Coordinated multi-wavelength rapid timing of X-ray binaries

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Henk Spruit

What is the source of the optical power of X-ray binaries?



Comparison to blackbody optical reprocessing model

Reprocessed emission

$\propto$

f(incident flux, area of reprocessor)

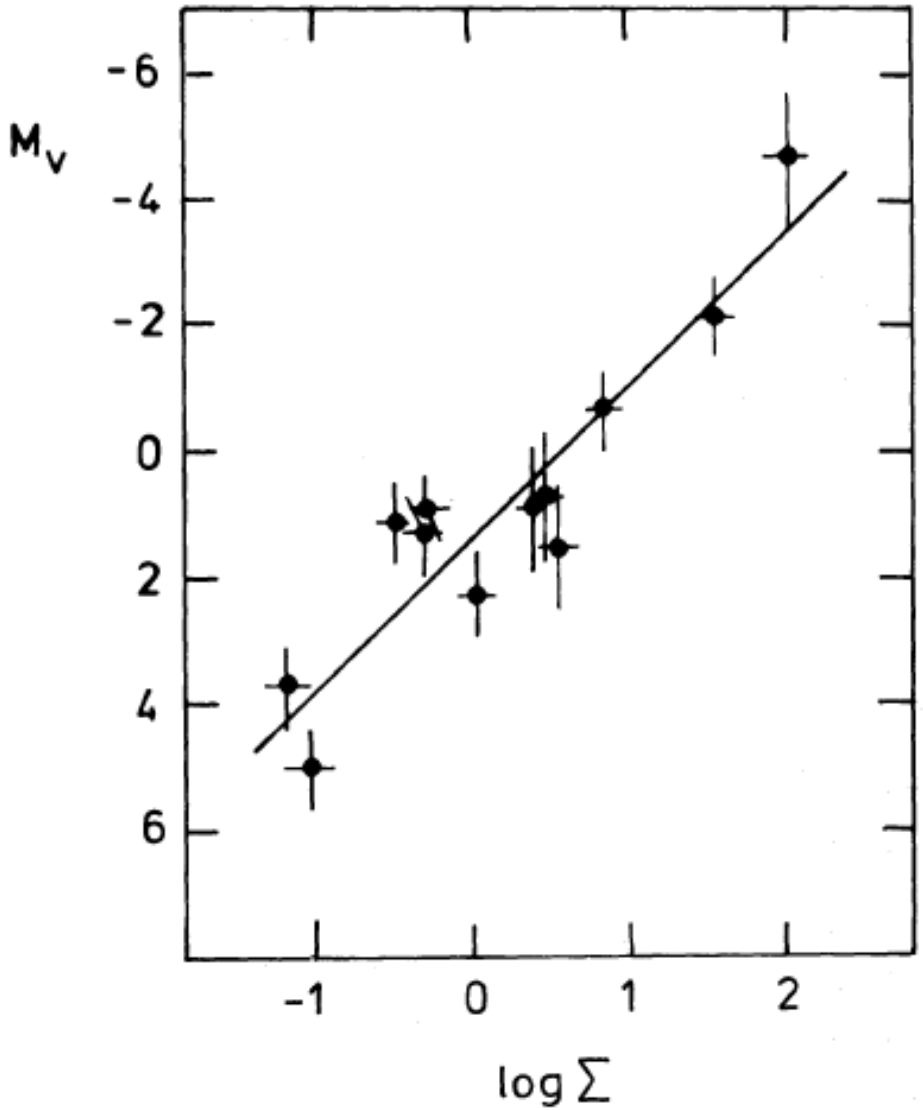
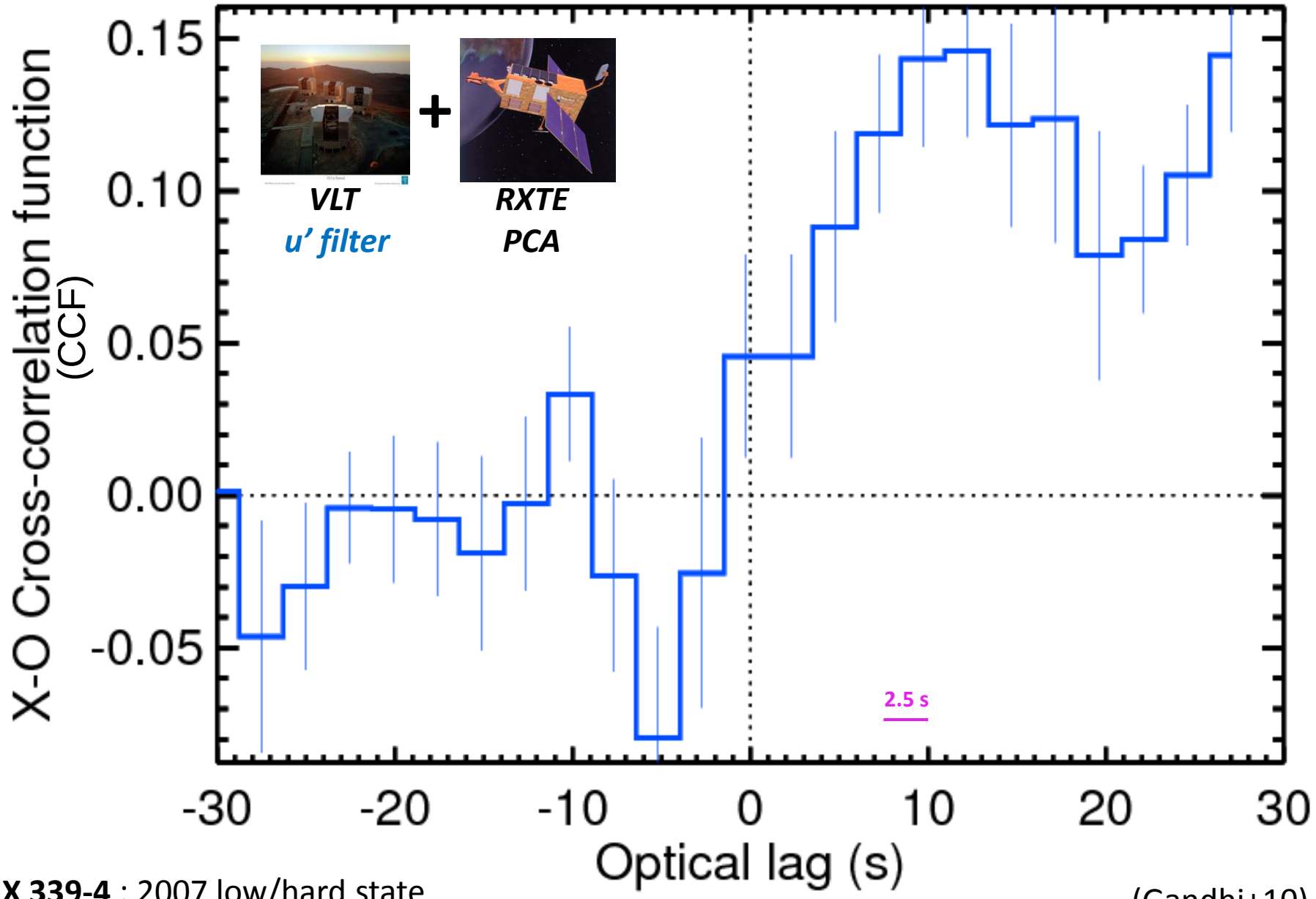


Fig. 2. Relation between the absolute visual magnitude M_V and $\Sigma = (L_X/L_{Edd})^{1/2}\ (P/\ 1\text{hr})^{2/3}$. The straight line represents the least-squares fit (see text)

(van Paradijs & McClintock 1994)

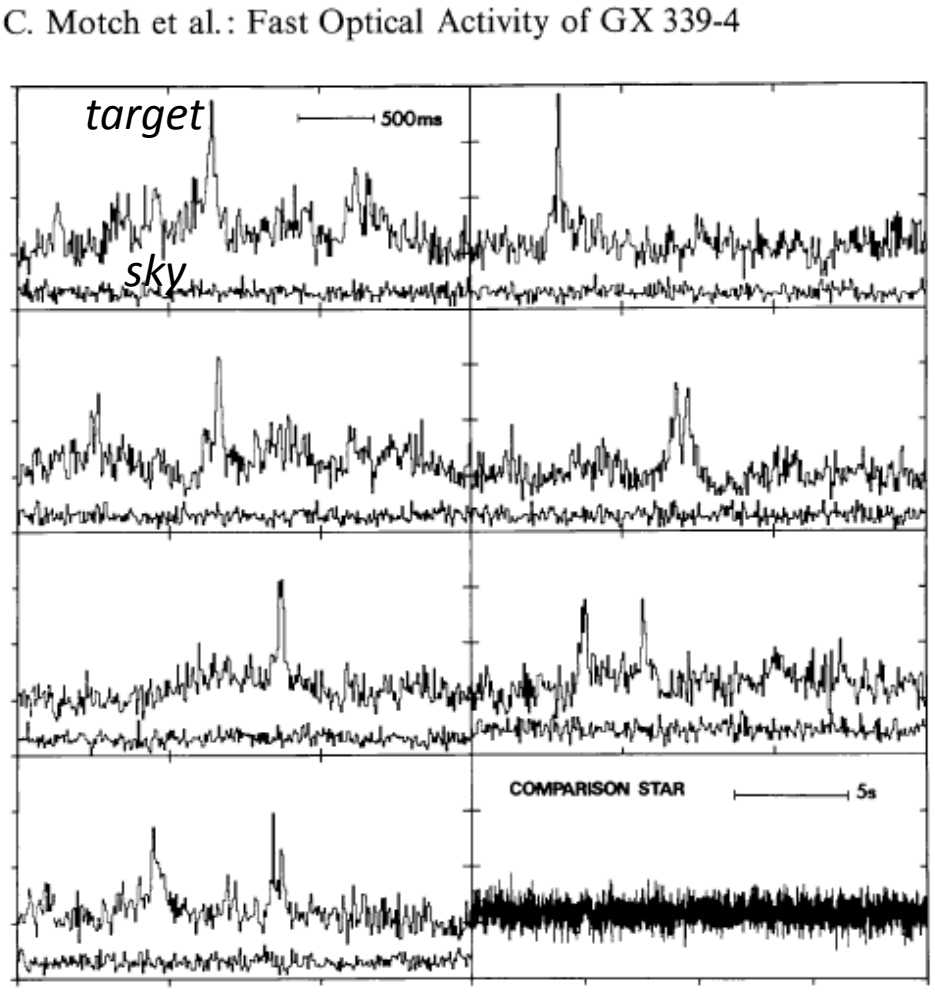
Optical and X-ray simultaneous timing



GX 339-4 : 2007 low/hard state

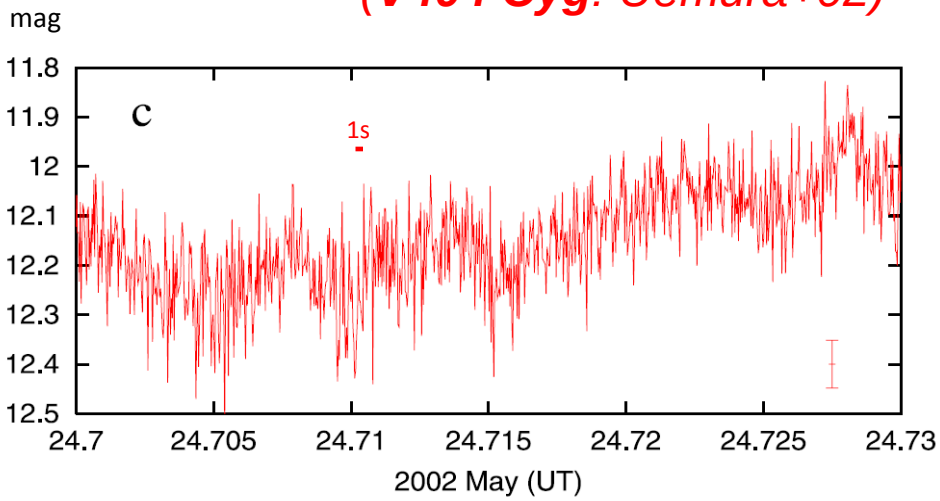
(Gandhi+10)

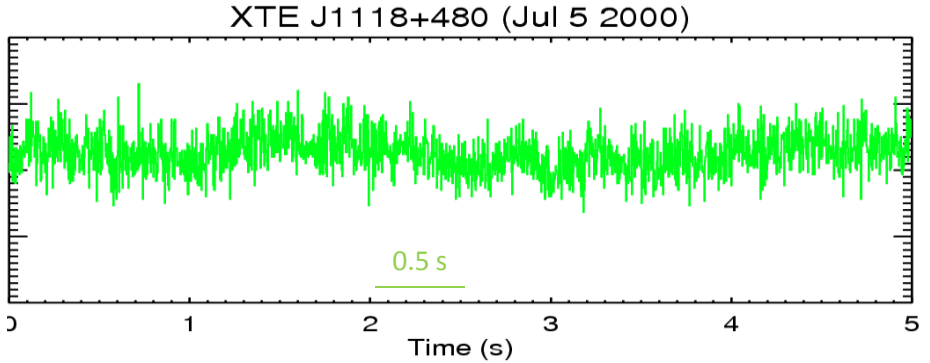
Speedy aperiodic optical variations in X-ray binaries



(***GX 339-4***: Motch+82)

(***V404 Cyg***: Uemura+02)





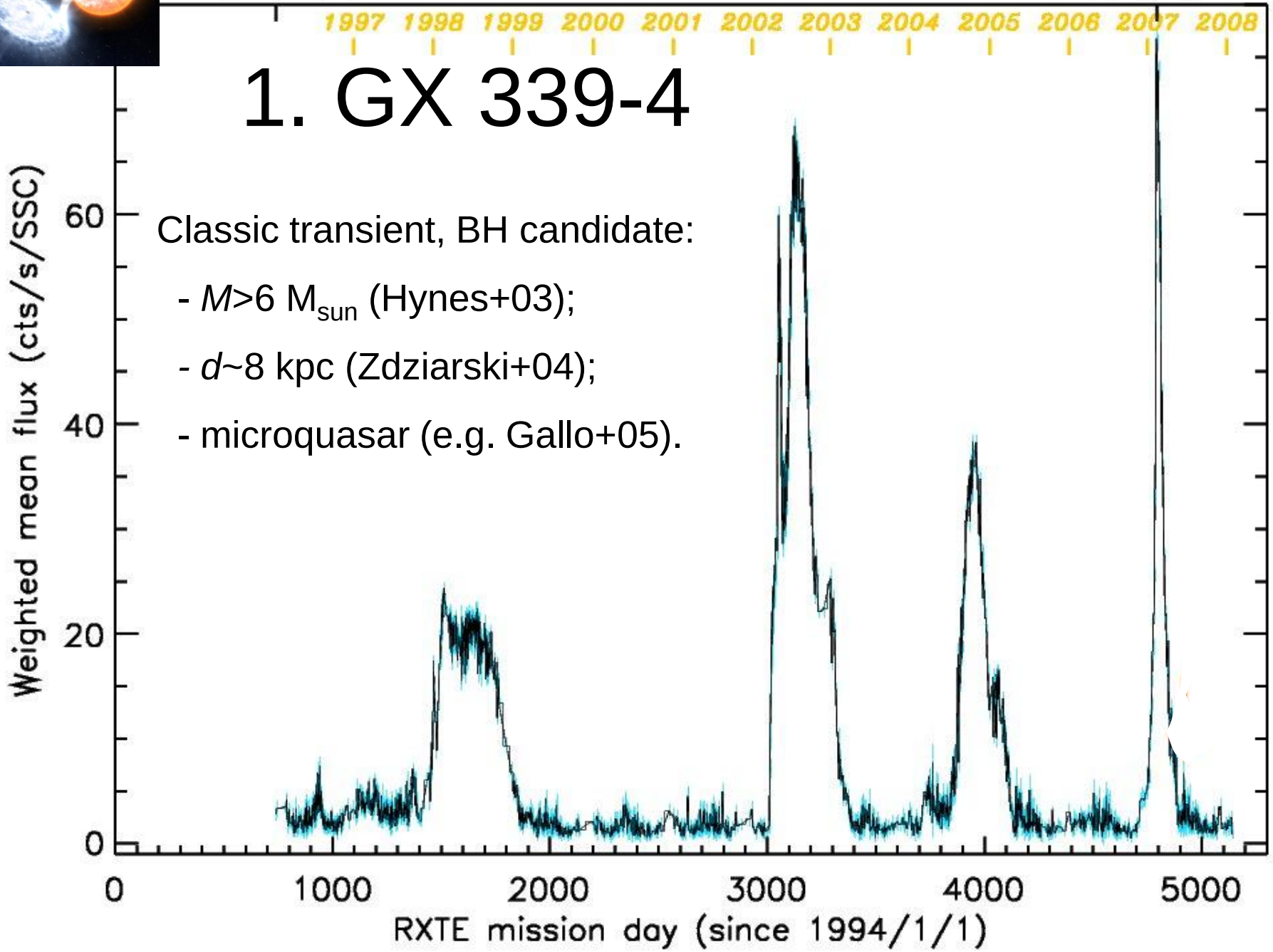
(***XTE J1118+480***: Kanbach+01)



1. GX 339-4

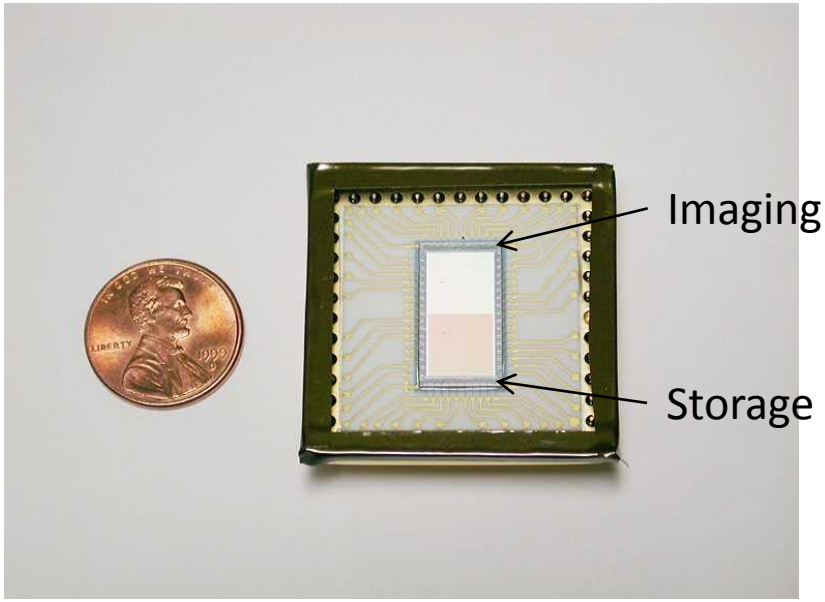
Classic transient, BH candidate:

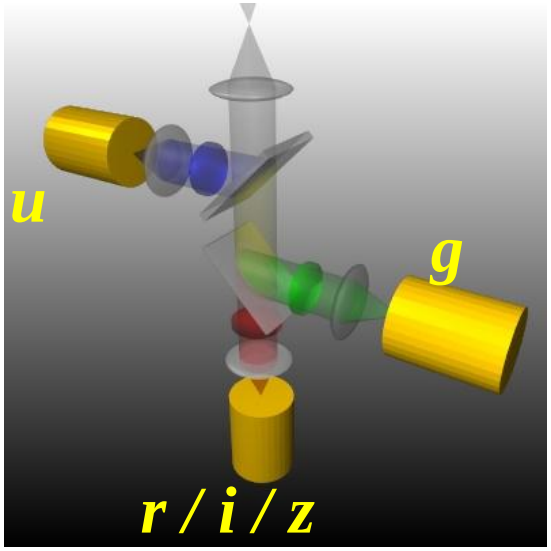
- M>6 M_{sun} (Hynes+03);
- d~8 kpc (Zdziarski+04);
- microquasar (e.g. Gallo+05).



ULTRACAM (on the VLT): ultra-fast, triple-beam CCD camera

- Frame-transfer CCDs with negligible dead-time
- Speeds ~ 500 frames / sec
- Beam splitters => 3 filter simultaneous imaging







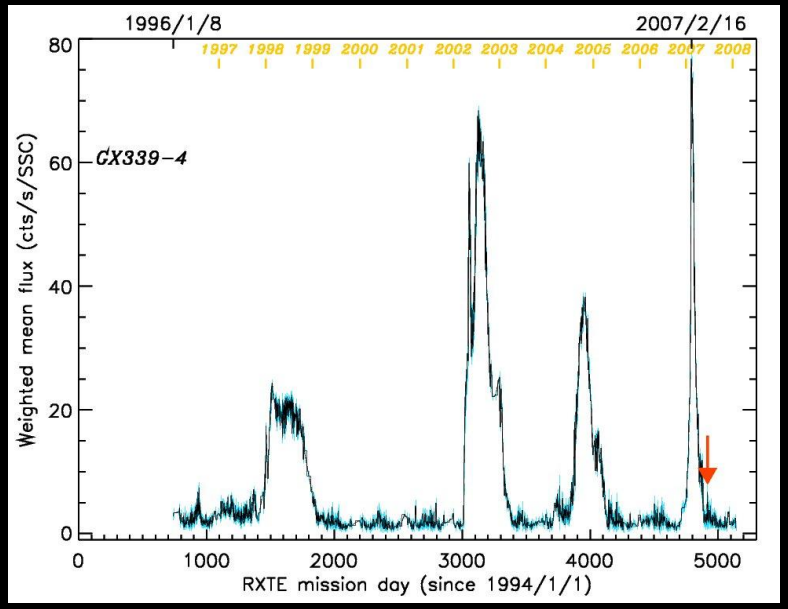
ULTRACAM Mounted on Visitor Focus of MELIPAL

ESO PR Photo 19a/05 (9 June 2005) ©ESO

ULTRACAM @VLT

http://www.shef.ac.uk/physics/people/vdhillon/ultracam/

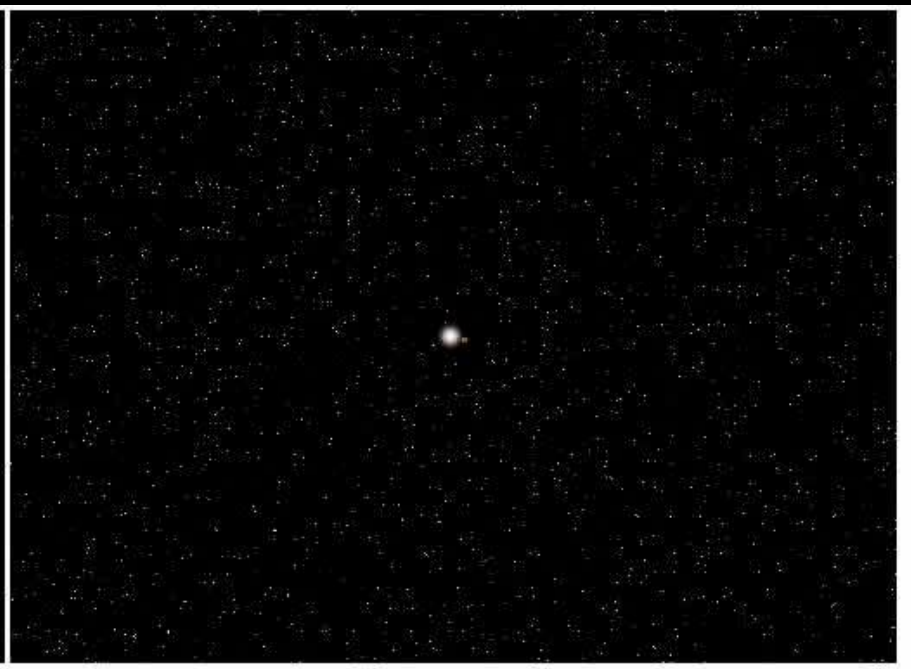
1. GX 339-4



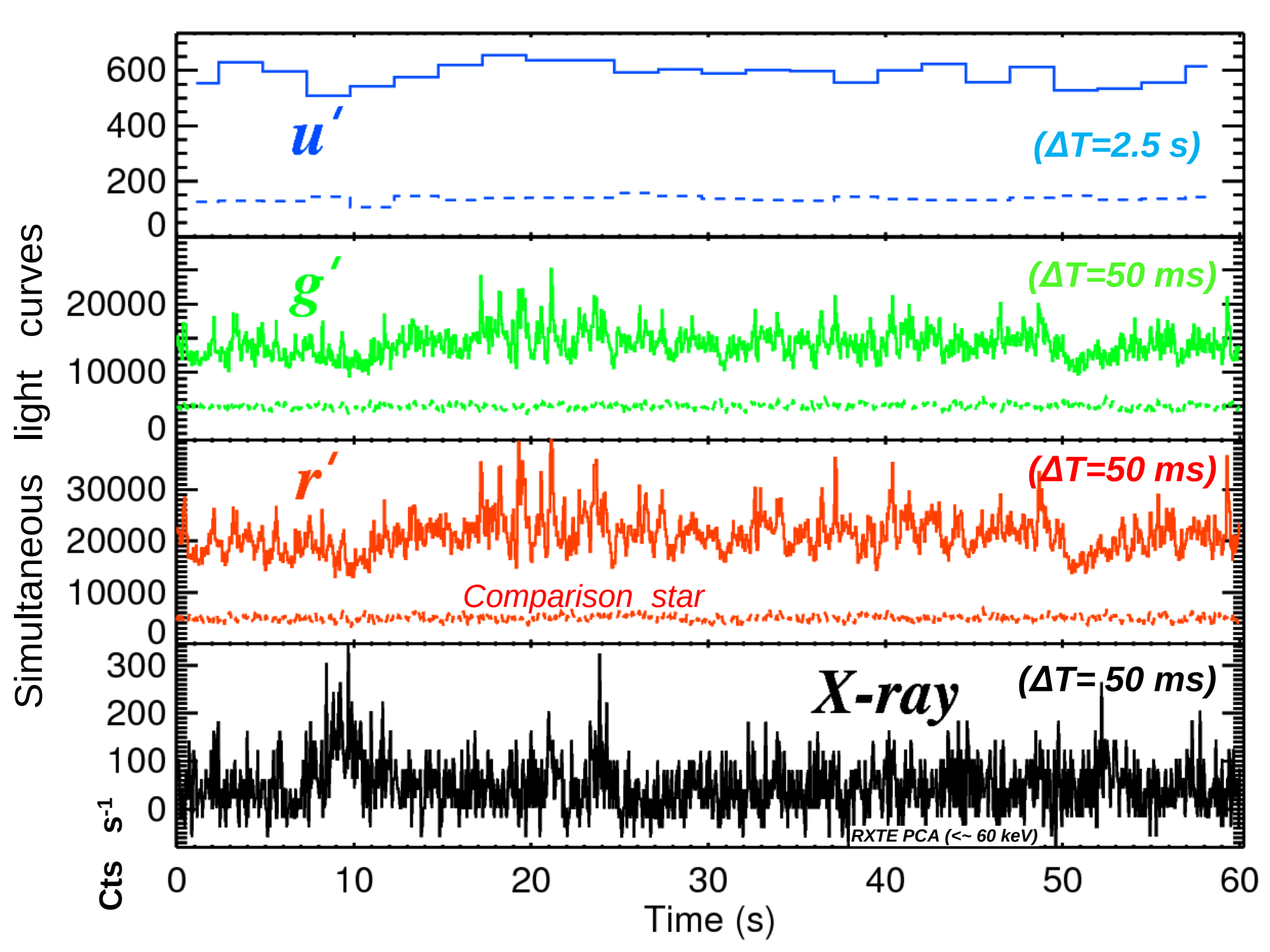
ΔT=50 ms

ULTRACAM

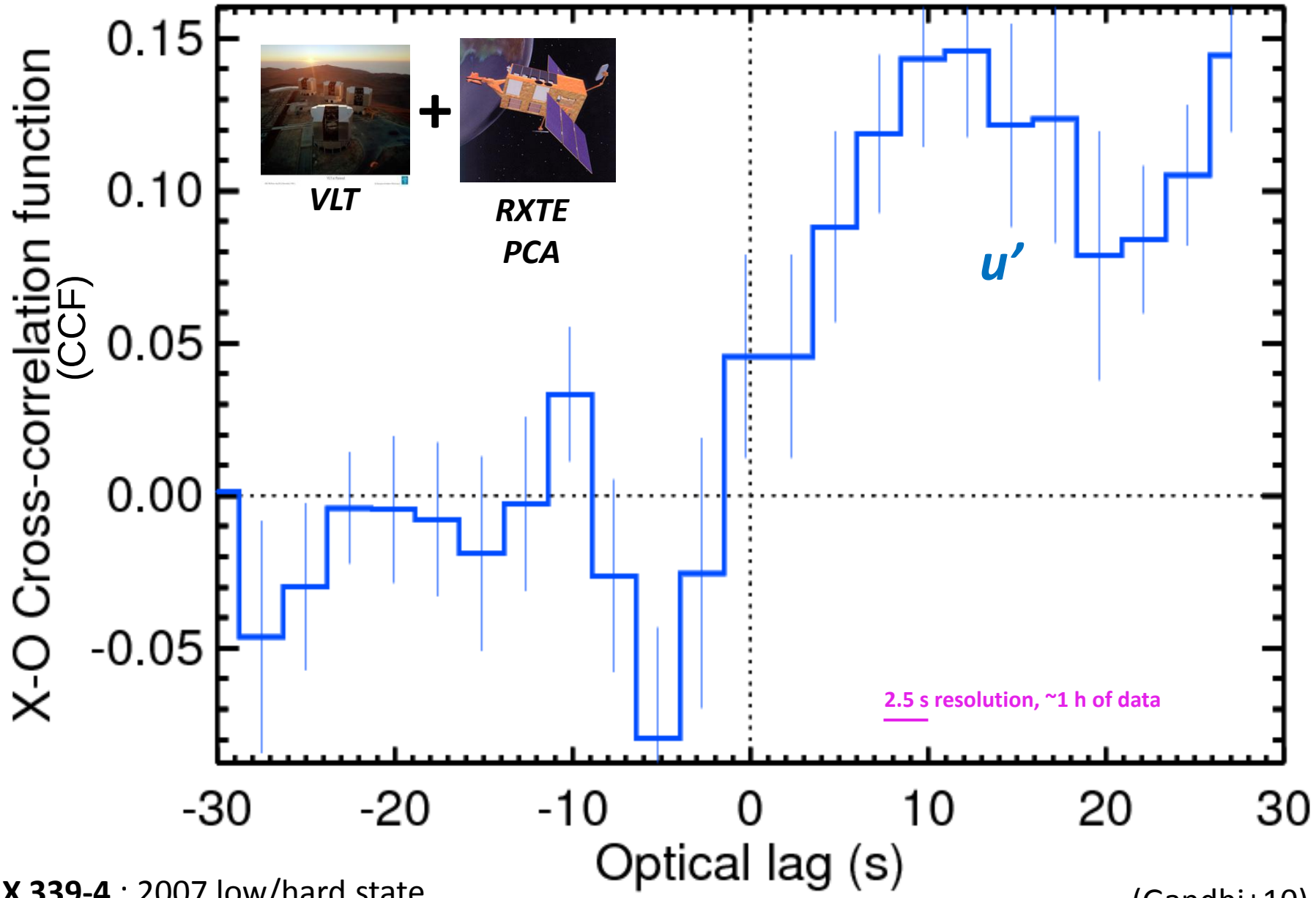




Animation: binsim


Simultaneous light curves
u′
(ΔT=2.5 s)
g′
(ΔT=50 ms)
r′
(ΔT=50 ms)
Comparison star
X-ray
(ΔT= 50 ms)
RXTE PCA (<~ 60 keV)
Cts s-1
Time (s)
600
400
200
0
20000
10000
0
30000
20000
10000
0
300
200
100
0
0
10
20
30
40
50
60

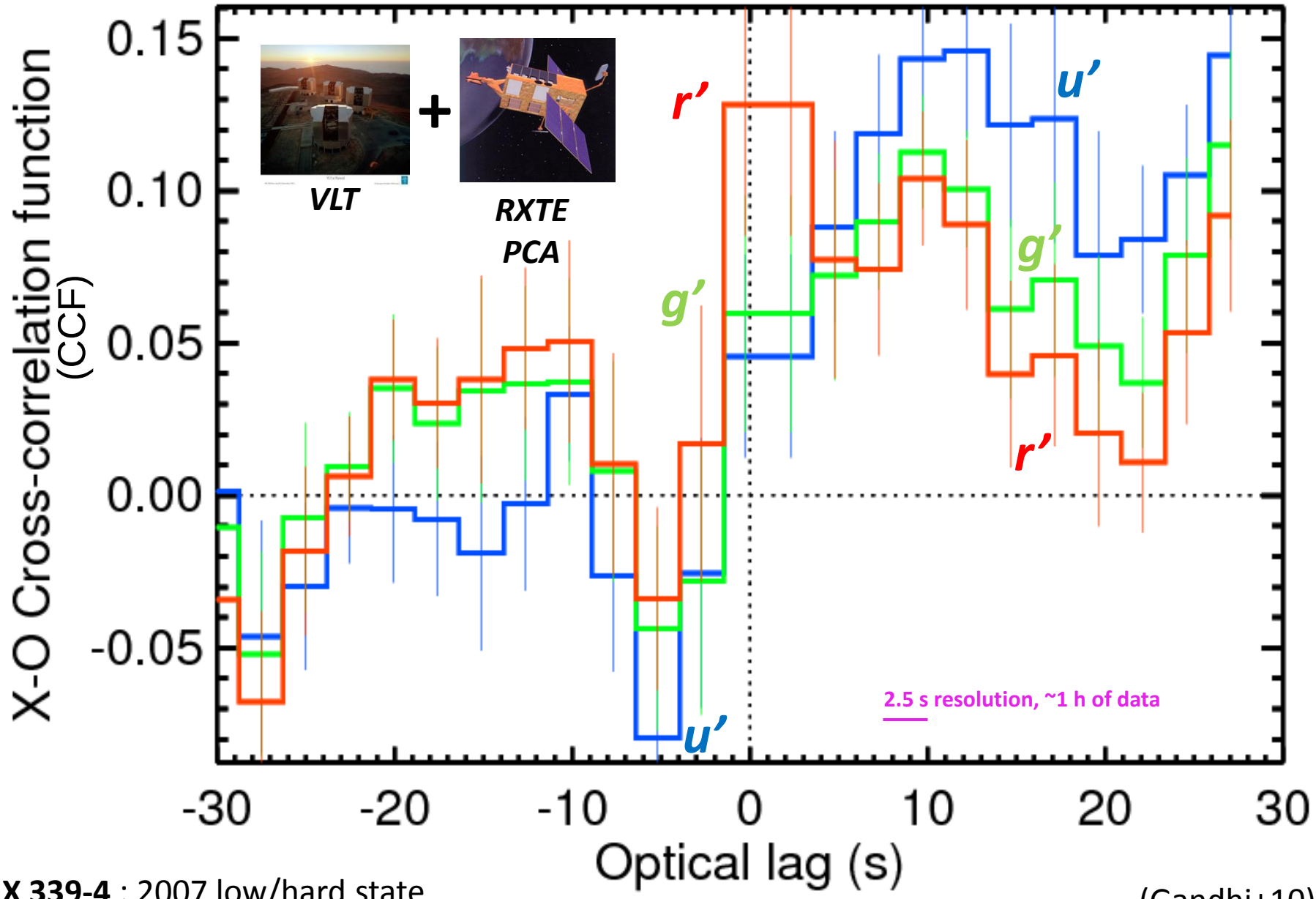
Optical and X-ray simultaneous timing



GX 339-4 : 2007 low/hard state

(Gandhi+10)

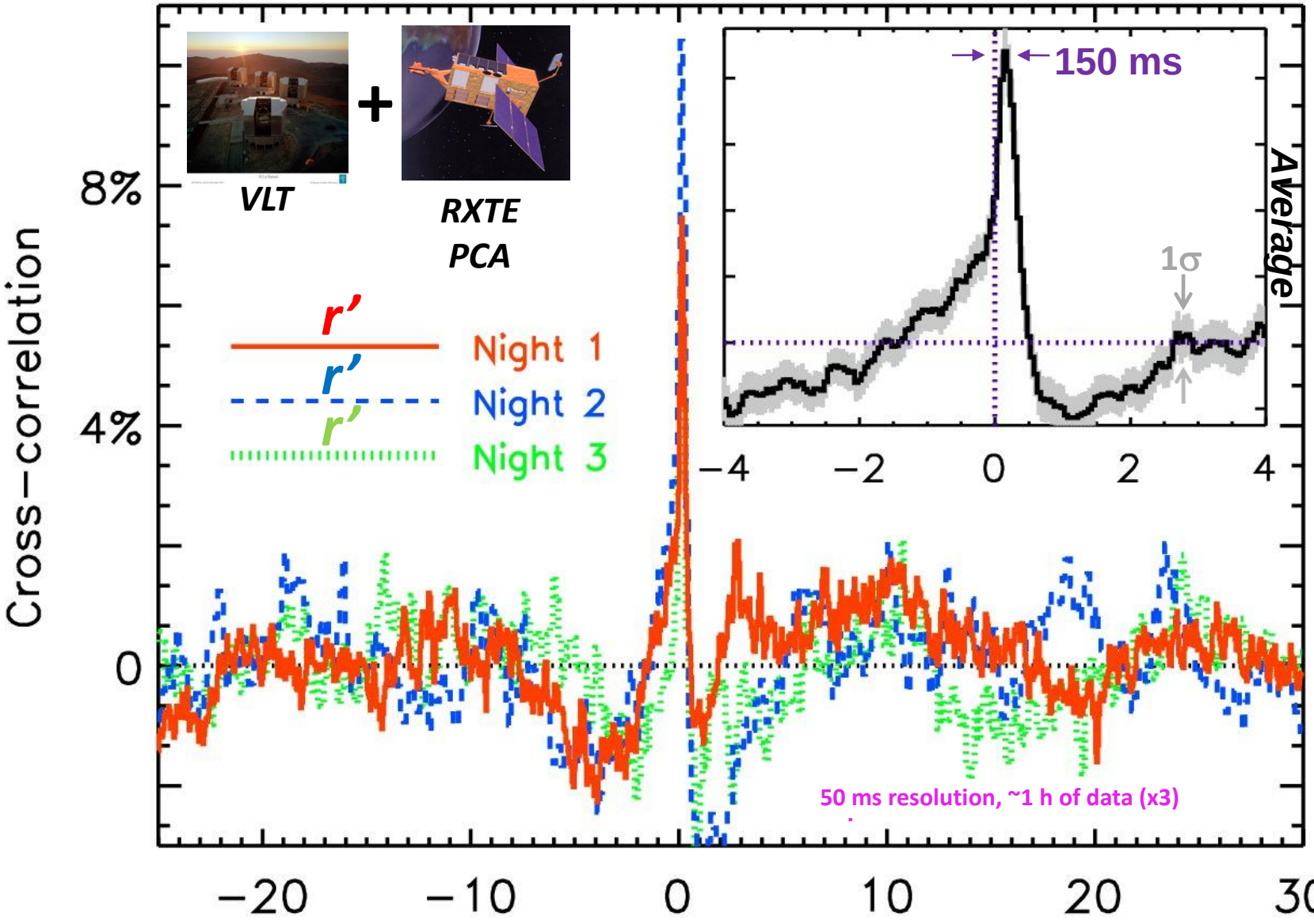
New fast red component in CCF?



GX 339-4 : 2007 low/hard state

(Gandhi+10)

Sub-second X-O Cross Correlation Function (CCF)

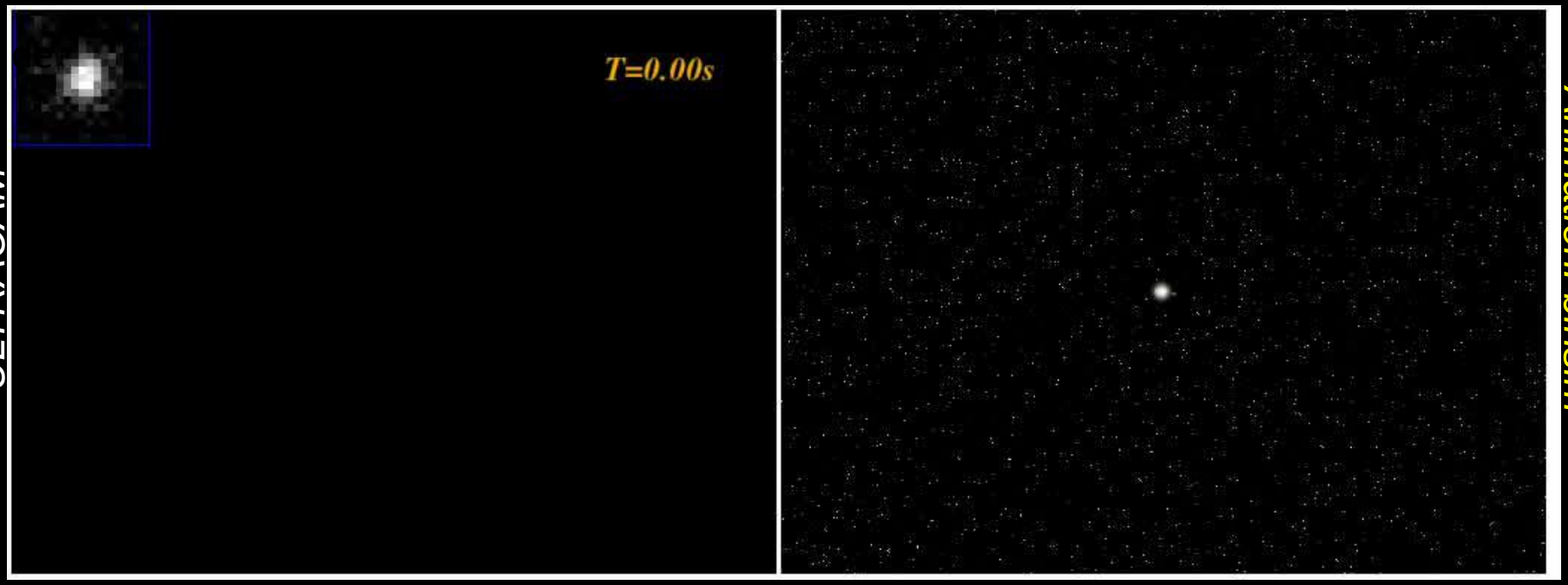


GX 339-4 : 2007 low/hard state

(Gandhi+ 2008)

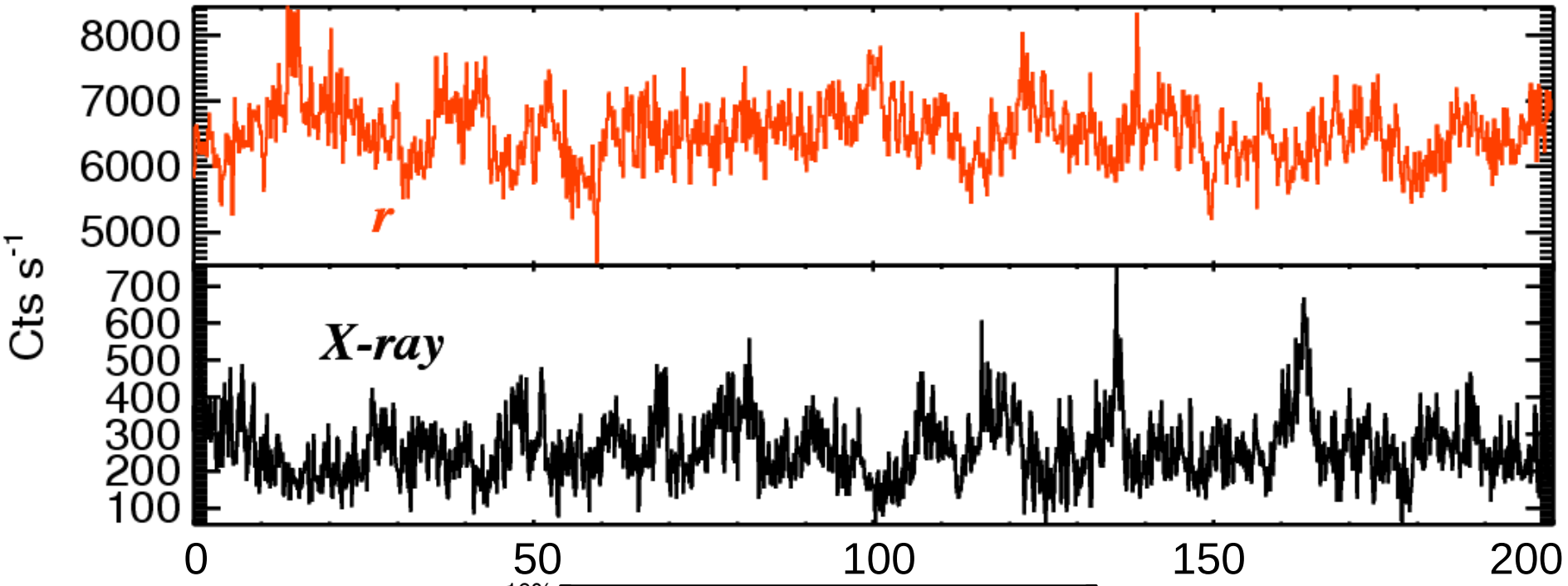
2. Swift J1753.5-0127

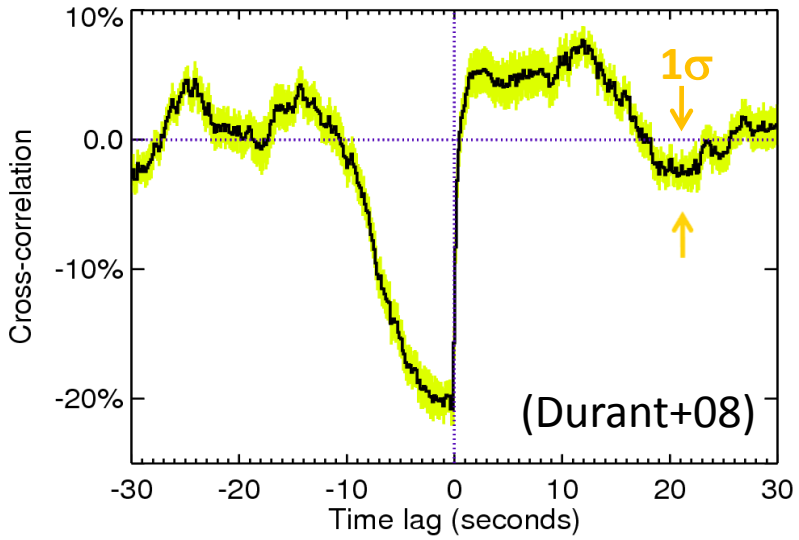
- Galactic halo BH transient
- Very short period ~ 3h (Zurita+08)
- Lives in the low/hard state



ΔT=39 ms

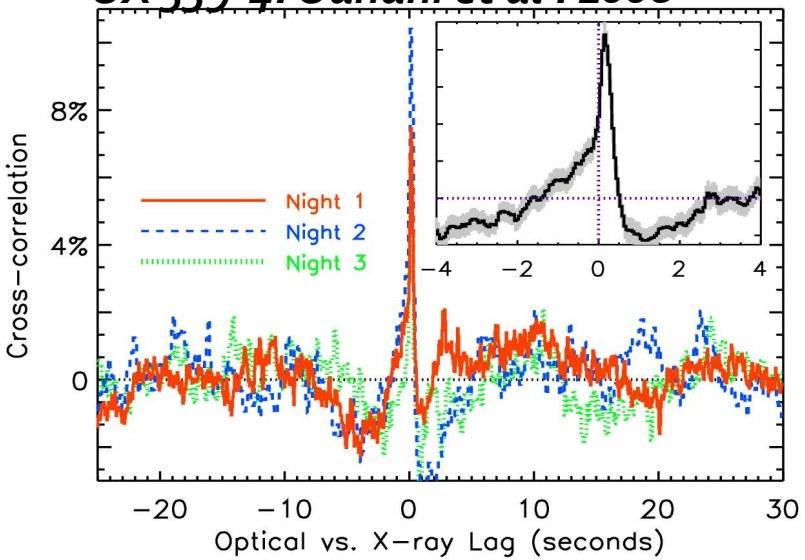
Swift J1753.5-0127



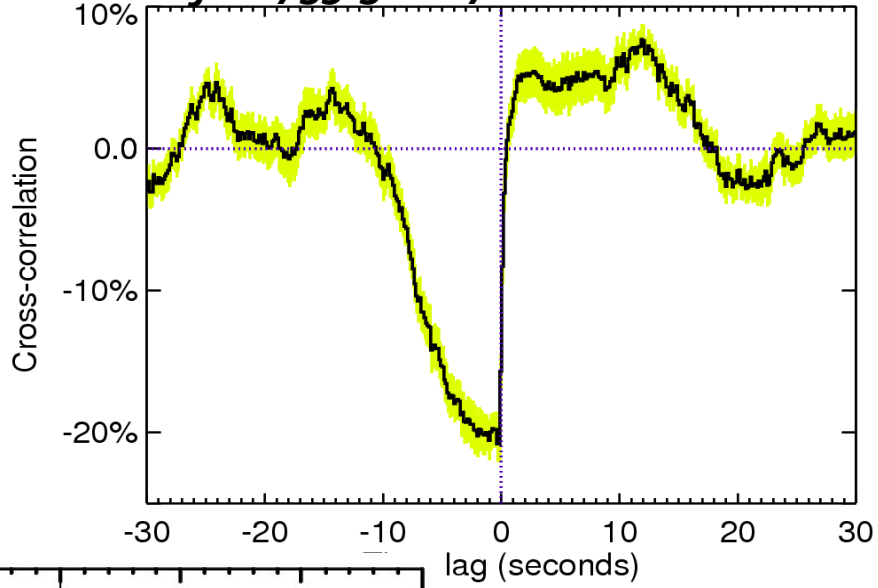


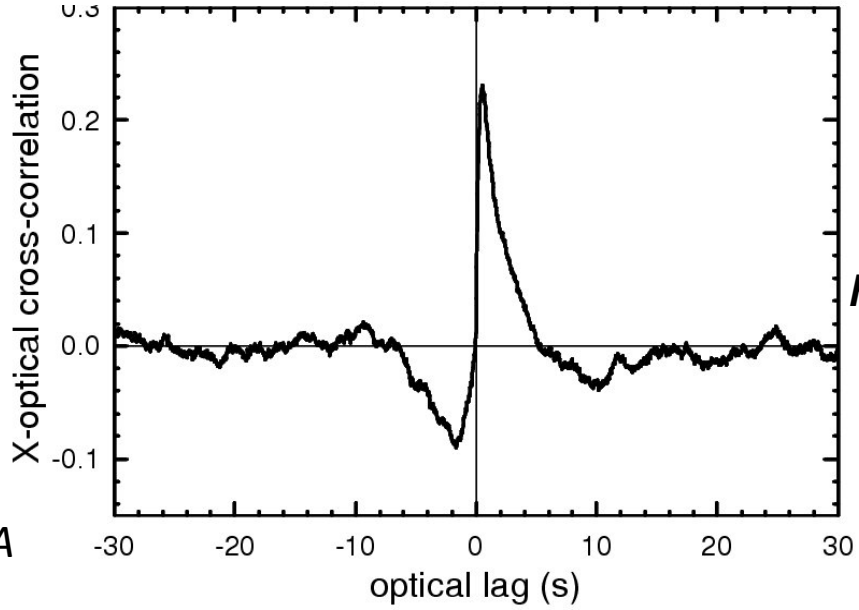
Asymmetric and complex optical/X-ray cross-correlation functions in X-ray binaries

GX 339-4: Gandhi et al . 2008



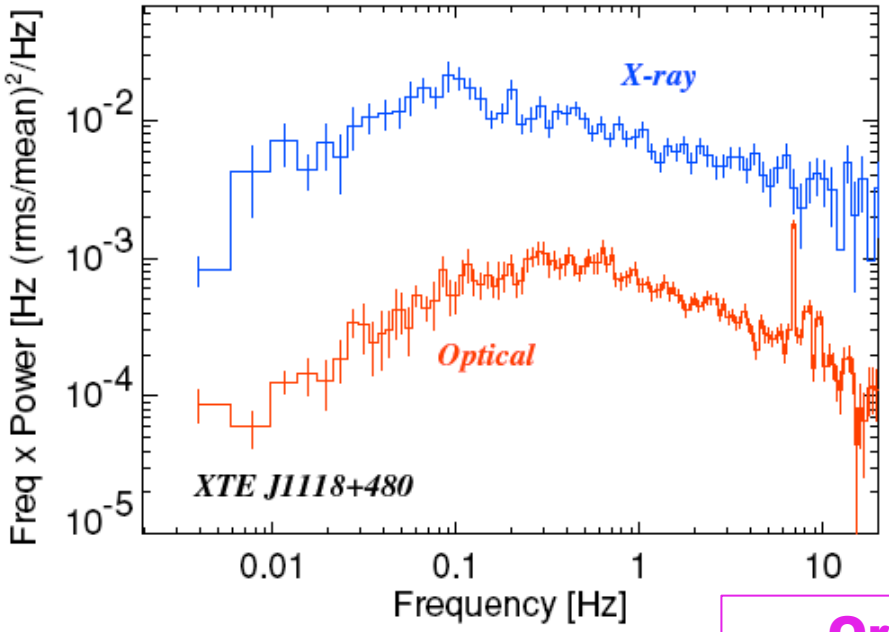
Swift J1753.5-0127: Durant et al. 2008

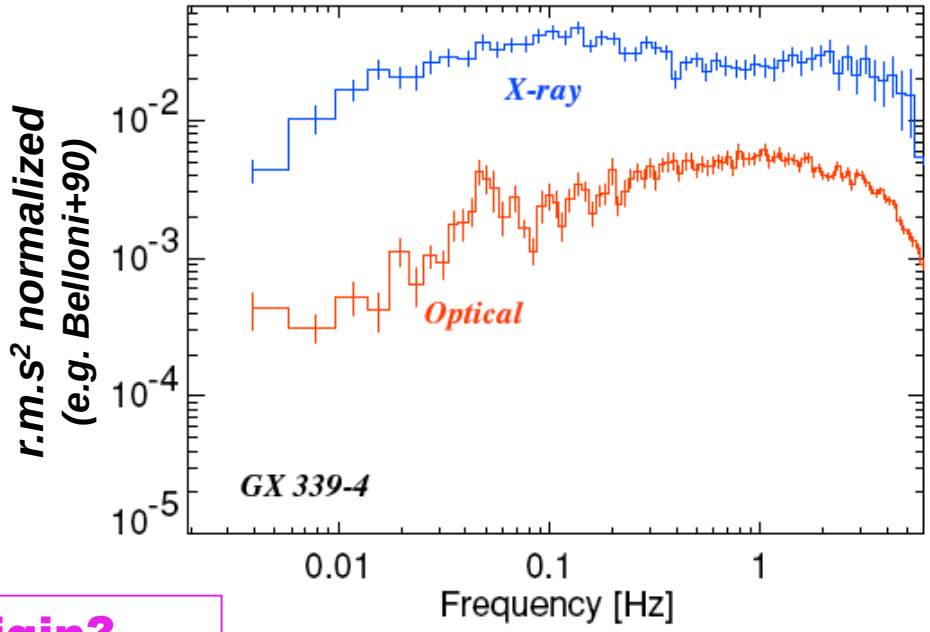




XTE J1118+480: Kanbach et al. 2001

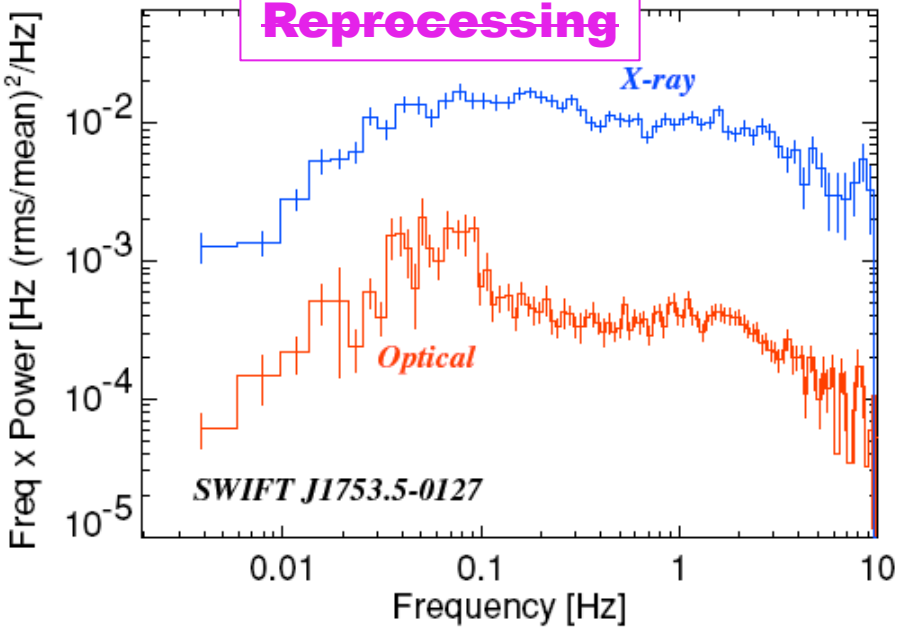
All X-ray data: RXTE PCA





Optical power spectra reminiscent of X-rays

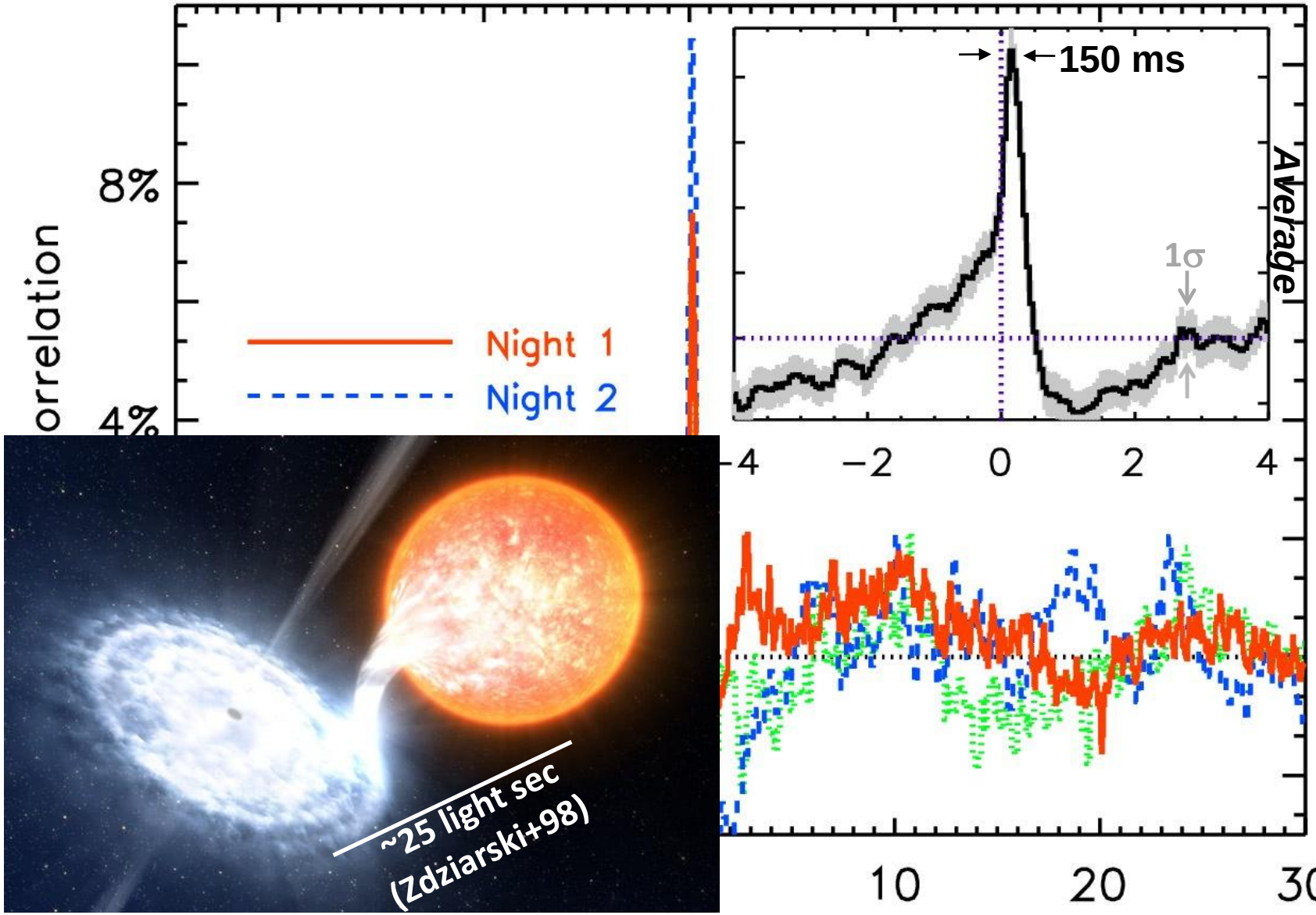
Origin?
~~**Reprocessing**~~



X-ray: PCA
Optical: Either r' or g' or white

(Gandhi 2009)

1. Small time delay

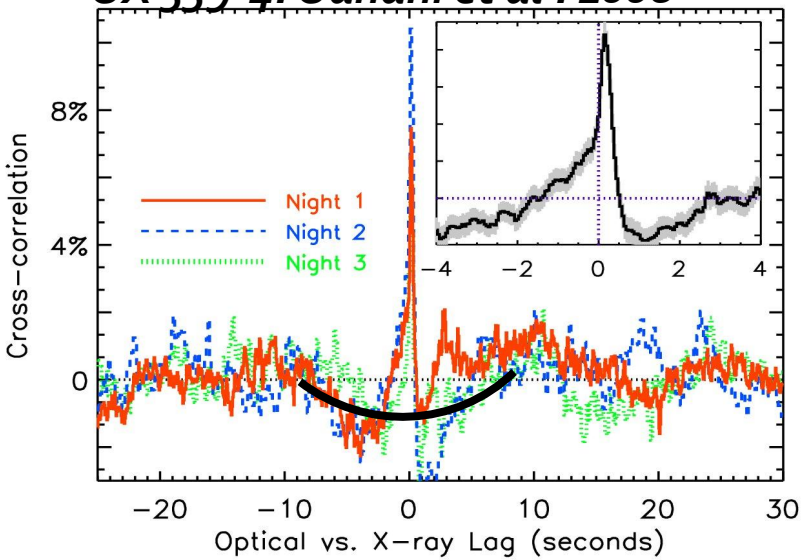


Optical Lag (seconds)

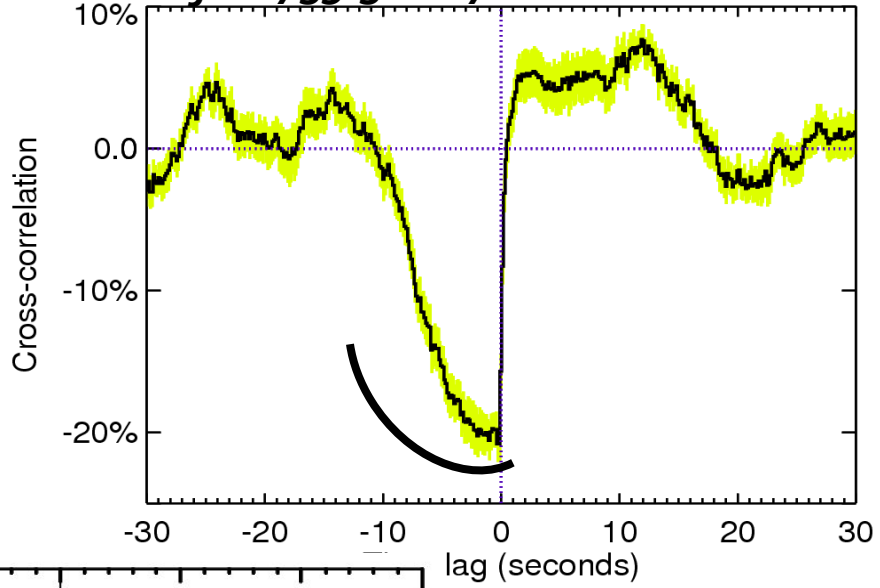
(Gandhi+ 2008)

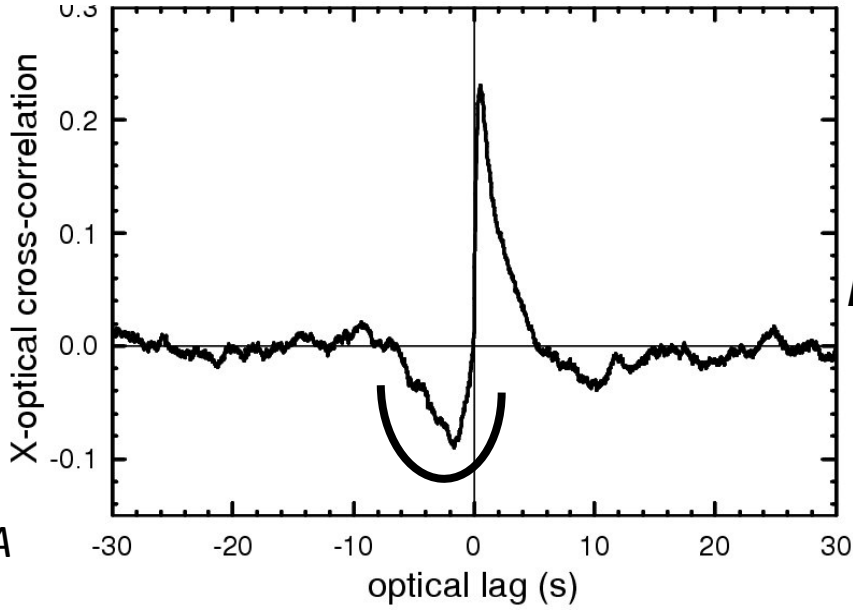
2. Anti-correlation

GX 339-4: Gandhi et al . 2008



Swift J1753.5-0127: Durant et al. 2008





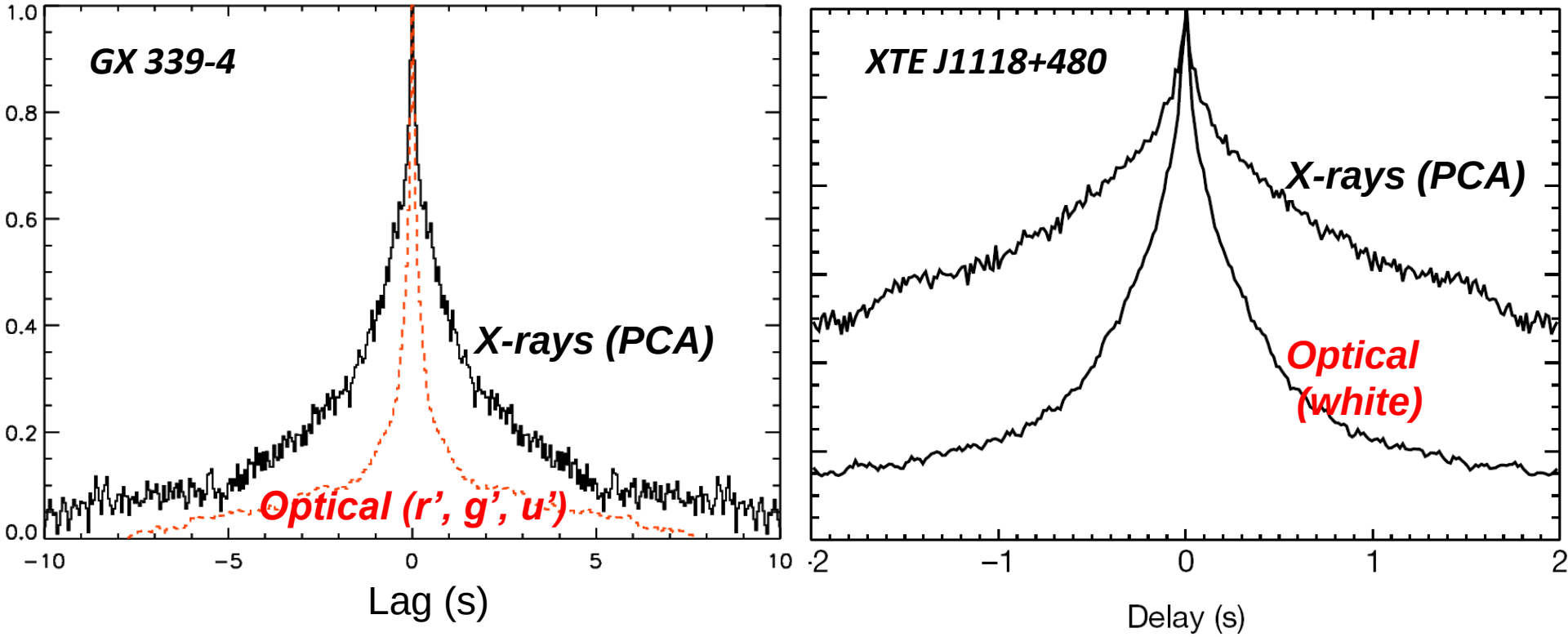
XTE J1118+480: Kanbach et al. 2001

All X-ray data: RXTE PCA

3. Small optical coherence times

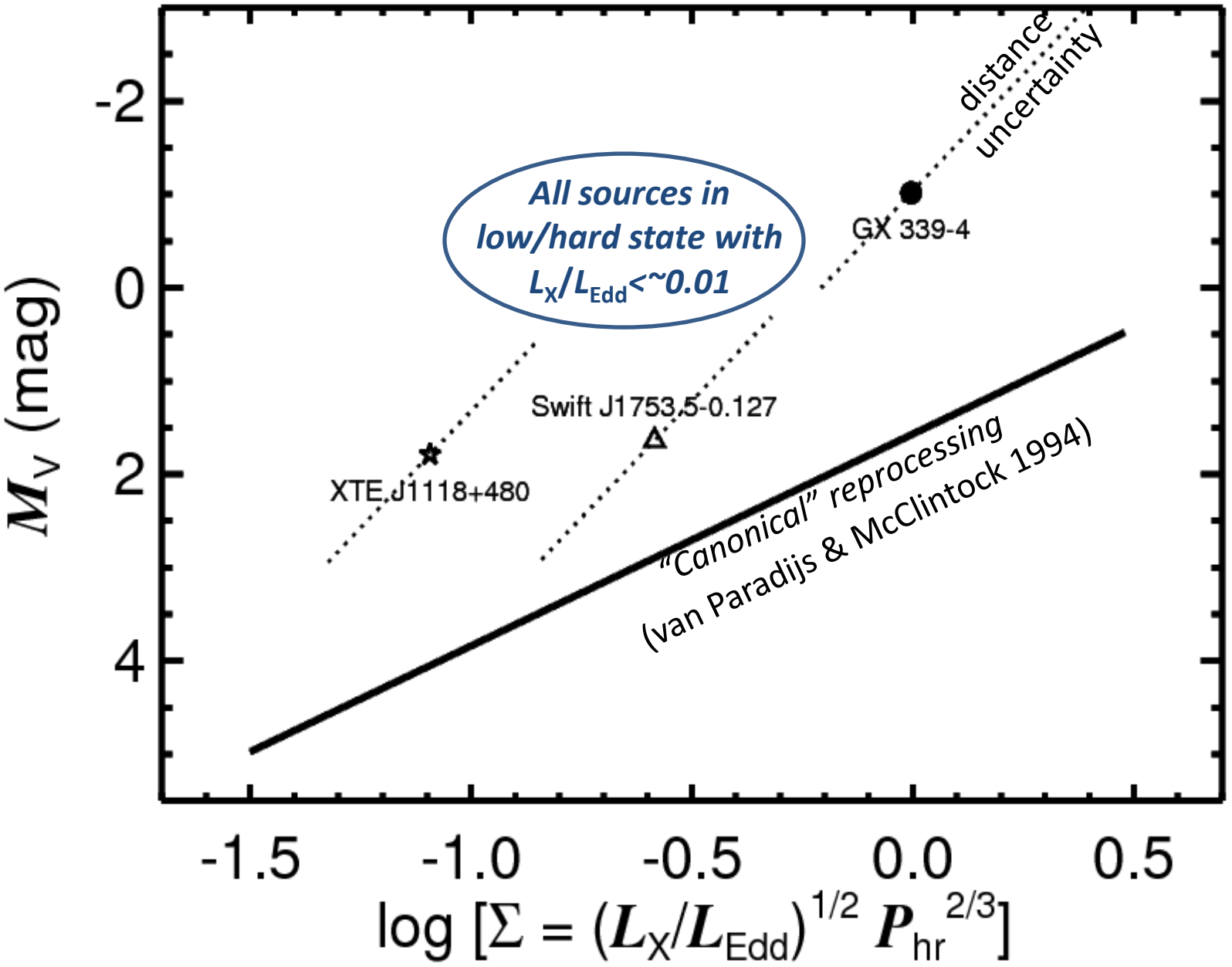
Auto Correlation Function

(Poisson corrected)



Optical ACFs narrower than X-ray ACF for two sources

4. How much reprocessing is expected?



Speedy optical variability: scales and power

- Fastest flares have timescales <~ 20-100 ms.

  => R <~ 10^4 km <~ 10^3 R_G

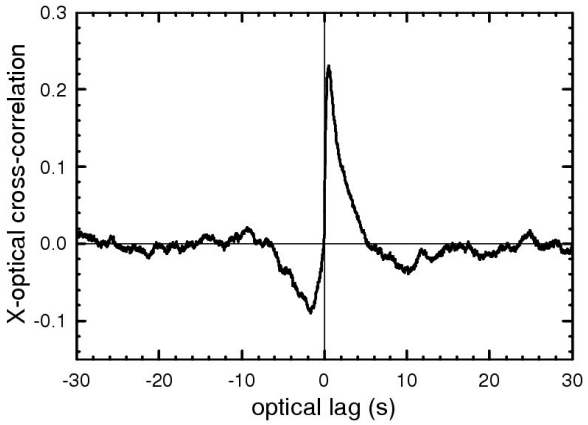
- Brightness temperature

  => T_B >~ 10^7 K

- Equipartition

  => B > 10^4 G

Models for XTE J1118+480



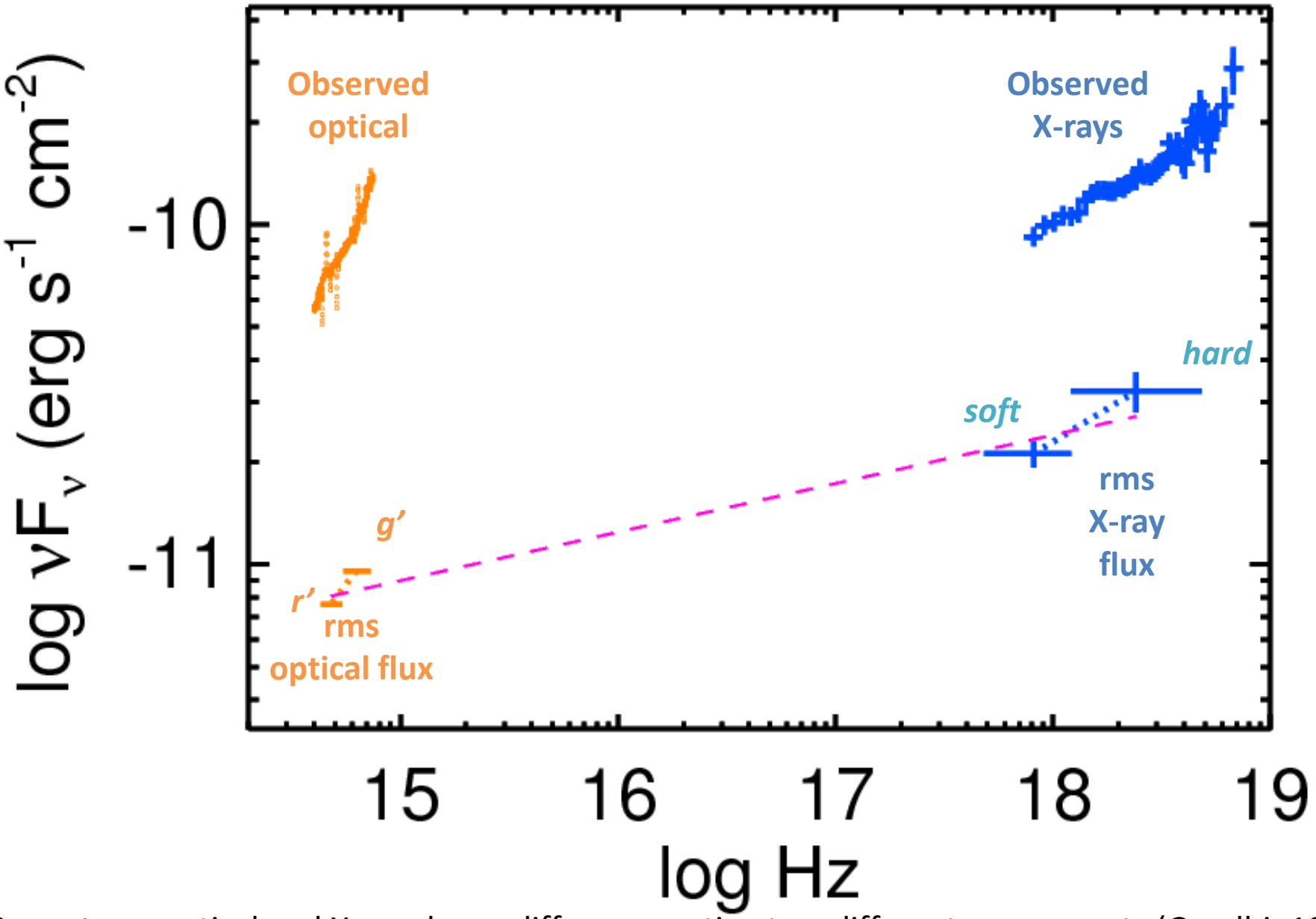
⇨ Optical (cyclo)synchrotron.

⇨ Interaction between components.

- Merloni+00 *Magnetic corona*
- Esin+01 *Advection flow (ADAF)*
- Markoff+01 *Pure jet*
- Malzac+04 *Magnetic 'reservoir' jet/corona*
- Yuan+05 *ADAF+jet*

…

GX 339-4: Two separate components? Or one?



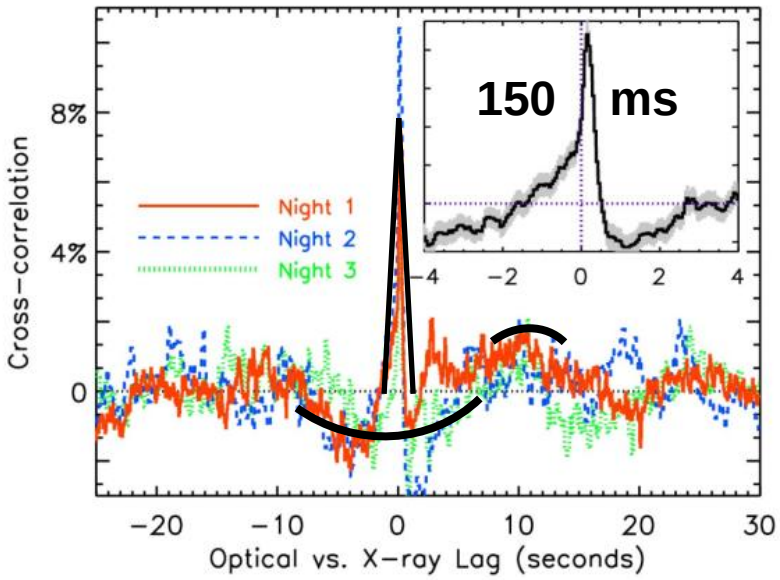
RMS spectrum optical and X-ray slopes differ, suggesting two different components (Gandhi+10).

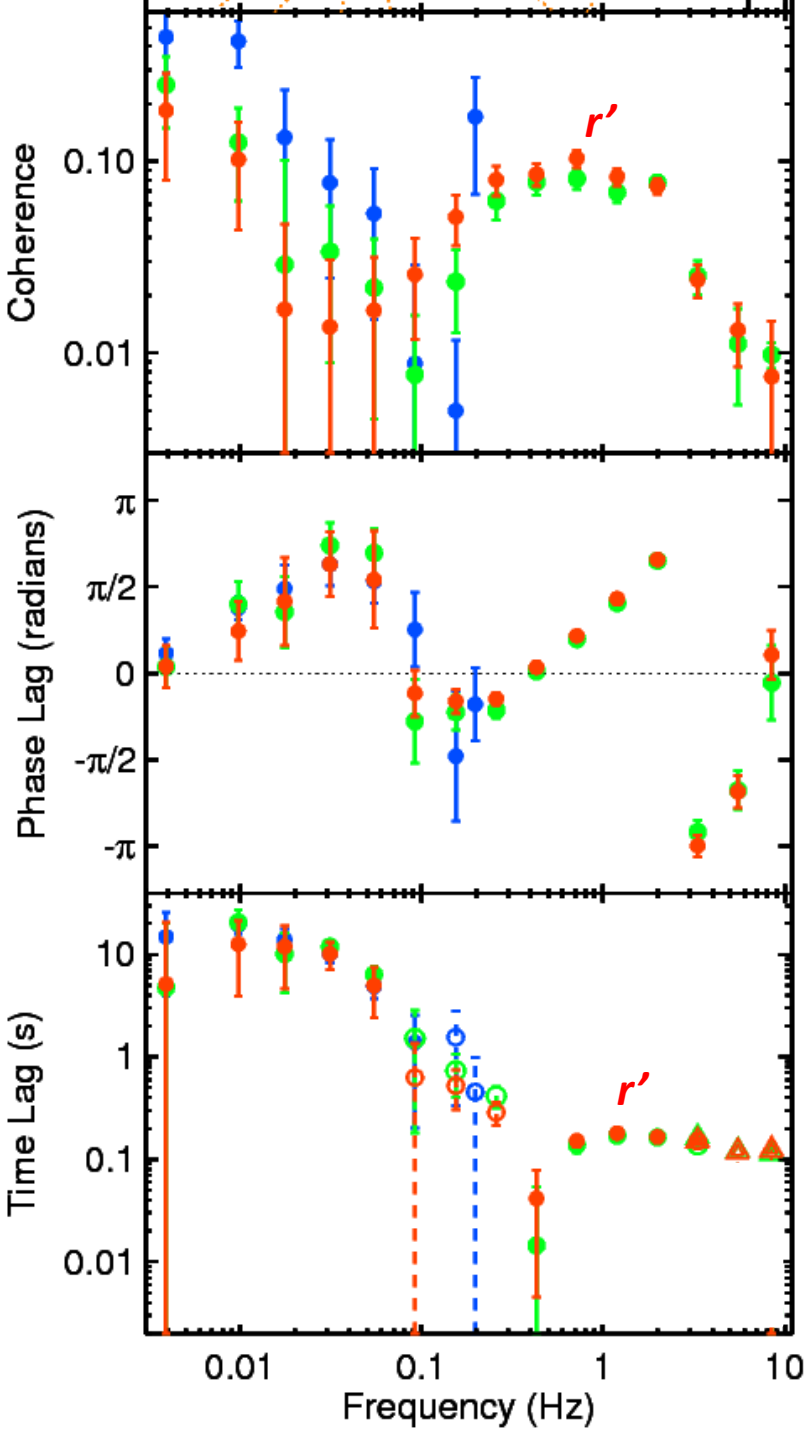
Optical/X-ray coherence and lags

Coherence = $\frac{|\langle X^* O \rangle|^2}{\langle |X^2| \rangle \langle |O^2| \rangle}$

Phase lag = arg ($X^* O$)

Time lag = $\frac{\text{Phase lag}}{2\pi f}$





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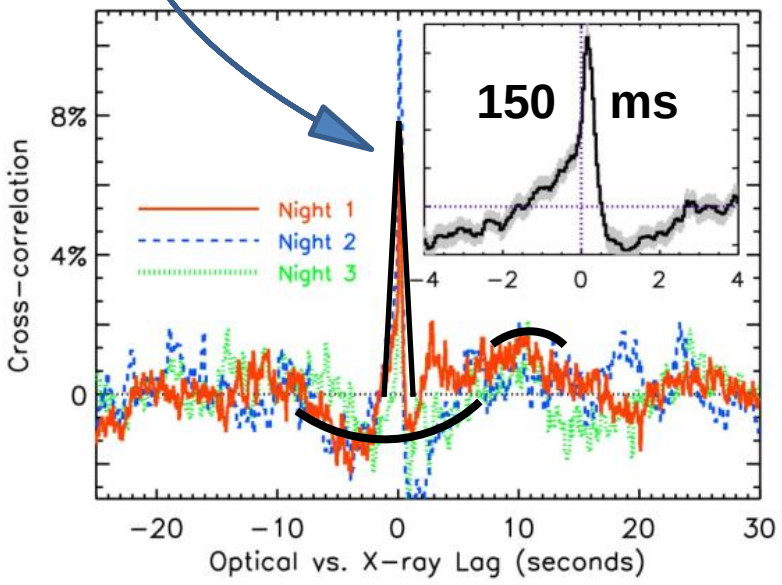

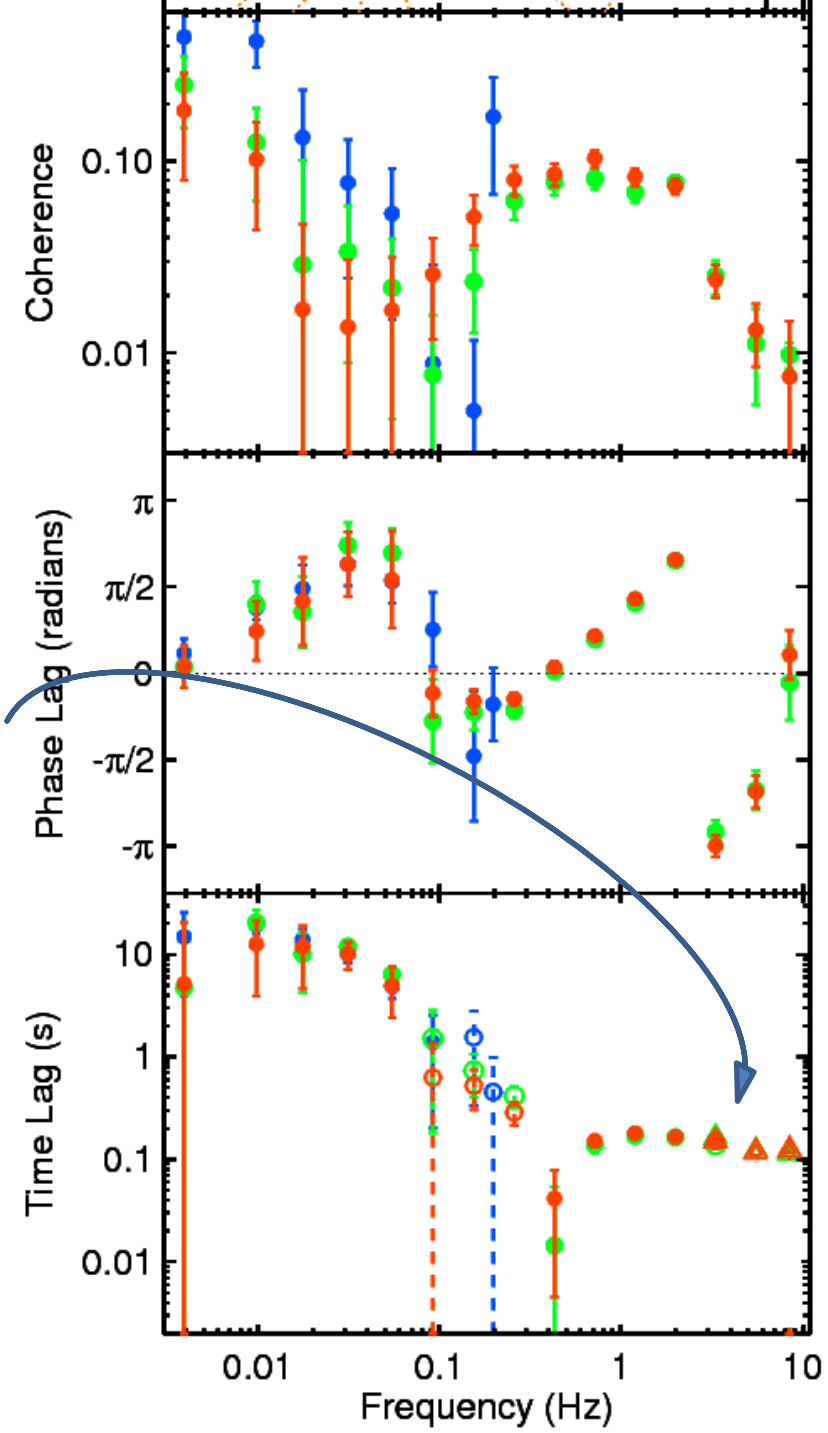

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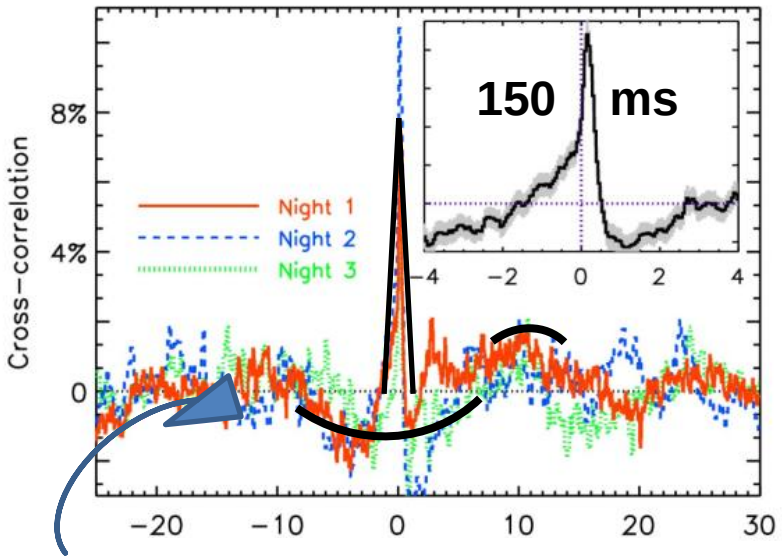
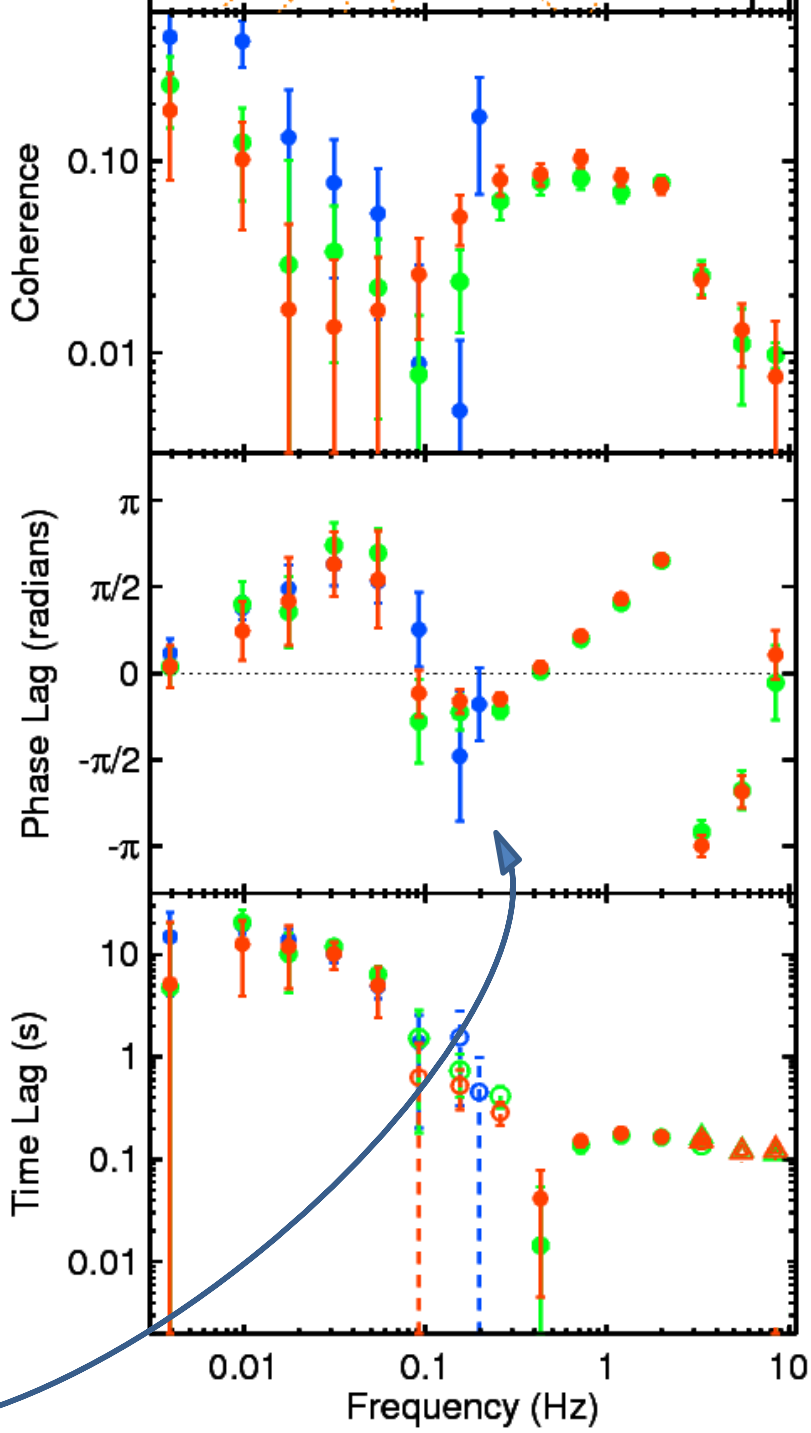


Fast component

Intermediate negative component



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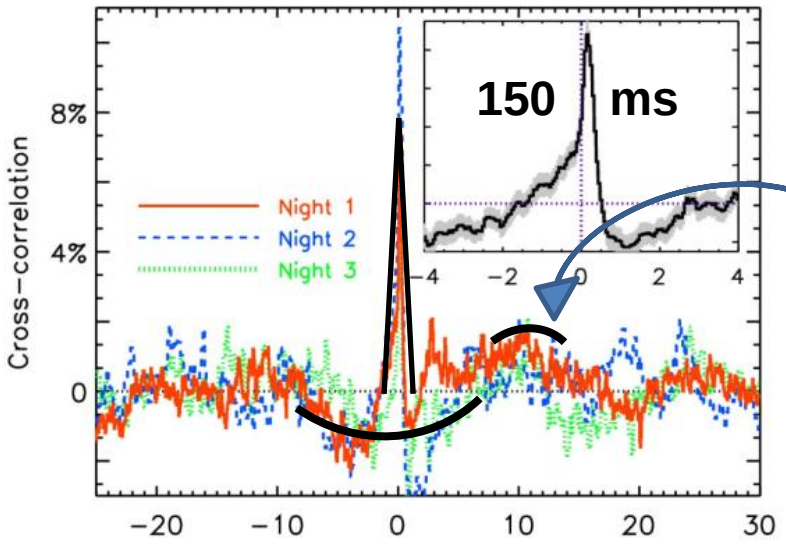
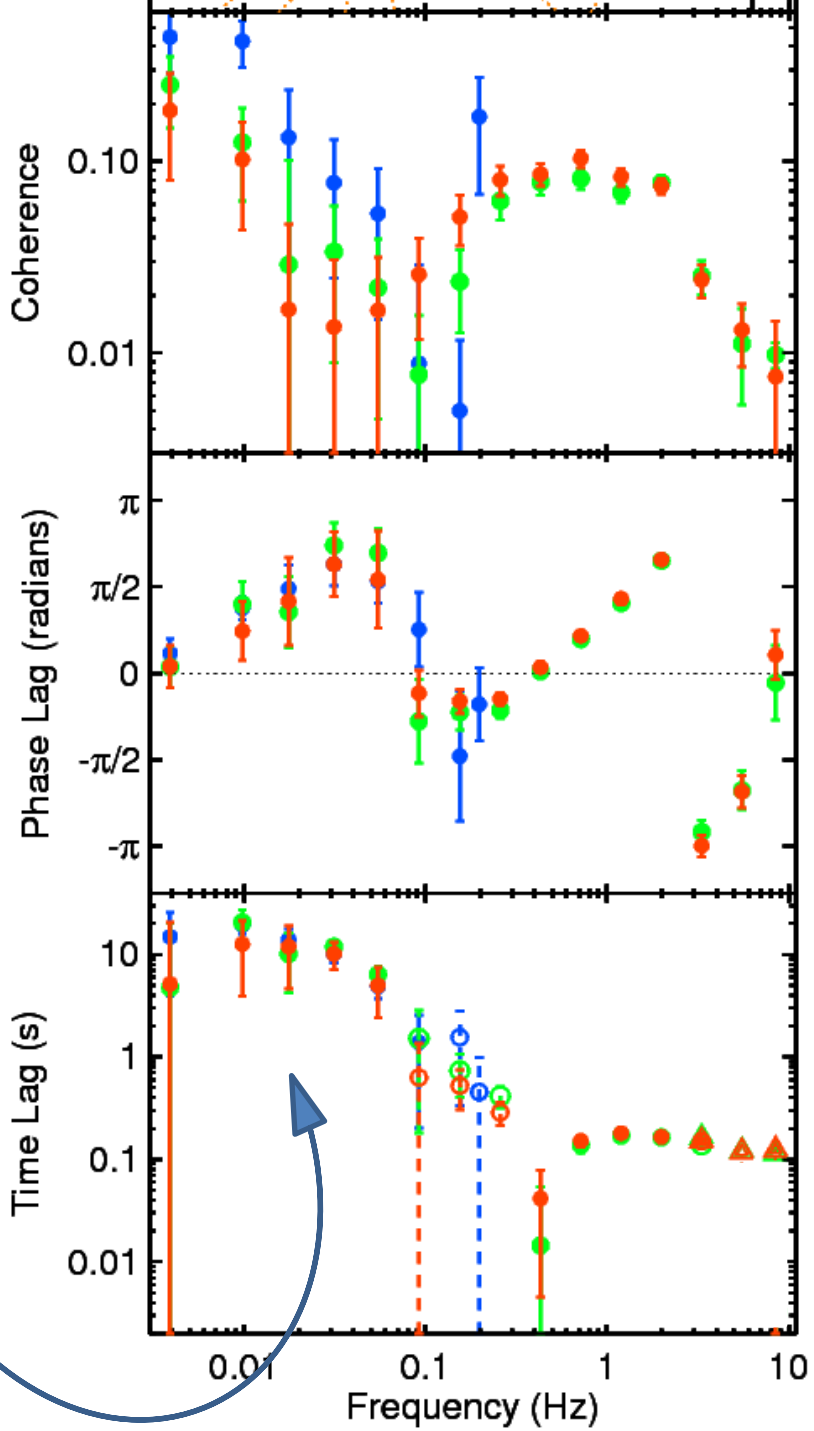


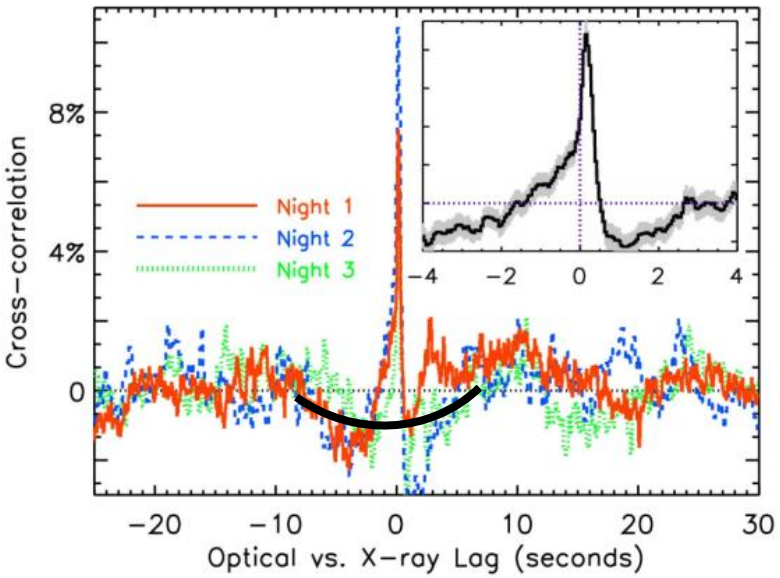
Fast component

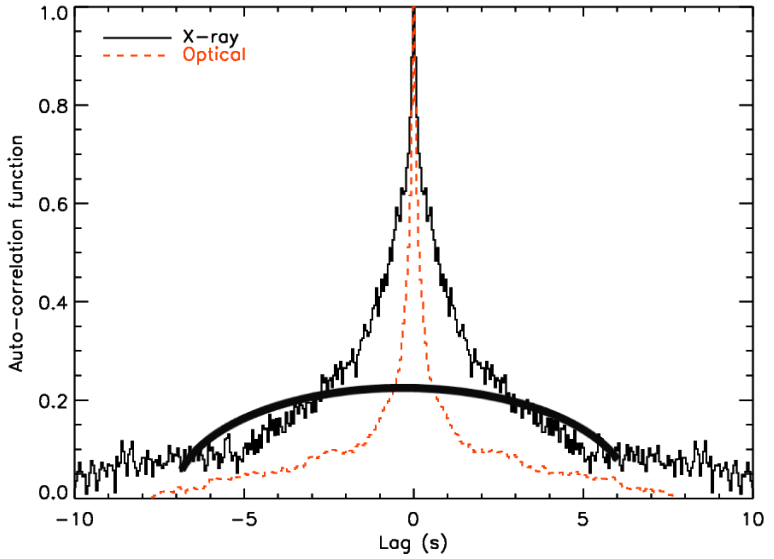
Intermediate negative component

Slow reprocessing

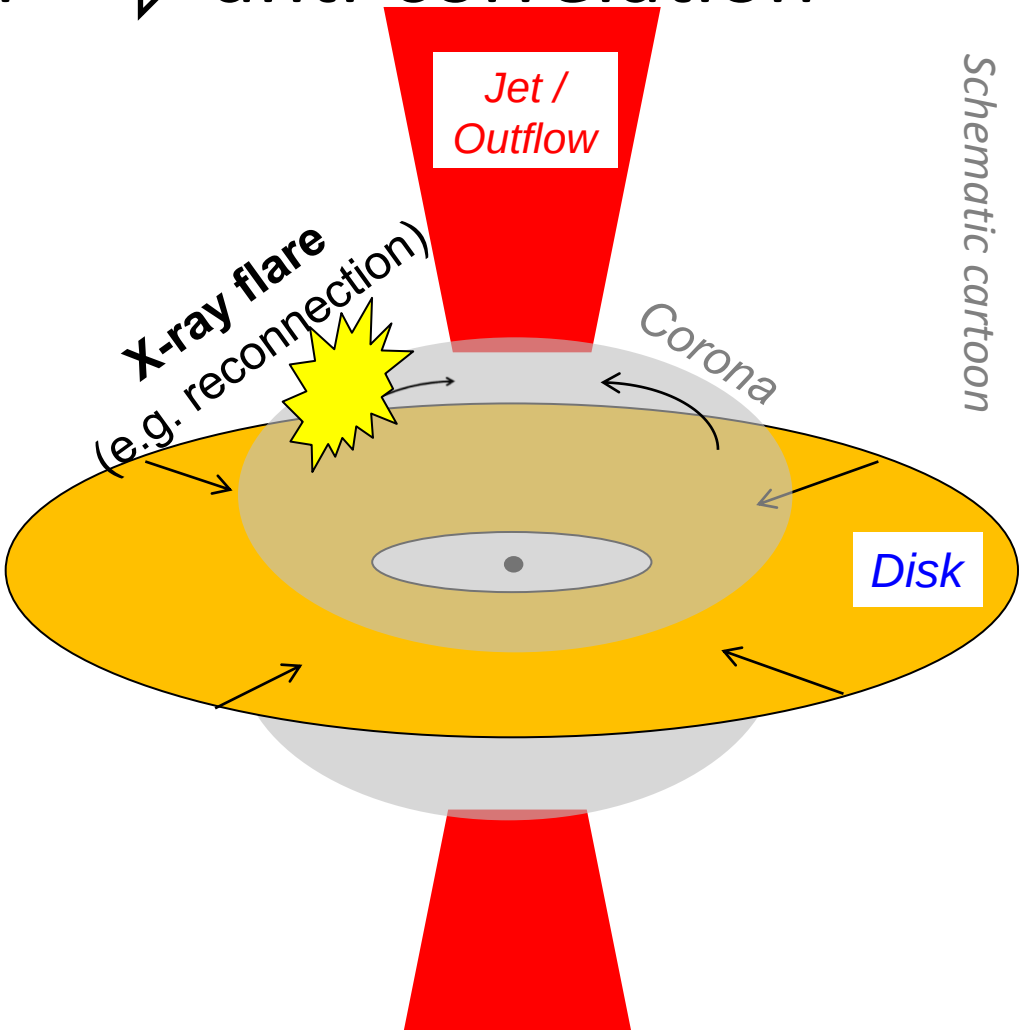


B field dissipation ⇨ anti-correlation





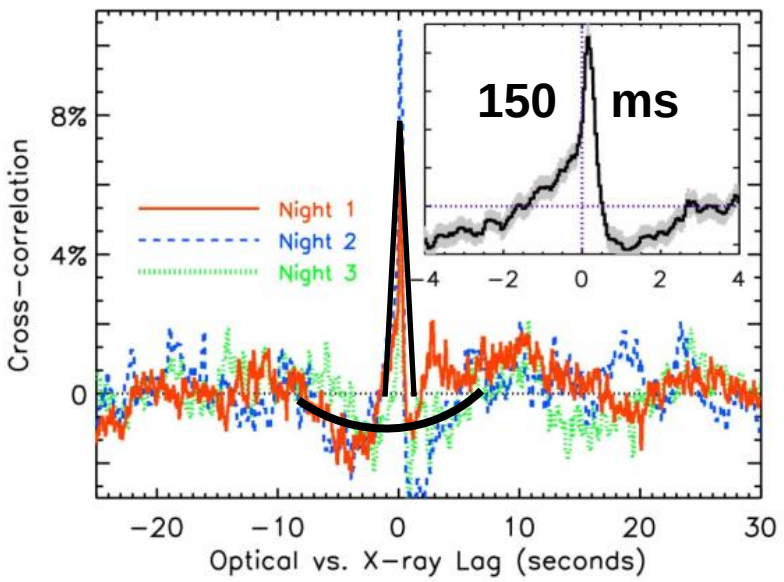
(Gandhi+10)



Release of <u>coronal</u> *B* energy density

⇒ ↓ optical cyclosynchrotron

Jet ⇨ positive correlation



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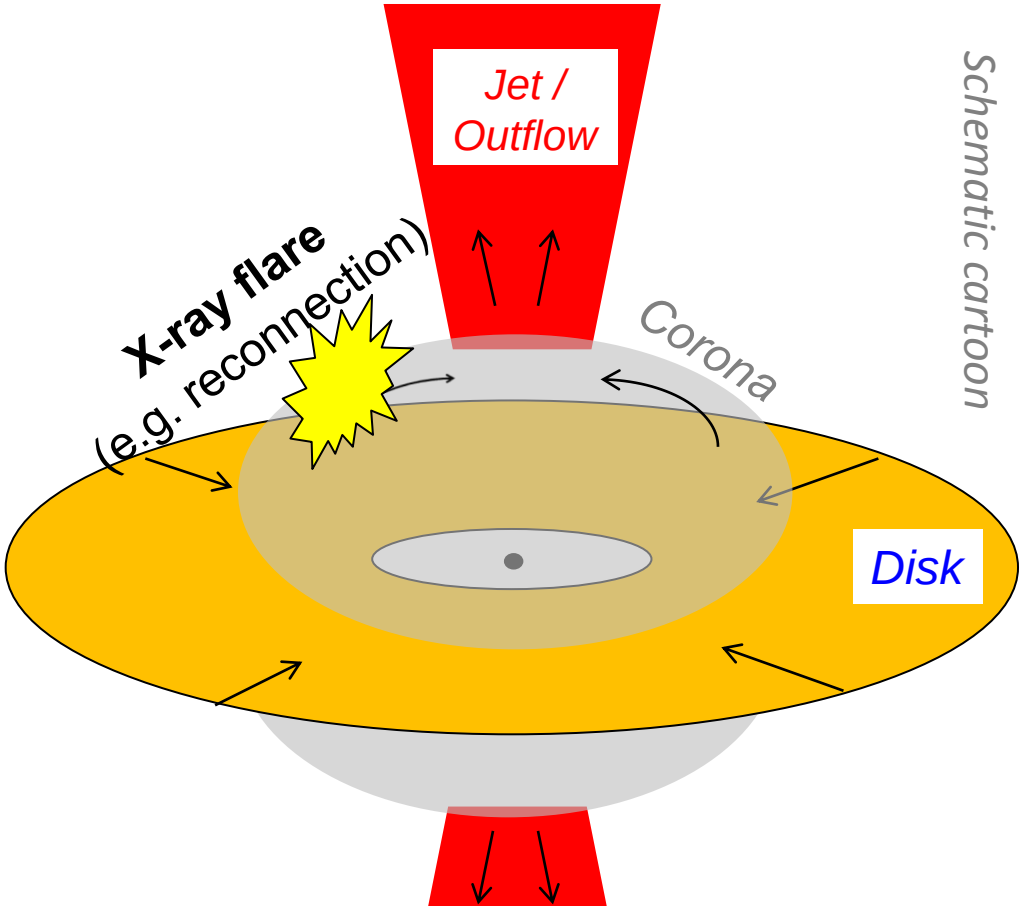


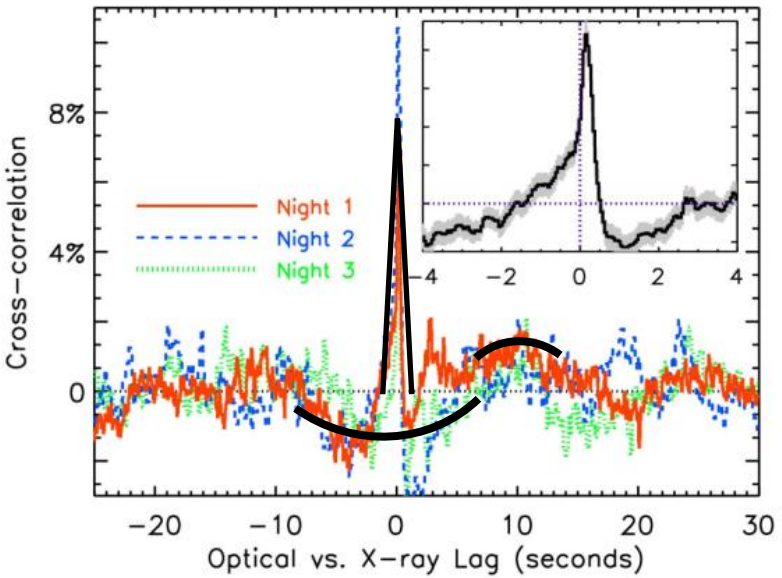
Time delay of 150 ms => ↑ jet optical (cyc)syn, at

1. 5000 R_G @ lightspeed, or
2. 50 R_G @ $v_{Alvenic}$, for jet poloidal field perturbations on times ~ tens x $t_{dynamical}$ ~ 100 ms; (Livio+03; Malzac+04)

Inferences from CCF characteristic times

Positive correlation delay => perturbation delay from <u>disc/corona</u> to <u>jet</u>

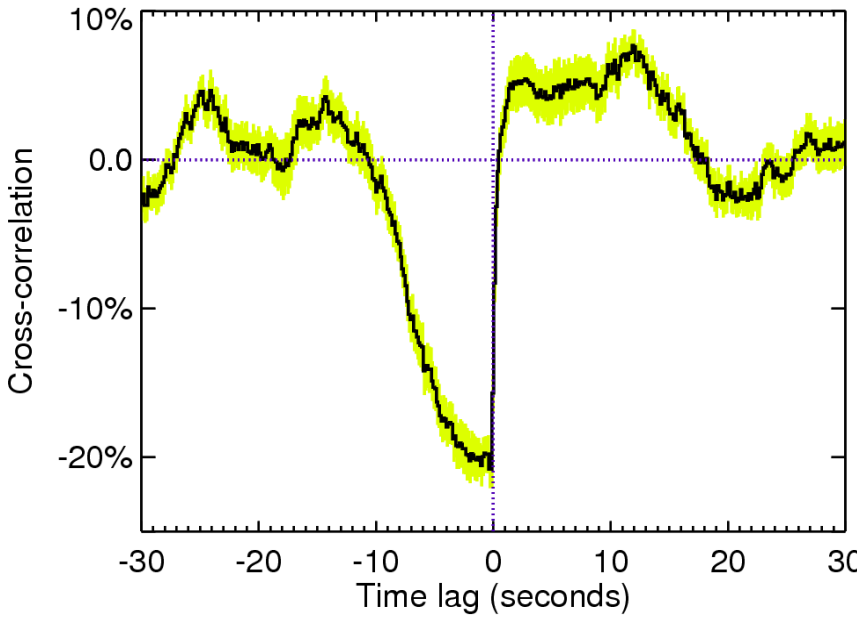
Slow positive correlation delay => constrain reprocessing in outer <u>disc</u>

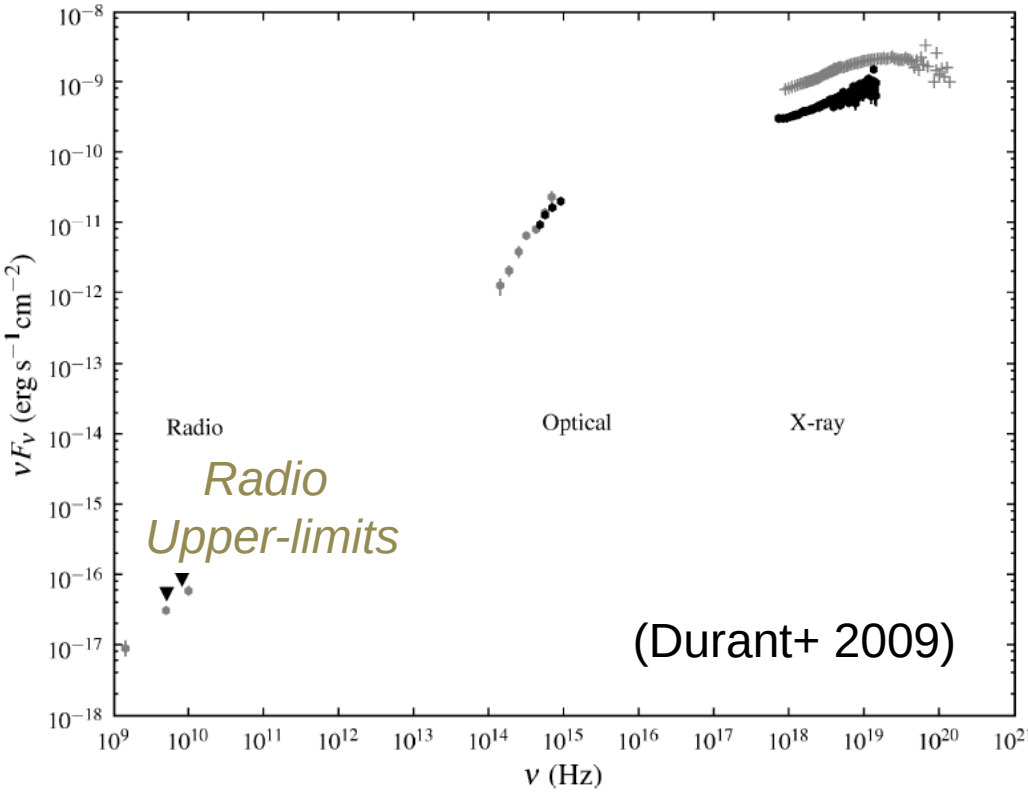


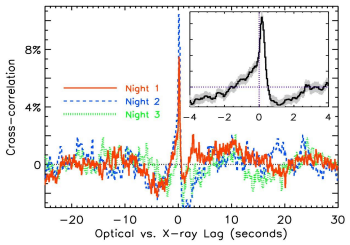
Anti-correlation time => size of <u>corona/hot flow</u> and/or strength of X-ray flaring episodes.

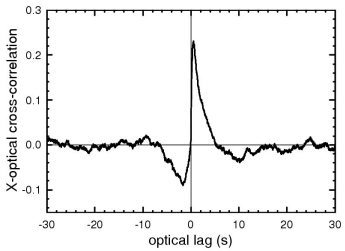
(Gandhi+10)

Swift J1753.5-0127: Weak positive CCF and faint jet



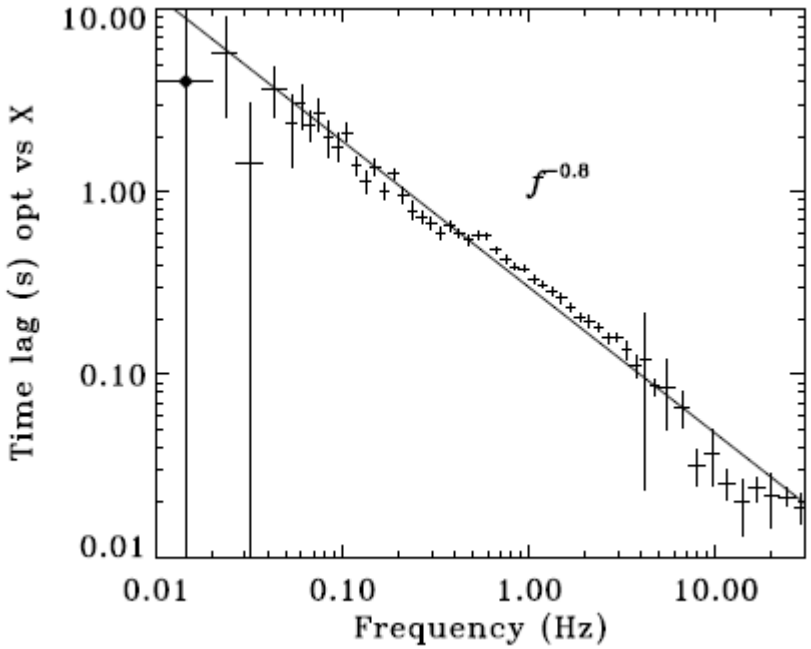




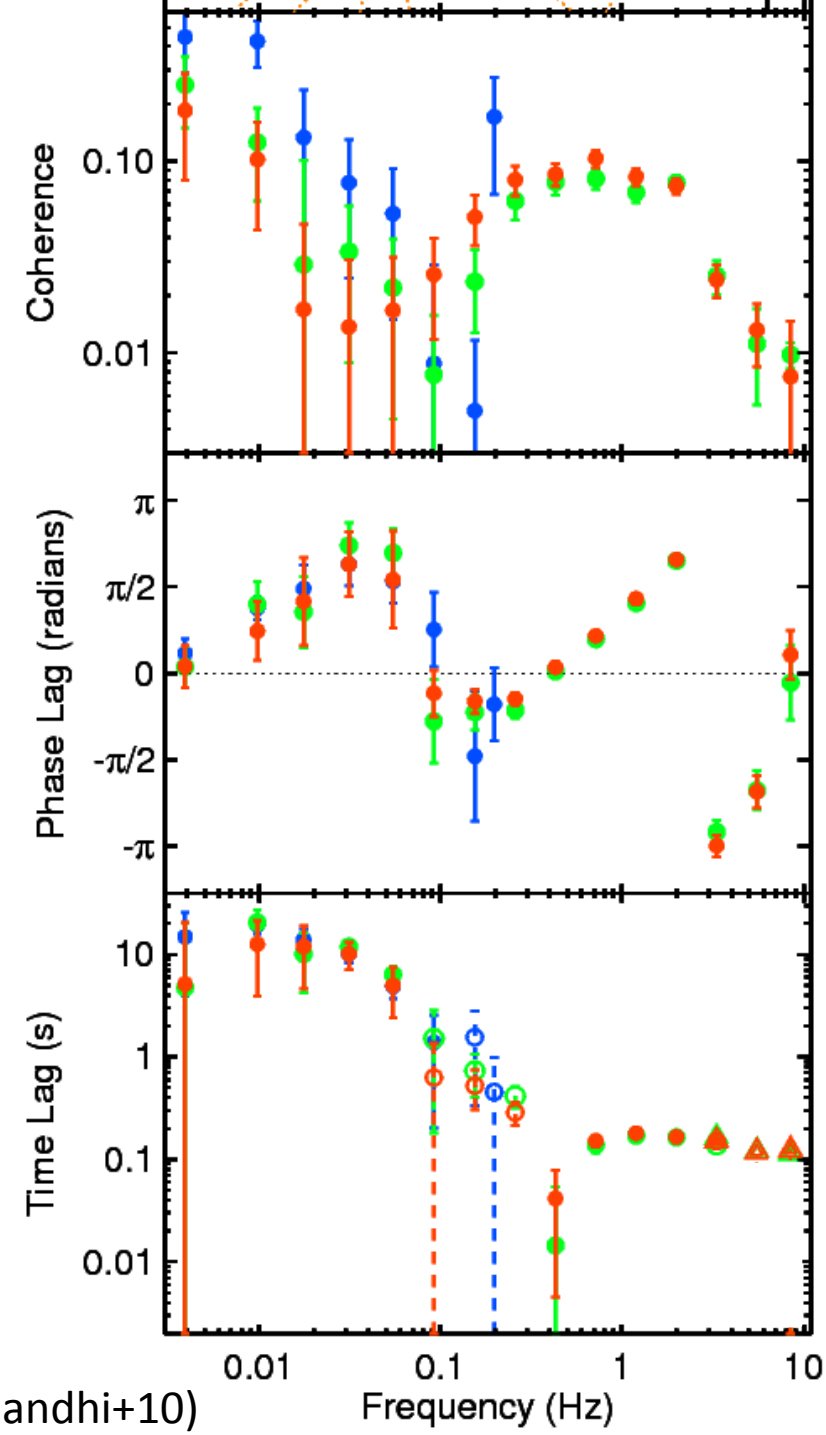


← Strong jetted sources have sharp positive correlation (Gandhi+10)

XTE J1118+480: different time lags behaviour

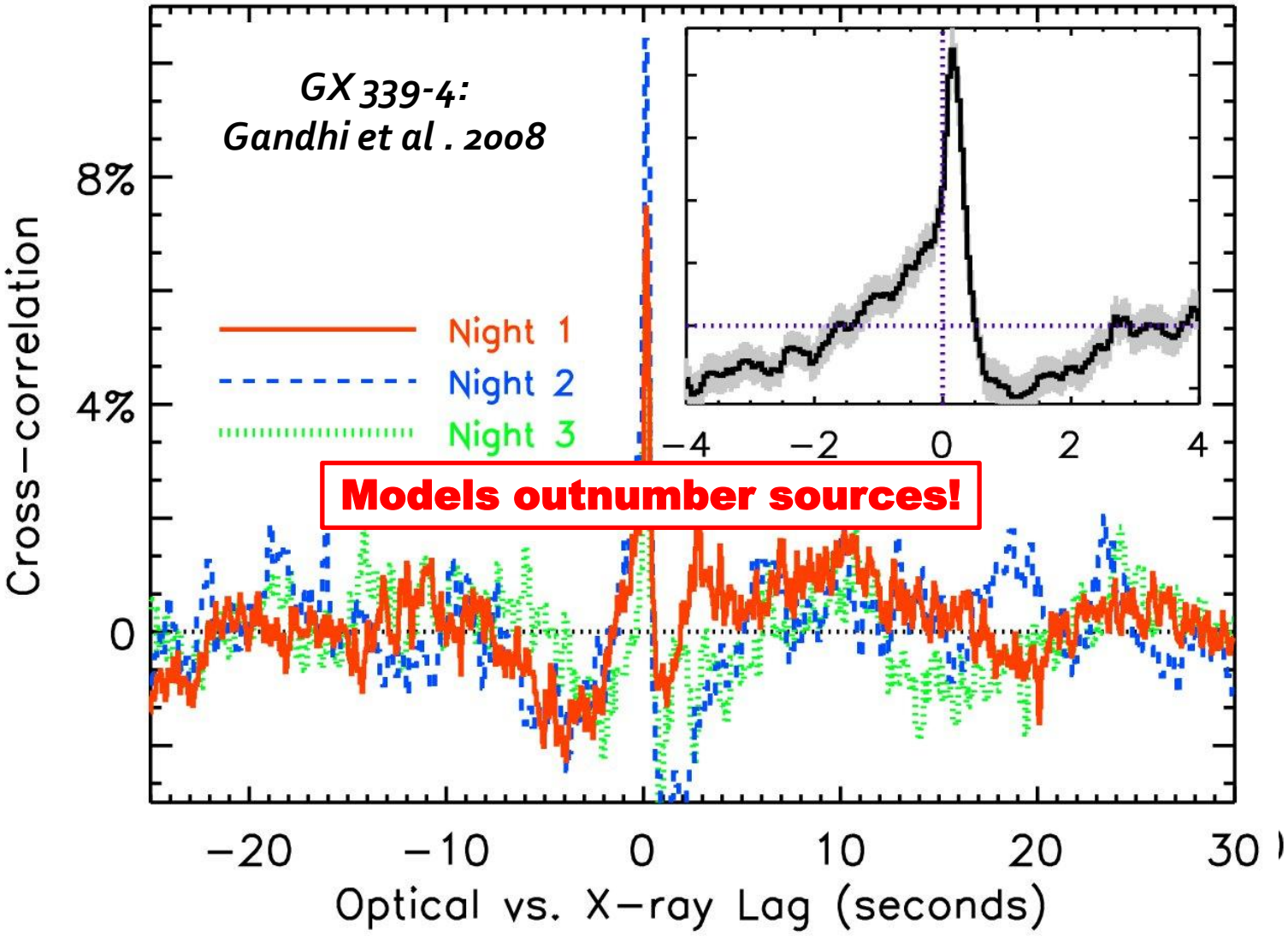


(Malzac+03)

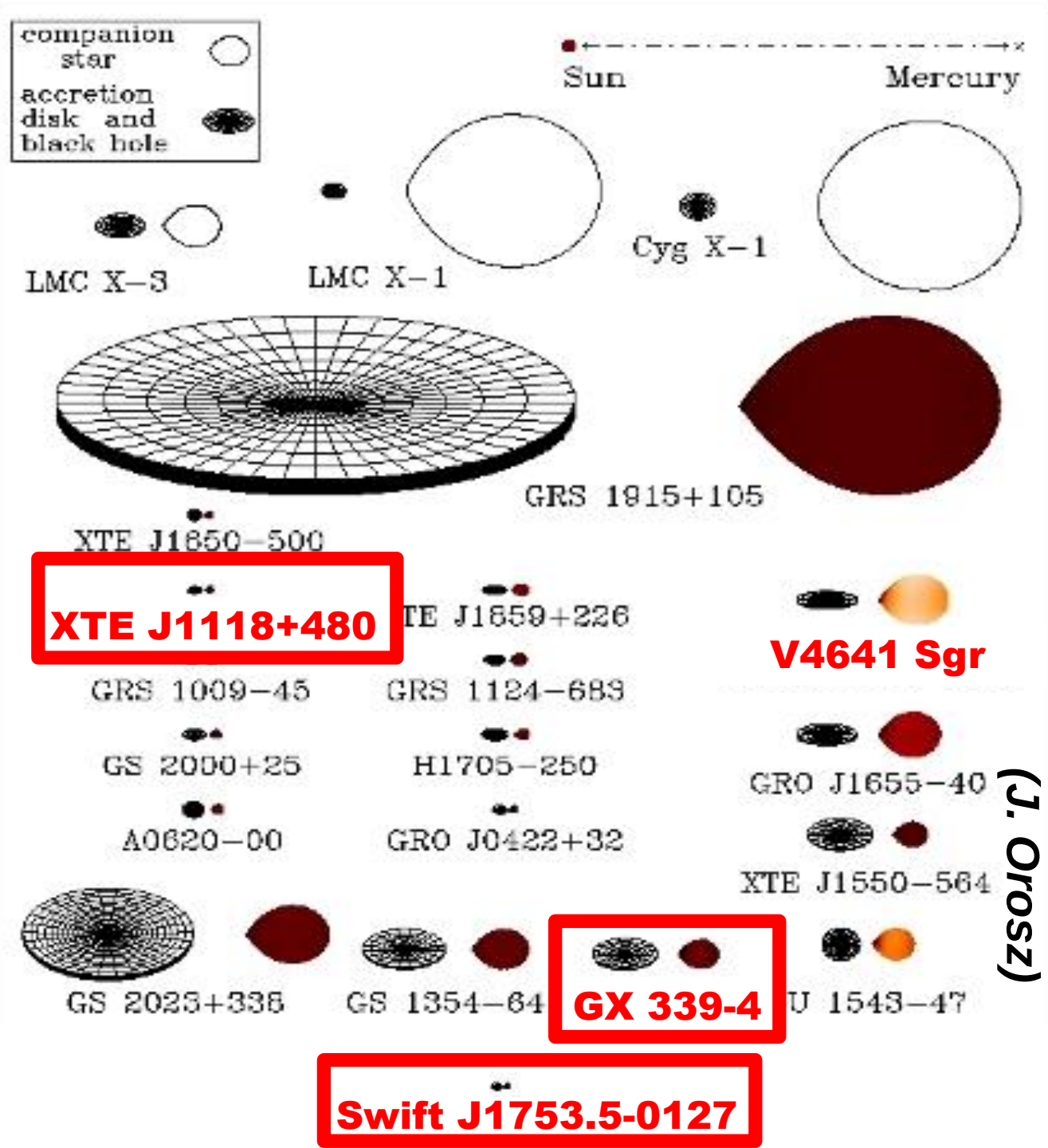


(Gandhi+10)

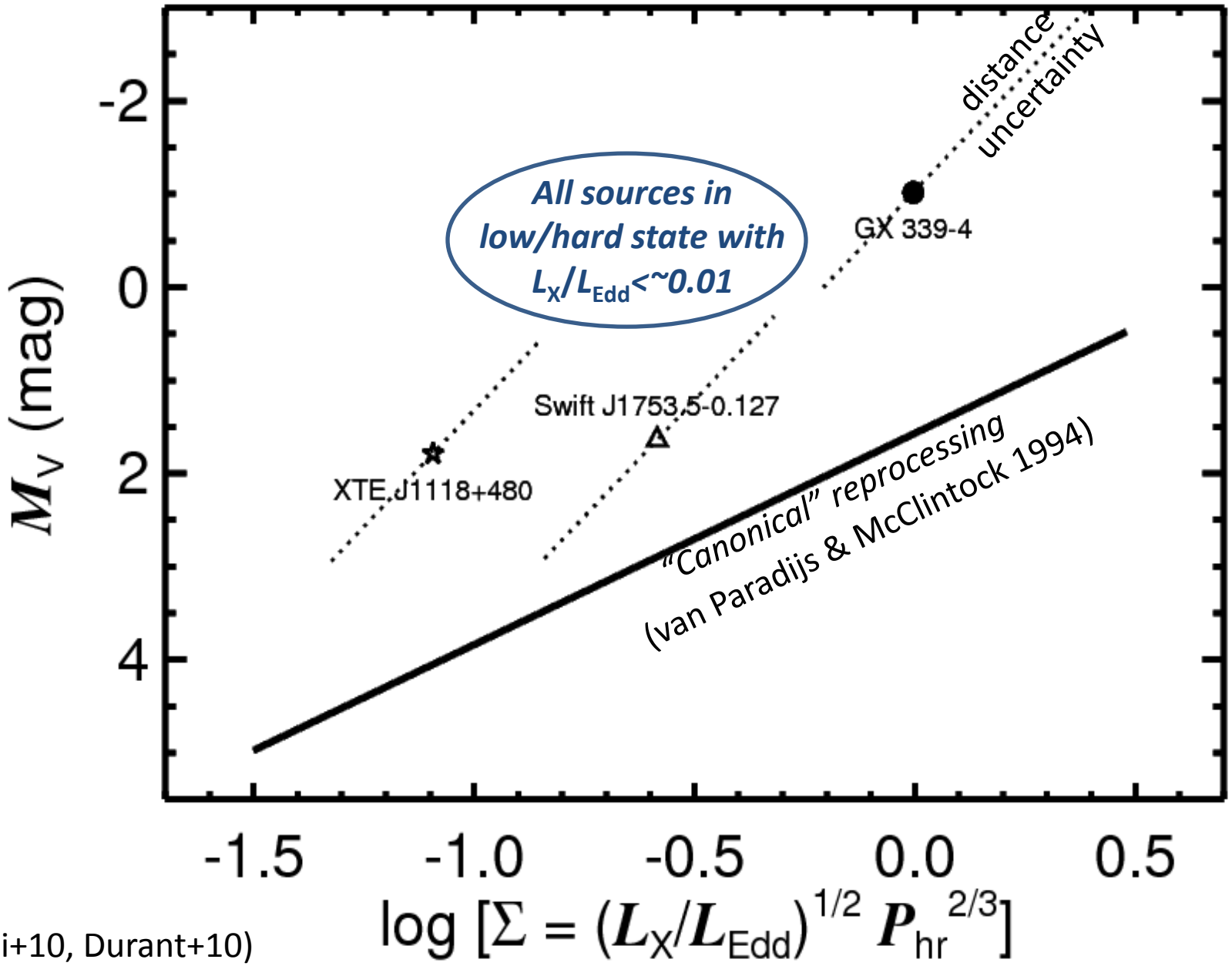
Complex optical/X-ray correlations



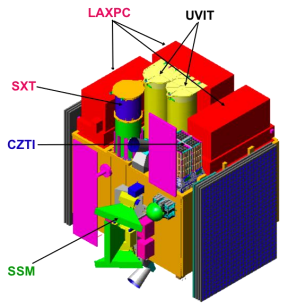
Anything special about these sources?



High optical:X-ray flux ratios

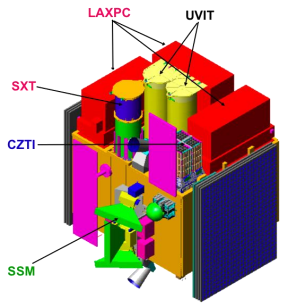


(Gandhi+10, Durant+10)



Astrosat studies

1. “Systematic” search of all known (bright) XRBs for aperiodic variations with a single mission.



1. "Syst riations

	UVIT/OPT	SXT	LAXPC	CZTI	SSM
Detector	UV: photon counting CCD Opt: CCD photometer	X-ray CCD (at the focal plane)	Proportional Counter	CdZnTe detector array	Position-sensitive proportional counter
Imaging property	imaging	imaging	non-imaging	imaging (< 100 keV)	imaging
Optics	Twin Ritchey-Chretien 2 mirror system	Conical foil (~Wolter-I) mirrors	Collimator	2-D coded mask	1-D coded mask
Bandwidth	130-320 nm	0.3-8 keV	3-100 keV	10-150 keV	2-10 keV
Geometric Area (cm^2)	1250	250	10800	1000	180
Effective Area (cm^2)	60 (depends on filter)	125@0.5 keV 200@1-2 keV 25@6 keV	6000@5-30 keV	500 (<100 keV) 1000 (>100 keV)	~40@2 keV 90@5 keV (Xe gas)
Field of View	0.50° dia	0.35° (FWHM)	1° x 1°	6° x 6° (< 100 keV) 17° x 17° (> 100 keV)	
Energy Resolution	<100 nm (depends on filter)	2%@6 keV	9%@22 keV	5%@10 keV	19%@6 keV
Angular Resolution	1.8 arcsec	3-4 arcmin (HPD)	1-5 arcmin in scan mode only	8 arcmin	~10 arcmin
Time resolution	10 ms	2.6s, 0.3s, 1ms	10 microsec	1 ms	1 ms
Typical obs. time per target	30 min	0.5 - 1 day	1 - 2 days	2 days	5 min
Sensitivity (Obs. Time)	21st magnitude (5σ) (1800s)	10 microCrab (5σ) (10000s)	0.1 milliCrab (3σ) (1000s)	0.5 milliCrab (3σ) (1000s)	~30 milliCrab (3σ) (300s)

Known low mass X-ray binaries

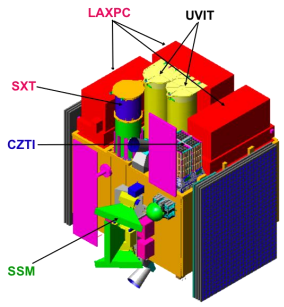
(Liu+07)

			V mag		*X-ray flux*		
1	IGR J00291+5934	T, P, R			52.00	2.460000	
49	4U 1700+24		7.80	<	0.50	404.000000	2A 1704+241
177	3A 1954+319	T	10.70	<	1.50		4U 1954+31
9	1A 0620-00	T, U, R	11.20		50000.00	7.750000	N Mon 1975
37	H 1617-155	Z, M, R	12.20		14000.00	18.900000	Sco X-1
17	XTE J1118+480	T, M, R	12.25		40.00	4.080000	
181	GS 2023+338	T, U, R	12.70		0.03	155.400000	
25	4U 1456-32	T, B, R	12.80		0.10	15.100000	Cen X-4
46	2A 1655+353	P, D, E	13.00		15.00	40.800000	Her X-1
3	GRO J0422+32	T, R	13.20		2800.00	5.092000	
18	GS 1124-684	T, U, R	13.30		3000.00	10.380000	N Mus 1991
45	GRO J1655-40	T, D, M, R	14.20		1600.00	62.880000	XN Sco 1994
186	4U 2142+38	B, Z, R	14.70		450.00	236.200000	Cyg X-2
16	GRS 1009-45	T, U	14.71		800.00	6.840000	N Vel 1993
171	4U 1908+005	T, B, A, R	14.80	<	0.10	18.950000	Aql X-1
29	4U 1543-47	T, U, R	14.90	<	1.00	26.800000	
157	2A 1822-371	P, E	15.10		10.00	5.570000	
14	2S 0921-630	D, E	15.30		3.00	216.200000	
168	XTE J1859+226	T, M, R	15.31		1300.00	9.160000	
48	4U 1659-487	T, U, M, R	15.50		1.50	42.140000	GX 339-4
183	4U 2129+12	G, B?, D, E, R?	15.80		6.00	17.100000	
134	Swift J1753.5-0127	T, M?, R	15.90		140.00		
53	4U 1705-250	T	15.90	<	2.00	12.540000	N Oph 1977
185	4U 2129+47	B, E	16.40		9.00	5.240000	

High mass X-ray binaries

(Liu+06)

25	4U 0900-40	P, E, C	8.90		8.900	B0.5 Ib	Vela X-1	GP Vel
13	EXO 051910+3737.7		7.51			B0 IVpe	1H 0521+373	HD 34921
21	1H 0739-529		7.62			B7 IV-Ve		SAO 235515
18	1WGA J0648.0-4419	P	8.27		1.550	sdO6	RX J0648.1-4419	
69	RX J1744.7-2713		8.40			B0.5V-IIIe		HD 161103
50	1H 1555-552		8.60			B2IIIn		SAO 243086
112	1H 2202+501		8.80			Be		V2175 Cyg
77	SAX J1819.3-2525	T, R	8.80	13.50	2.800	B9III	XTE J1819-254	
104	4U 1956+35	U, R	8.90		5.000	O9.7 Iab	Cyg X-1	V1357 Cyg
14	1A 0535+262	T, P, C	8.90	9.60	111.000	O9.7IIIe	H 0535+262	HD 245770
15	1H 0556+286		9.20			B5ne		
11	XTE J0421+560	T, R	9.25	11.83	19.410	sgB[e]		
108	RX J2030.5+4751		9.27			B0.5V-IIIe		BD +47 3129
32	2S 1145-619	P, T	9.30		187.500	B0.2IIIe	2E 1145.5-6155	HD 102567
1	IGR J00370+6122		9.65		15.665	B0.5II-III	1RXS J003709.6+612131	LS I +61 161
101	1H 1936+541		9.80			Be		
113	4U 2206+543	C	9.85		9.570	O9.5Ve	3A 2206+543	
30	IGR J11215-5952	T	9.96			B1Ia		
51	IGR J16195-4945		10.08			B1-2Ia	AX J1619.4-4945	
8	1E 0236.6+6100	R	10.70		26.496	B0Ve		V615 Cas
76	SAX J1818.6-1703	T	10.70			B3III		
12	RX J0440.9+4431	P	10.78			B0.2Ve		BSD 24-491
34	4U 1223-624	P, T, C	10.80		41.590	B1-1.5 Ia	GX 301-2	WRA 977
3	2S 0114+650	P, C?	11.00		11.600	B0.5 Ib		LS I +65^o^010
79	RX J1826.2-1450	R	11.23		3.900	ON6.5V((f))		
27	RX J1037.5-5647	P, T	11.30			B0V-IIIe	4U 1036-56	
6	RX J0146.9+6121		11.45			B1Ve		V831 Cas
20	3A 0726-260	T, P	11.60		34.500	O8-9Ve	4U 0728-25	
19	XTE J0658-073	T, P, C	12.05	12.38		O9.7Ve	MXB 0656-072	
28	1A 1118-615	P, T	12.10			O9.5Ve		WRAY 15-793
35	IGR J12349-6434	T, P	12.46			O-A		
23	RX J0812.4-3114	T, P	12.48		81.300	B0.2IVe		V572 Pup
73	IGR J17544-2619	T	12.65			O9Ib	1RXS J175428.3-262035	
17	SAX J0635.2+0533	P	12.83		11.200	B2V-B1IIIe	SAX J0635+0533	
33	1E 1145.1-6141	P	13.10		14.400	B2Iae		
5	IGR J01363+6610	T	13.29			B1Ve		
29	4U 1119-603	P, E, C	13.30		2.090	O6.5 II-III	Cen X-3	
42	4U 1258-61	P, T?	13.50	14.20	133.000	B0.7Ve	GX 304-1	^*^2 (MMV)
88	AX 1845.0-0433	T	13.96			O9.5I	IGR J18450-0435	
98	3A 1909+048	E, R	14.20		13.100	pec		V1343 Aql
110	SAX J2103.5+4545	P, T	14.20		12.680	B0Ve		
103	KS 1947+300	P, T	14.24		40.400	B0Ve	GRO J1948+32	
111	1H 2138+579	P, T, C	14.29			B1-B2Ve	Cep X-4	
47	4U 1538-52	P, E, C	14.40		3.730	B0 Iab		^*^12
4	4U 0115+634	T, P, C	14.50	16.30	24.300	B0.2Ve	4U 0115+63	
66	XTE J1739-302	T	14.89			O8Iab(f)	IGR J17391-3021	
109	GRO J2058+42	P, T	14.92		55.030	O9.5-B0IV-Ve	CXOU J205847.5+414637	
114	SAX J2239.3+6116	T, P	15.10		262.000	B0V-B2IIIe	1H 2214+589	
9	V 0332+53	T, P, C	15.10	15.40	34.250	O8.5Ve	EXO 0331+530	



UVIT exposure time calculator

http://oryx.ras.ucalgary.ca/UVIT/

1) Point source

flat in λF_λ,

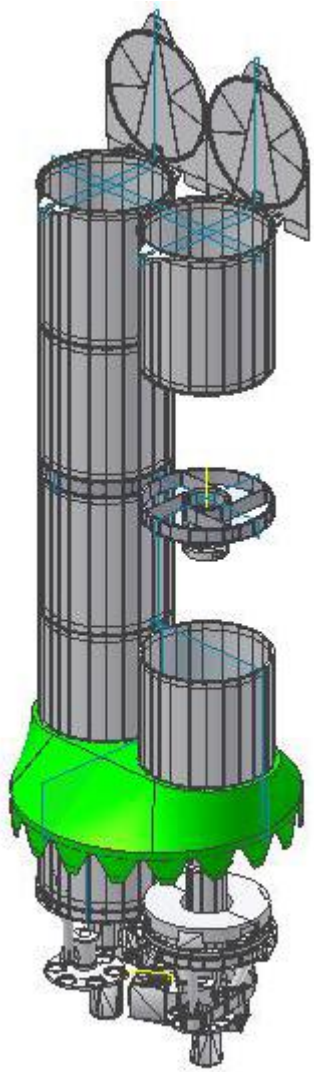
V=14.5,

=> <u>S/N=5 in ~3s.</u>

2) B8V star at 6 kpc

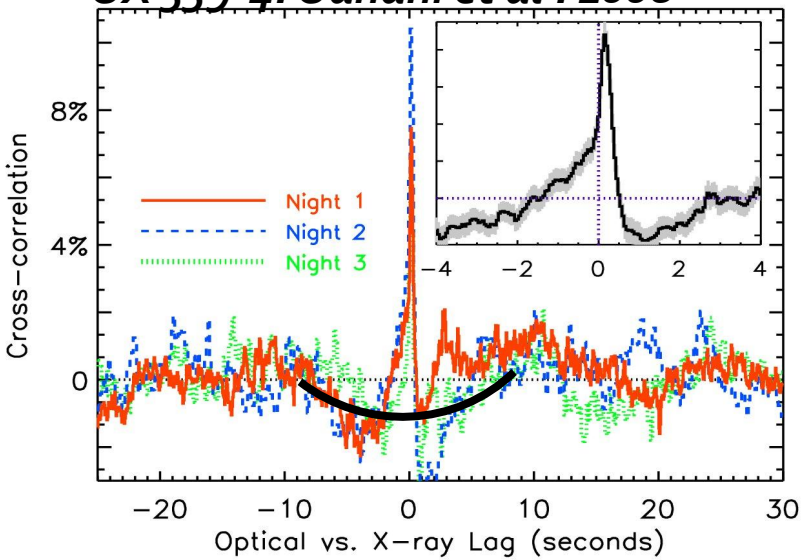
A_V=1,

=> <u>S/N=5 in 2 s.</u>

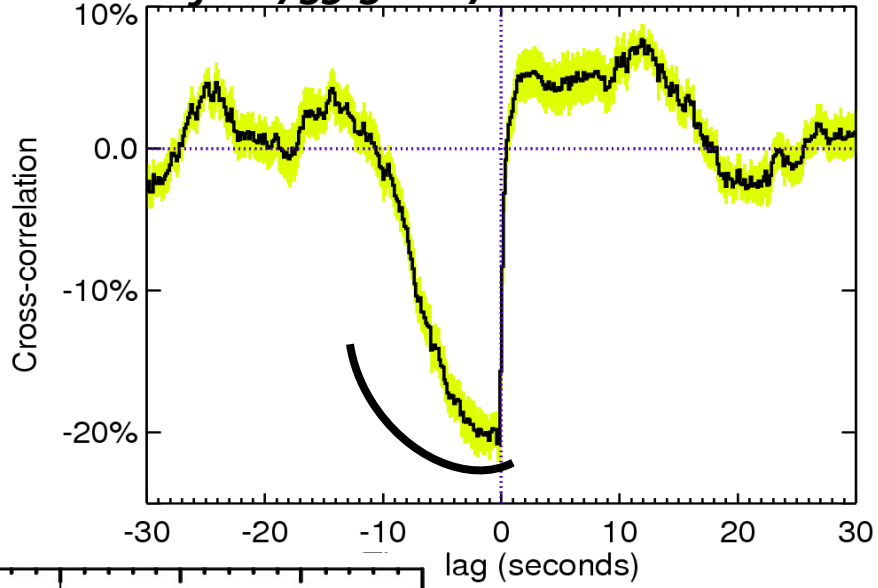


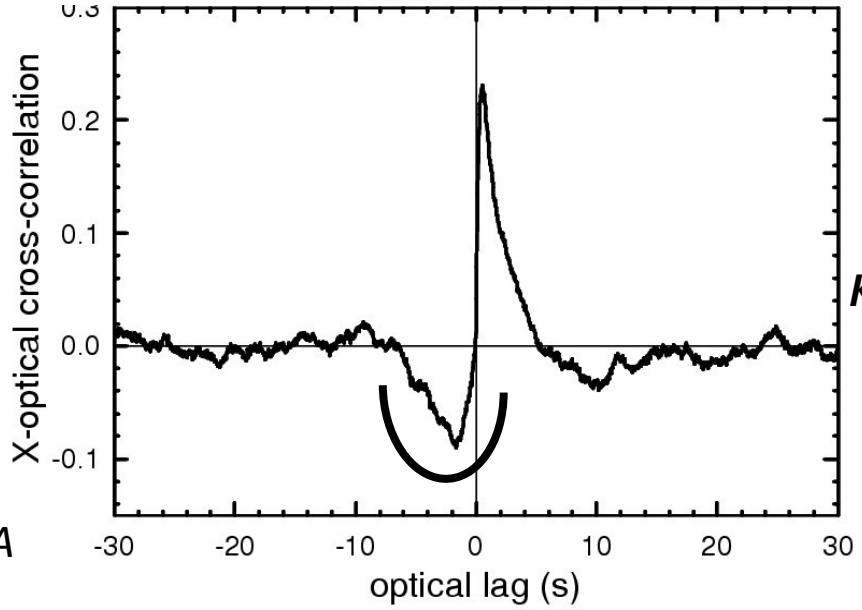
Study the slower anti-correlation

GX 339-4: Gandhi et al . 2008



Swift J1753.5-0127: Durant et al. 2008

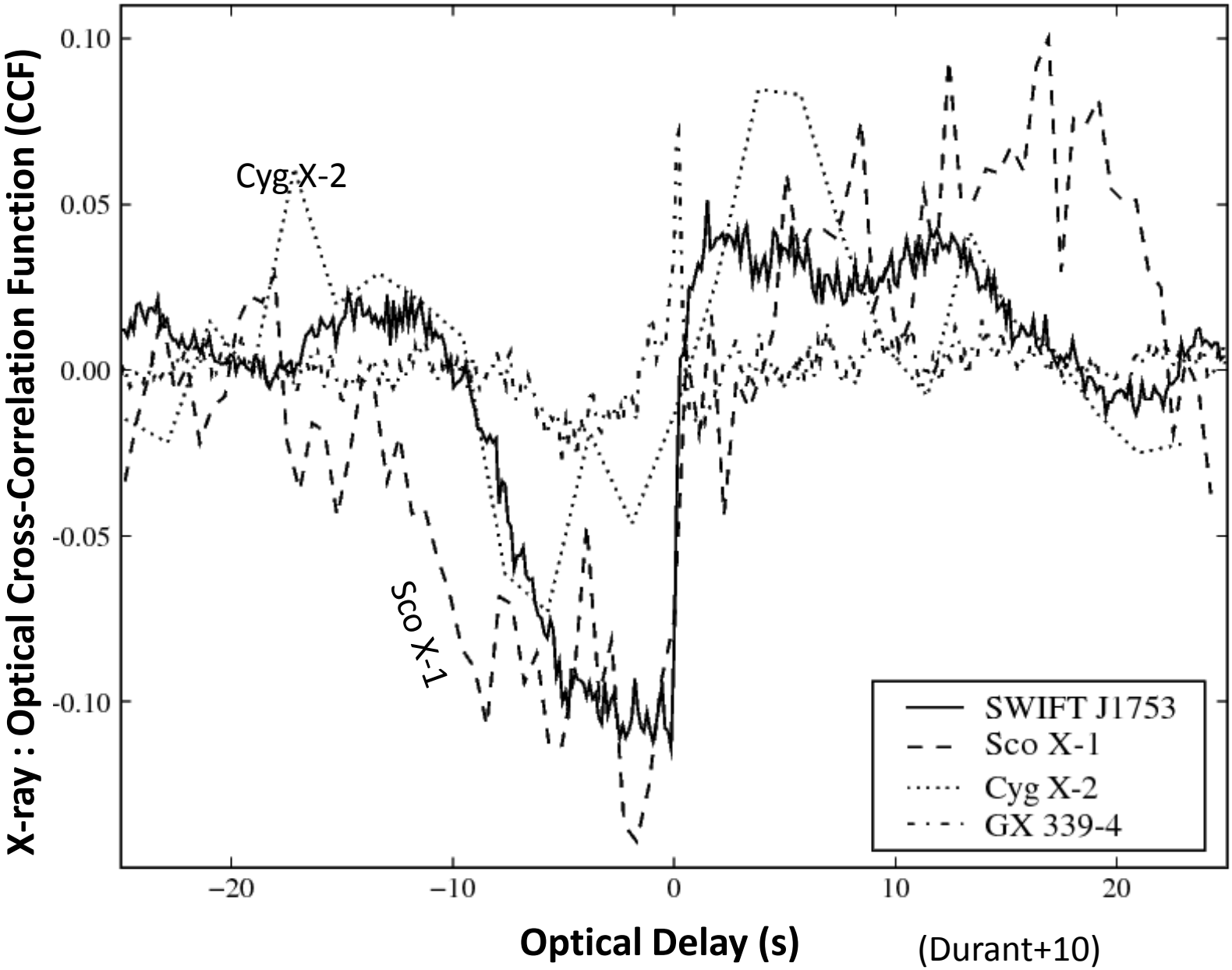




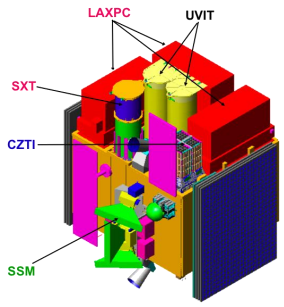
XTE J1118+480: Kanbach et al. 2001

All X-ray data: RXTE PCA

Neutron star binaries



(Durant+10)



Astrosat studies

1. “Systematic” search of all known (bright) XRBs for aperiodic variations
   - study anti-correlation
   - range of timescales

Broad range of stochastic timescales

Disc timescales:

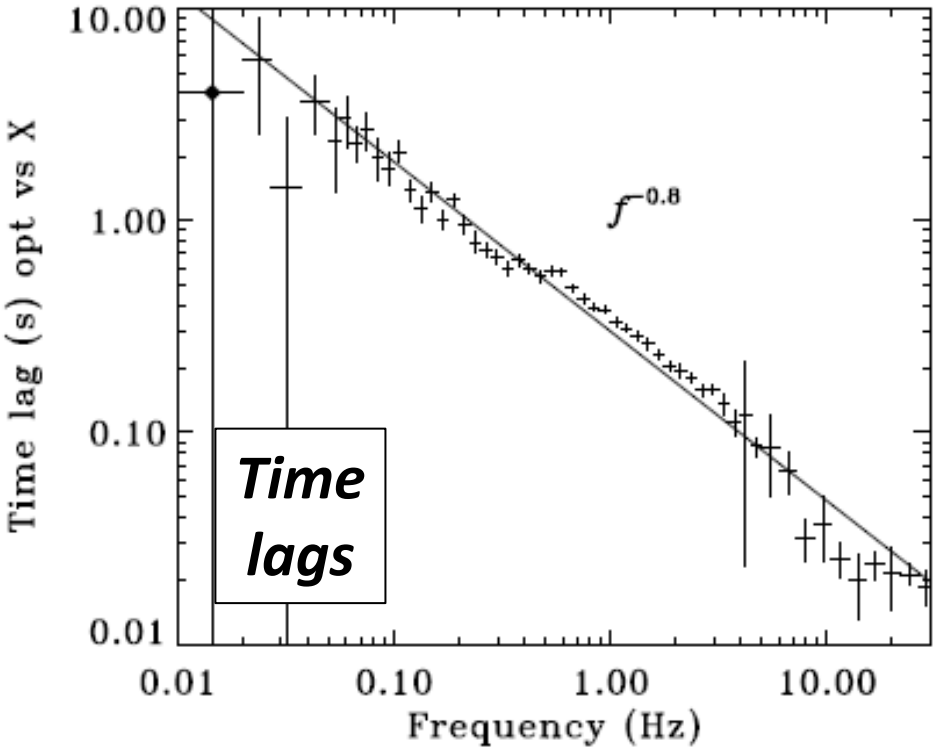
$$t_{\text{light-cross}} < t_{\text{dyn}} \sim t_z \sim \alpha t_{\text{th}} \sim \alpha(H/R)^2 t_{\text{visc}}.$$

(e.g. A. King)

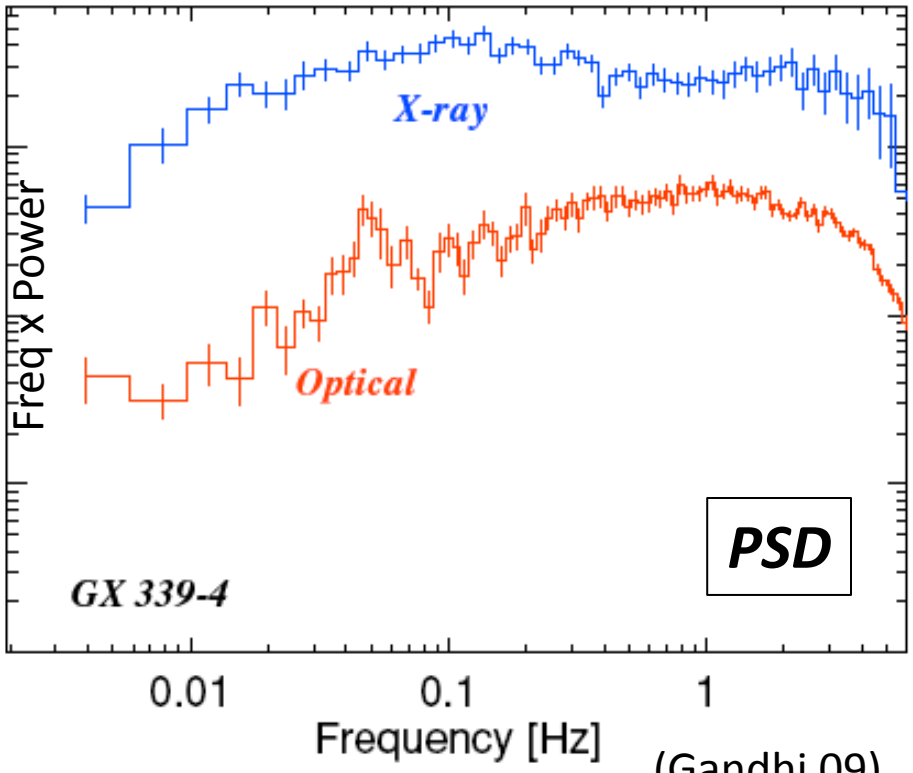
ms ~ few seconds

seconds ~ days

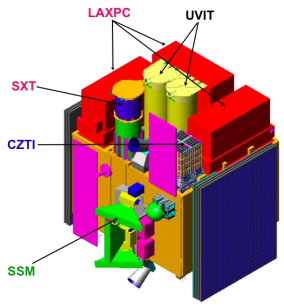
days ~ months



(Malzac+03)



(Gandhi 09)

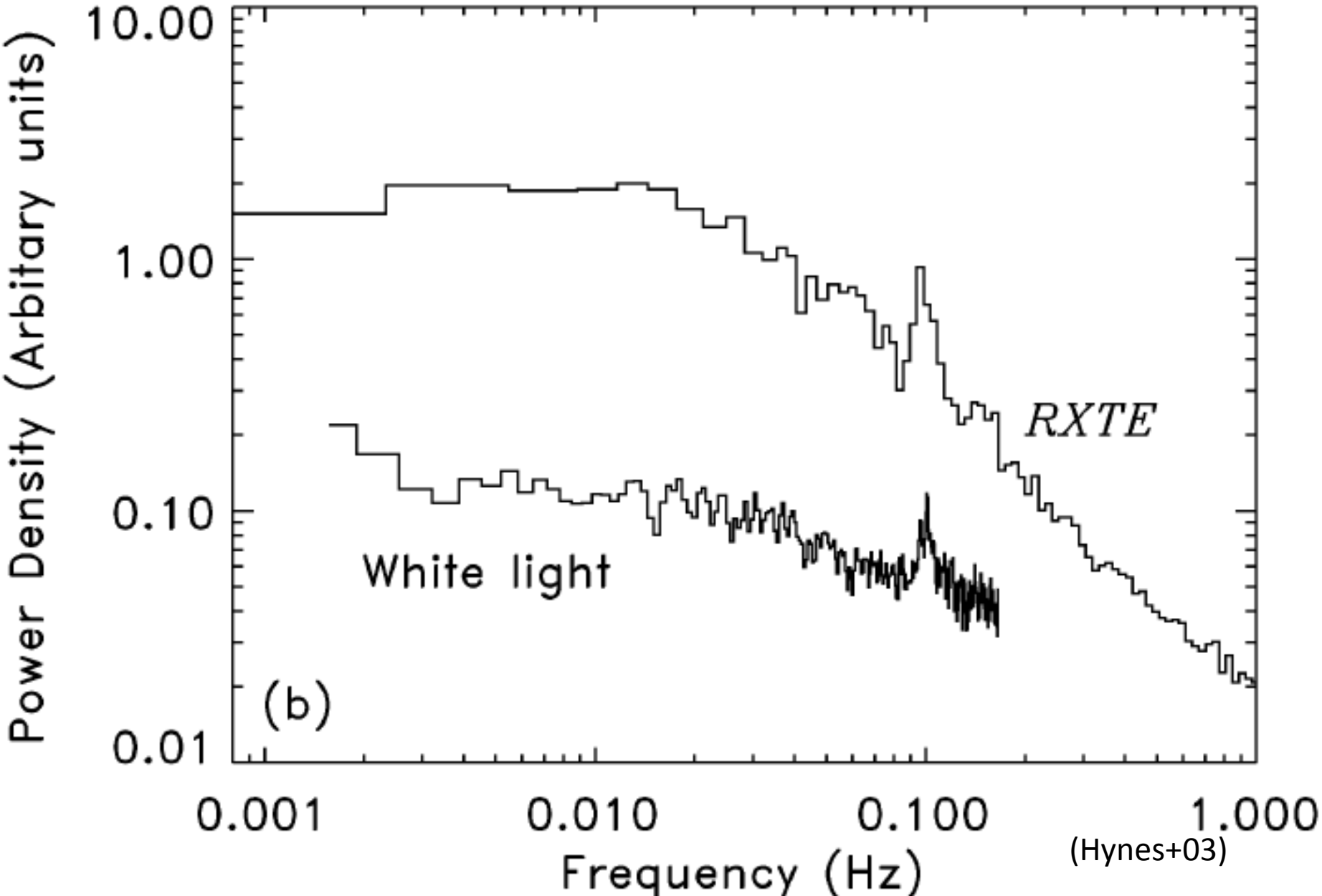


Astrosat studies

1. "Systematic" search of all known (bright) XRBs for aperiodic variations
   - study anti-correlation
   - range of timescales

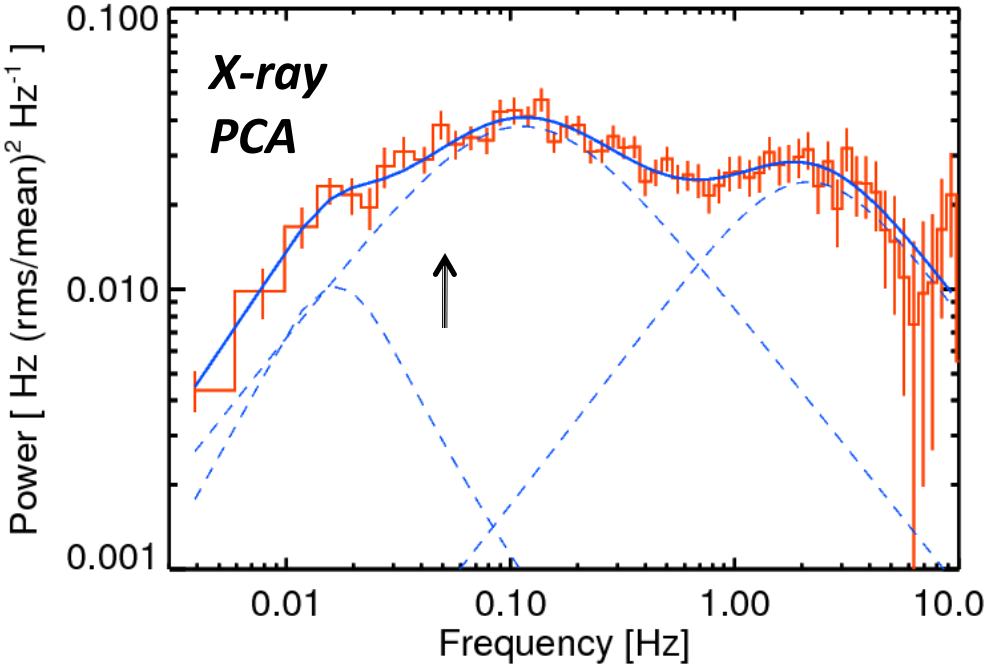
2. Search for optical/UV low frequency QPOs, and understanding them.

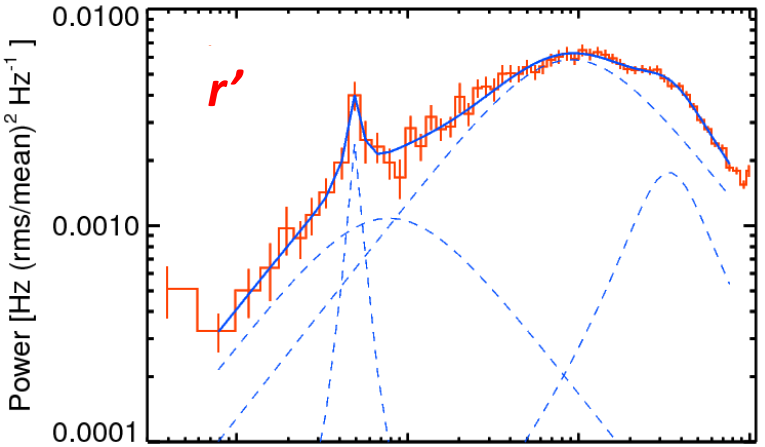
XTE J1118+480: QPO in both optical and X-rays

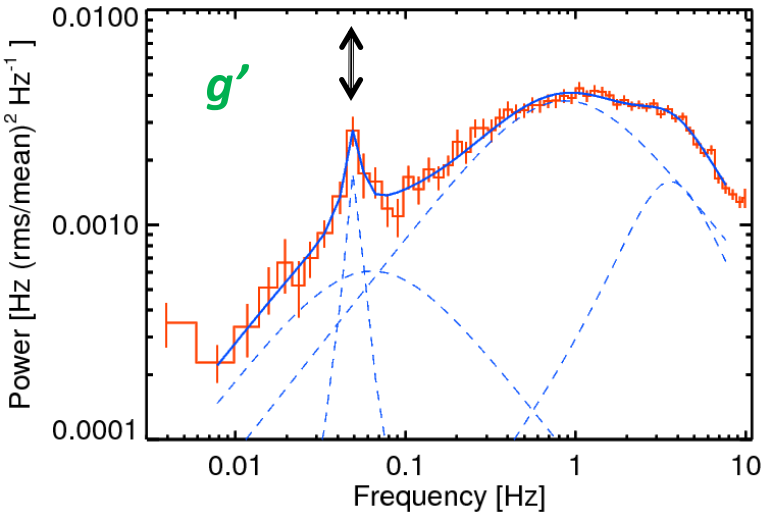


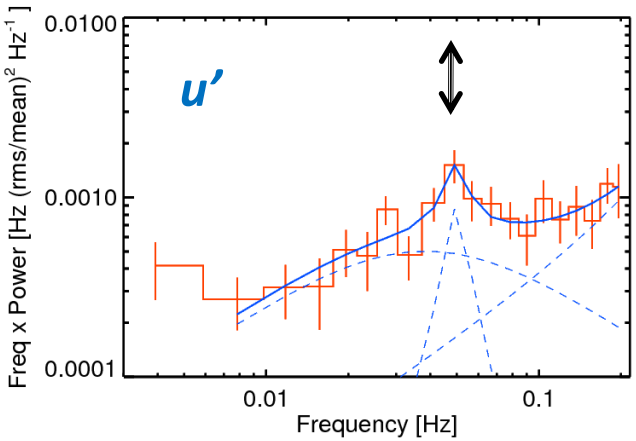
(Hynes+03)

GX 339-4: Broad band optical noise and QPO



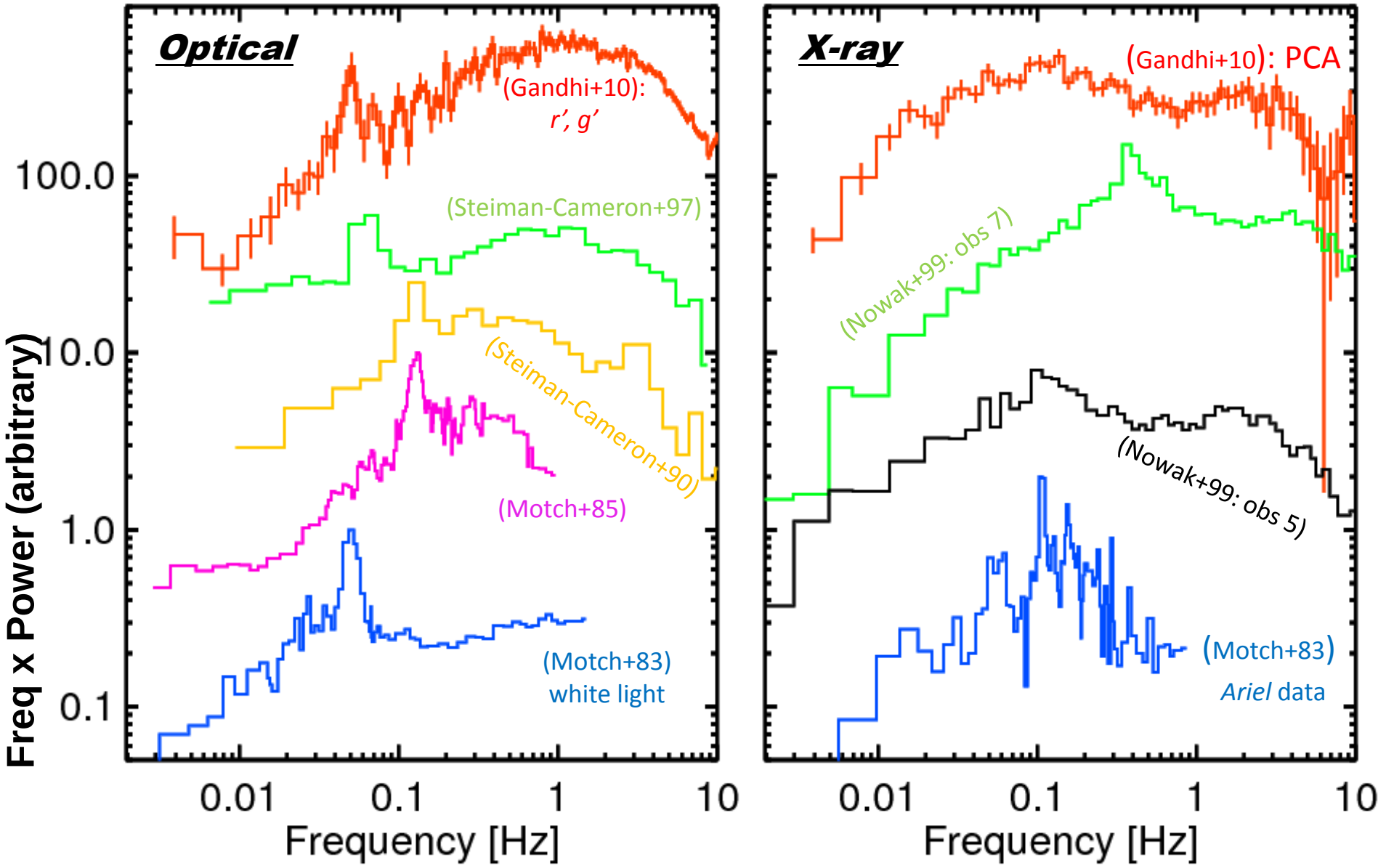


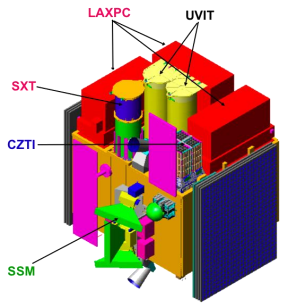




(Gandhi+10)

Optical QPO quite “stable” in GX 339-4





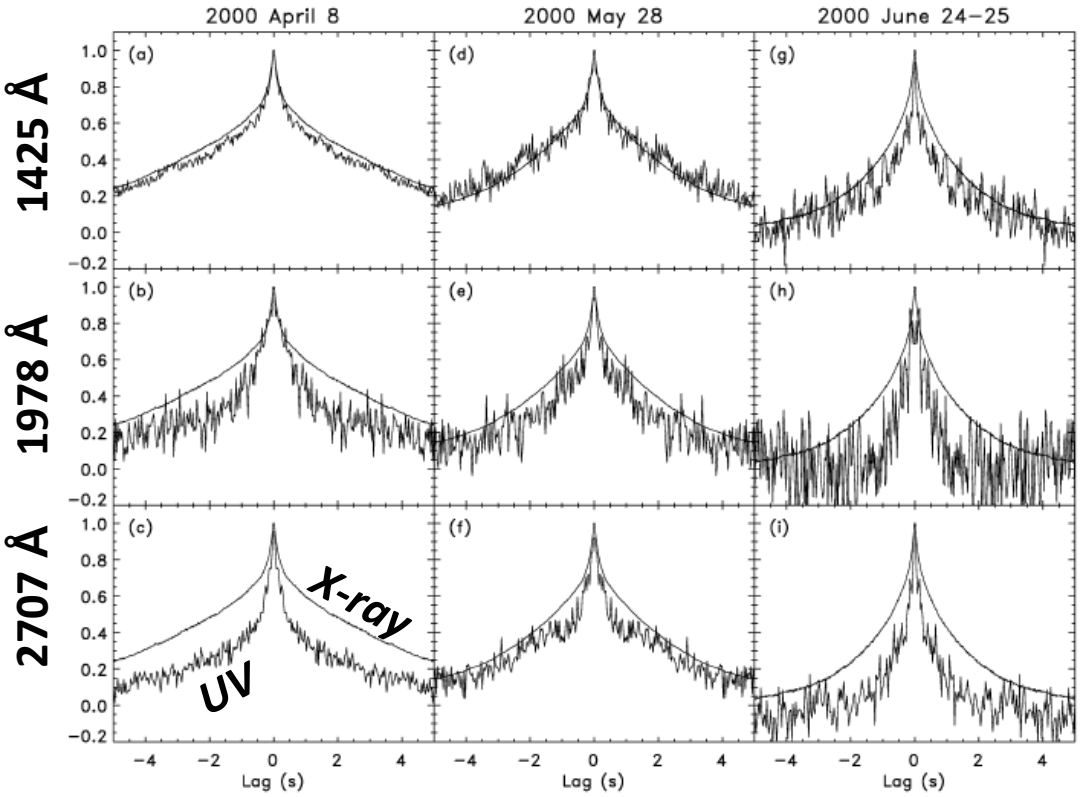
Astrosat studies

1. "Systematic" search of all known (bright) XRBs for aperiodic variations
   - study anti-correlation
   - range of timescales

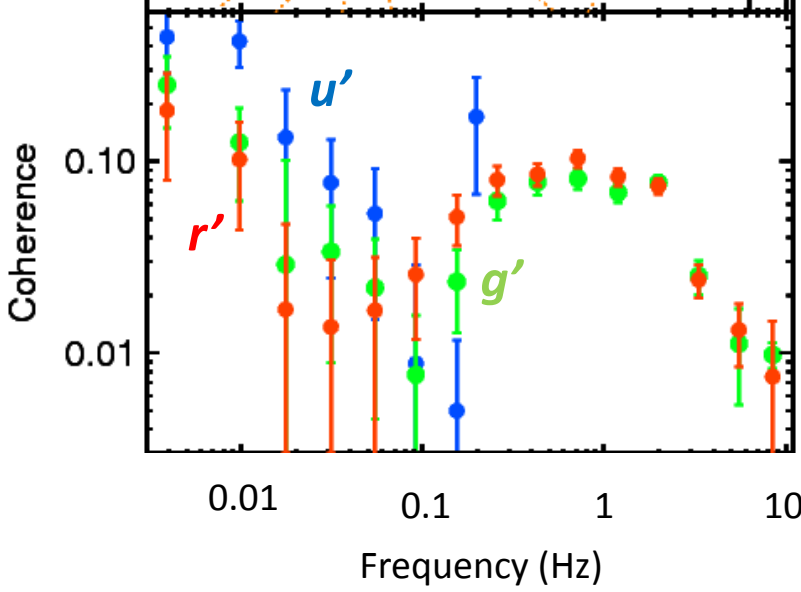
2. Search for optical/UV low frequency QPOs, and understanding them.

3. FUV/NUV and hard X-ray sensitivity: unique to Astrosat

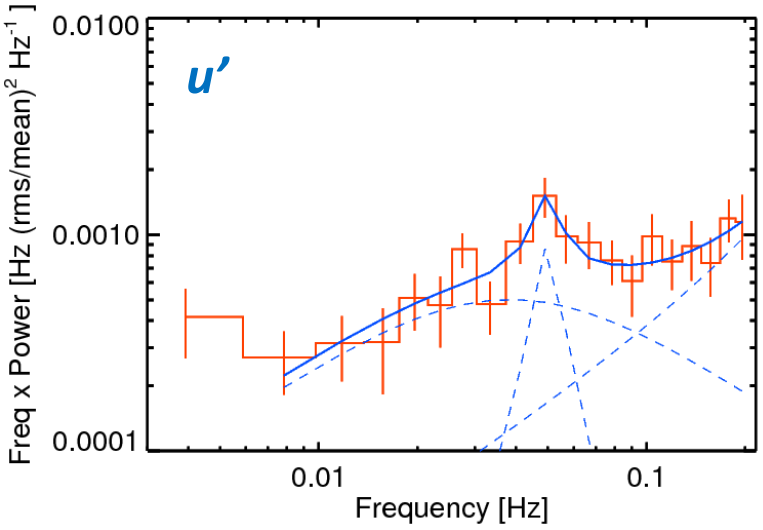
Stochastic variations are present in UV



XTE J1118+480: NUV ACF narrow than X-rays (Hynes+03)



GX 339-4
(Gandhi+10)

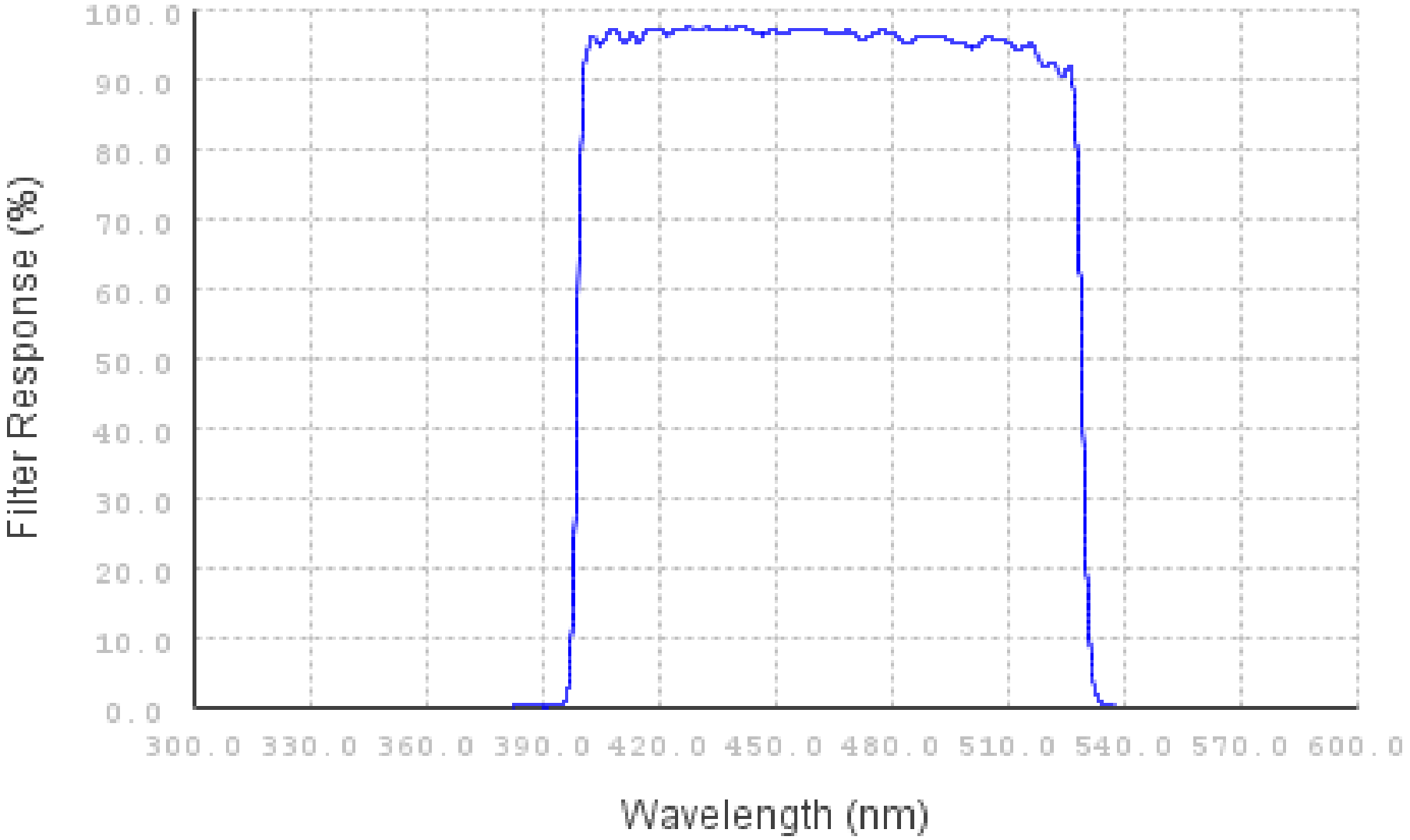


Other aspects: technical issues

- Filters: how red is it possible to go?
  - Detector QE?
  - Filter-less operation?

- Absolute timing : can we tie it to LAXPC timing?
  - To what accuracy?

VIS3 filter response



Other aspects: technical issues

- Filters: how red is it possible to go?
  - Detector QE?
  - Filter-less operation?

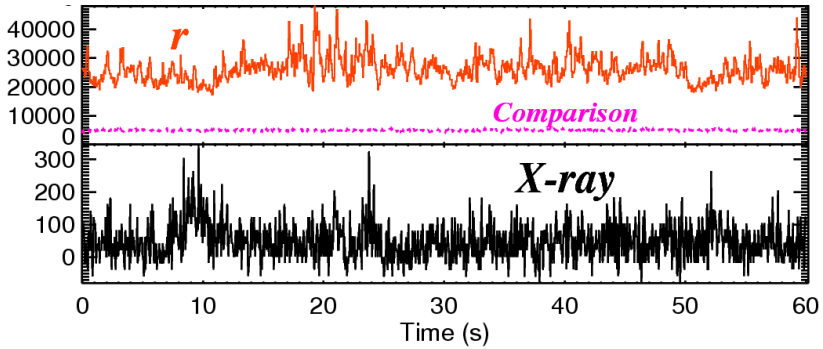
- Absolute timing : can we tie it to LAXPC timing?
  - To what accuracy?

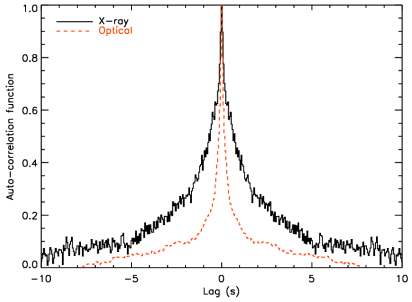
Summary

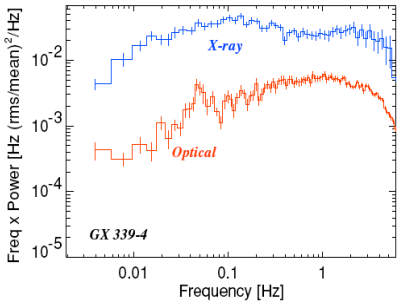
- Rapid optical flaring in low/hard state observations of several binaries.

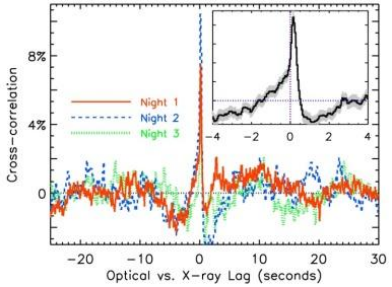
- Optical not reprocessed simply.

- Complex CCF
  => jet/corona/disk interaction.









Optical timing gives independent constraints.

Such studies truly exploit multi-wavelength capability of *Astrosat* on ~s timescales.