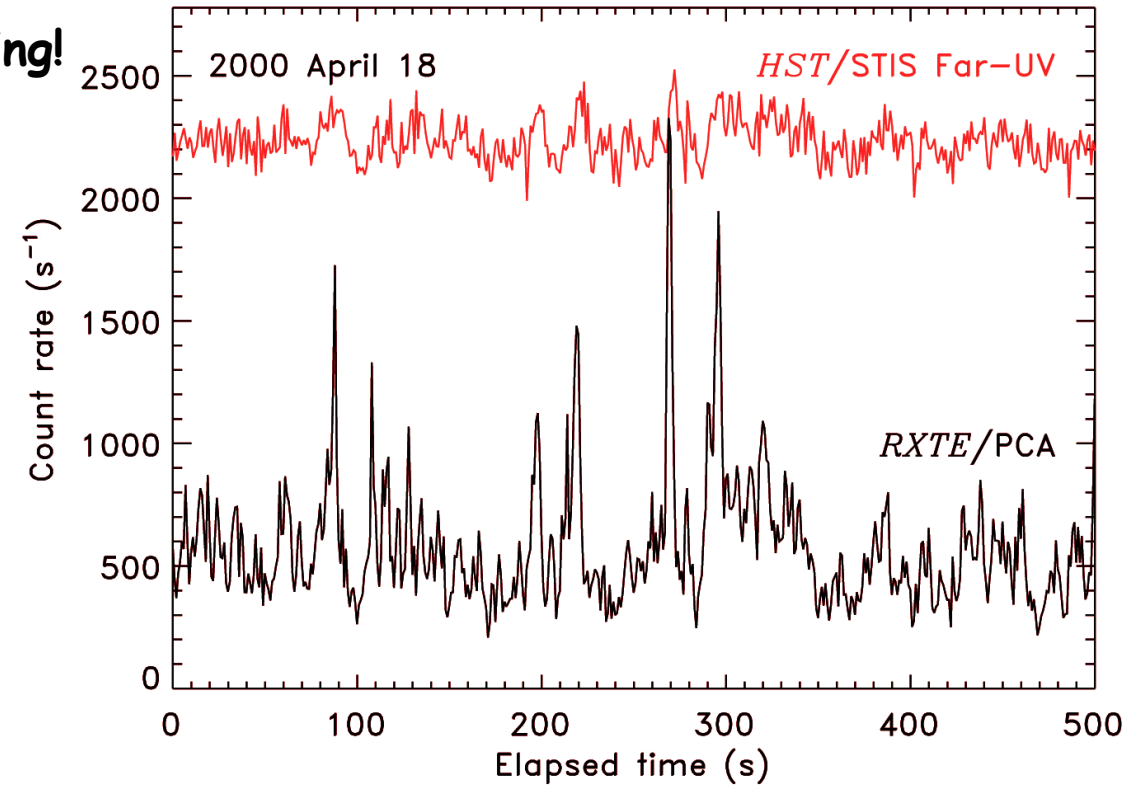


The Cautionary Tale of XTE J1118+480

X-ray, UV, optical, IR variability

- Large amplitudes
- Short timescale sharp signals
- Clear correlations
- Perfect for echo-mapping!

What could go wrong?



From Hynes et al. (2003, 345, 292)

X-ray/Optical Observations

Auto-correlation function

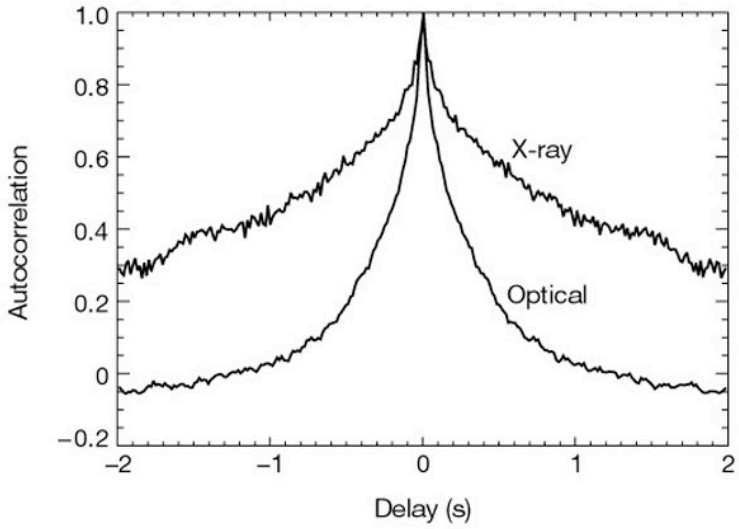
- Optical narrower than X-rays
- Echo smearing should always broaden it

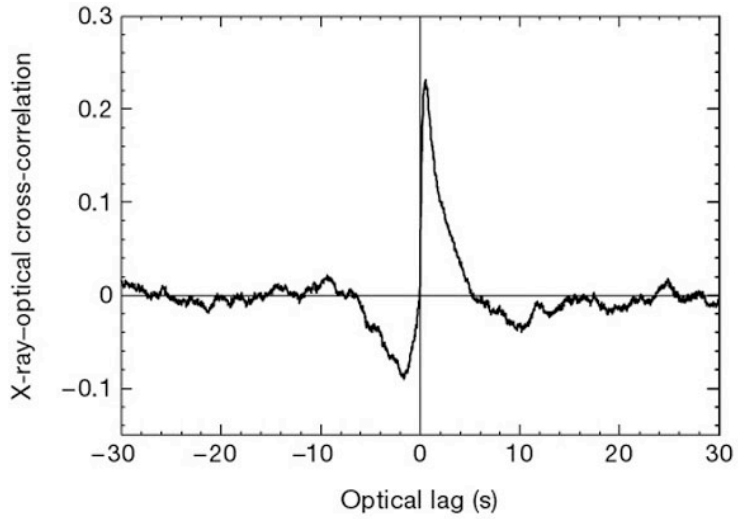
Cross-correlation function

- 'Precognition Dip' at negative lags

Synchrotron?

- Behavior inconsistent with reprocessing
- Fast variations ⇒ high brightness temperature



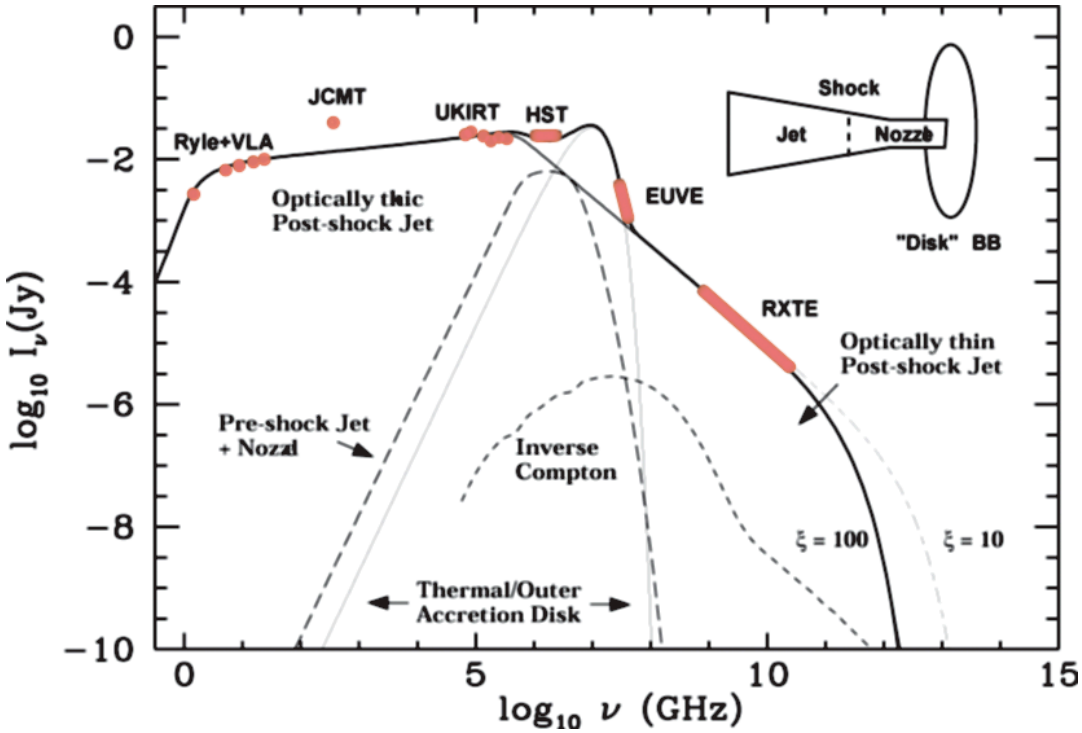


Figs. From Kanbach et al. (2001, Nature, 414, 180); see also Spruit & Kanbach (2002, A&A, 391, 225), Malzac et al. (2003, A&A, 407, 335)

Jet Model for XTE J1118+480

Several incarnations

- Markoff et al. (2001, A&A, 372, L25)
  - Jet synchrotron from radio to X-rays
- See also Malzac et al. (2004, MNRAS, 351, 253) and Yuan et al. (2005, ApJ, 620, 905)



From Markoff et al. (2001, A&A, 372, L25)

IR Photometry of XTE J1118+480

Second outburst of XTE J1118+480 in January 2006

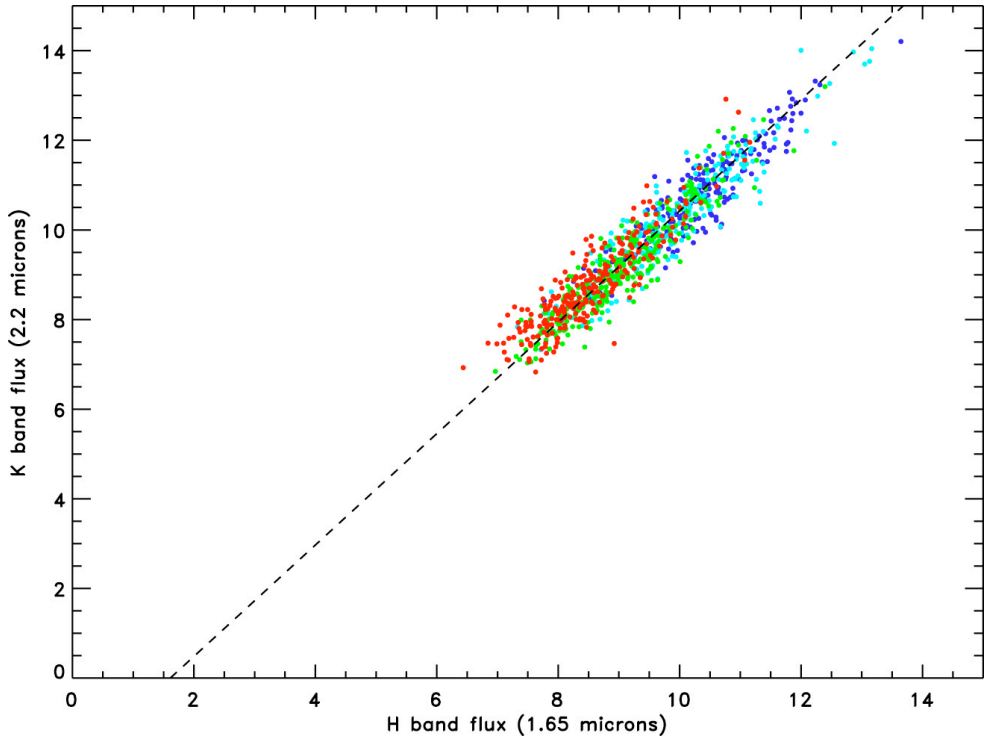
- KPNO 2.1m + SQIID simultaneous J,H,K photometry

No lightcurves

- 2s exposure, but 40s deadtime!
- Severely undersampled

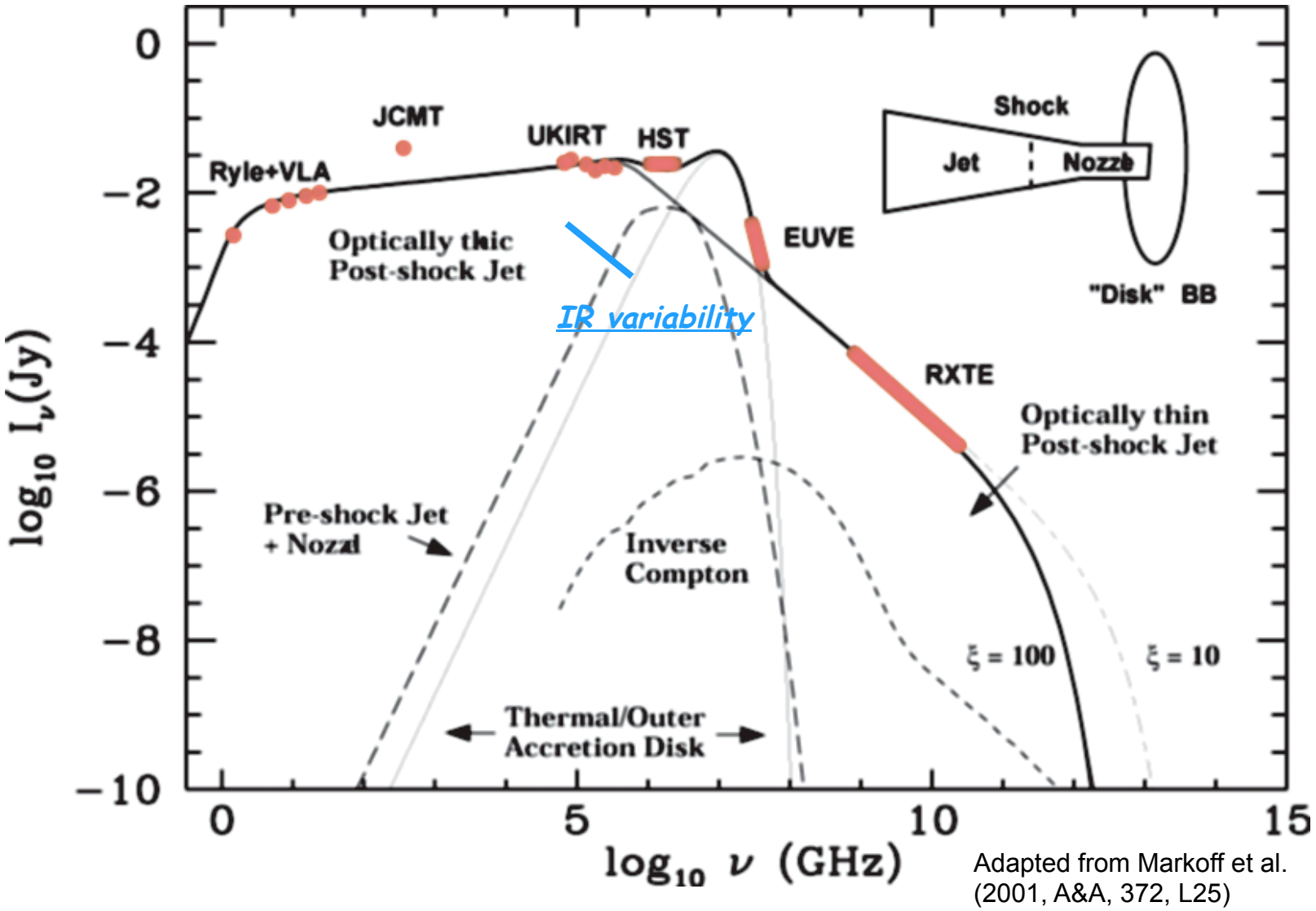
Snapshot colors

- Each 2s observation gives JHK spectral energy distribution
- Can isolate SED of variable component



From Hynes et al. (2006, ApJ, 651, 401)

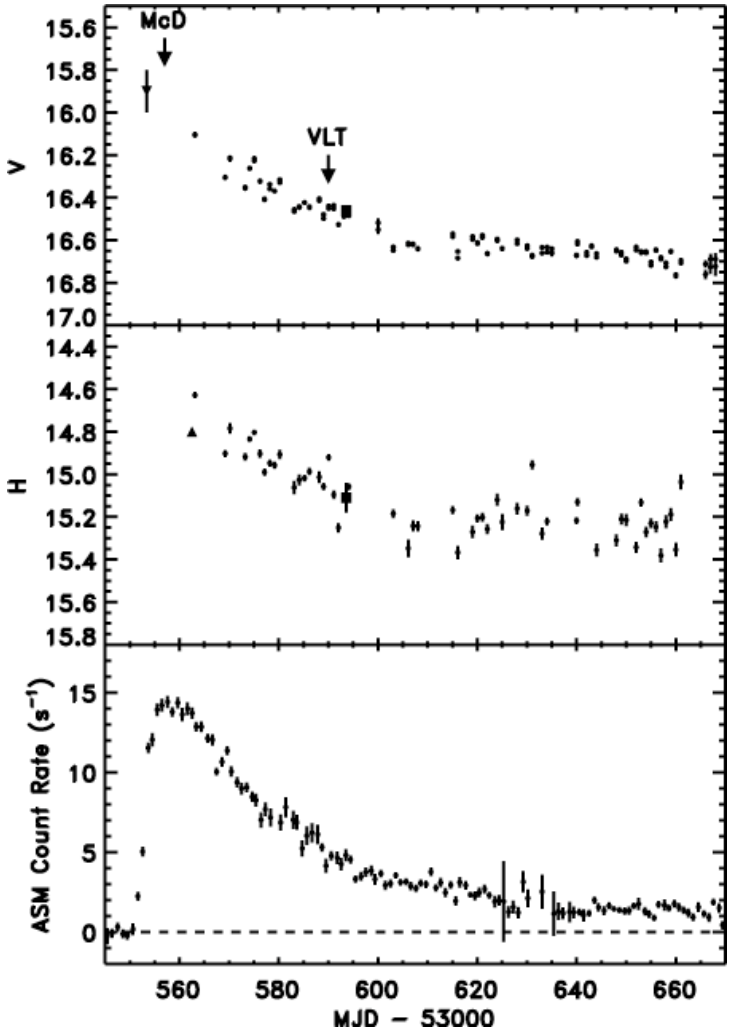
IR Variability in a Jet Model



Adapted from Markoff et al. (2001, A&A, 372, L25)

Swift J1753.5-0127

First Swift-discovered BH candidate in 2005

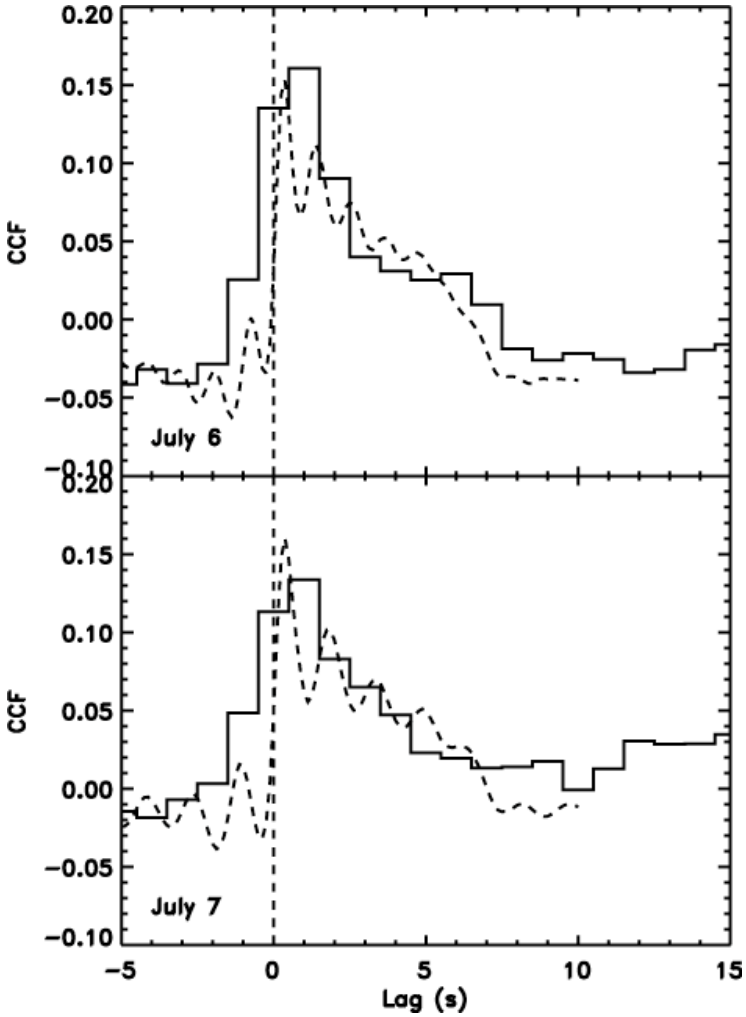


Swift J1753.5-0127 from Hynes et al. (2009, MNRAS 399, 281)

Swift J1753.5-0127 at Outburst Peak

Model CCF using disk transfer functions

- Known:
  - 3.24hr binary period (Zurita et al. 2008, ApJ, 681, 1458)
- Assumed:
  - $7M_{\odot}$ black hole
  - Mass ratio 0.1
  - Inclination 60°

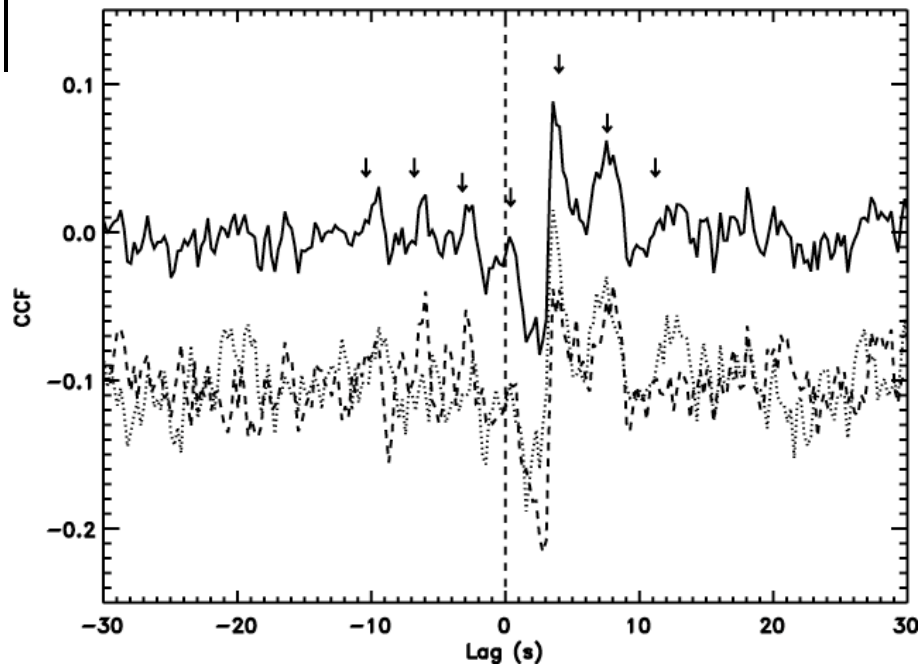


From Hynes et al. (2009, MNRAS 399, 281)

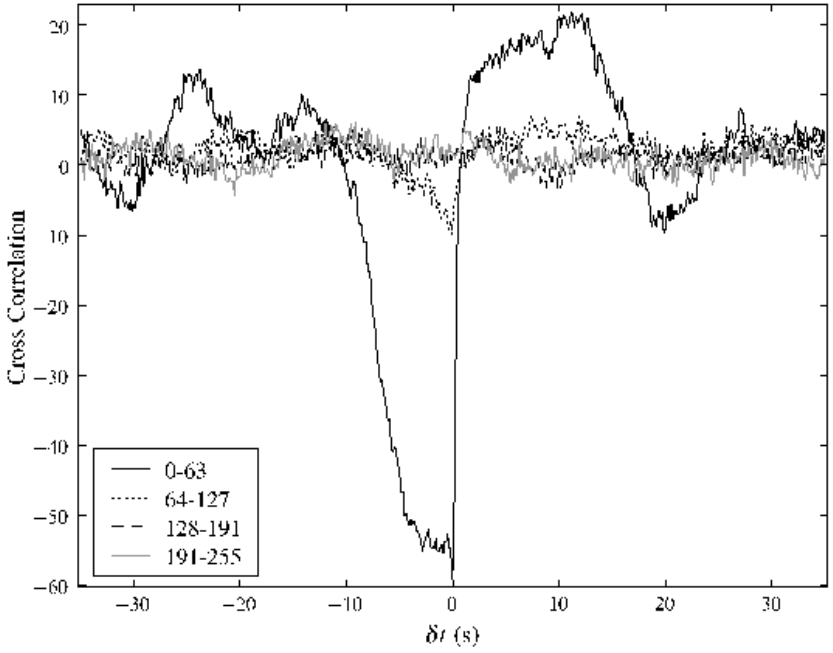
Swift J1753.5-0127 in Decline

Reminiscent of XTE J1118+480

- Repeatable dip + peak structure
- Multiple peaks due to 4 sec X-ray oscillation
- Similar behavior seen later (Durant et al. 2008, ApJ, 682, L45)

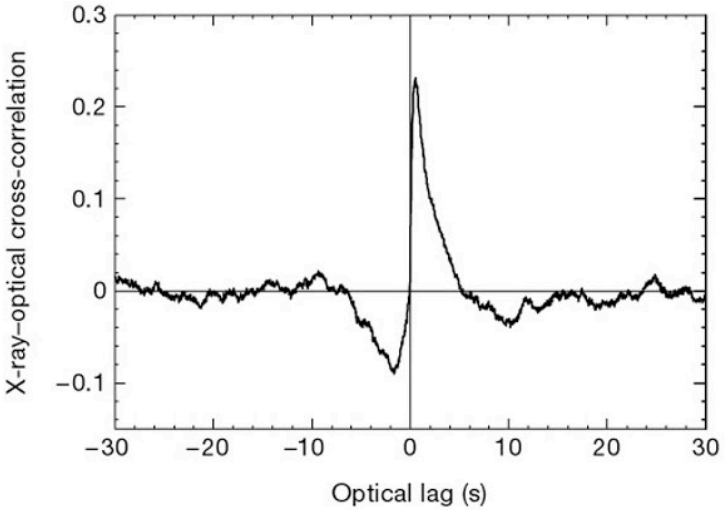


From Hynes et al. (2009, MNRAS 399, 281)

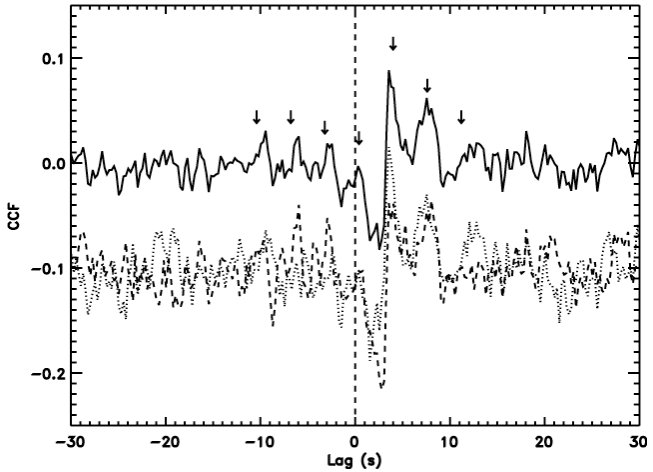


From Durant et al. (2008, ApJ, 682, L45)

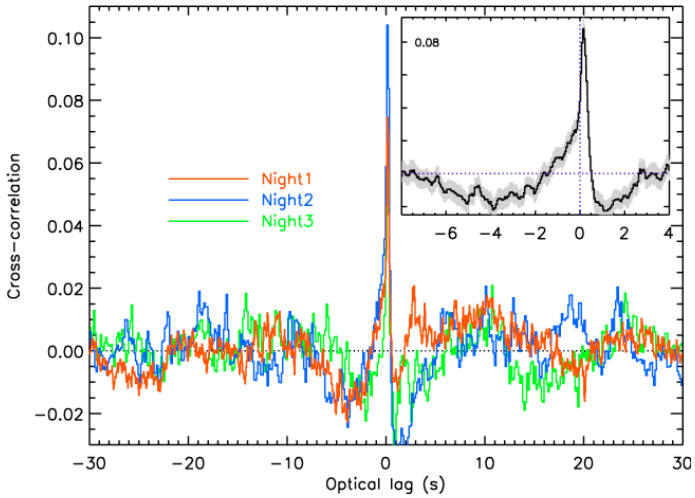
‘Odd’ Cross-correlations in LMXBs



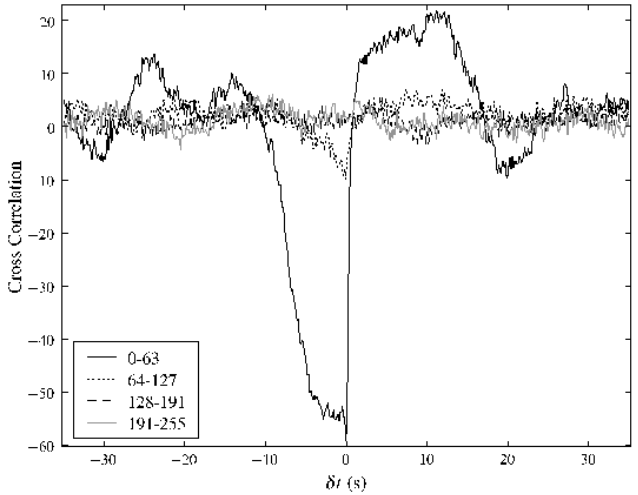
XTE J1118+480, from Kanbach et al. (2001, Nature, 414, 180)



Swift J1753.5-0127 from Hynes et al. (2009, MNRAS 399, 281)



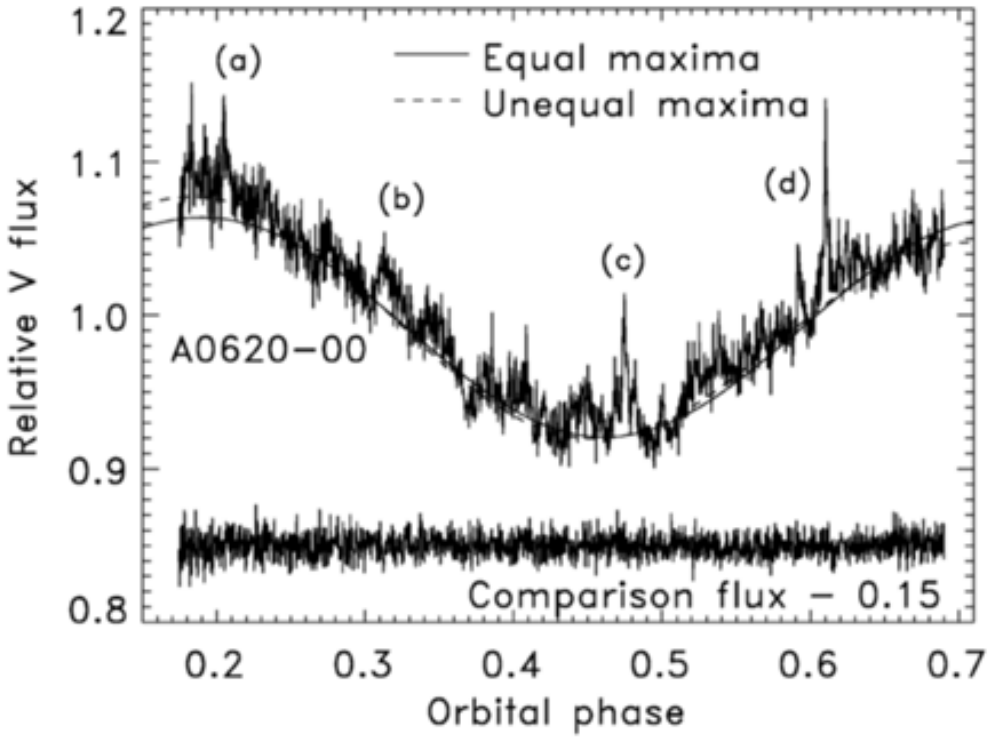
GX339-4 from Gandhi et al. (2008, MNRAS, 320, L29)

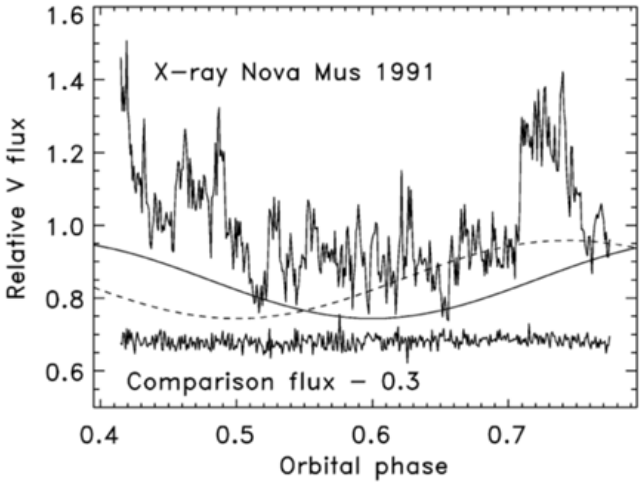


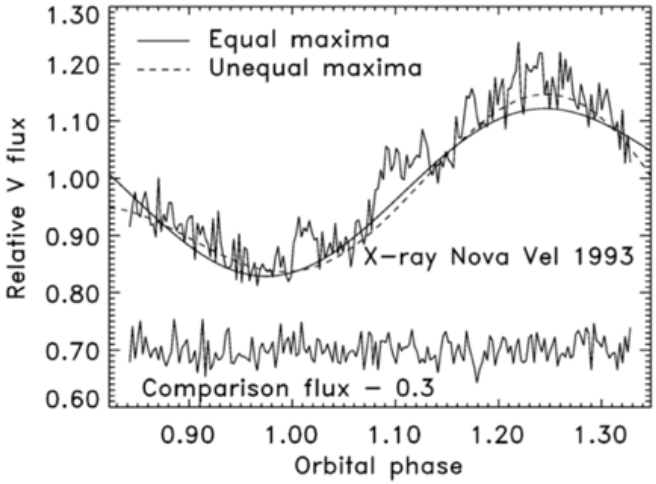
Swift J1753.5-0127 from Durant et al. (2008, ApJ, 682, L45)

Variability in Quiescent LMXBs

Optical variations ubiquitous





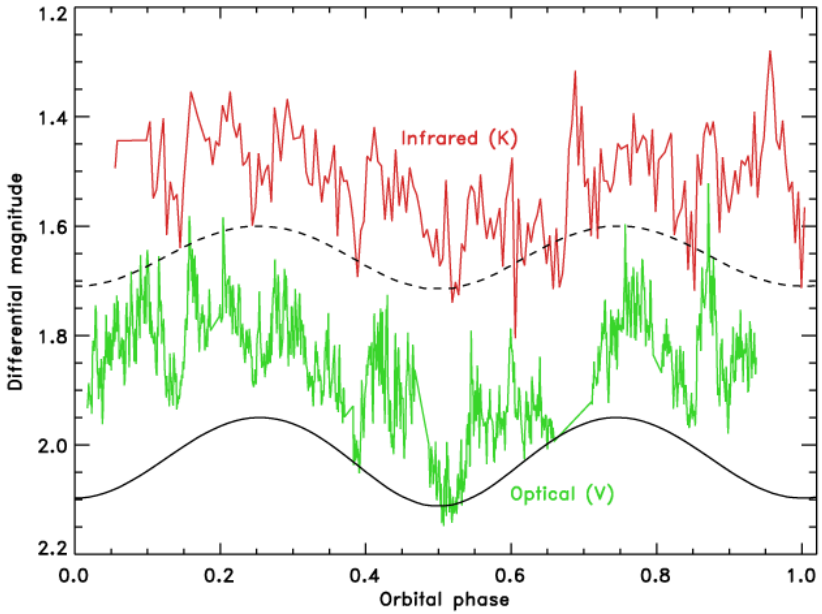


From Hynes et al. (2003, MNRAS, 340 447)

IR Variability in Quiescent LMXBs

Variability extends to IR

- Contamination of ellipsoidal modulations
- Extends spectral information



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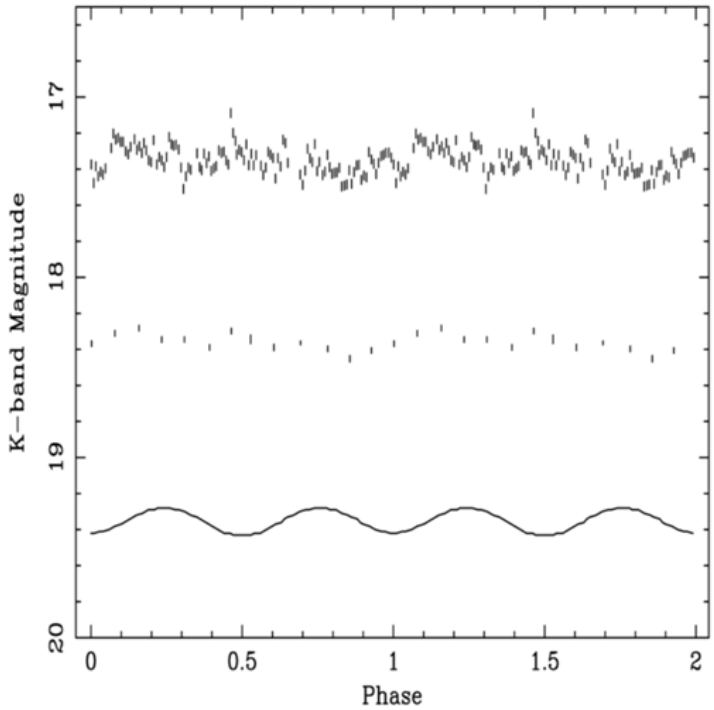
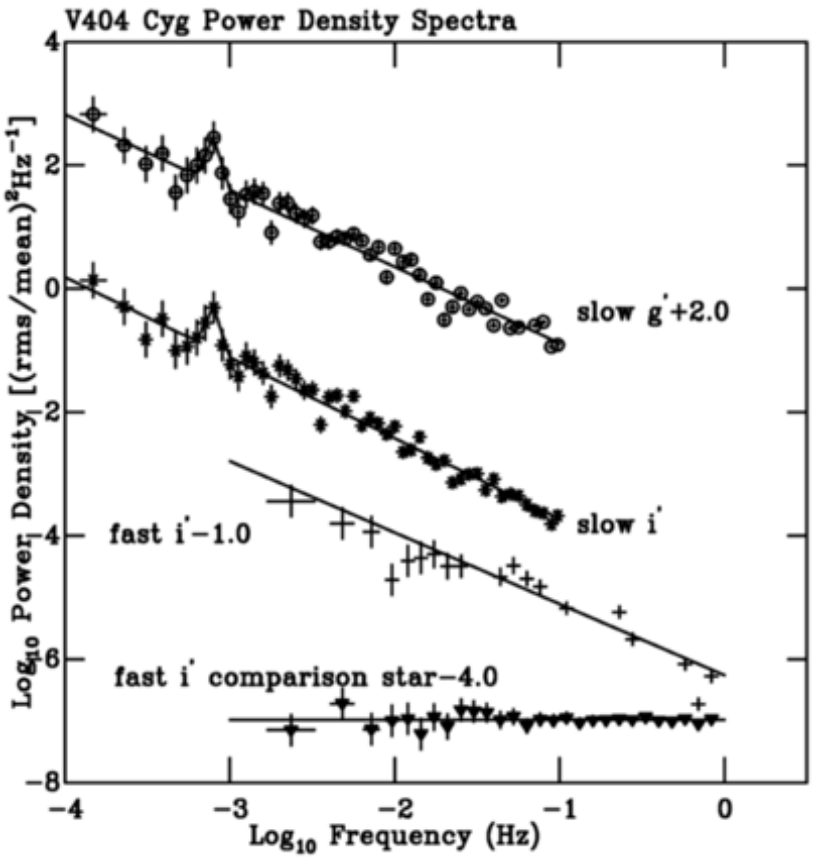
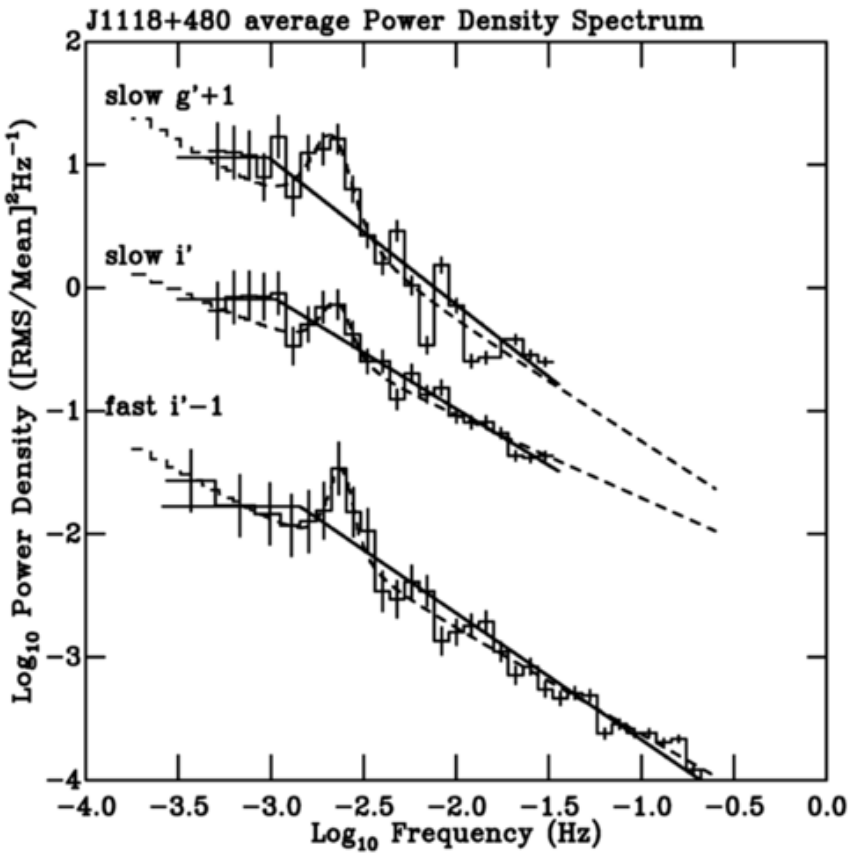


GRO J0422+32 from Reynolds et al. (2007, MNRAS, 375, 657)

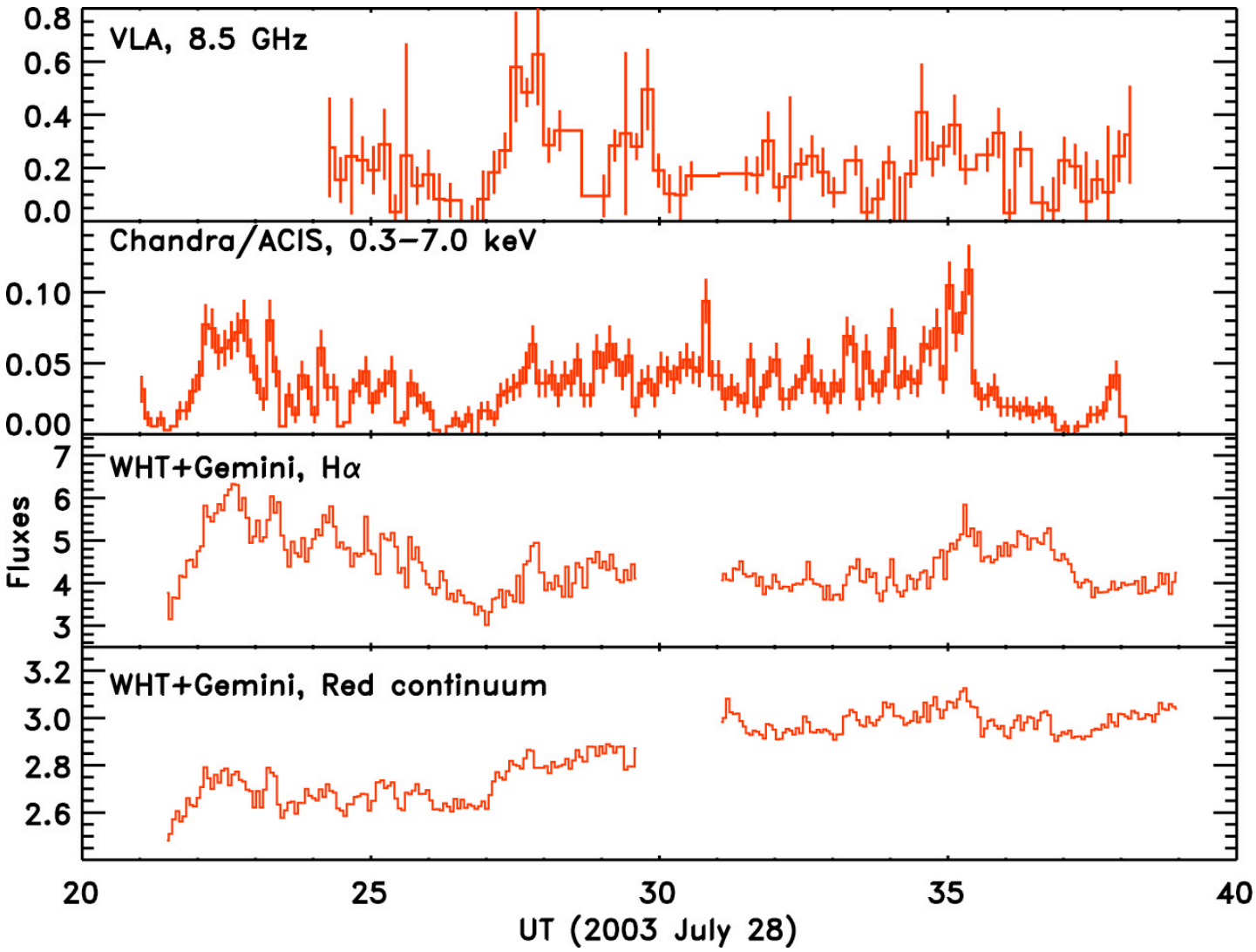
QPOs in Quiescent LMXBs





From Shahbaz et al. (2003, MNRAS, 346, 1116) and Shahbaz et al. (2005, MNRAS, 362, 975)

Multiwavelength Variability and Correlations

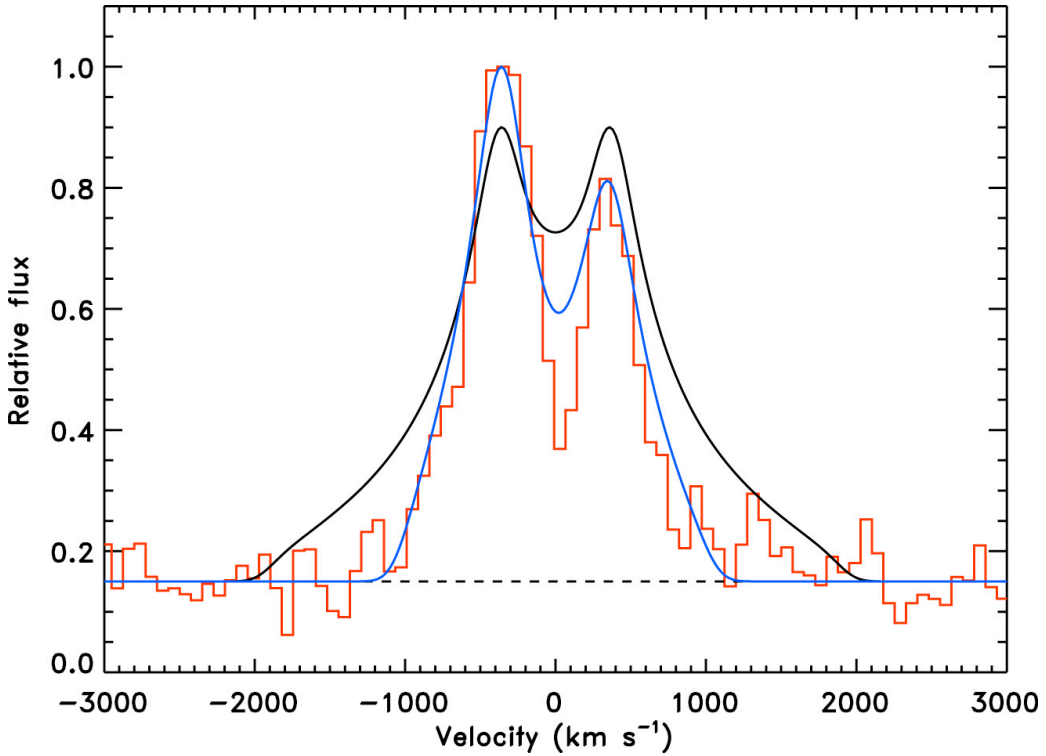


V404 Cyg from Hynes et al. (2004, ApJ, 611, L125 and 2009, MNRAS, 399, 2239)

Flare Line Profiles

Emission line flares correlated with X-ray

- Double-peaked profile
  ⇒ Whole disk flares simultaneously
- Timescale < dynamical
  ⇒ Irradiation driven



V404 Cyg from Hynes et al. (2004, ApJ, 611, L125)