New constraints on accretion from fast optical and X-ray timing of X-ray binaries

Poshak Gandhi

(International Top Young Fellow)

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Collaborators

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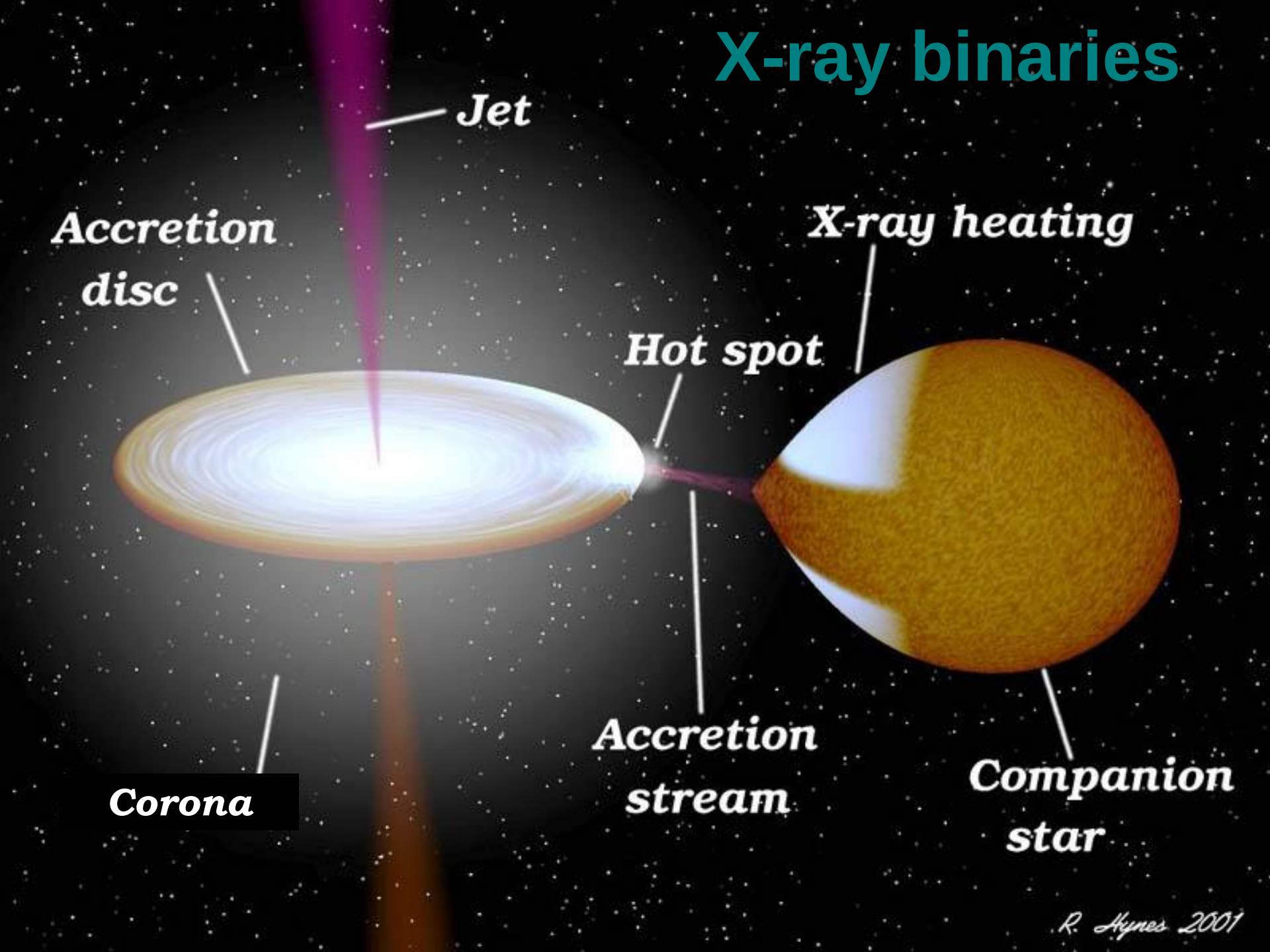
M. Durant, T. Shahbaz (Spain)
J. Miller (USA)
H. Spruit (Germany)
J. Malzac (France)

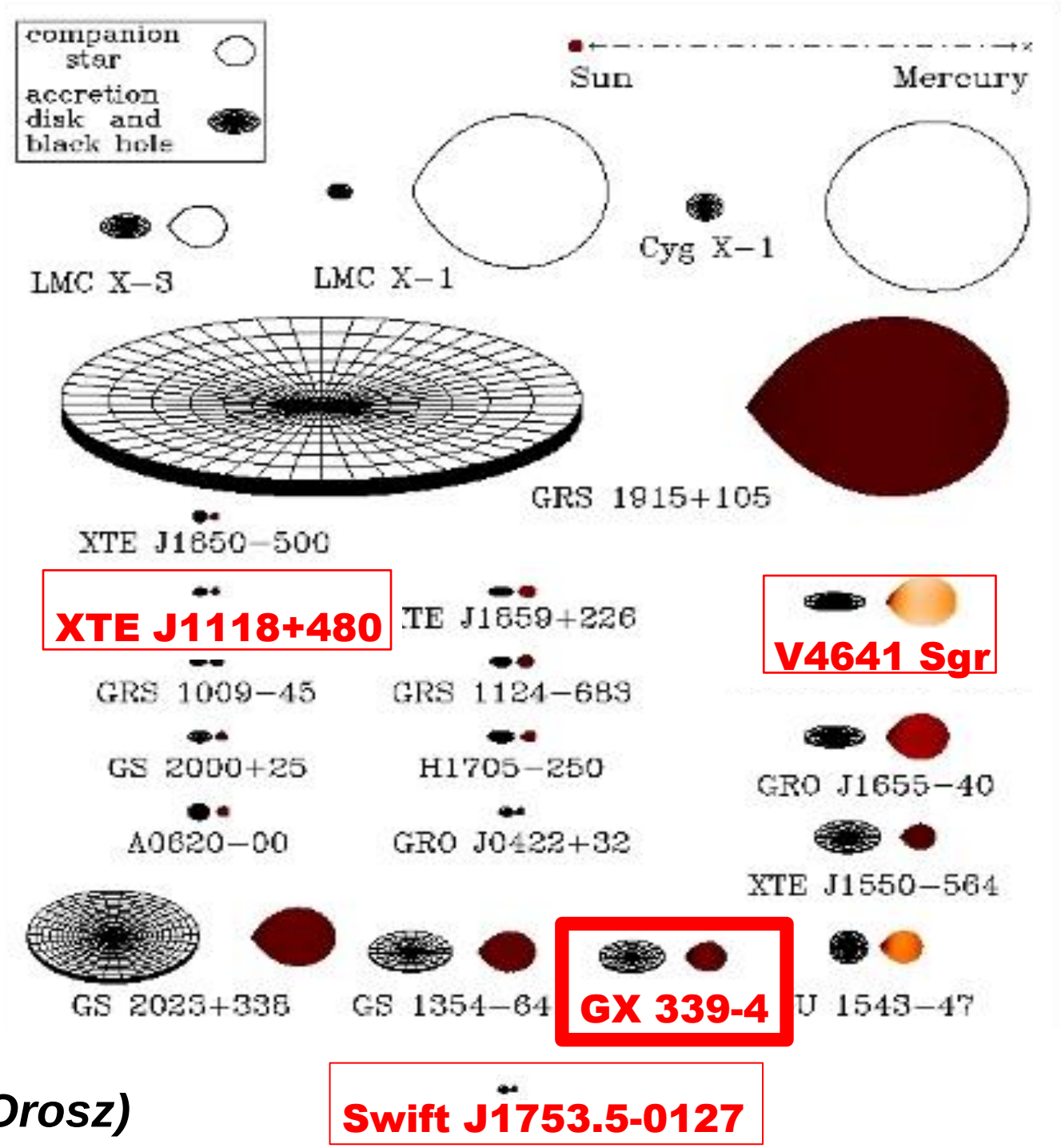
This talk

- Brief introduction
- **Coordinated multi-wavelength timing of GX 339-4 and Swift J1753**
- **Analyzing the fast and slow variability in detail**
- Implications and future prospects

X-ray binaries



X-ray binaries



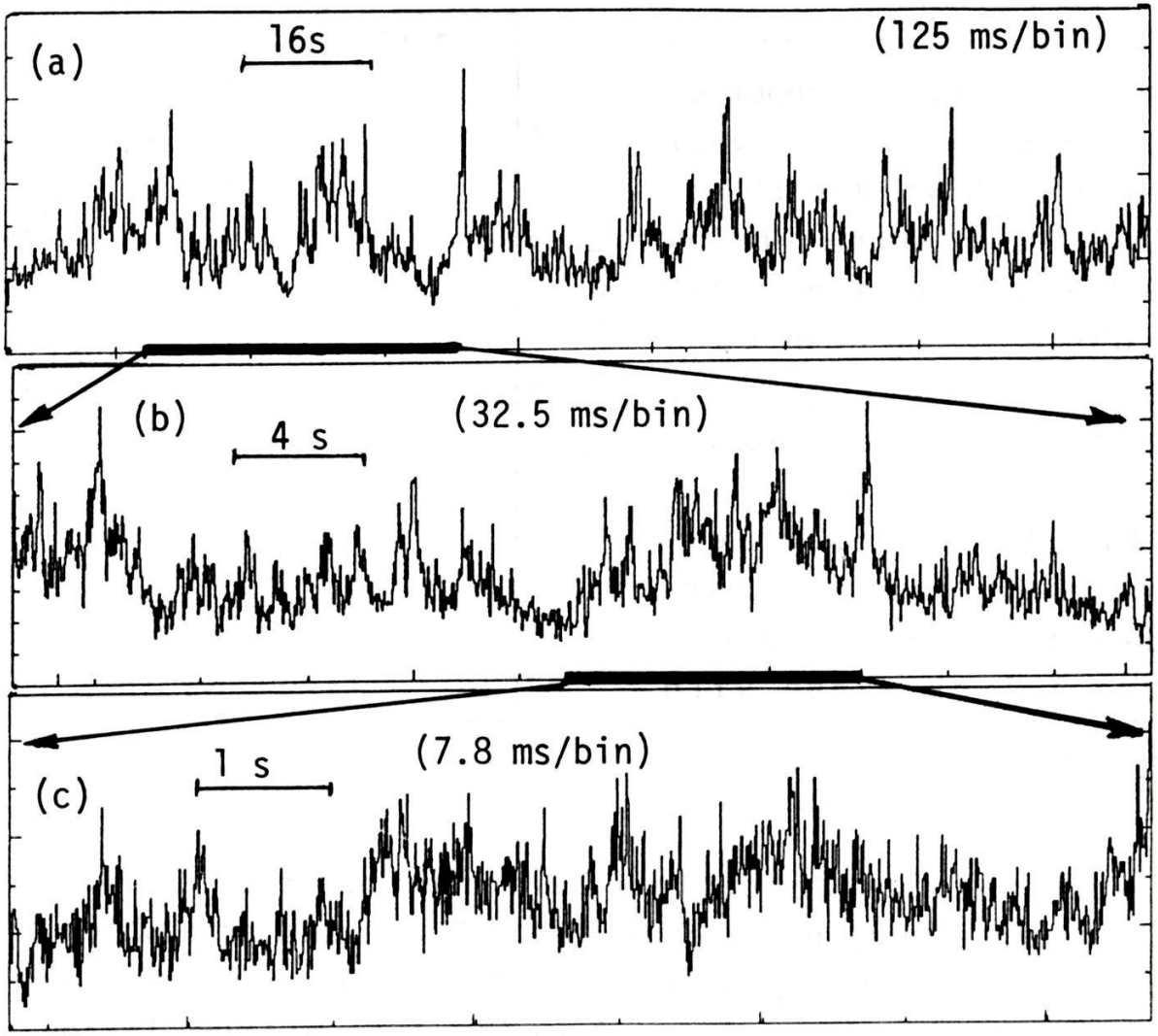
(J. Orosz)

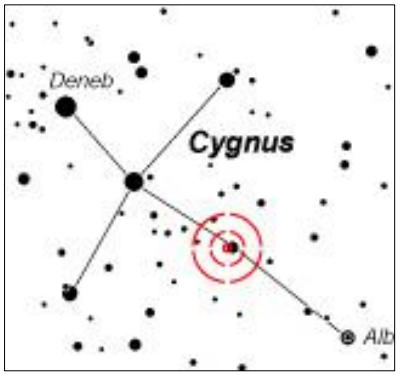
- One of the strongest Galactic BH candidates
  M>6 M_{sun} (Hynes+03); d~8 kpc (Zdziarski+04)

- Binary separation ~25 light-seconds
  => θ ~ 6 μas (GAIA, SIM?)

Timing studies of Galactic black holes

Rapid aperiodic flickering commonly seen in **X-rays**

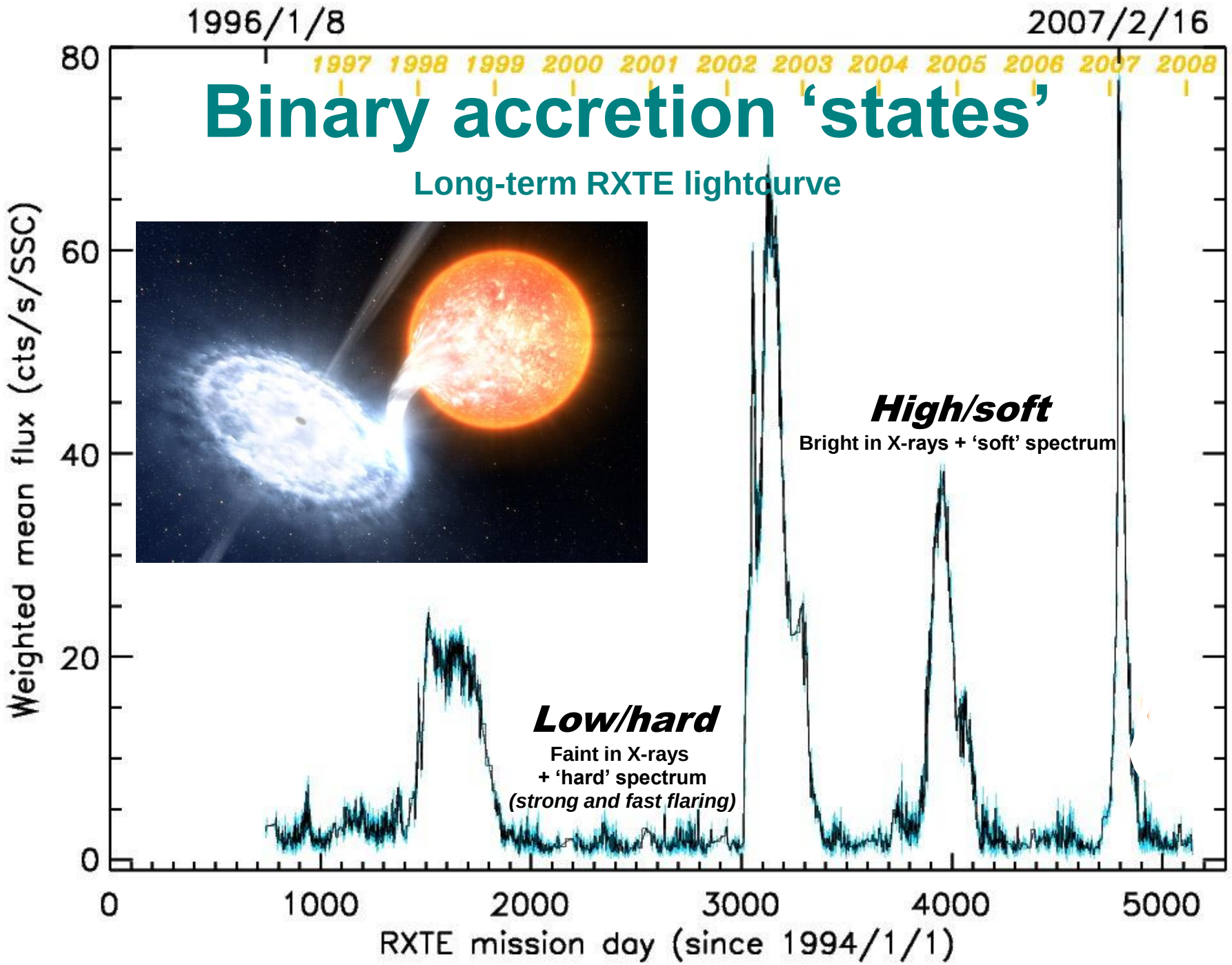




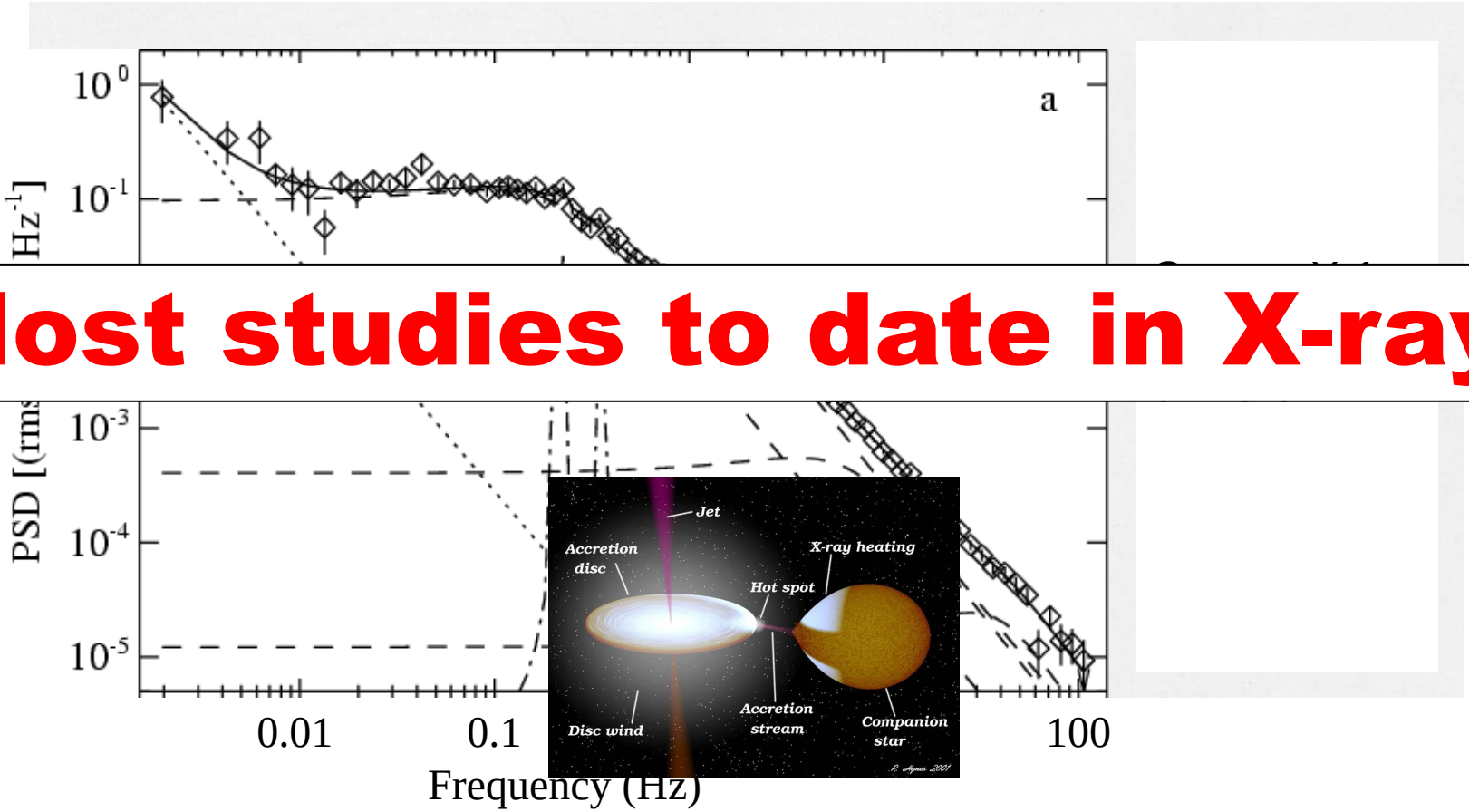
Black hole
Cygnus X-1

(Makishima 1988)
(Ginga data)

Binary accretion ‘states’



Timing studies of binaries

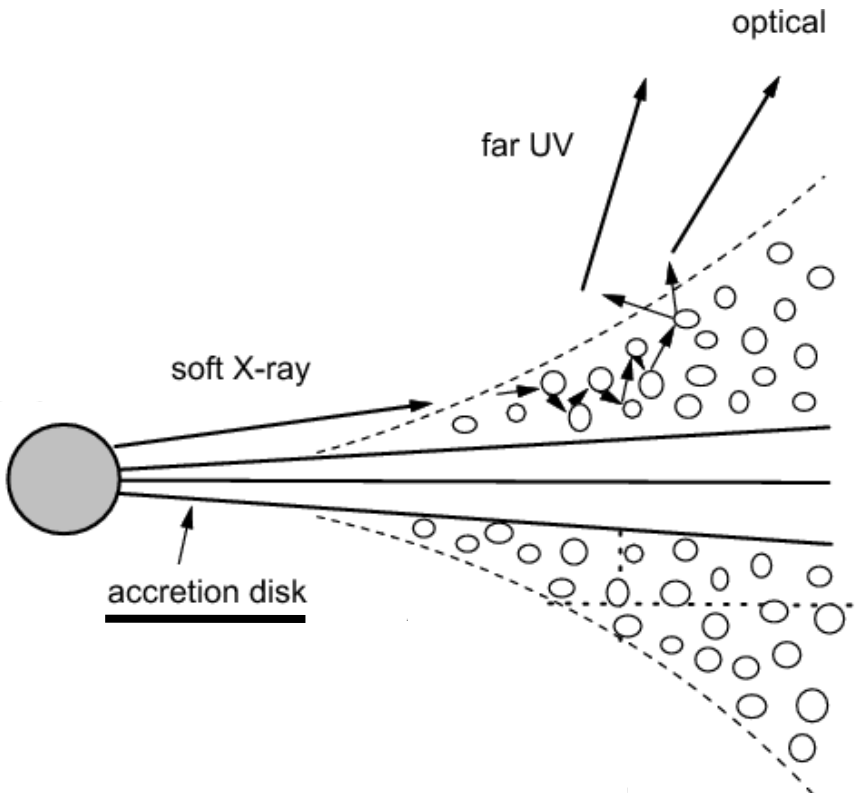


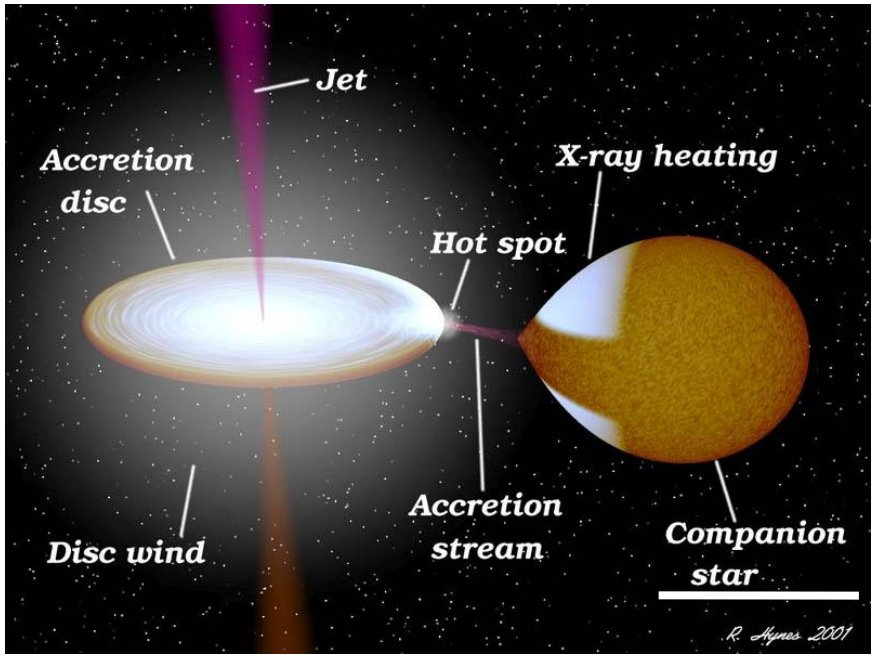
Most studies to date in X-rays

Rapid aperiodic X-ray flickering over large frequency ranges

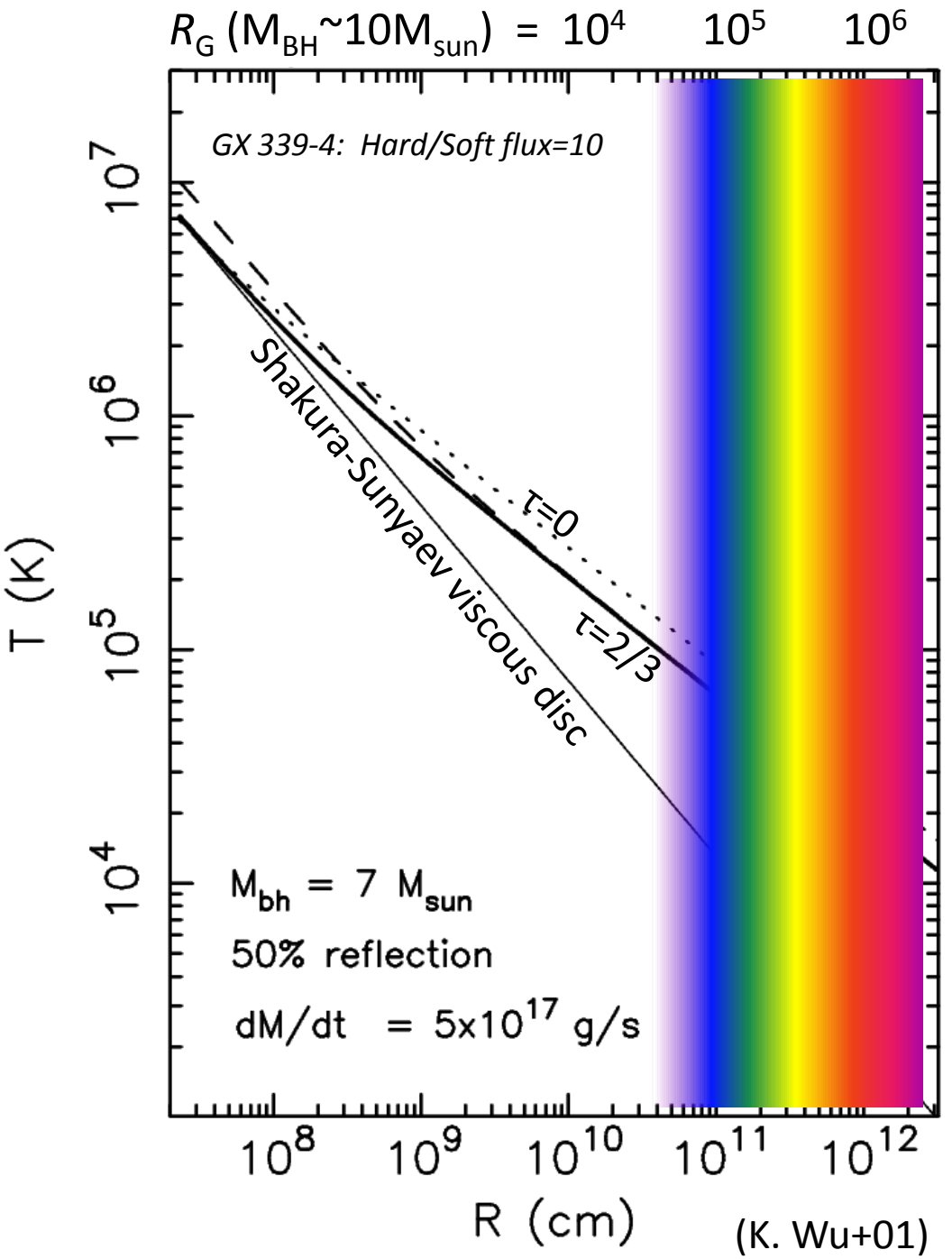
What is the source of the optical power of X-ray binaries?

Reprocessing of X-rays→optical?



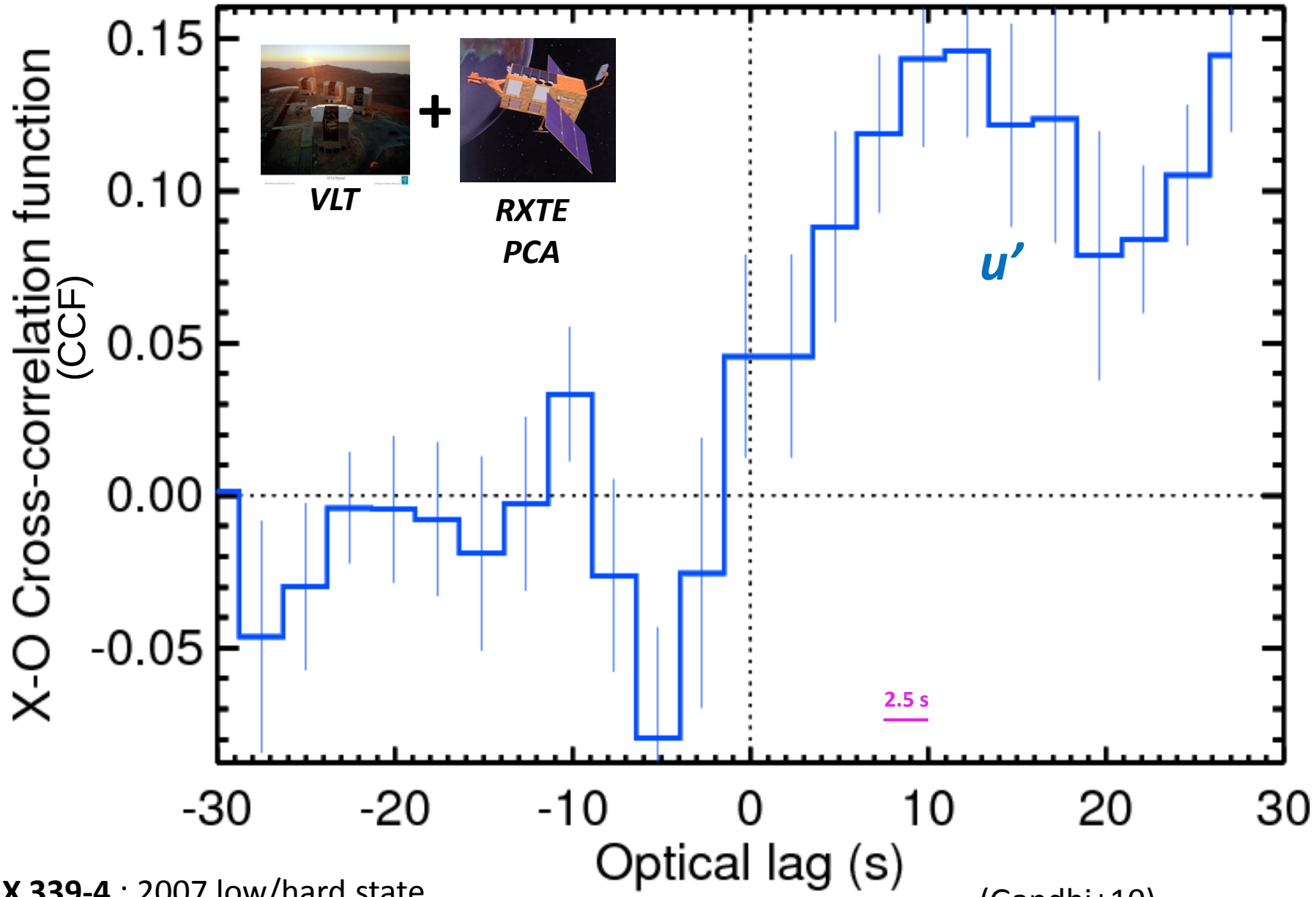


Irradiative heating of accretion discs



(K. Wu+01)

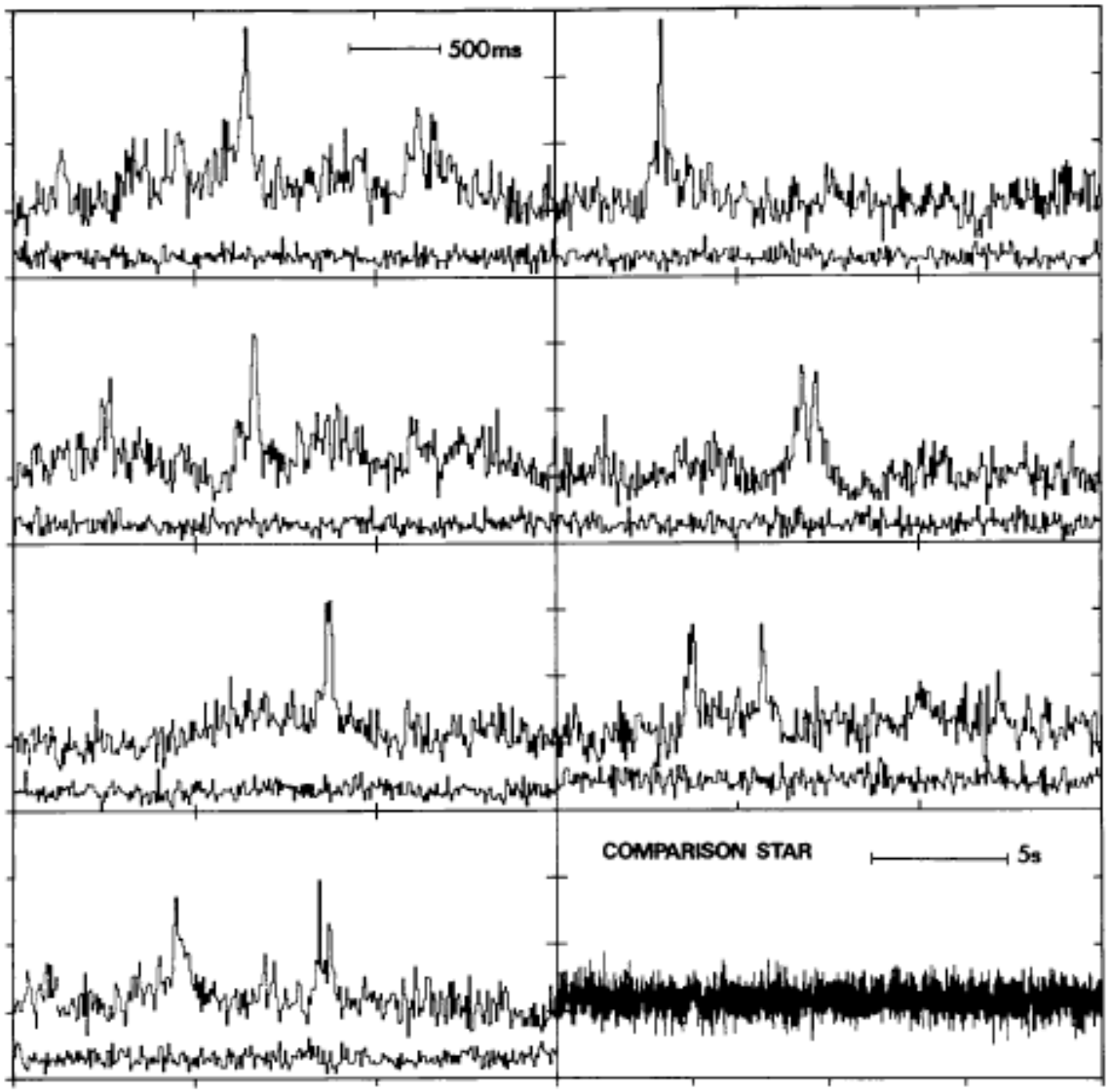
Optical and X-ray simultaneous timing



GX 339-4 : 2007 low/hard state

(Gandhi+10)

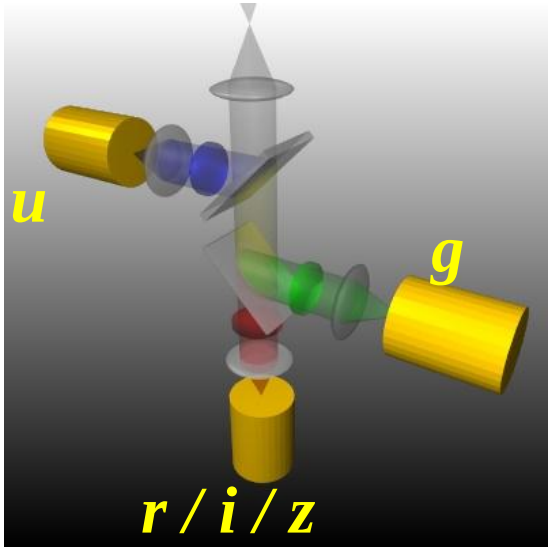
Speedy optical variations in X-ray binaries



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

ULTRACAM:
ultra-fast, triple-beam CCD camera

- High-speed light-weight camera
- Frame-transfer CCDs with negligible dead-time
- Speeds ~ 500 frames / sec
- 3 simultaneous optical filters
- Absolute timing ~ 1 ms



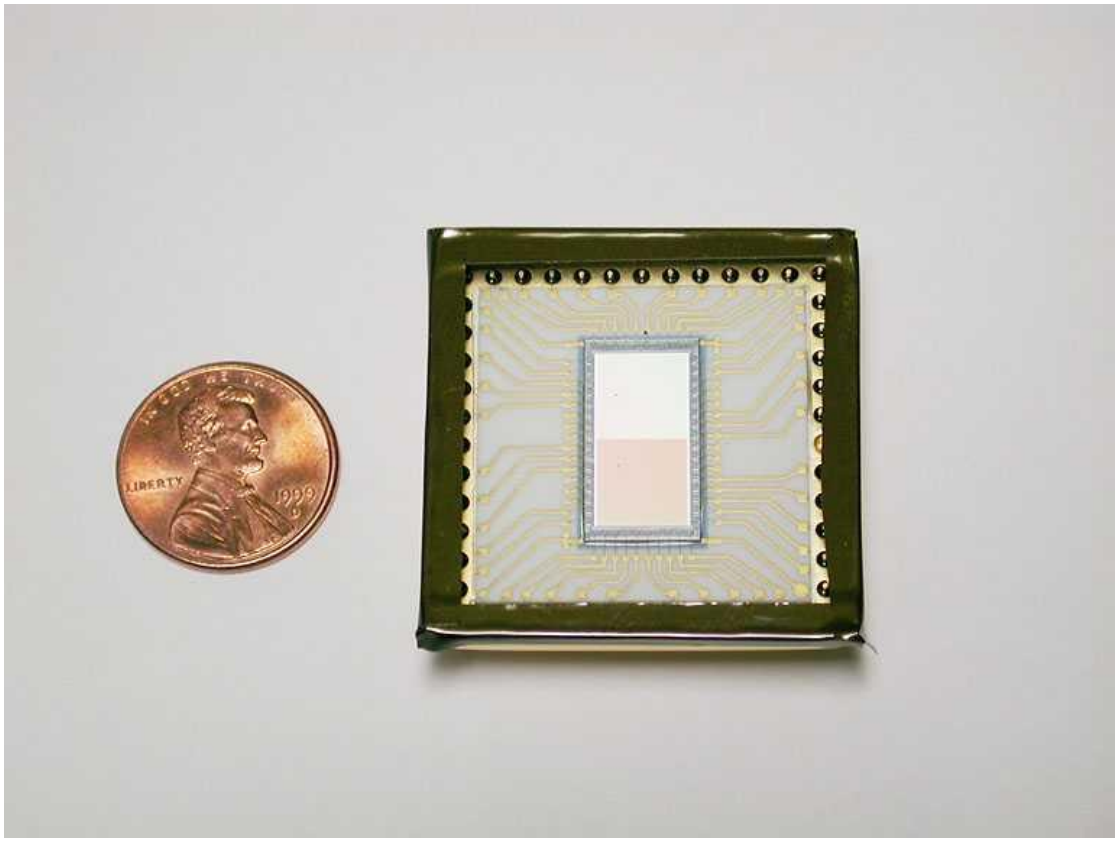
ULTRACAM Mounted on Visitor Focus of MELIPAL

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

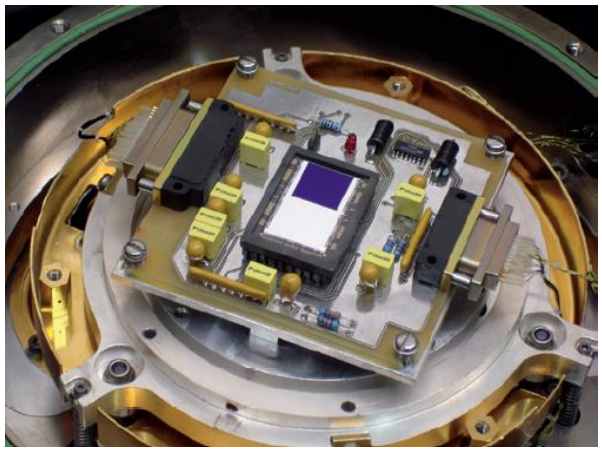
ULTRACAM @VLT

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

Frame transfer CCDs
Very low dead time; low read noise



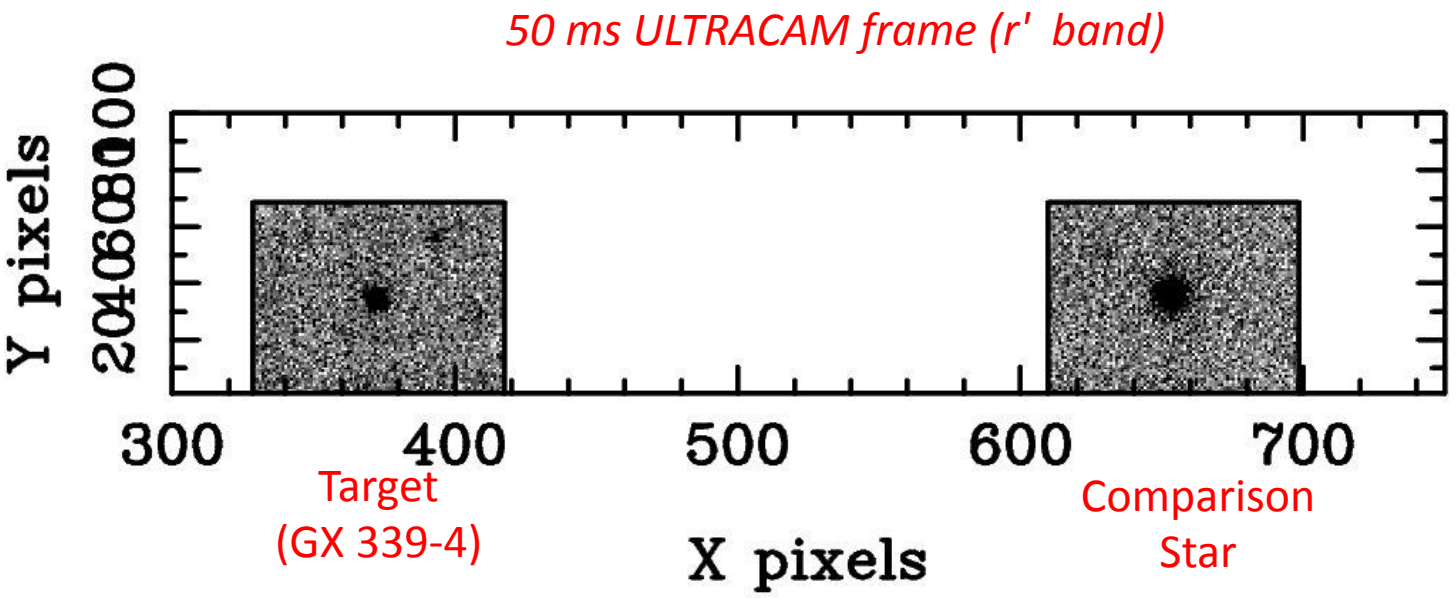
Frame transfer CCD actual size

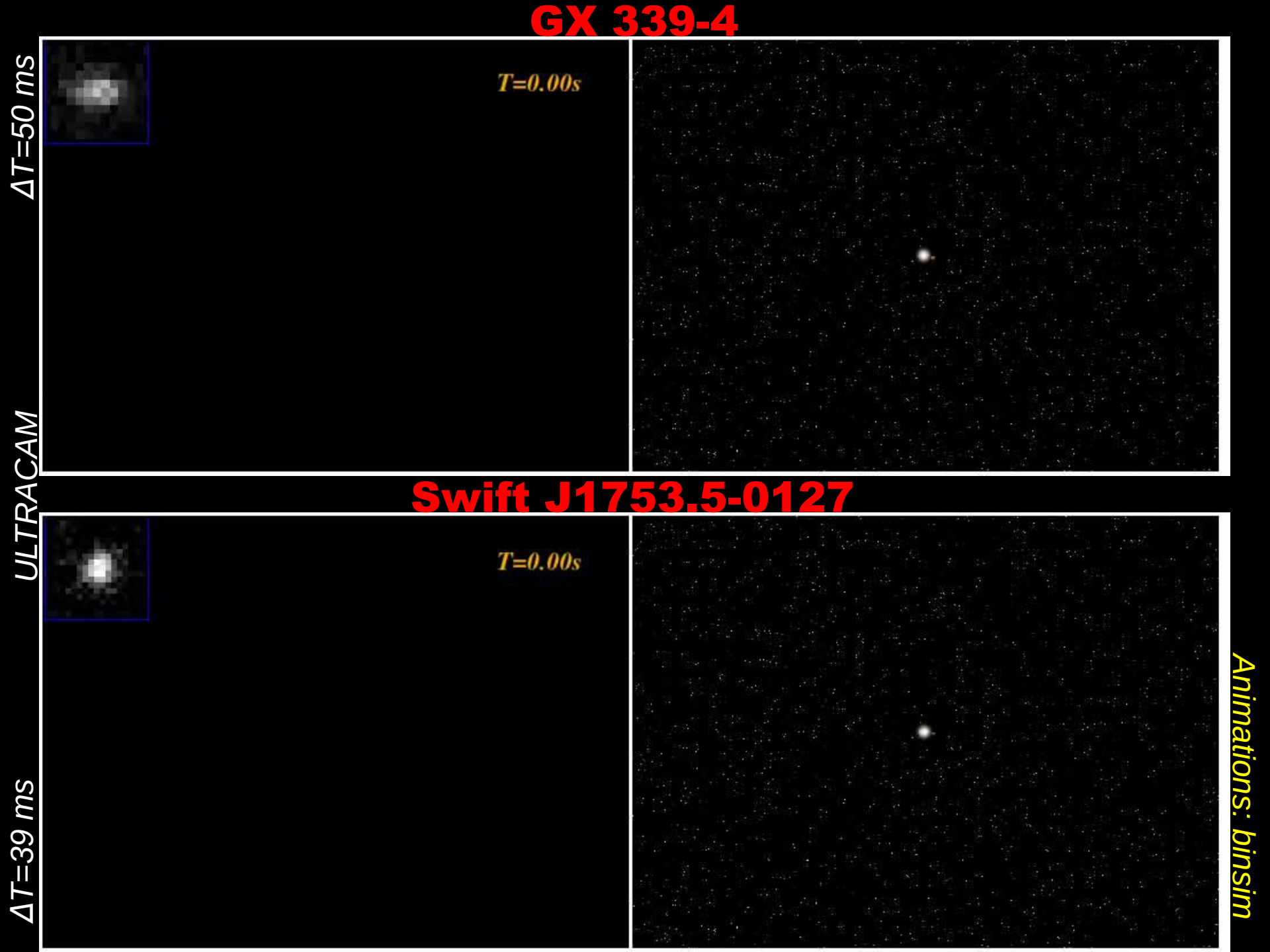


Frame-transfer EMCCD

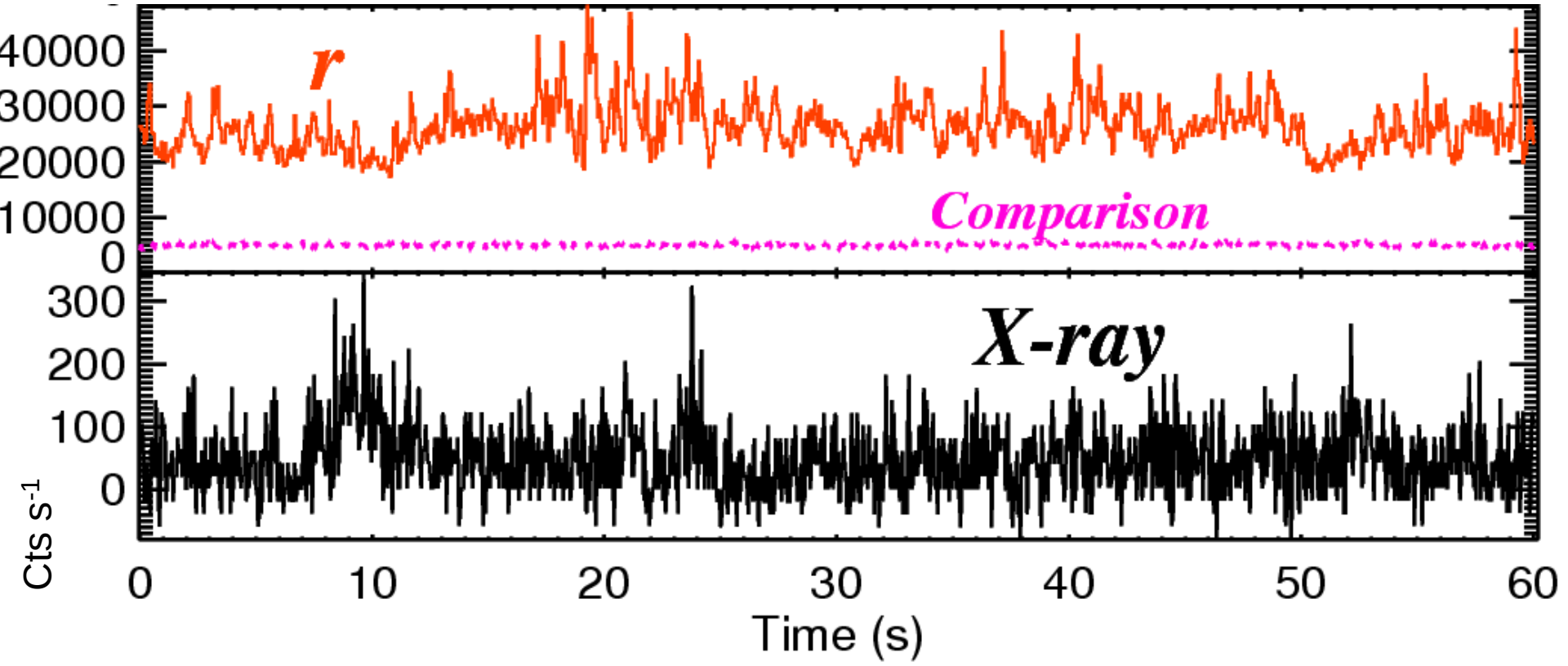
(Dhillon+07)

Observations

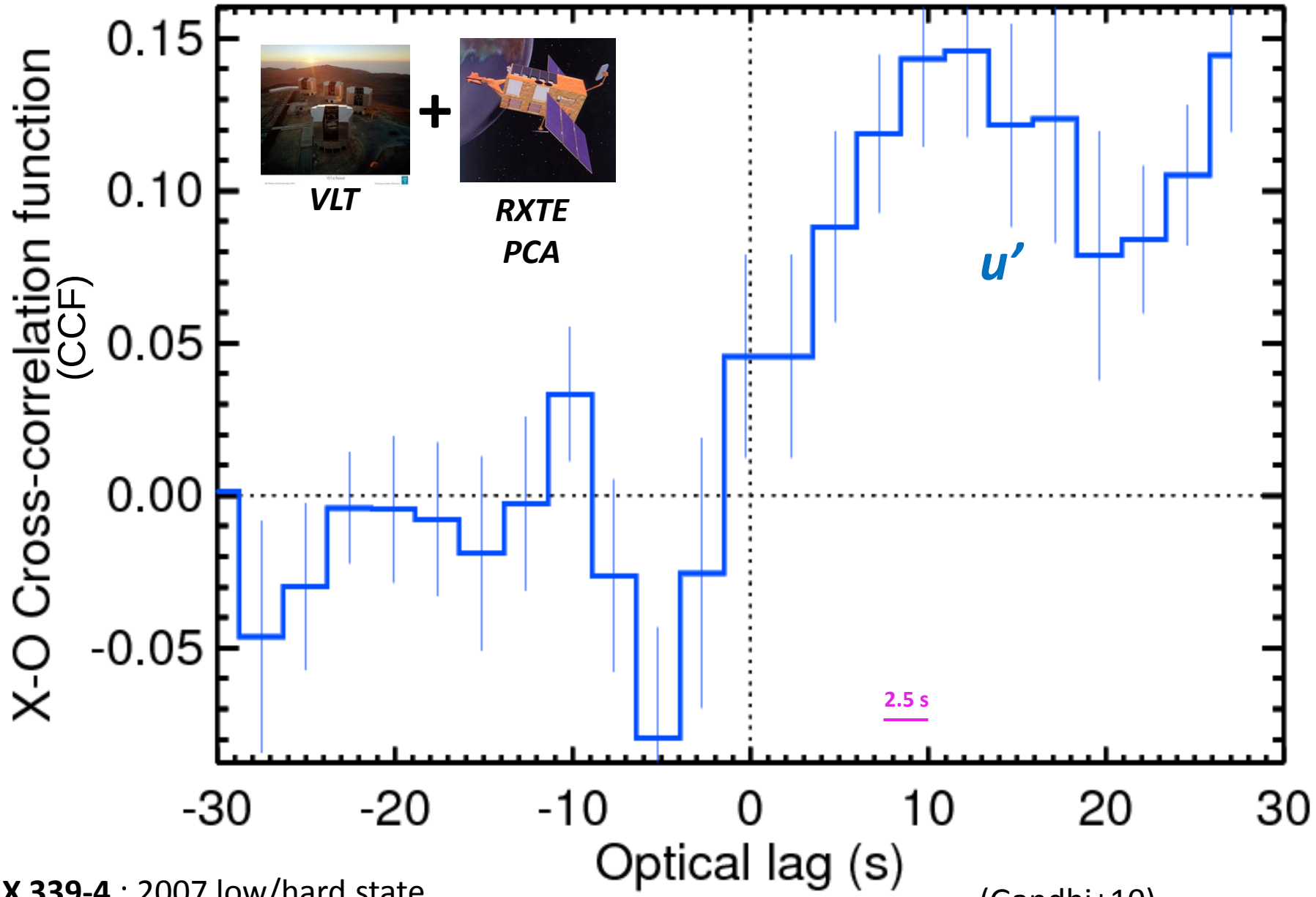



GX 339-4
T=0.00s
ΔT=50 ms
ULTRACAM
Swift J1753.5-0127
T=0.00s
ΔT=39 ms
Animations: binsim

Simultaneous light curves



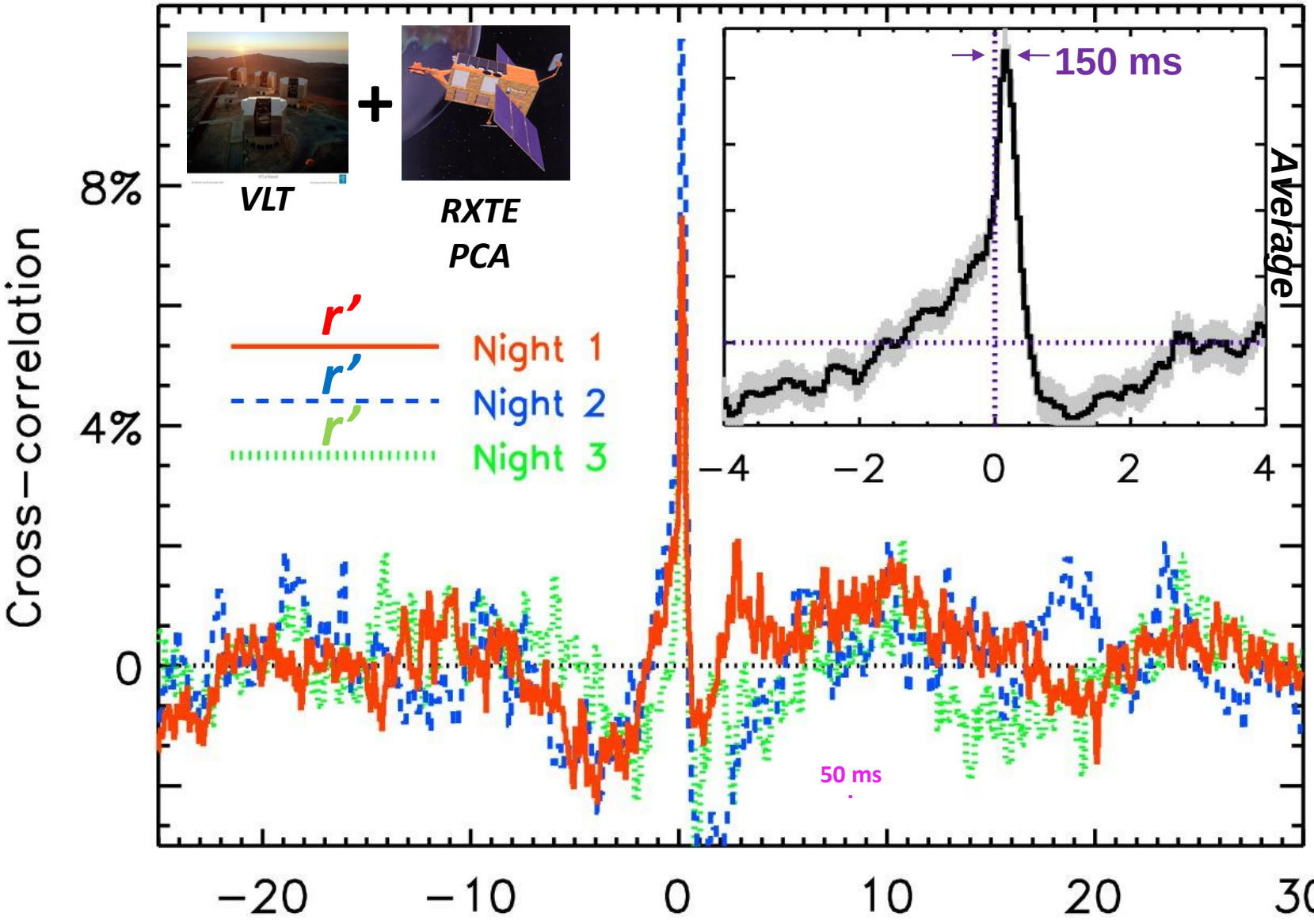
Optical and X-ray simultaneous timing



GX 339-4 : 2007 low/hard state

(Gandhi+10)

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

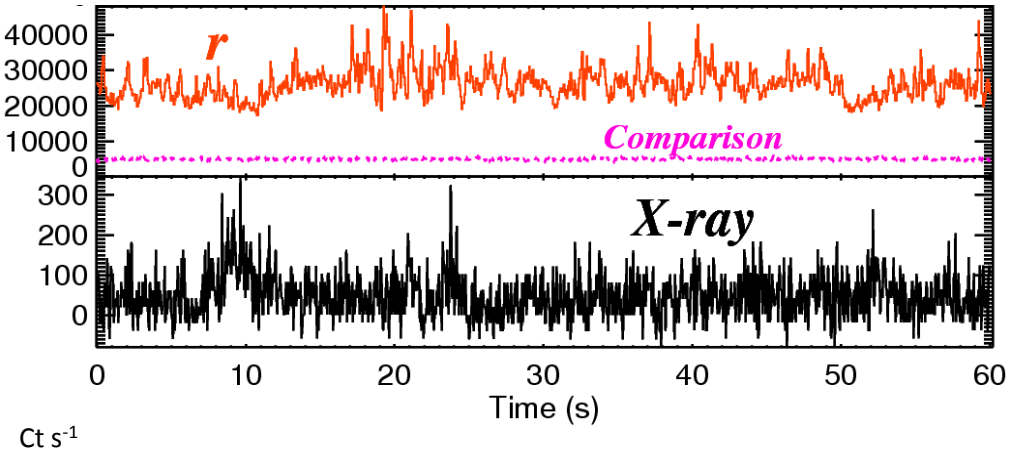


GX 339-4 : 2007 low/hard state

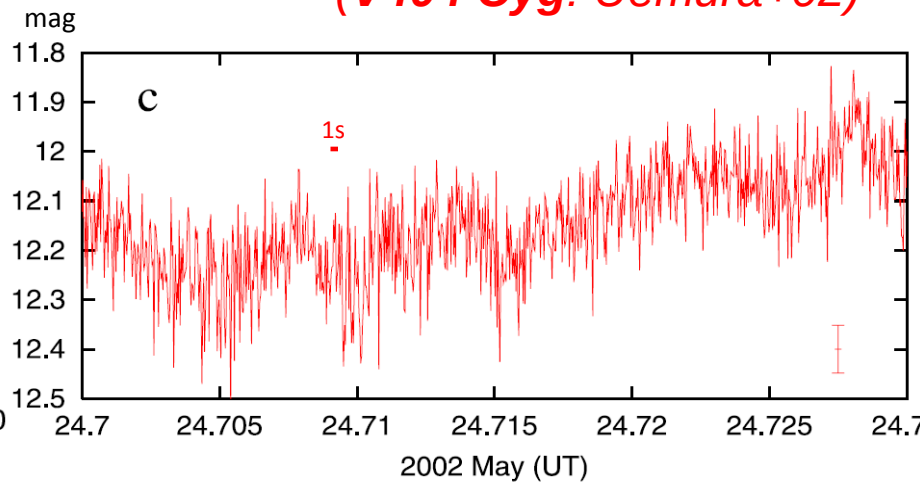
(Gandhi+ 2008)

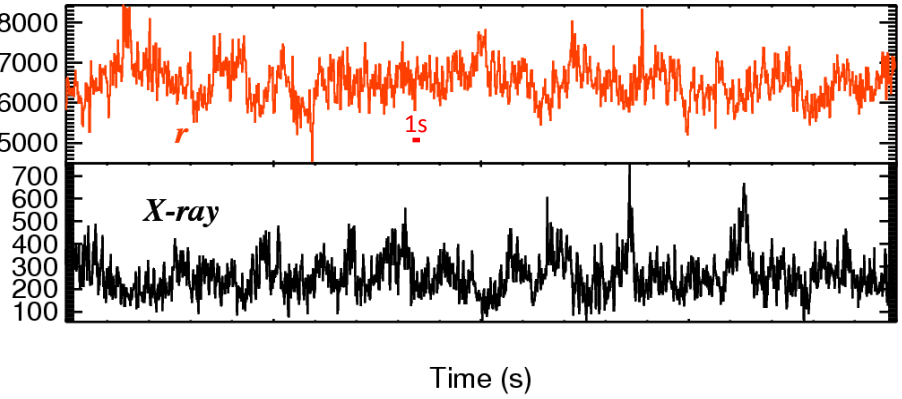
Speedy optical variations in X-ray binaries

*(**GX 339-4**: Gandhi+10)*

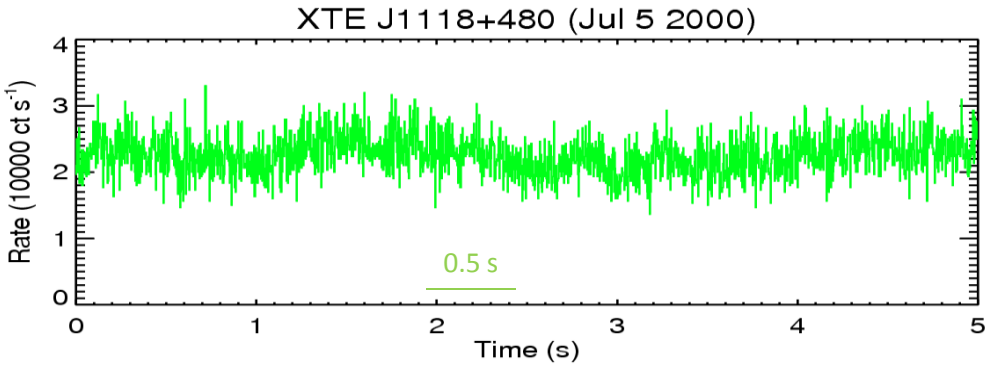


*(**V404 Cyg**: Uemura+02)*





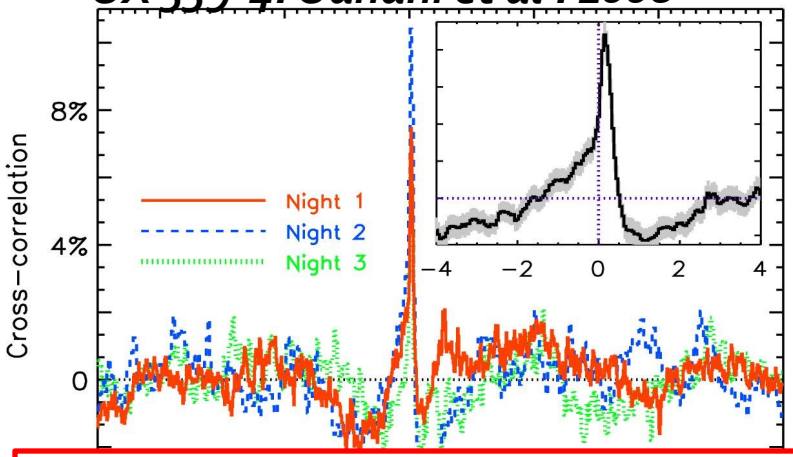
*(**Swift J1753.5-0127**: Durant+08)*



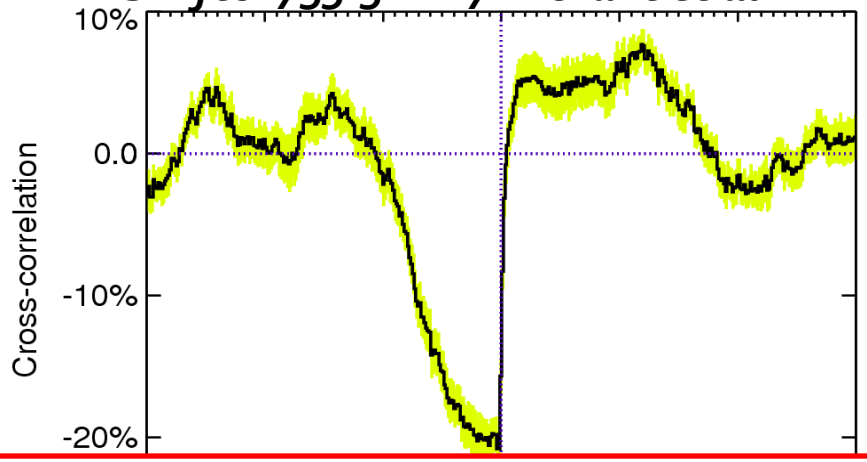
*(**XTE J1118+480**: Kanbach et al. 2001)*

Asymmetric and complex optical/X-ray cross-correlation functions in the low/hard state

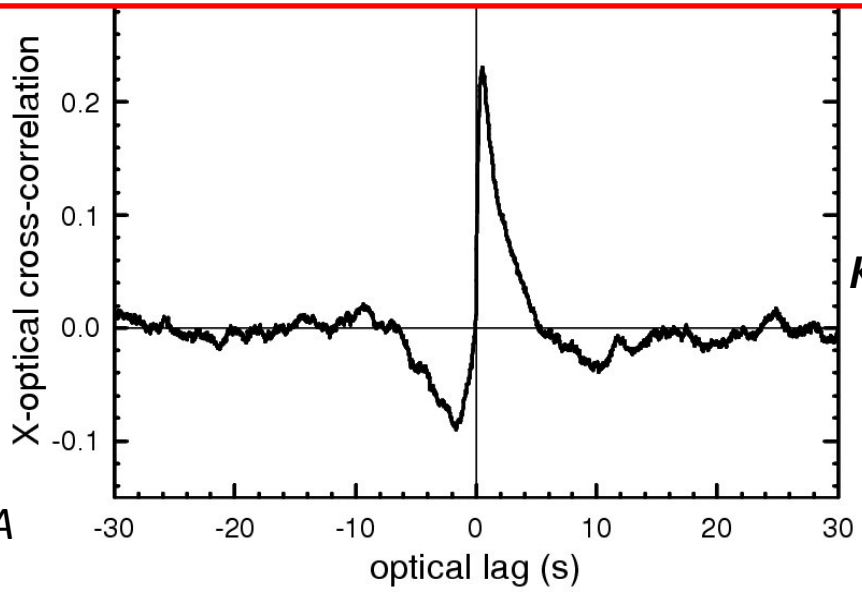
GX 339-4: Gandhi et al . 2008



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



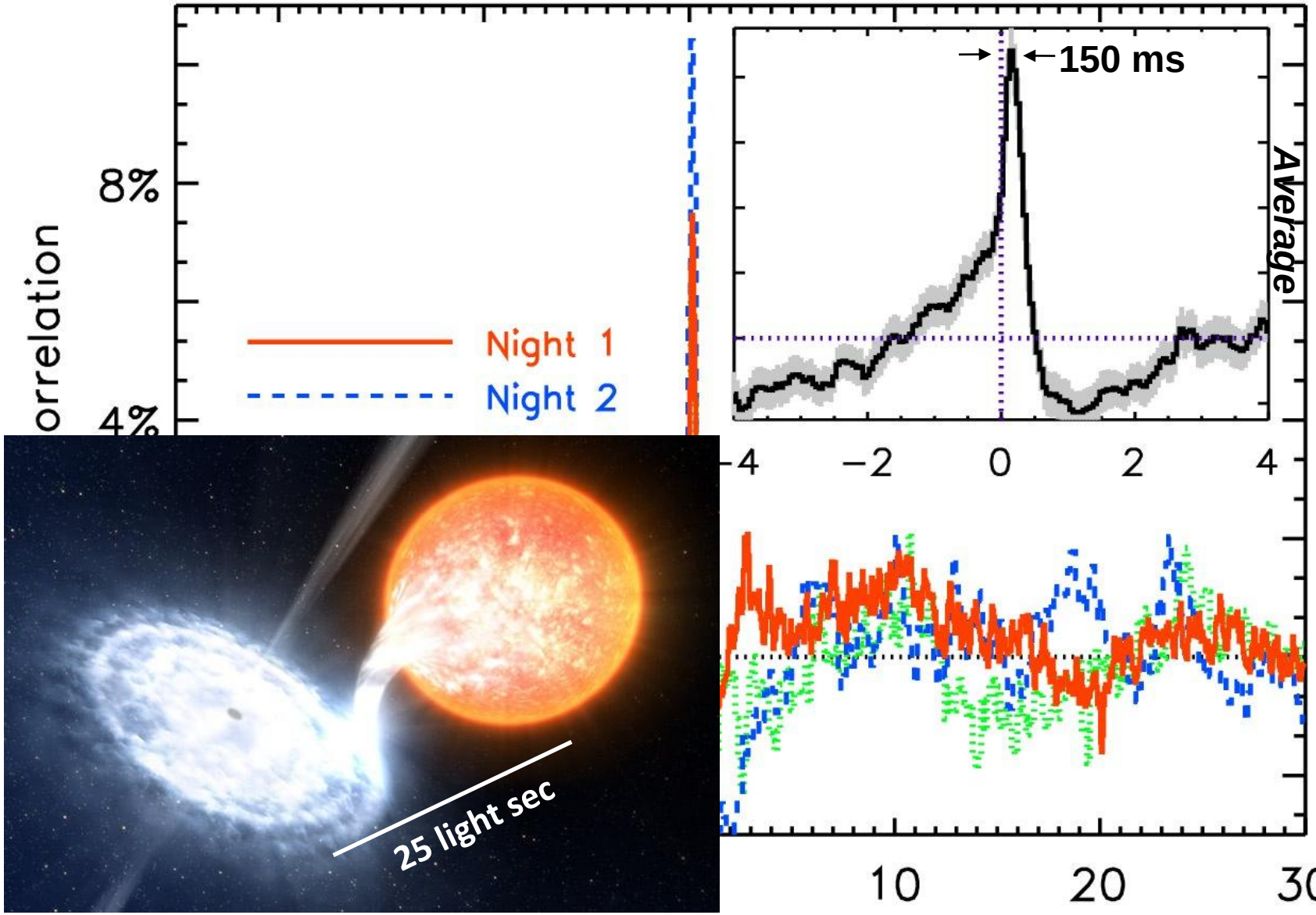
Rapid variability origin?:
~~Simple reprocessing models~~



XTE J1118+480: Kanbach et al. 2001

All X-ray data: RXTE PCA

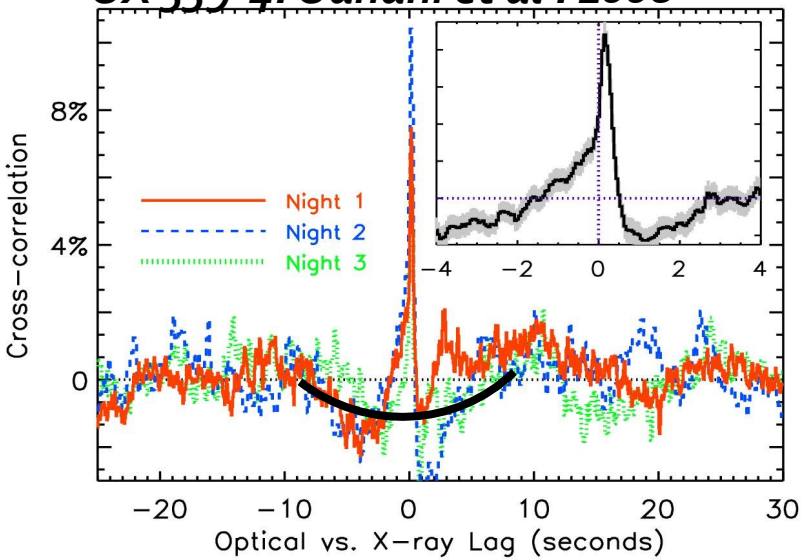
1. Small time delay



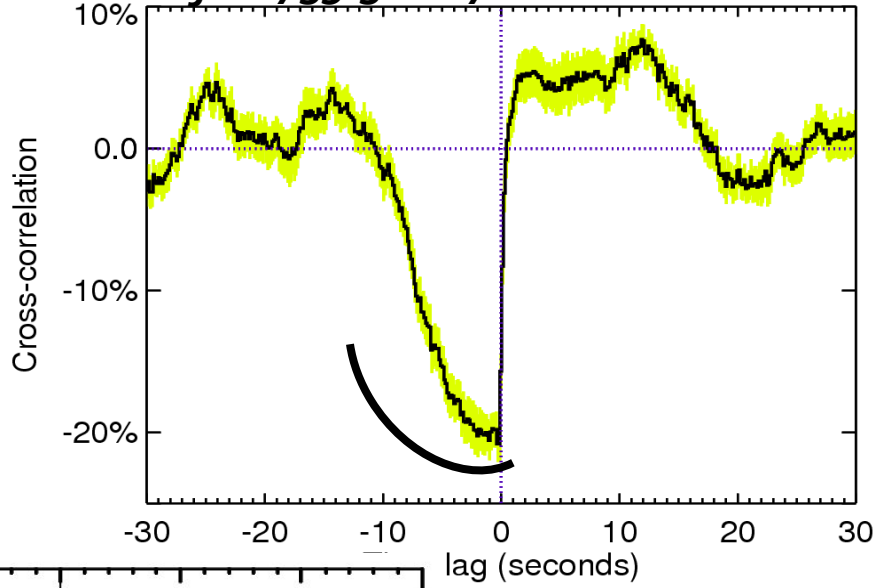
(Gandhi+ 2008)

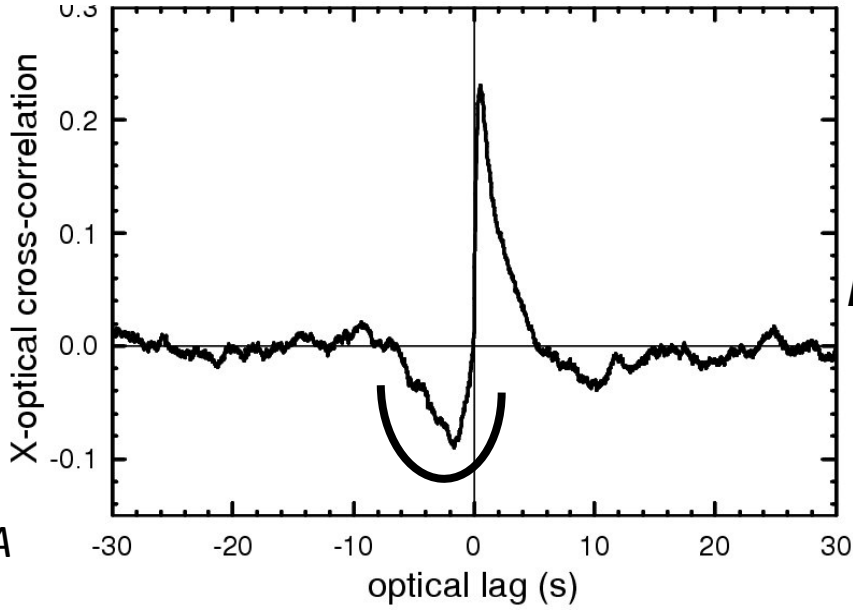
2. Anti-correlation

GX 339-4: Gandhi et al . 2008



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





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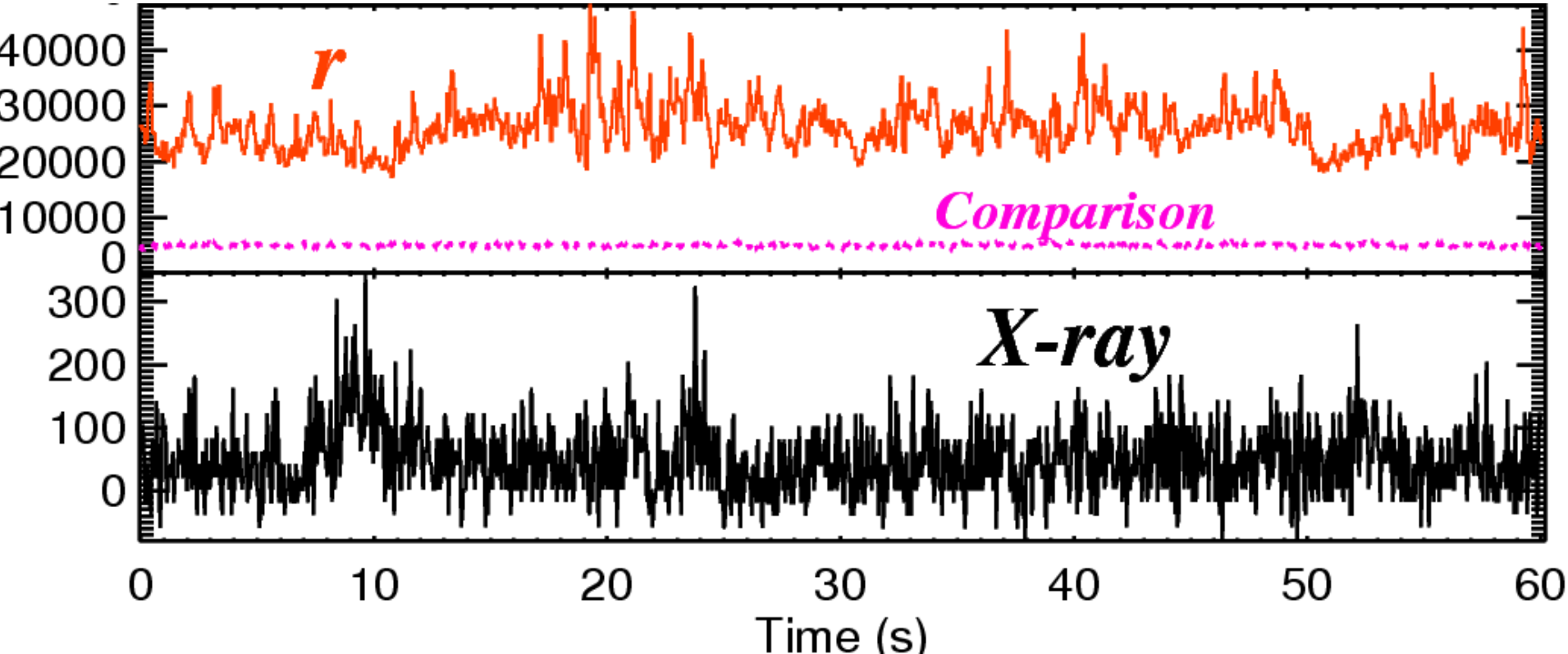
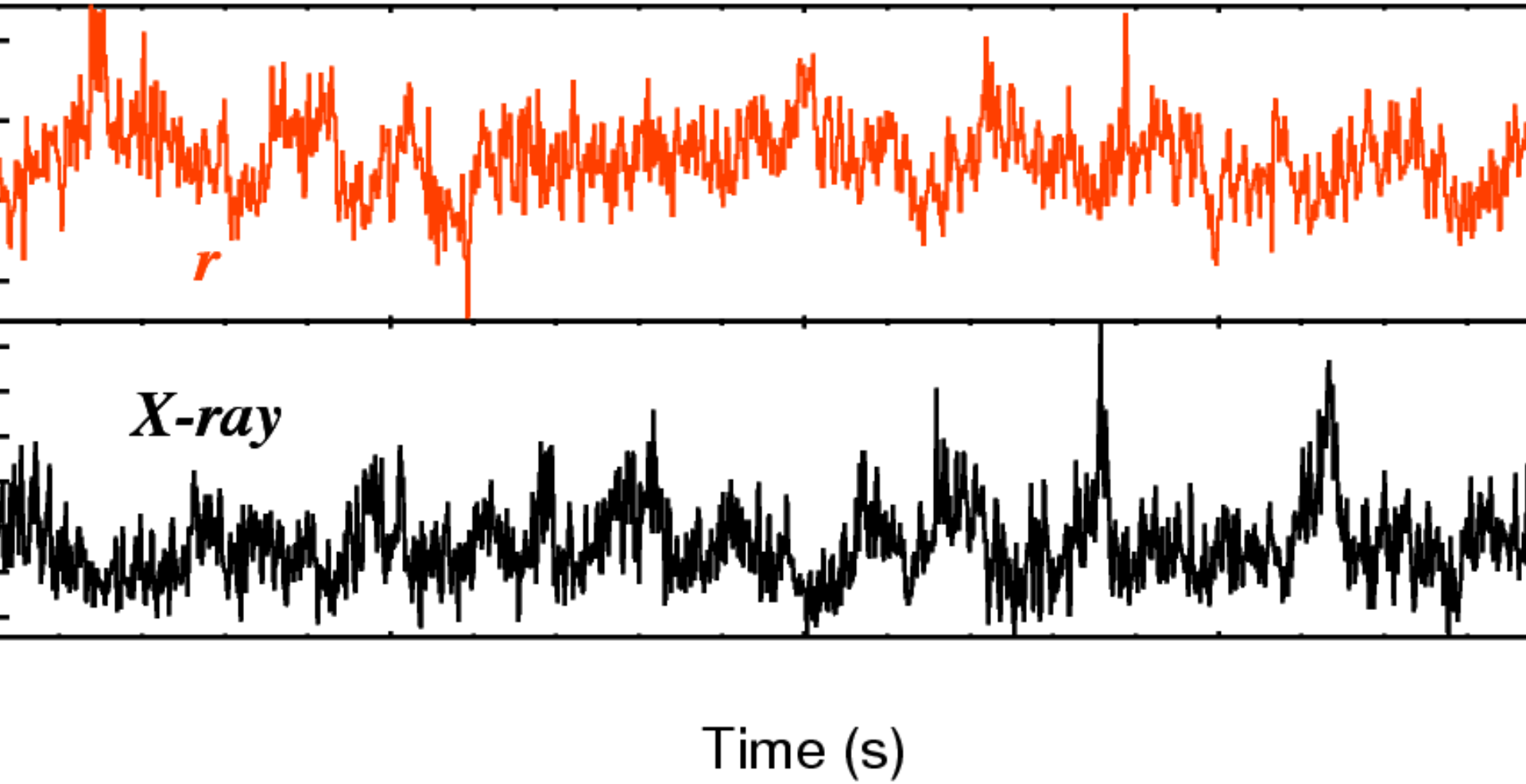
GX 339-4: Simultaneous light curves



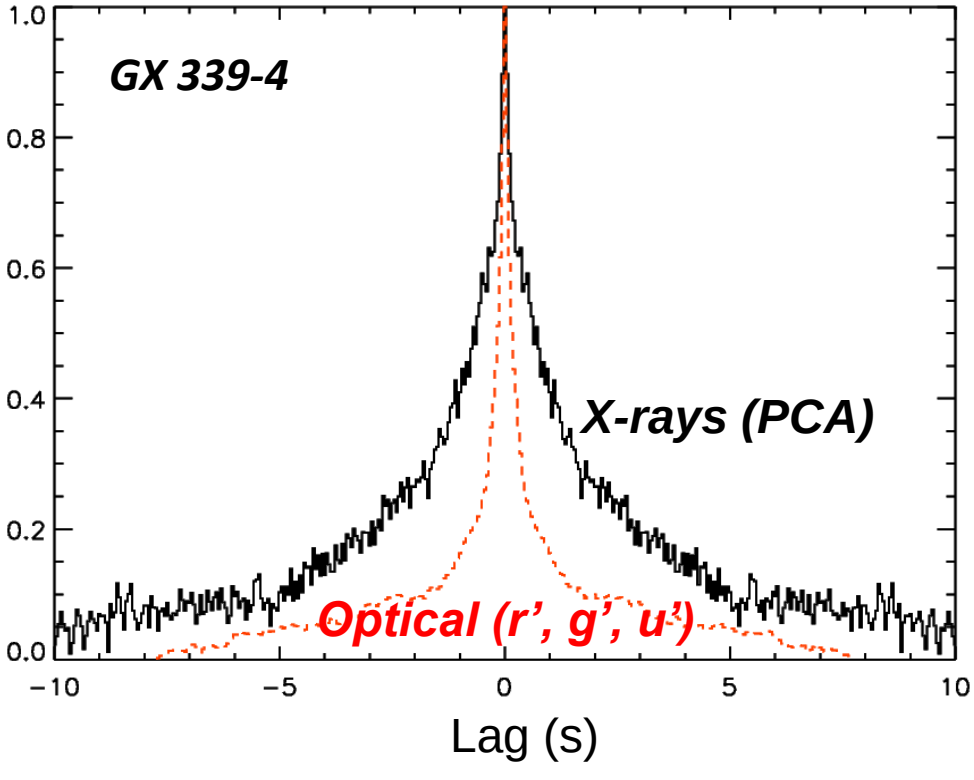
Swift J1753.5-0127: Simultaneous light curves

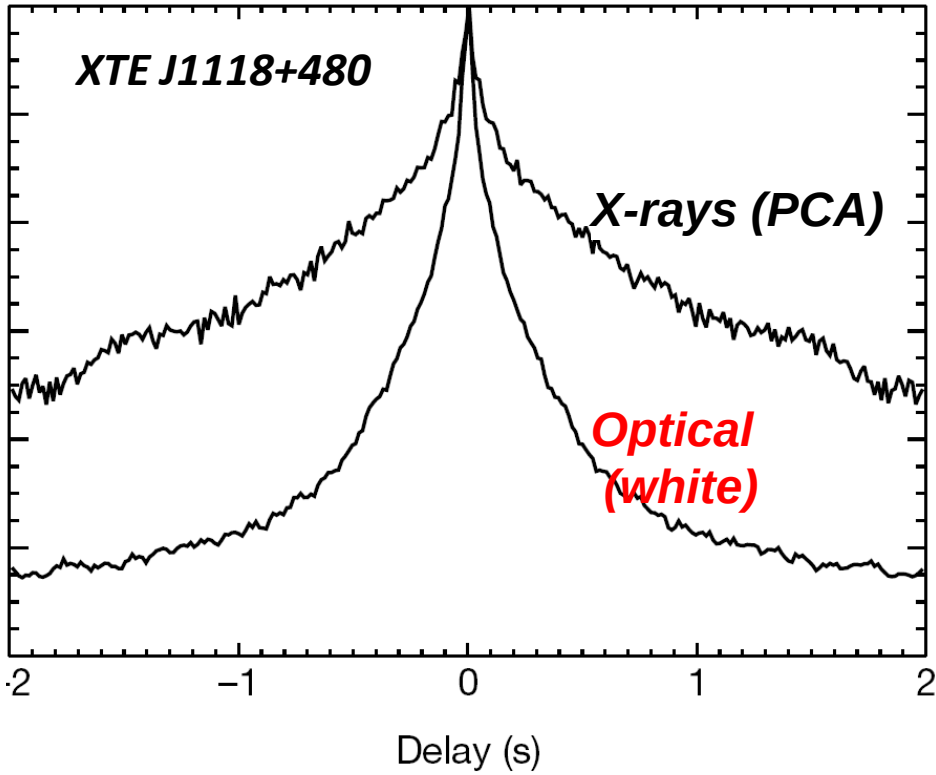


3. Small optical coherence times

Auto Correlation Function

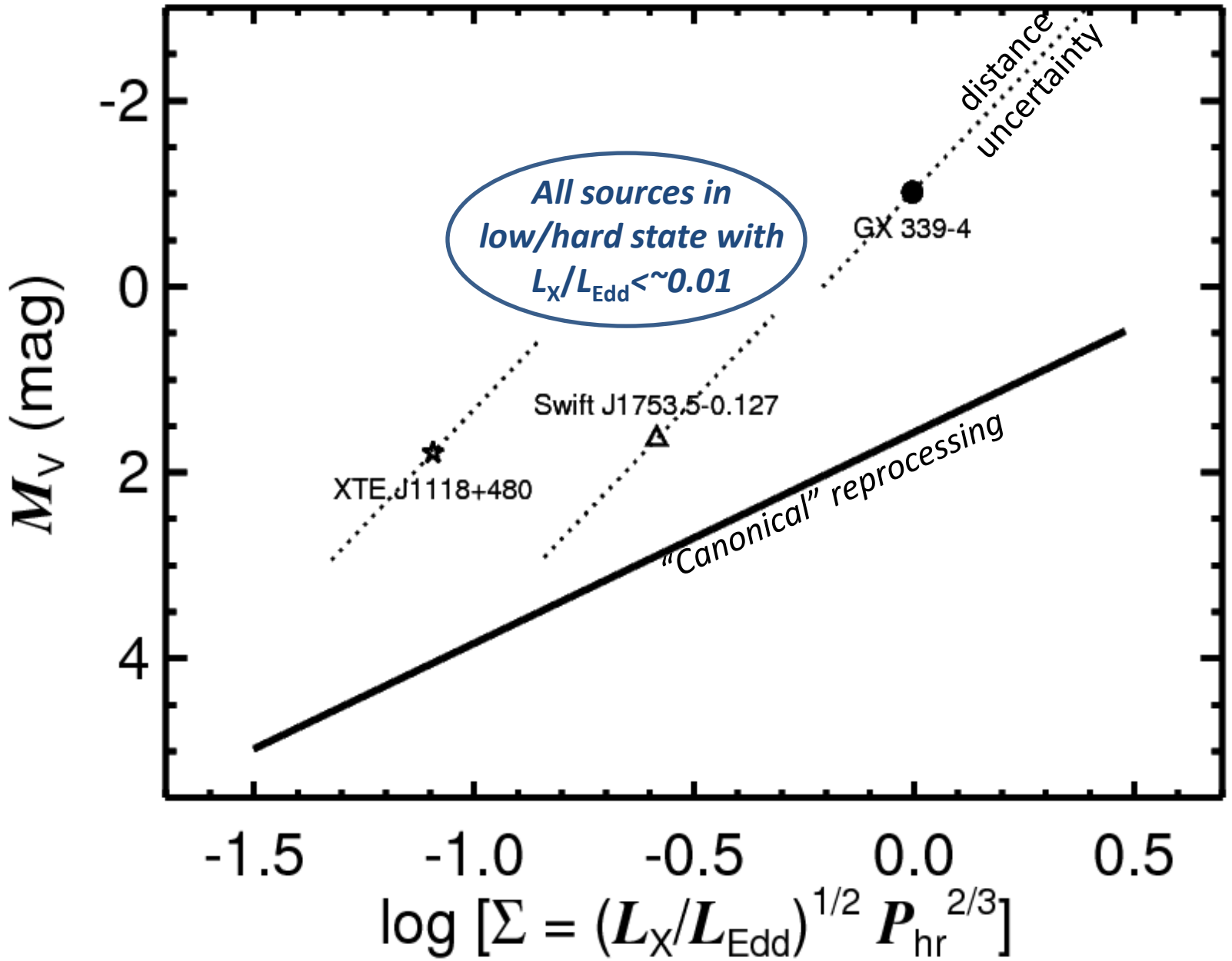
(Poisson corrected)





Optical ACFs narrower than X-ray ACF for two sources

4. How much reprocessing is expected?



(van Paradijs & McClintock 1994)

Speedy optical variability: scales and power

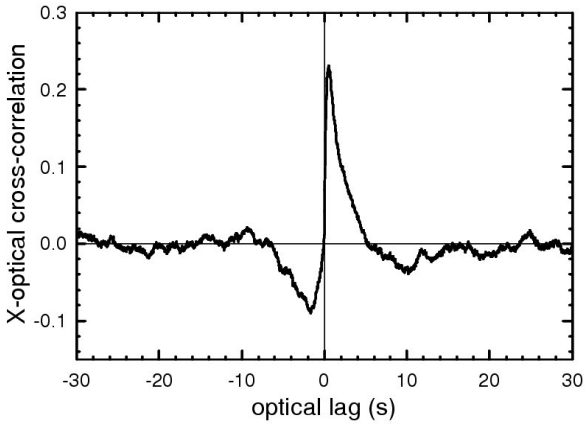
- Fastest flares have timescales <~ 20-50 ms.

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

- Brightness temperature

  => T_B >~ 10^7 K

Models for XTE J1118+480



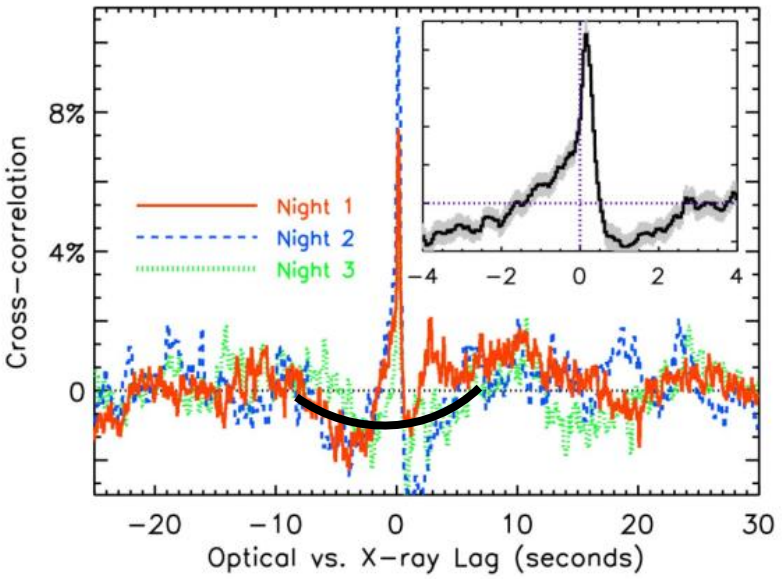
⇨ Optical (cyclo)synchrotron.

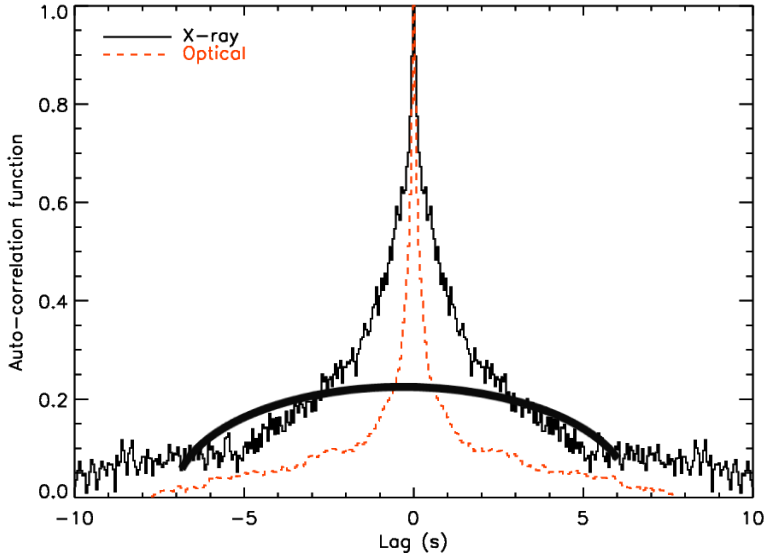
⇨ Interaction between components.

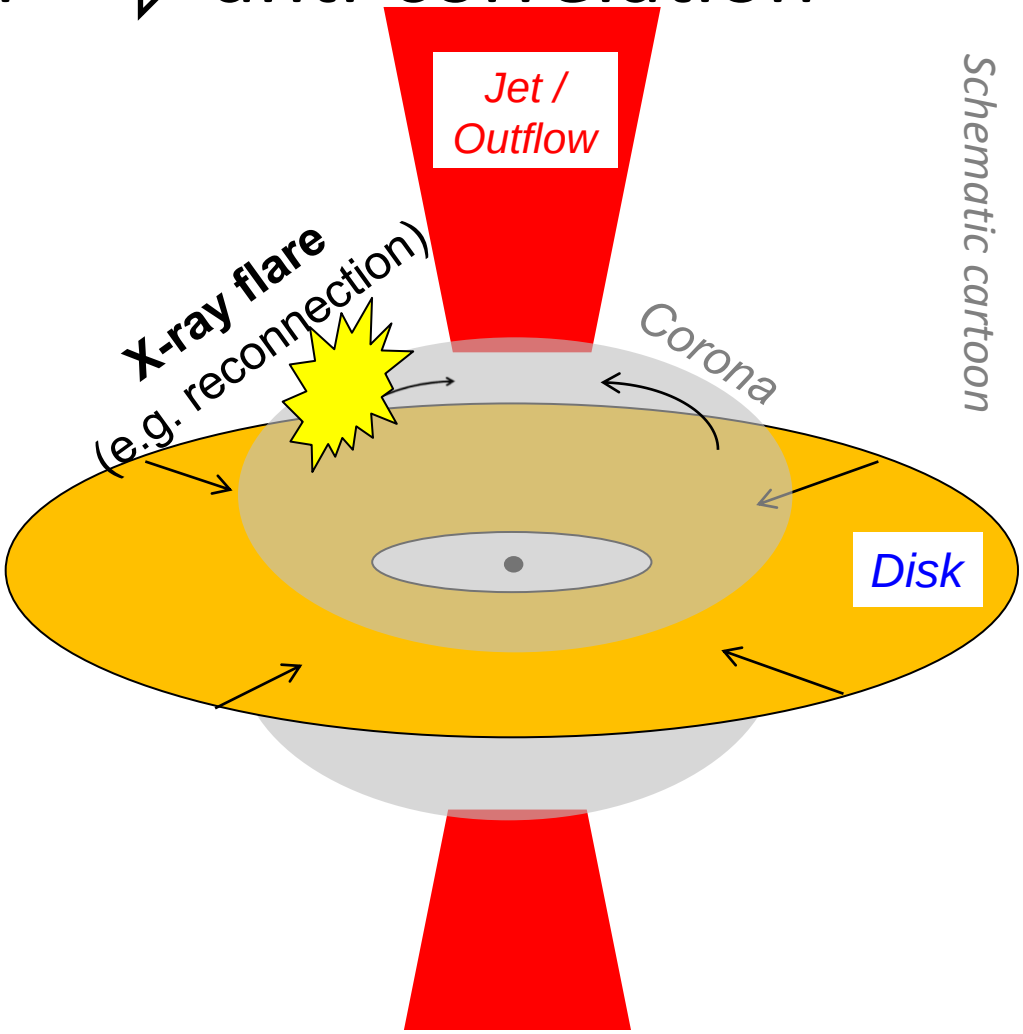
- Merloni+00 *Magnetic corona*
- Esin+01 *Advection flow (ADAF)*
- Markoff+01 *Pure jet*
- Malzac+04 *Magnetic 'reservoir' jet/corona*
- Yuan+05 *ADAF+jet*
- …

"The physical origin of the variability Is likely to be complicated."

B field dissipation ⇨ anti-correlation



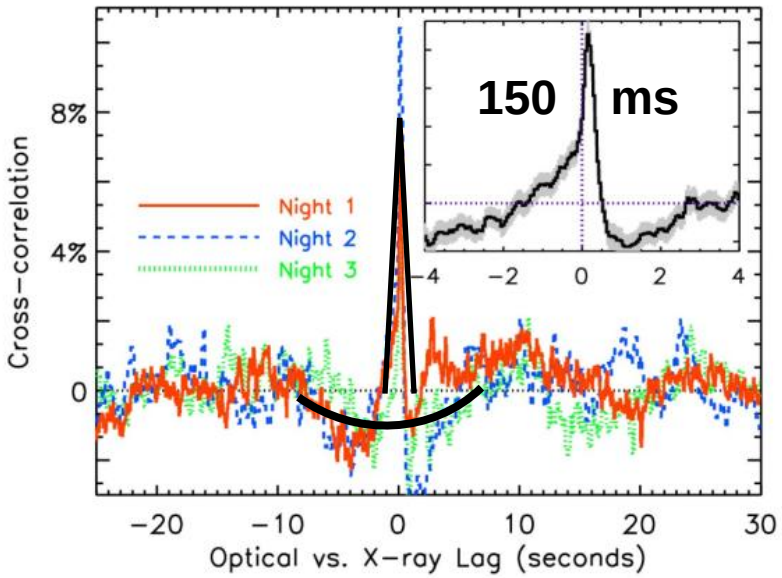


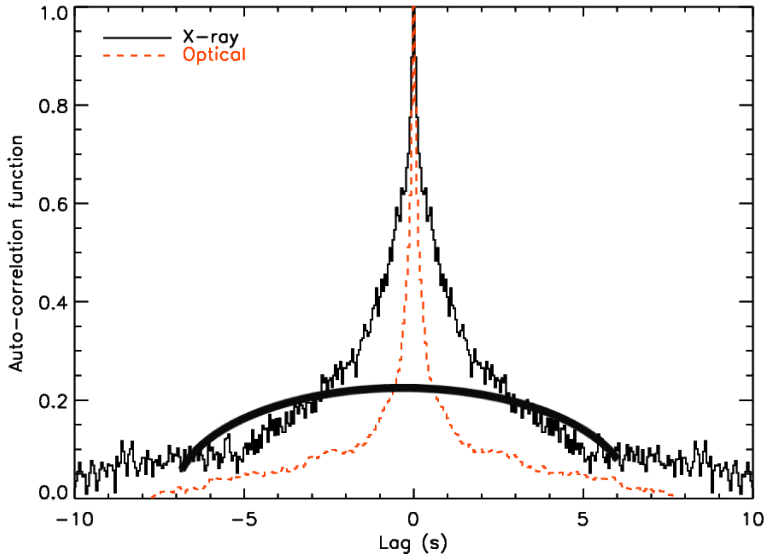


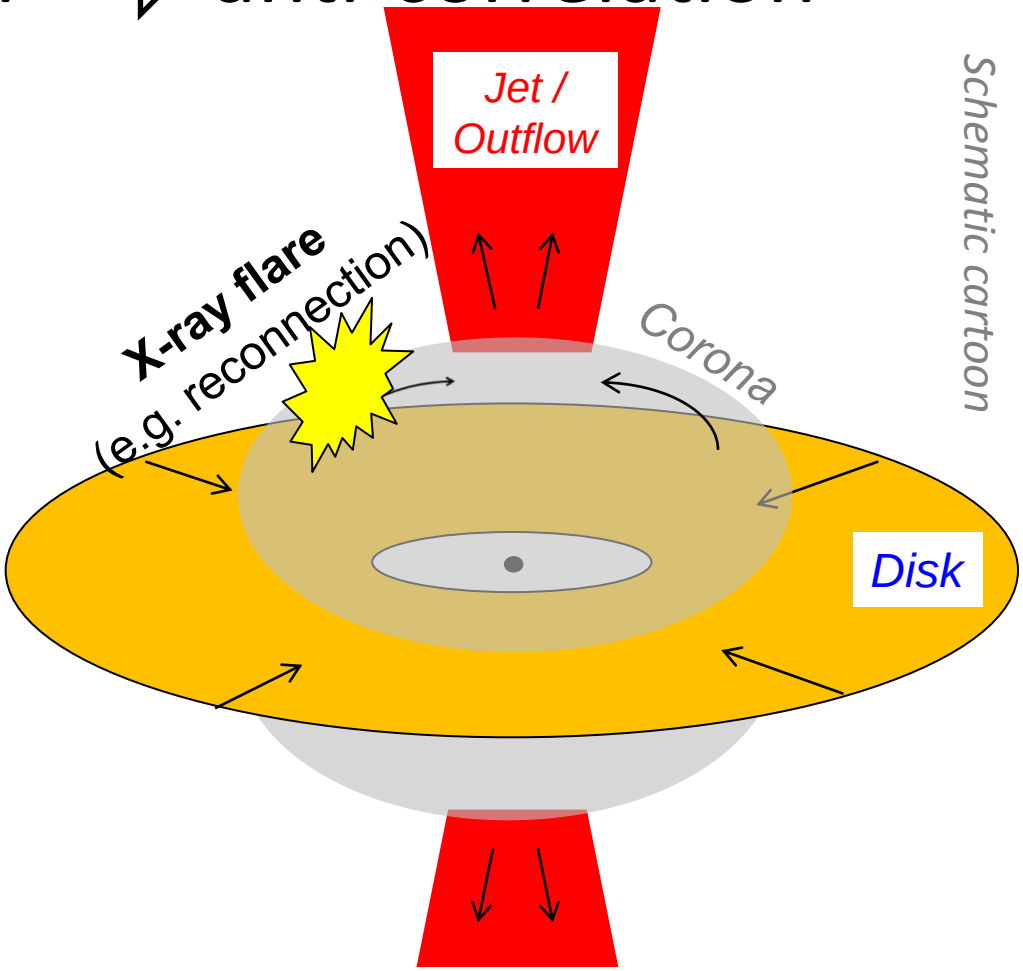
Release of <u>coronal</u> *B* energy density

⇒ ↓ optical cyclosynchrotron

B field dissipation ⇨ anti-correlation

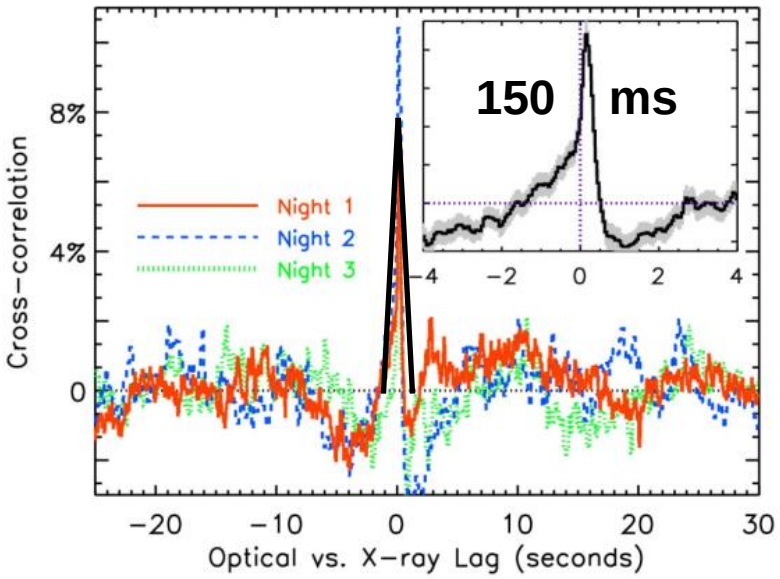






X-ray coronal flares lead to reordering of jet poloidal field (~ tens x $t_{dynamical}$ ~ 100 ms; Livio+03; Malzac+04)

CCFs characteristic times => interacting components



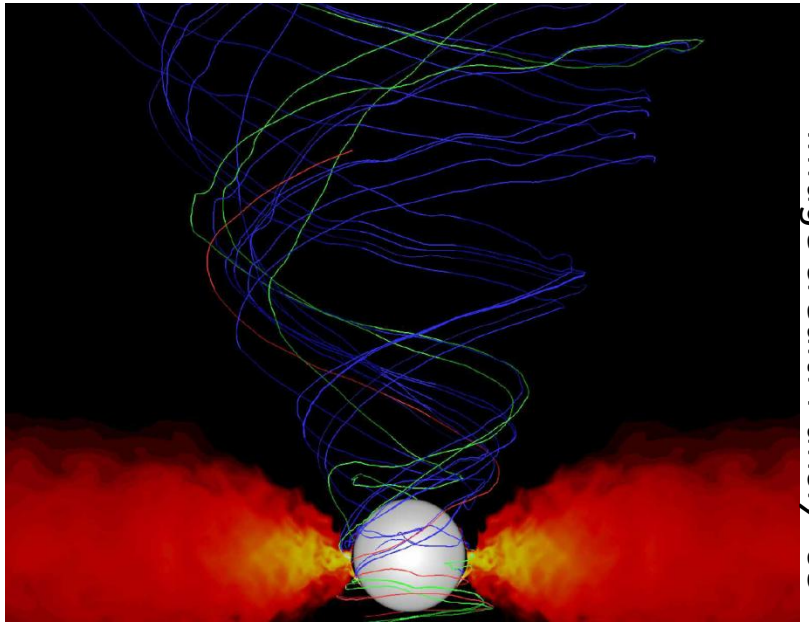


Image credit: Punsly+09

X-ray <u>coronal</u> flares lead to reordering of <u>jet</u> poloidal field
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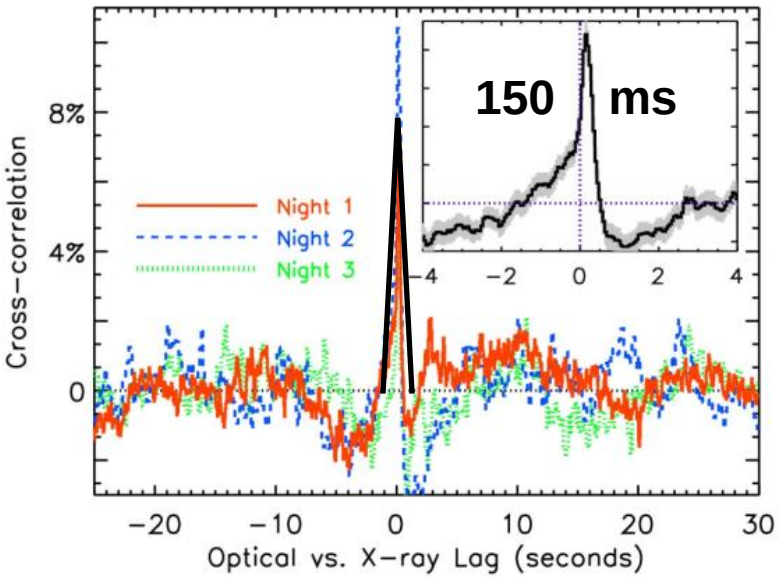
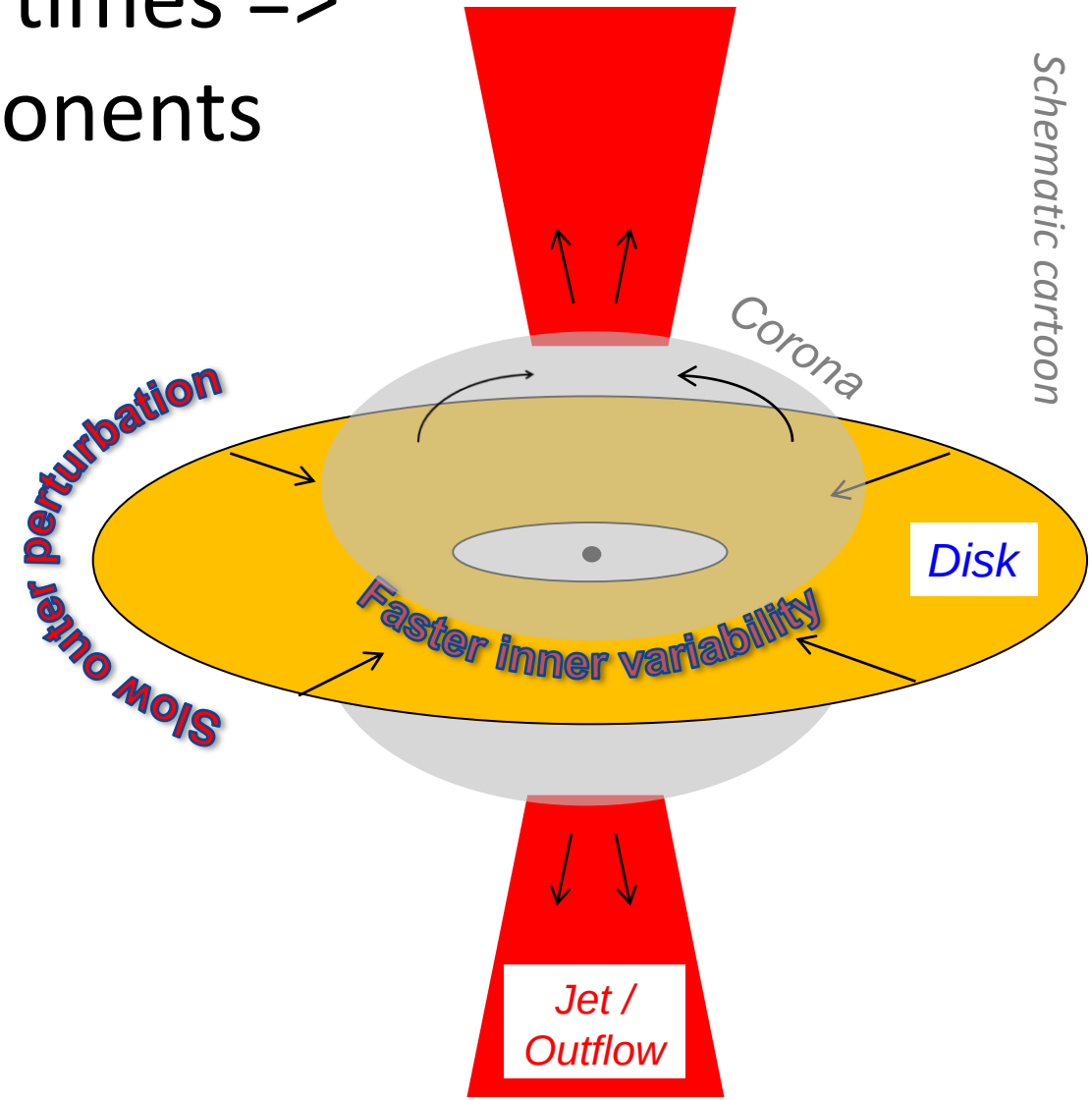
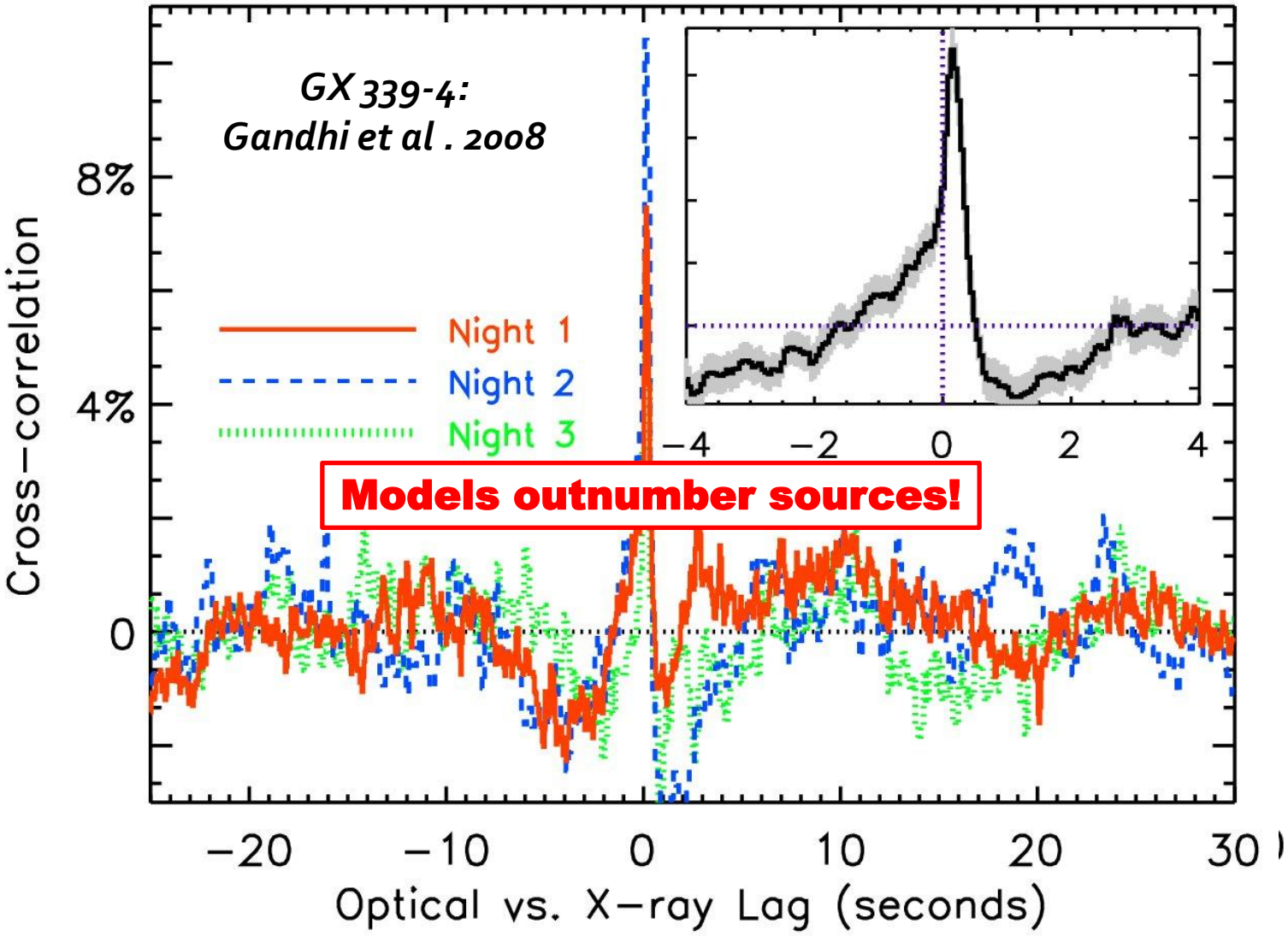




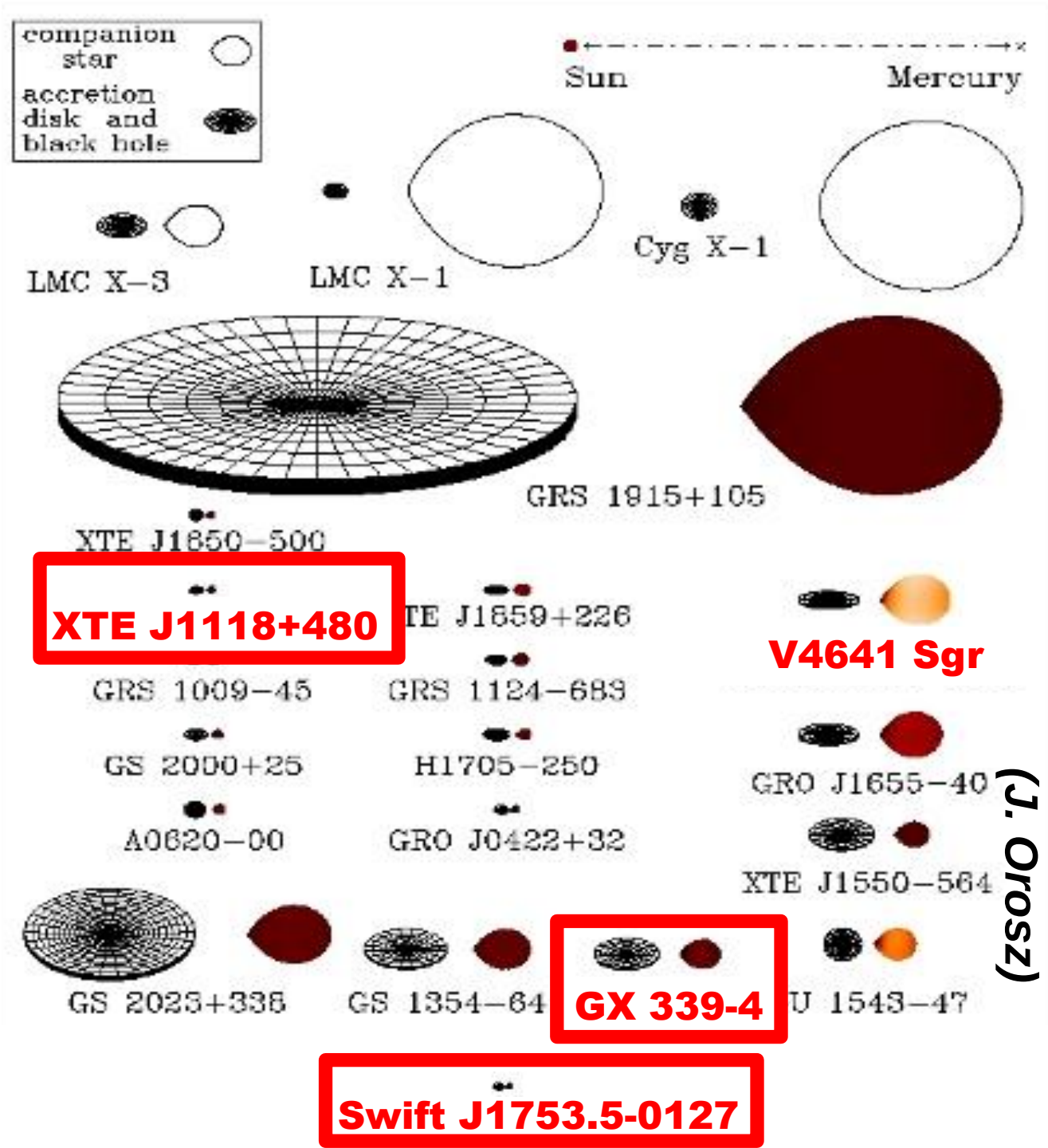
Propagation of perturbations : from <u>disc/corona</u> to <u>jet</u>

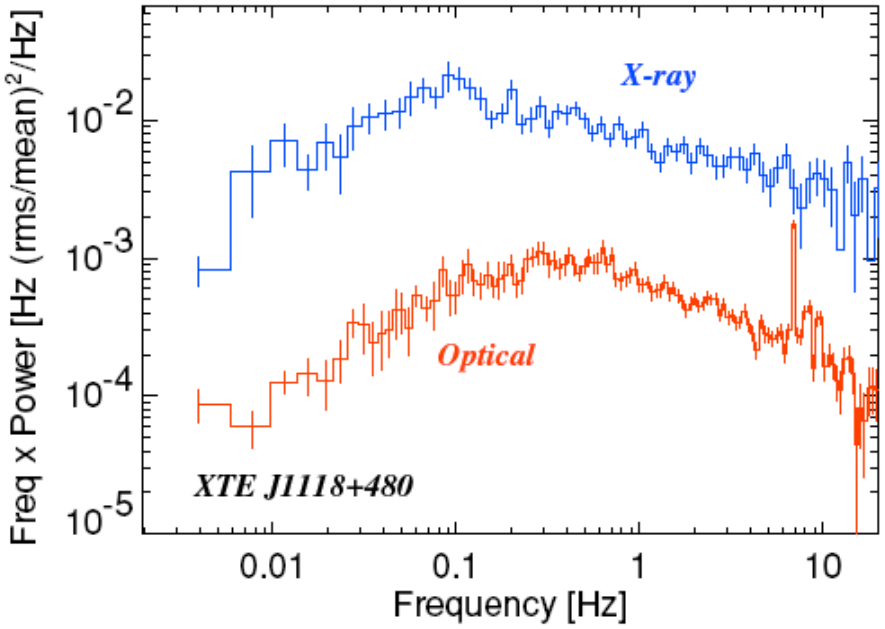
(150 ms ⇔ 50 R_G @ Alvenic speed, or 5000 R_G @ lightspeed)

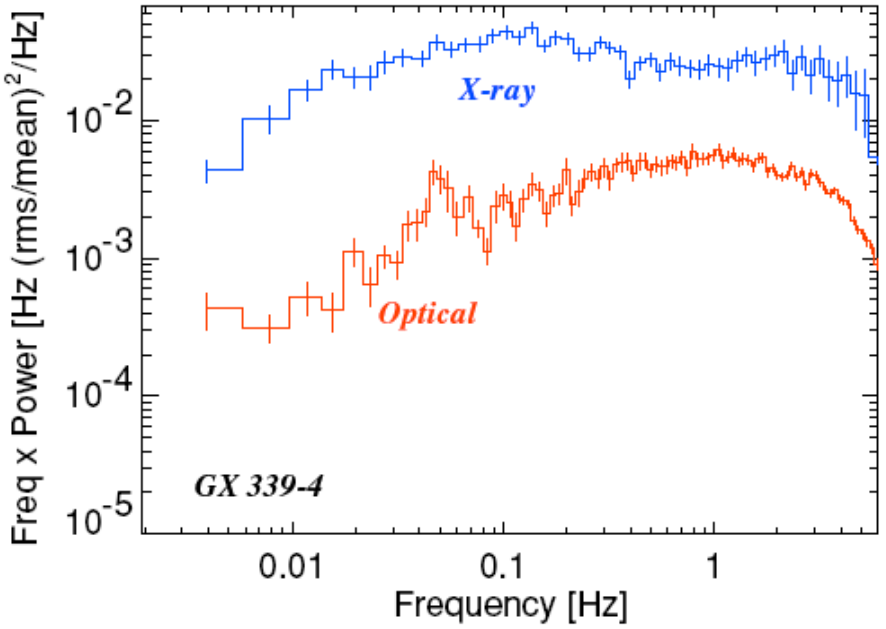
Complex optical/X-ray correlations



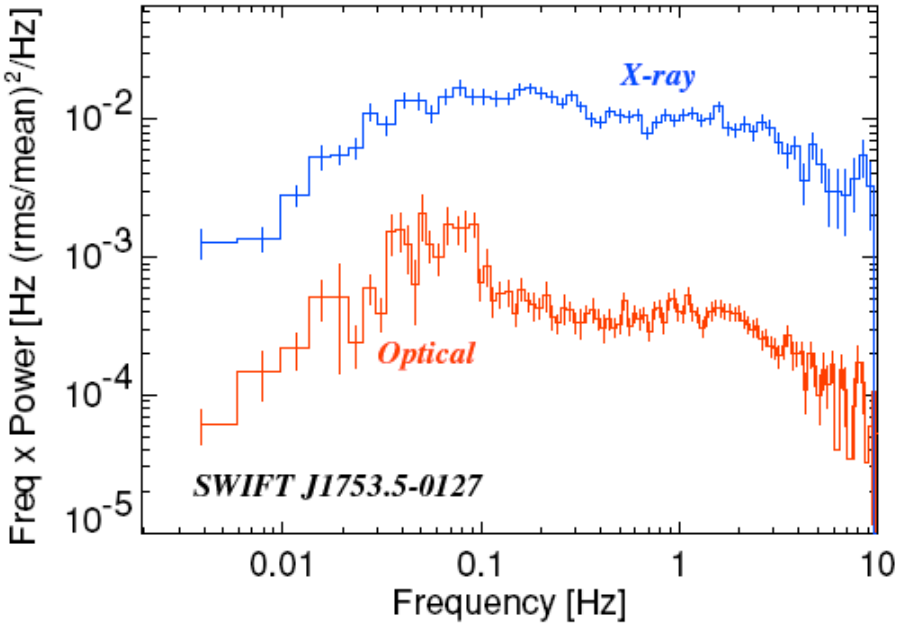
Anything special about these binaries?







Optical power spectra reminiscent of X-rays

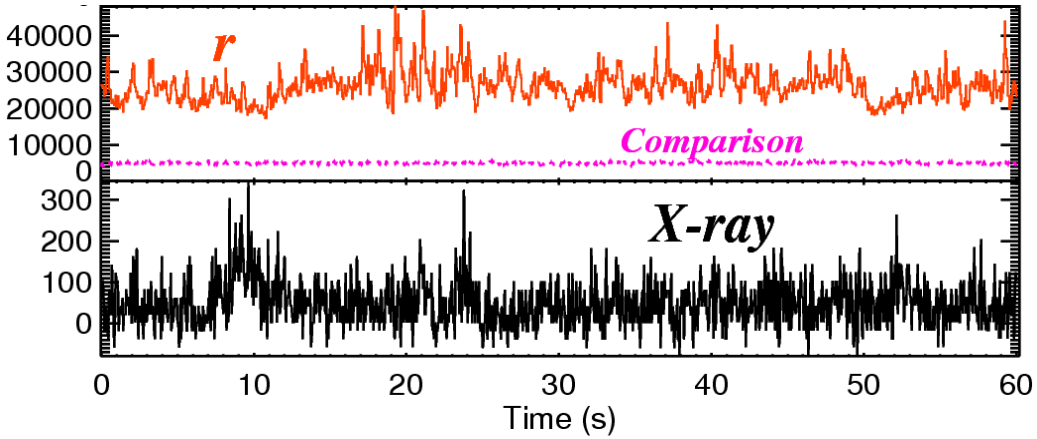


X-ray: PCA
Optical: Either r' or g' or white

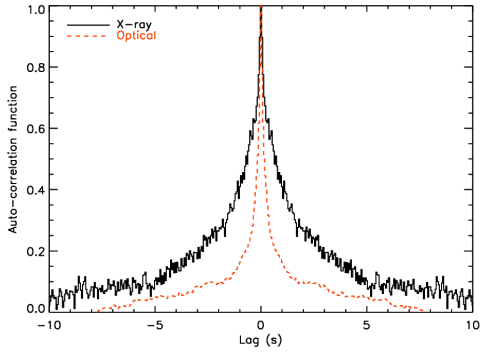
(Gandhi 2009)

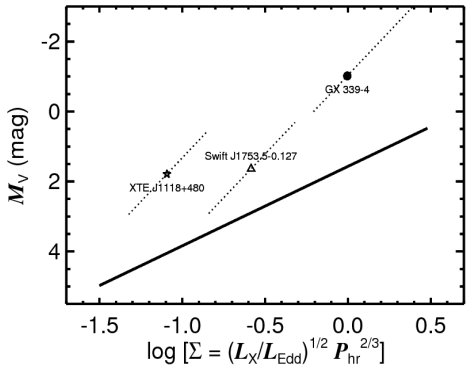
Summary

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

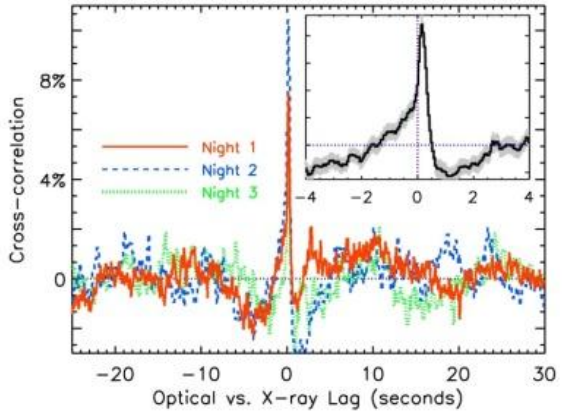


- Optical not reprocessed simply.

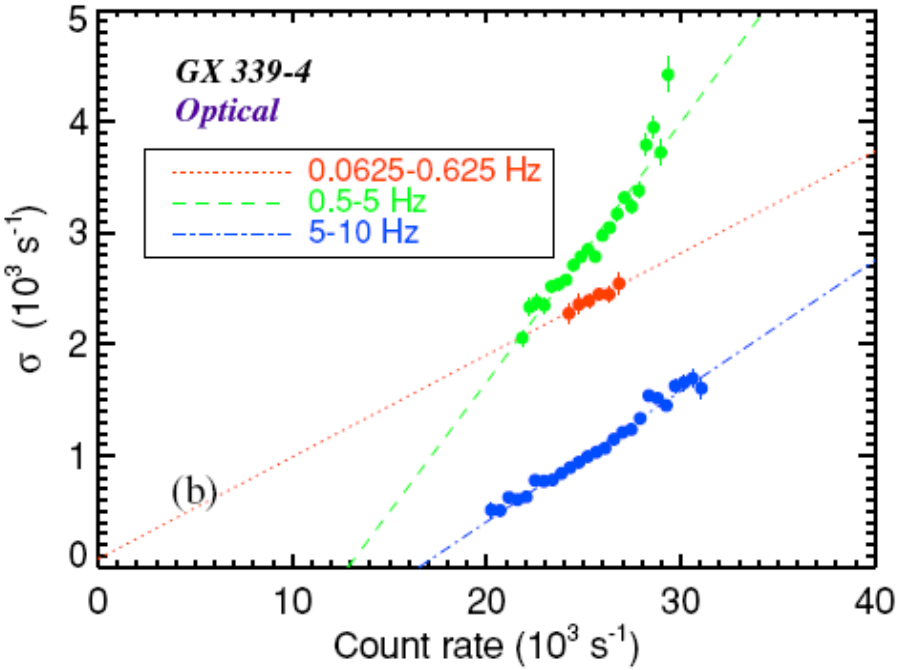


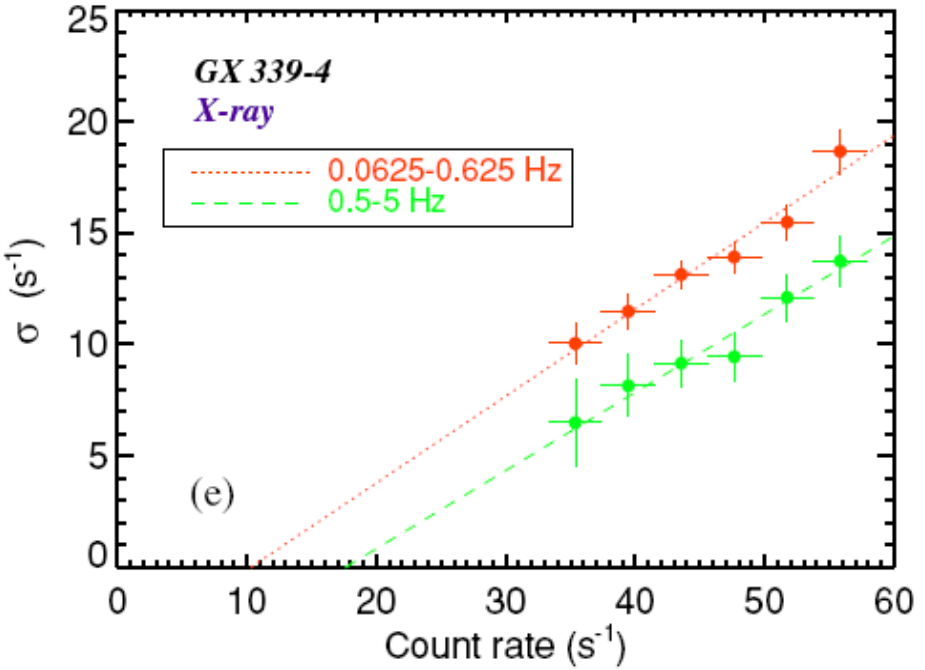


- Complex CCF
  => jet/corona/disk interaction.



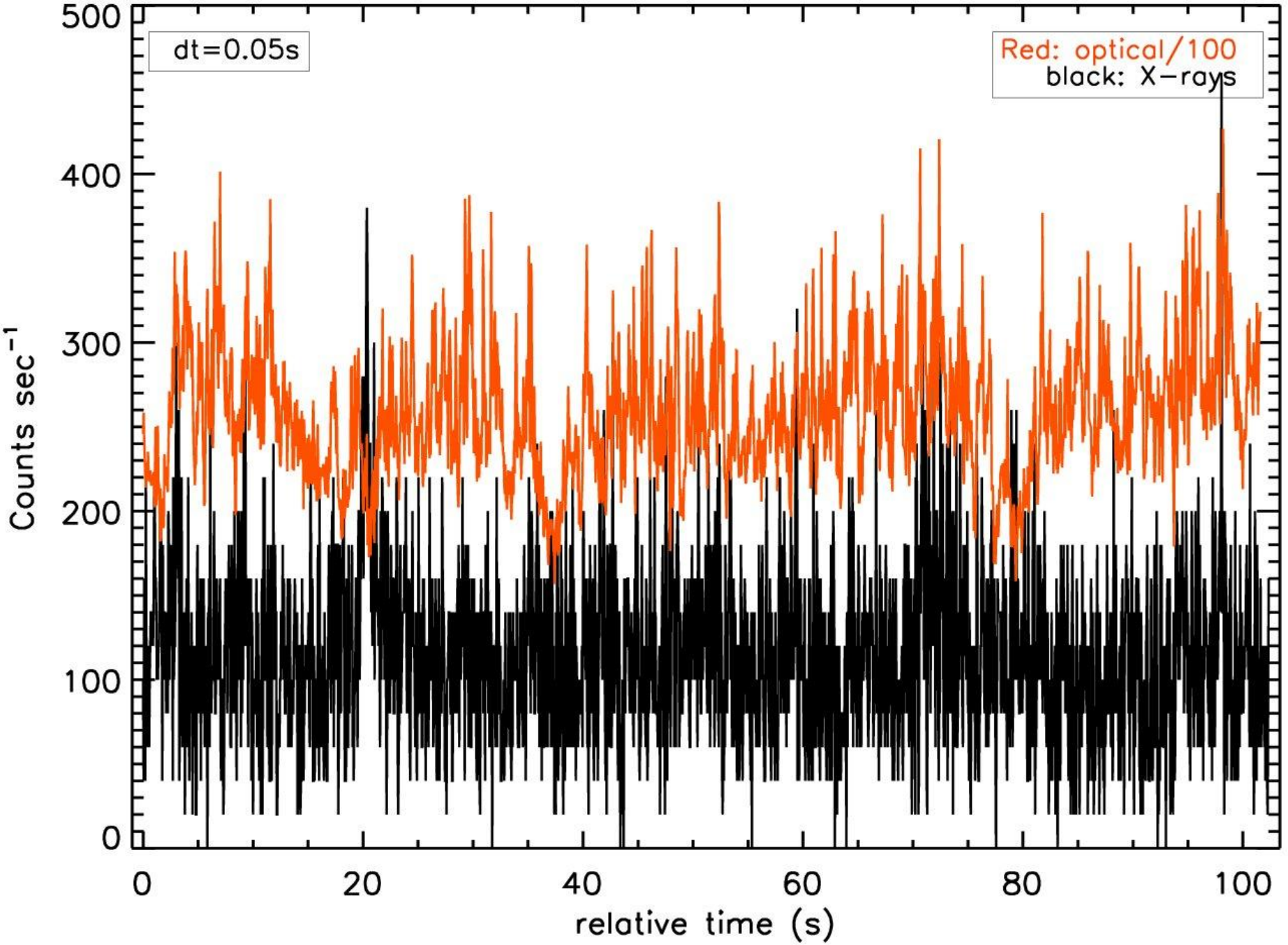
Testing variability models : flux dependence





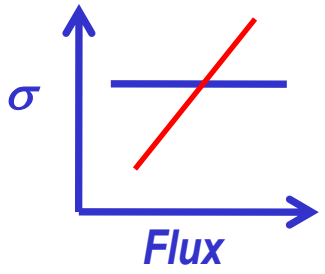
Measure variability of light curve sections
=> r.m.s. amplitude increases with flux

(Gandhi 2009, Uttley et al. 2001...2005)


dt=0.05s
Red: optical/100
black: X−rays
Counts sec^{-1}
relative time (s)
0
100
200
300
400
500
0
20
40
60
80
100

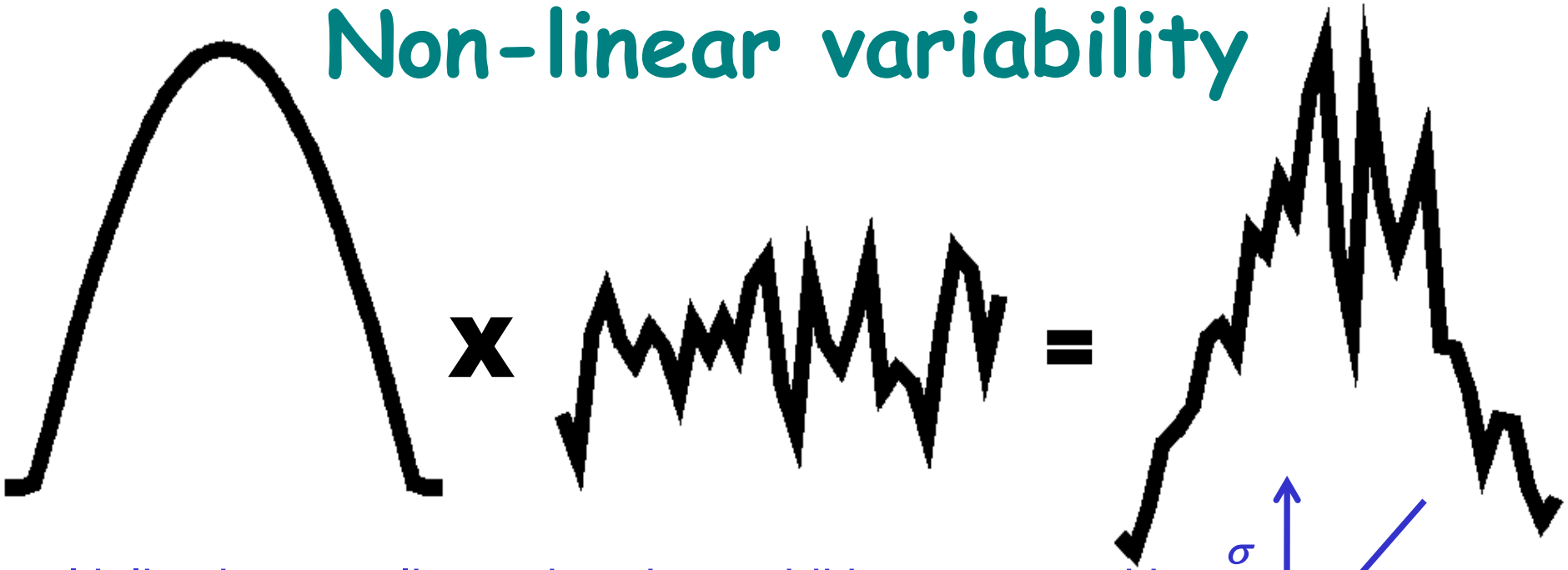
Additive shot models

Superposition of independent shots
=> Equal variability power at all fluxes



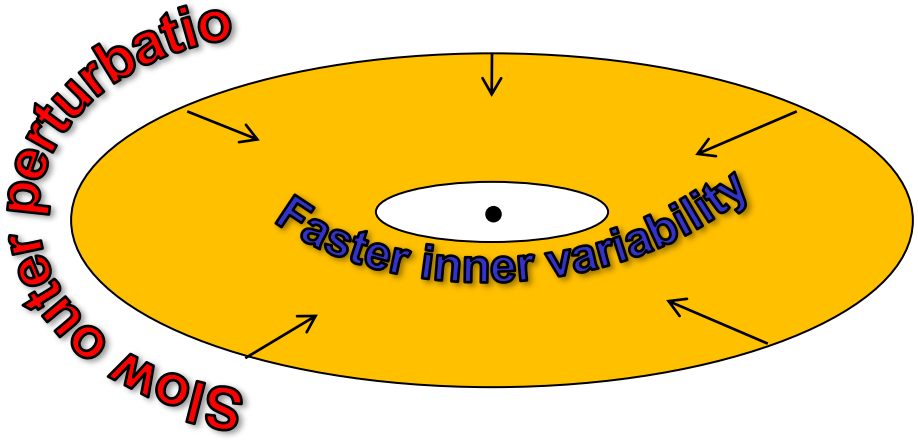
Ruled out in X-rays (Uttley et al. 2001...2005) and now optical (Gandhi 2009)

Non-linear variability

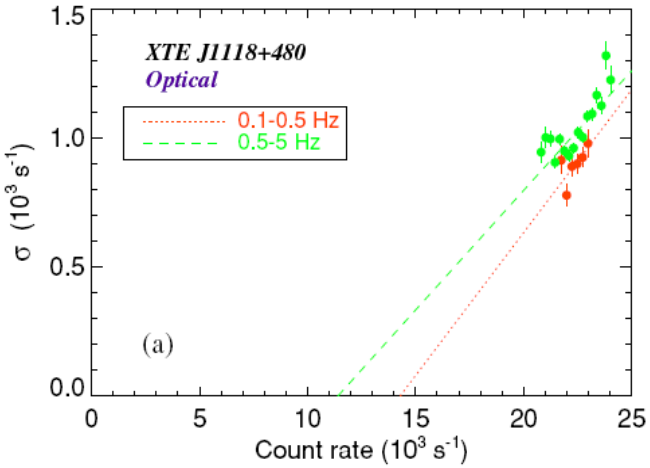


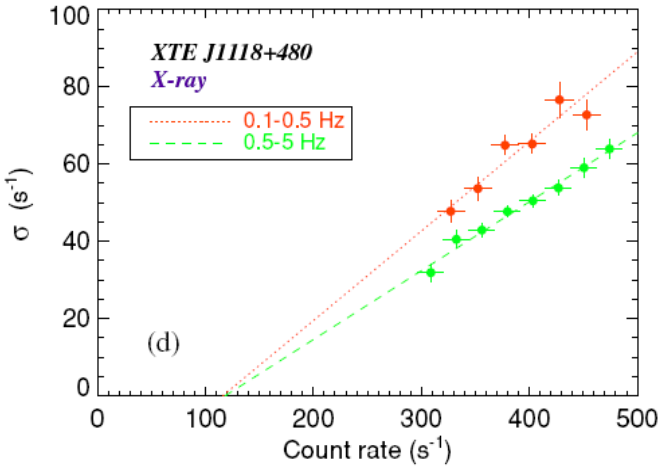
Multiplicative coupling rather than additive superposition

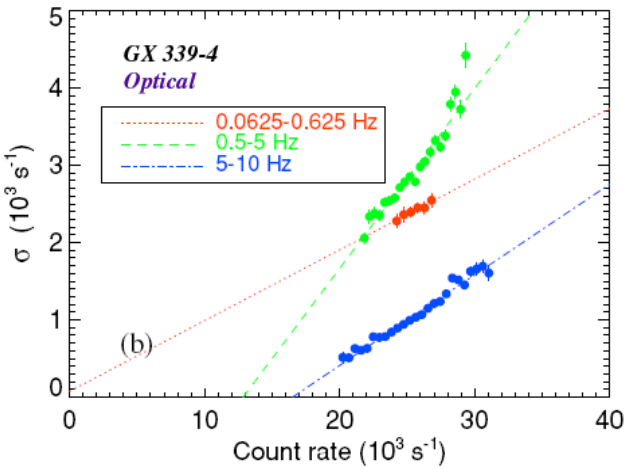
"Propagating perturbation models" (e.g. Lyubarskii 1987)

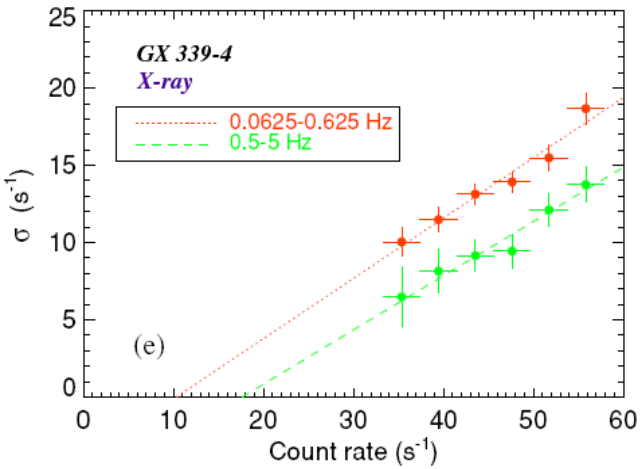


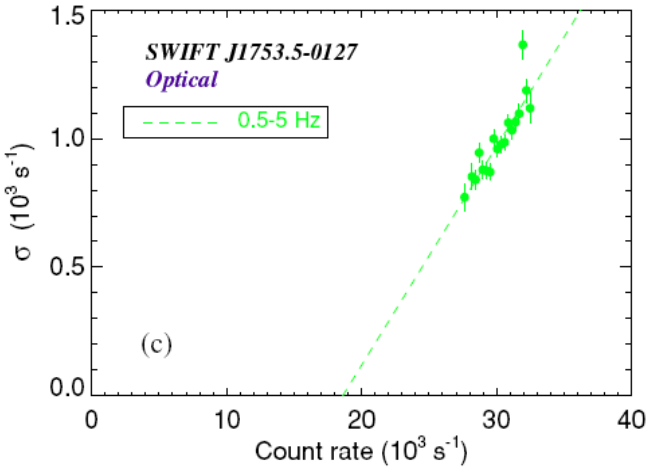
rms-flux relation in several binaries

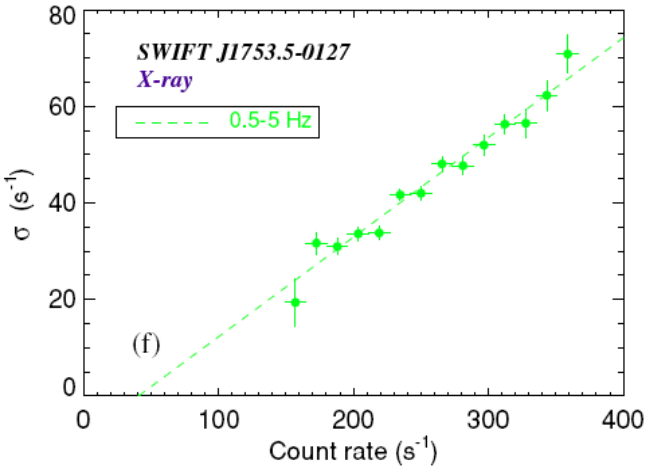












(Gandhi 2009)

Testing non-linearity
=> log-normal distribution

Multiplicative Coupling:

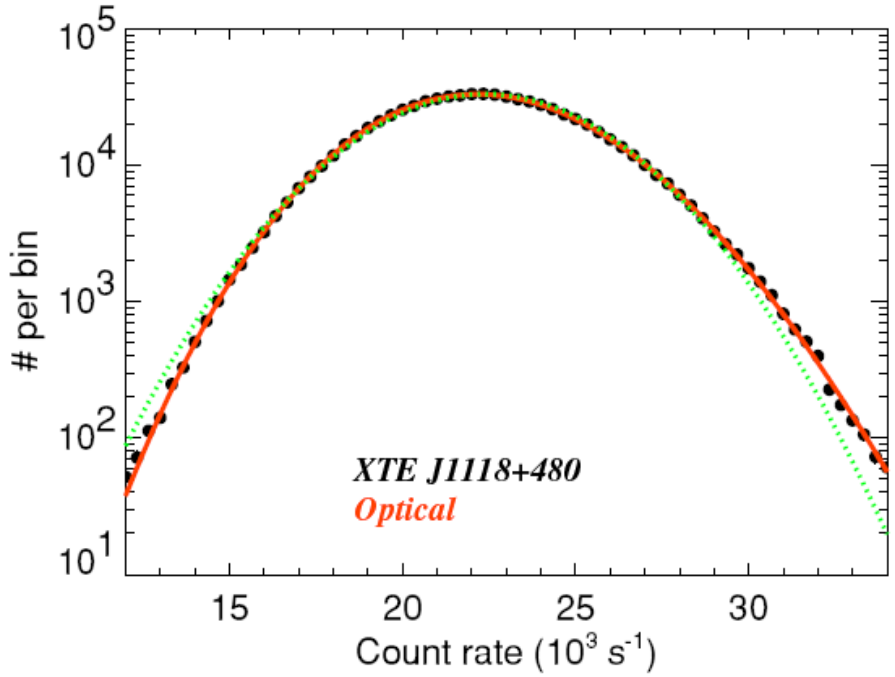
$$f(\mathrm{t}) \propto \prod_i x_i(t)$$

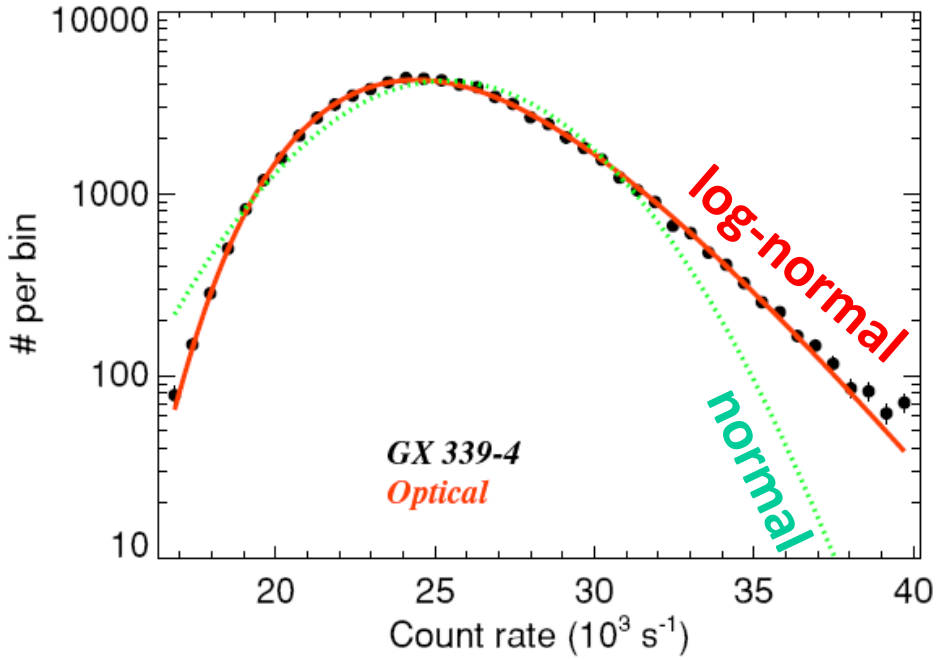
$$x_i(t) \propto A_\mathrm{i} \sin(2\pi\nu_\mathrm{i} t + \varphi_\mathrm{i})$$

=> log(light-curve amplitude) has normal distribution

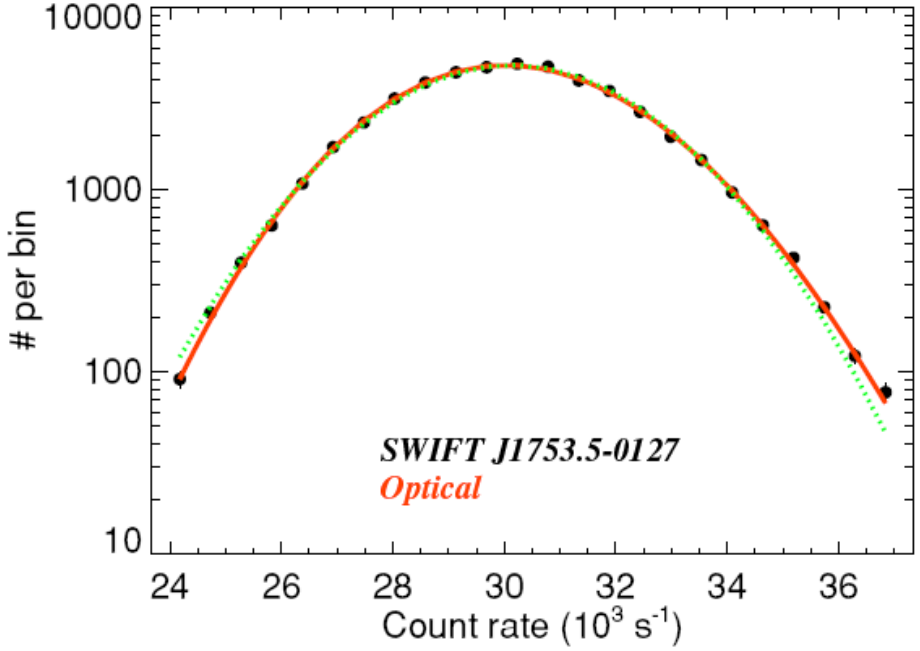
$$\log[f(t)] \propto \sum_i \log[x_\mathrm{i}\,(t)] \equiv \mathrm{N}(\bar{f},\, \sigma_f)$$

(Uttley et al. 2005)





Log-normal flare distribution of light curves



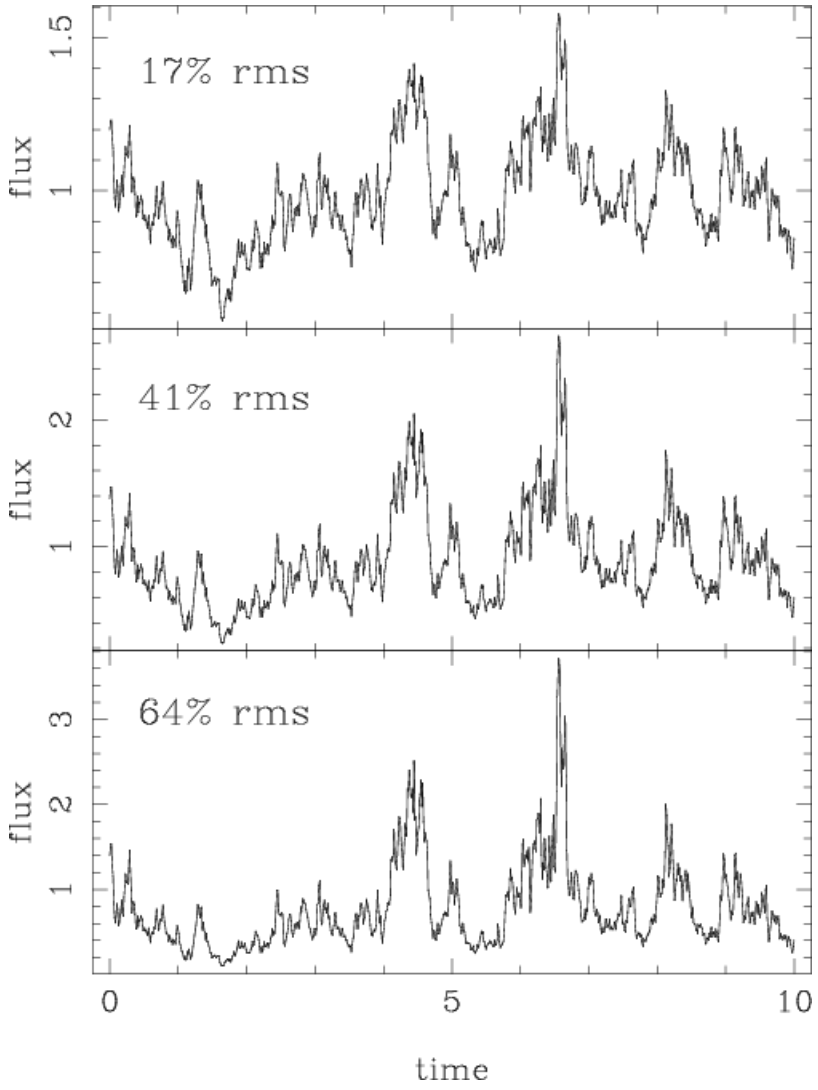
(Gandhi 2009)

Also seen
In AGN
=> universal

Flare amplitudes should be drawn from an *exponential* variate distribution

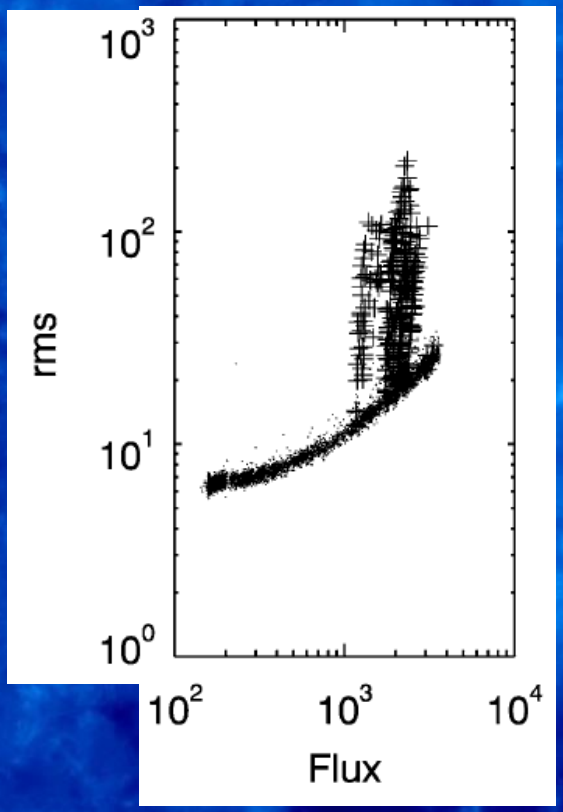
$$\log[f(t)] \equiv \mathrm{N}(\bar{f},\ \sigma_f)$$

$$\Rightarrow f(t) \equiv \exp[\mathrm{N}(\bar{f},\ \sigma_f)]$$



(Uttley et al. 2005)

Variability correlations in the Solar corona



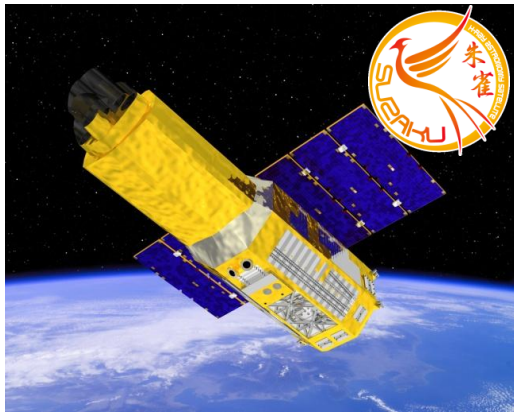
Solar radio burst (Wang+08)

Solar flares
+
coronal loops

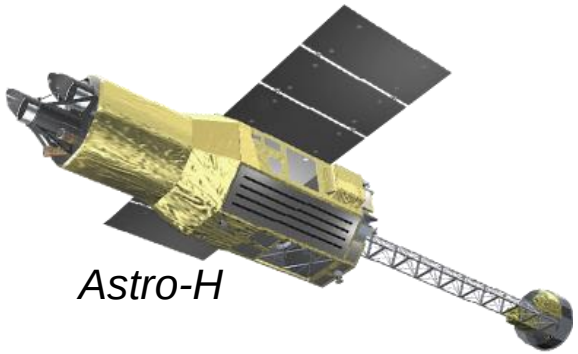
RMS-flux relation in the Solar corona

Image: NASA Stereo

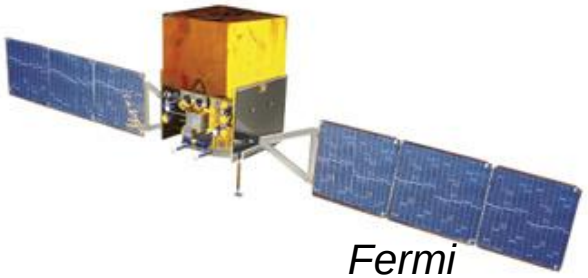
Future



Suzaku (p-sum mode)

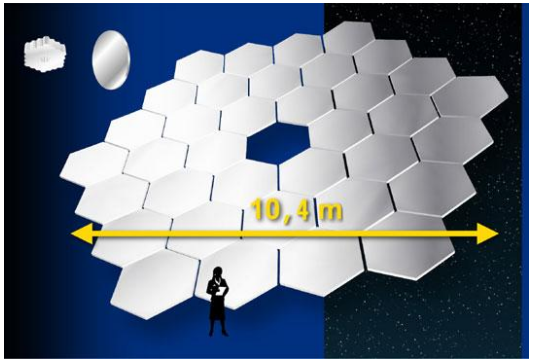


Astro-H



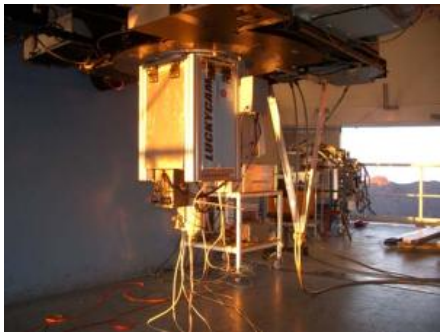
Fermi

VLT/FORS
High
Time Res
mode



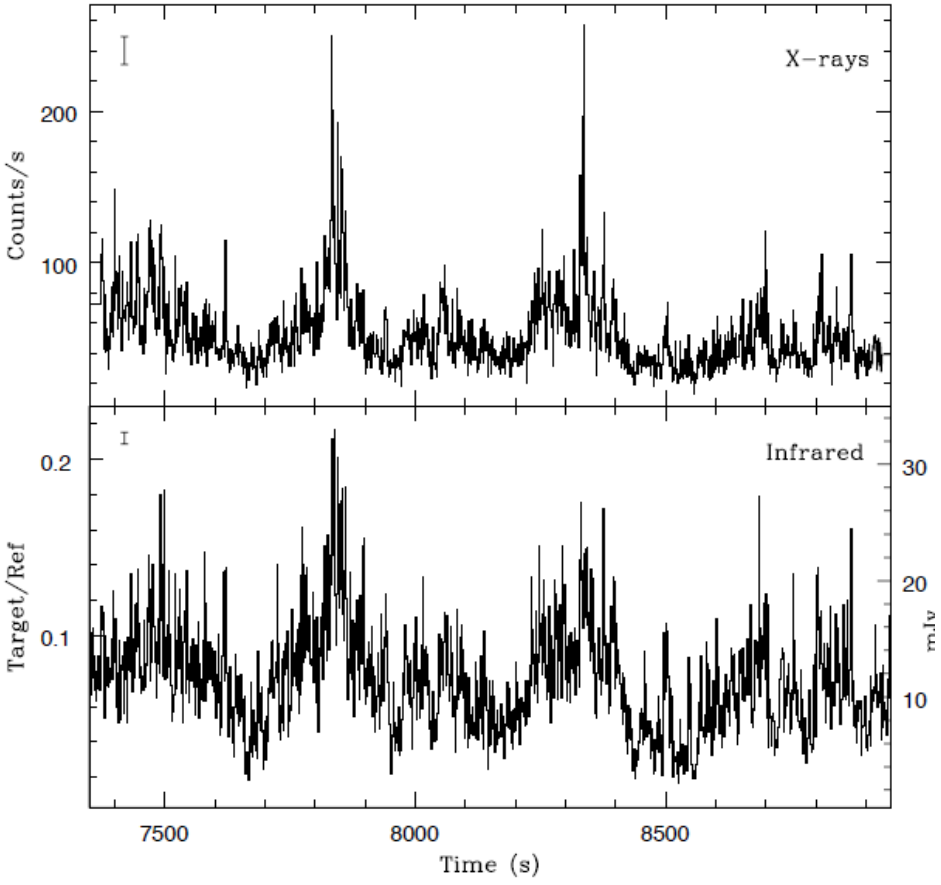
Gran Tel. Canarias 10.4 m
CIRCE
Fast infrared

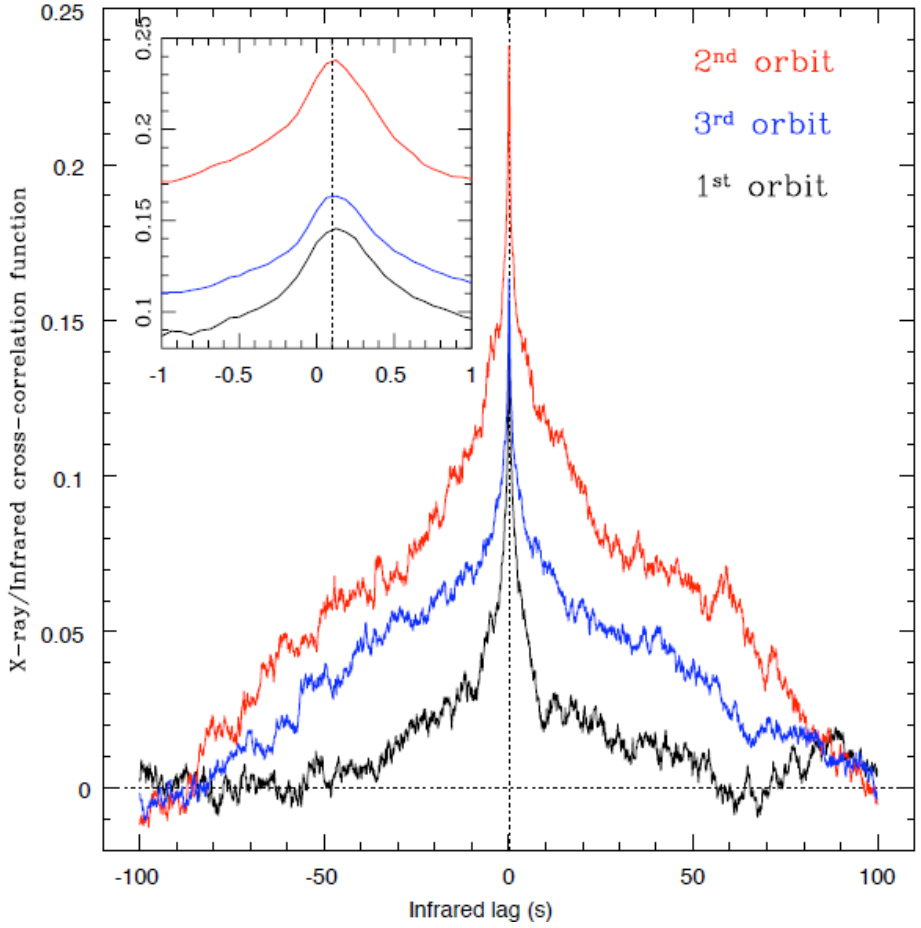
SALTICAM



'Lucky'
speckle
camera

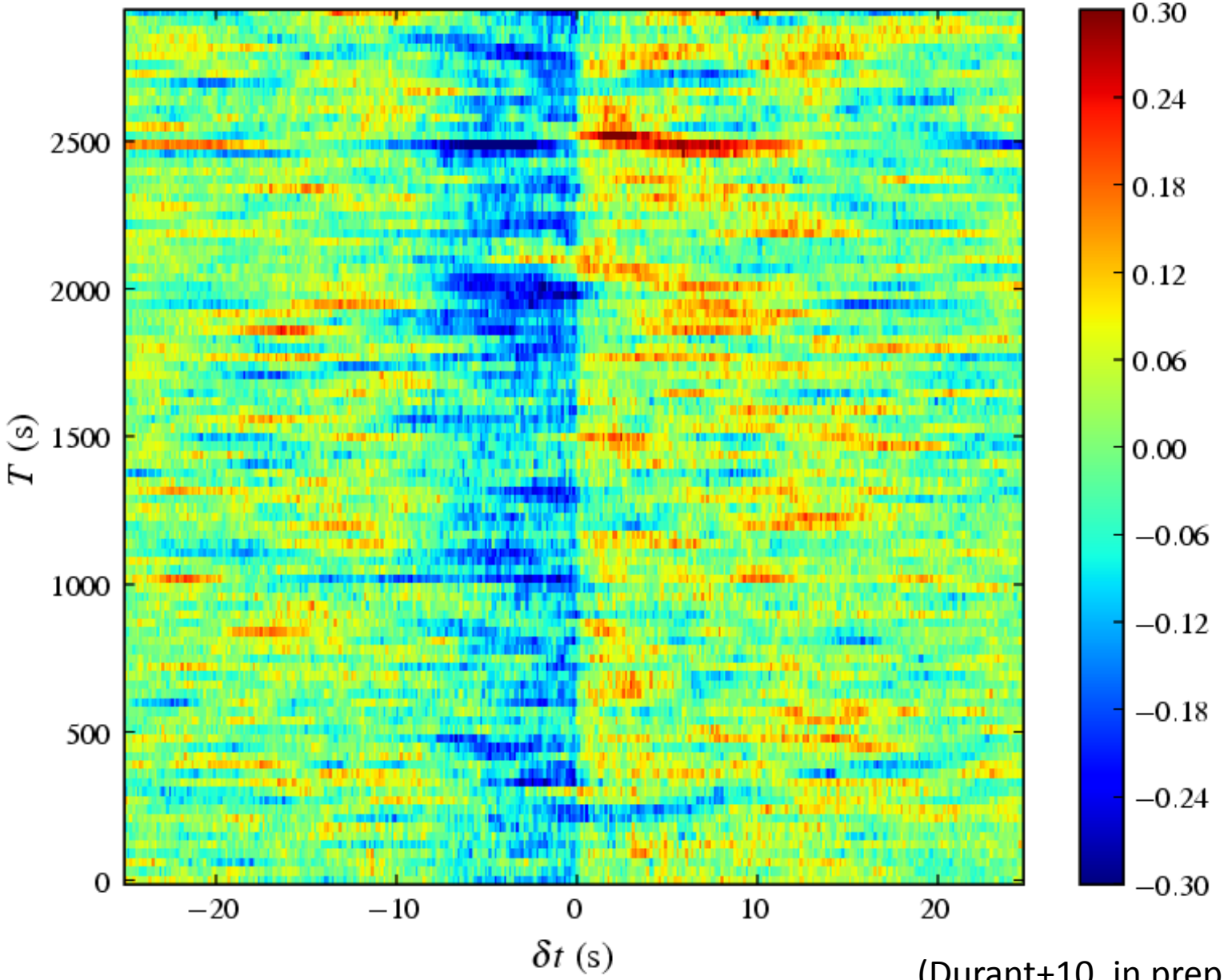
Next step: infrared?





(Casella+10)

Next step : tracking CCFs dynamically



(Durant+10, in prep)

Summary

- Optical timing ⇔ independent, complementary constraints to X-ray timing.
- How “close in” can optical timing take us?