FAST TIMING VARIABILITY IN X-RAY BINARIES : MOTIVATIONS, METHODS, & DIAGNOSIS

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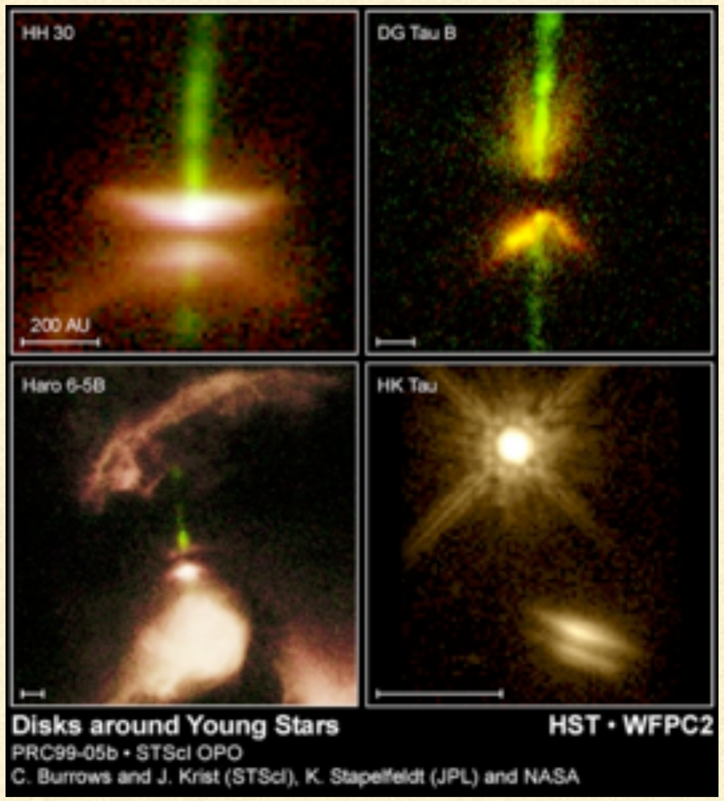
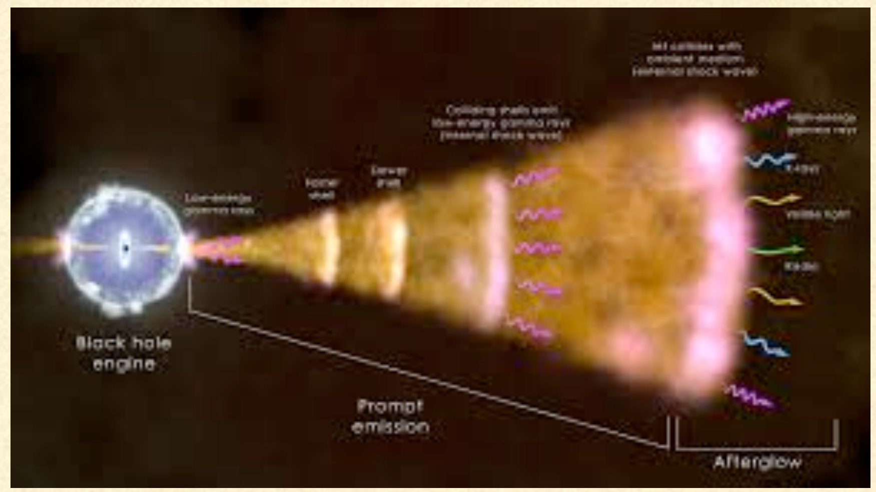
ACCRETION(-EJECTION) AN UBIQUITOUS PHENOMENON

Star formation……



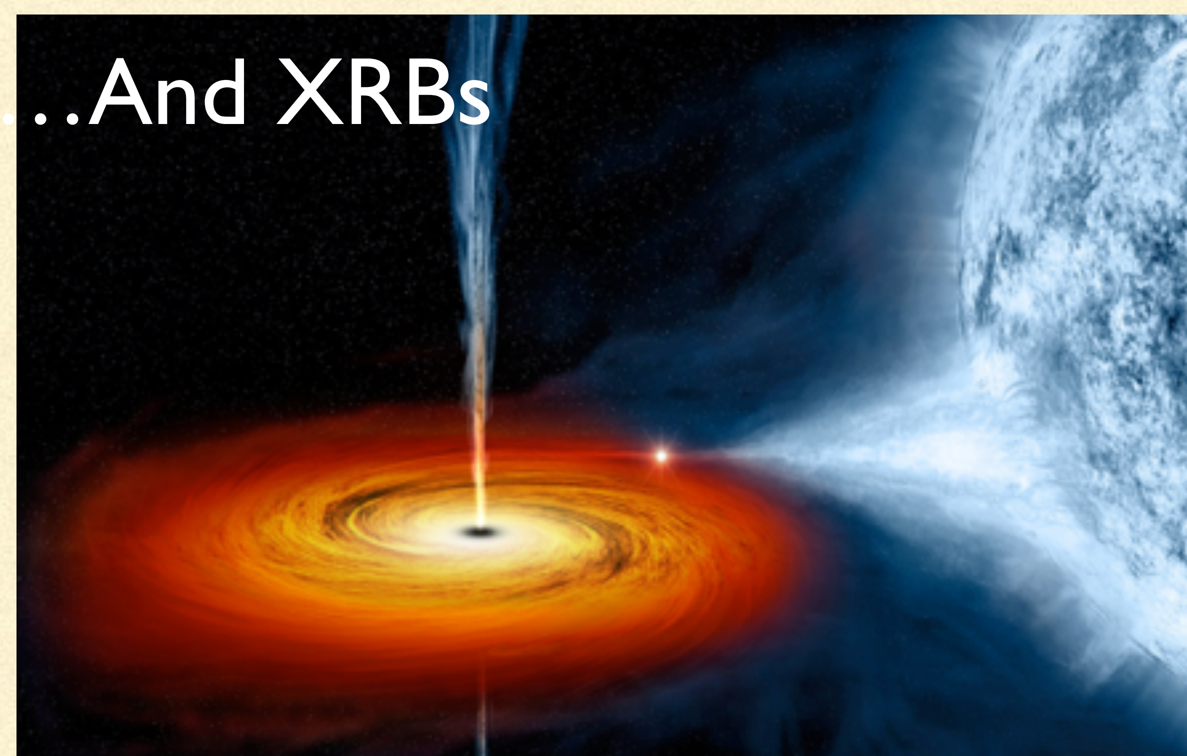
fate of the most massive stars



Centres of galaxies

Stars disrupted by black hole

..And XRBs



MICROQUASARS = LABS OF EXTREME PHYSICS

Fundamental physics:

- -Strong gravity
- -Black Holes
- -Plasma physics
- -Dense matter
- -Strong B field (NS)

Astronomy

- -Population
- -Star evolution
- -Link with Galactic evolution
- -Geometry of media

Astrophysics

- -Accretion
- -Acceleration
- -Feedback on ISM
- -Radiation
- -Matter-radiation
- -Fast variability

MOTIVATIONS & SPECTRAL METHODS

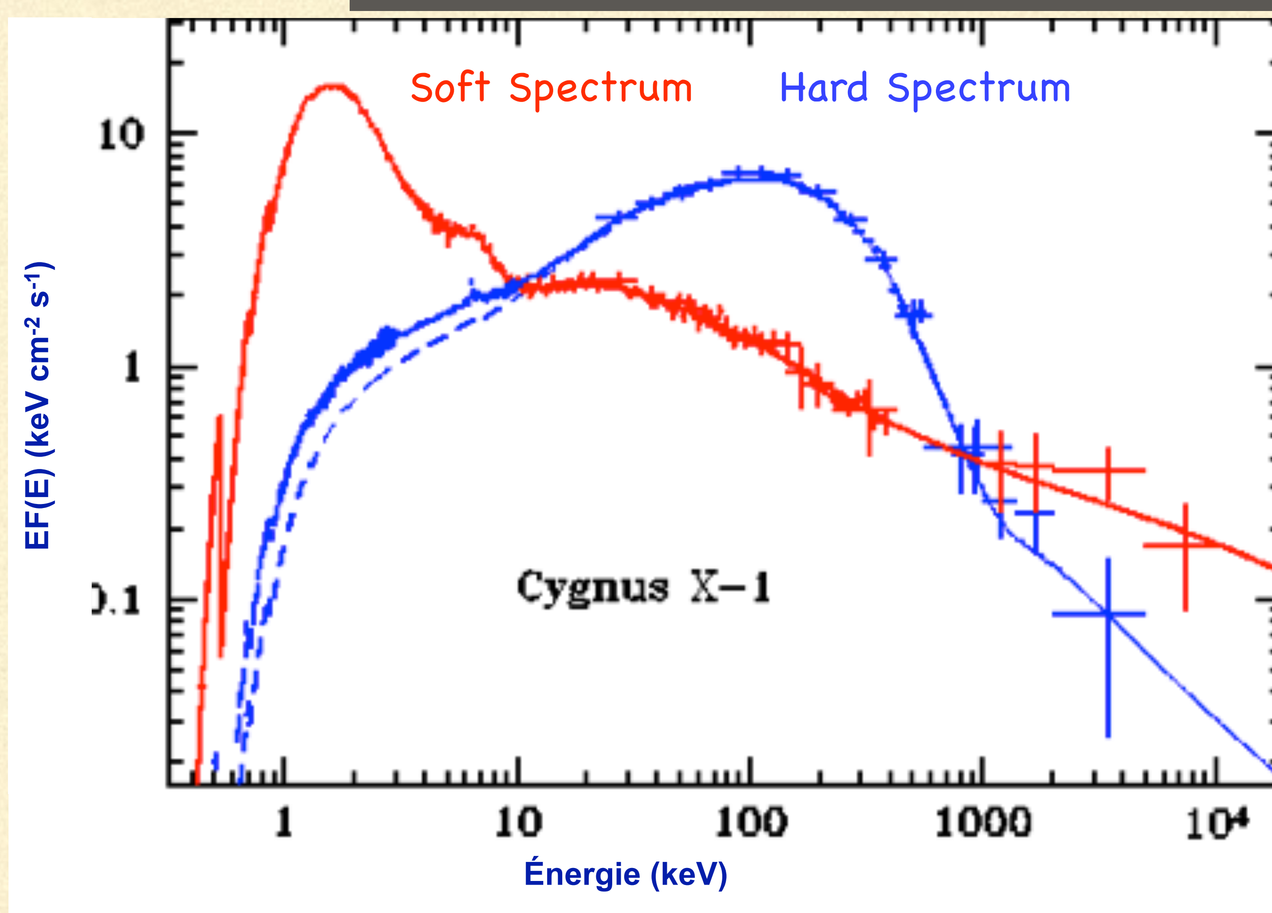
=>Close objects / Galactic (~8 kpc)

=>Bright

$$L_{\rm acc} = \eta c^2 \frac{dm}{dt} \quad \Rightarrow \quad L_{acc} = 10^{35} erg/s$$

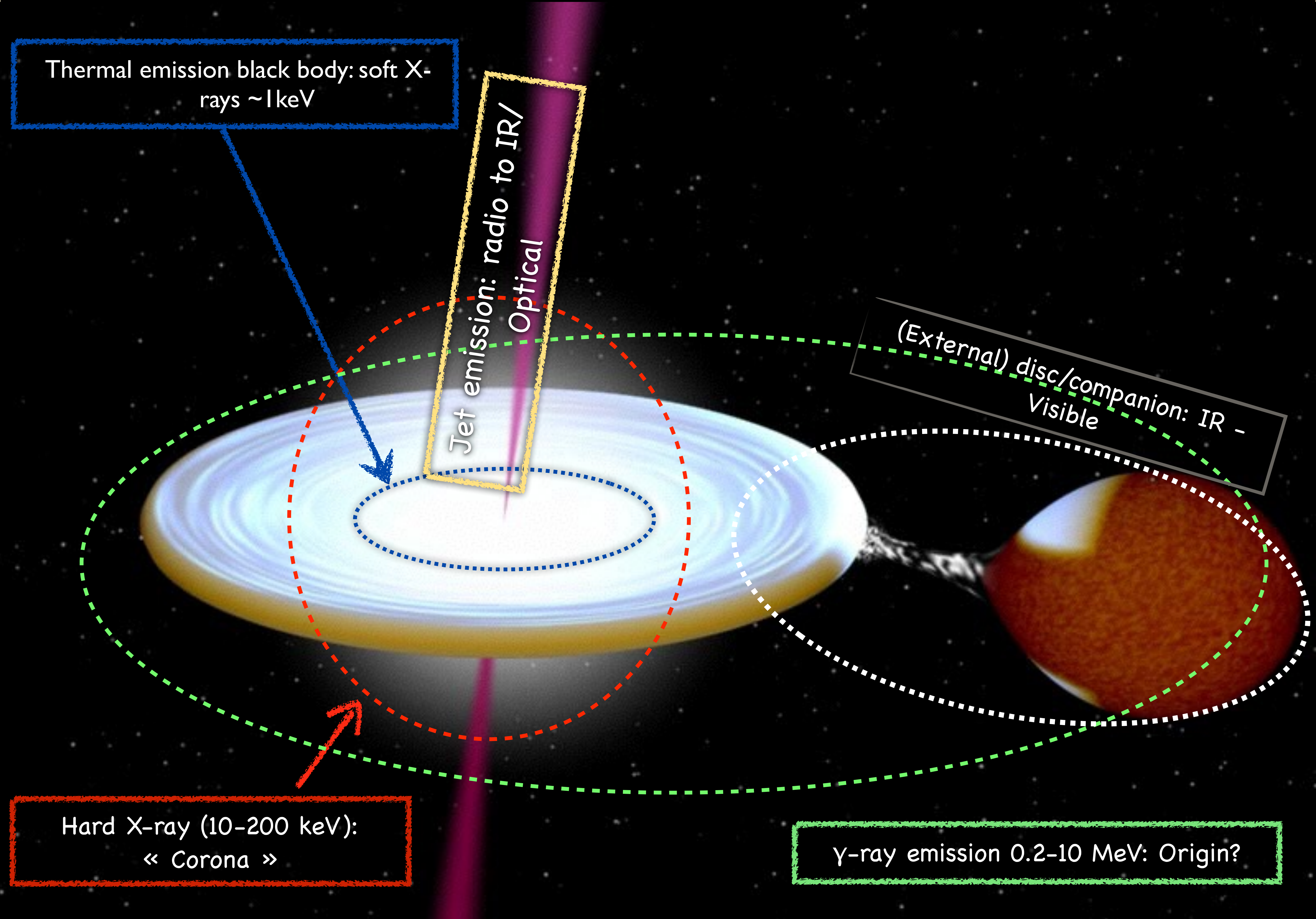
=>Strong X-ray emitters

$$T_b = (\frac{L_{acc}}{4\pi\sigma R_{OC}^2})^{0.25} \simeq 0.2 \text{ keV}$$



McConnell+ '02

BASIC VIEW: EMITTING MEDIA



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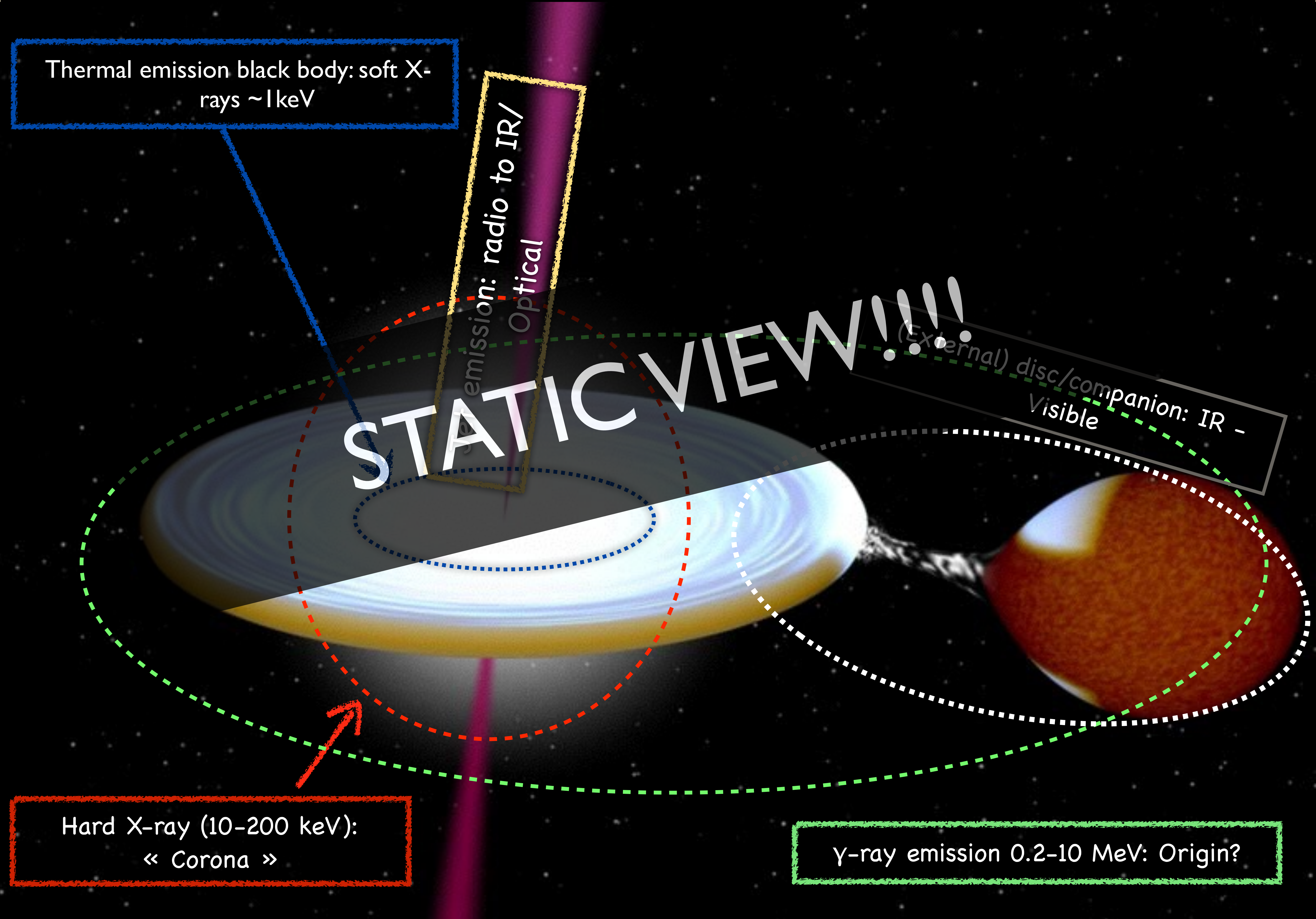
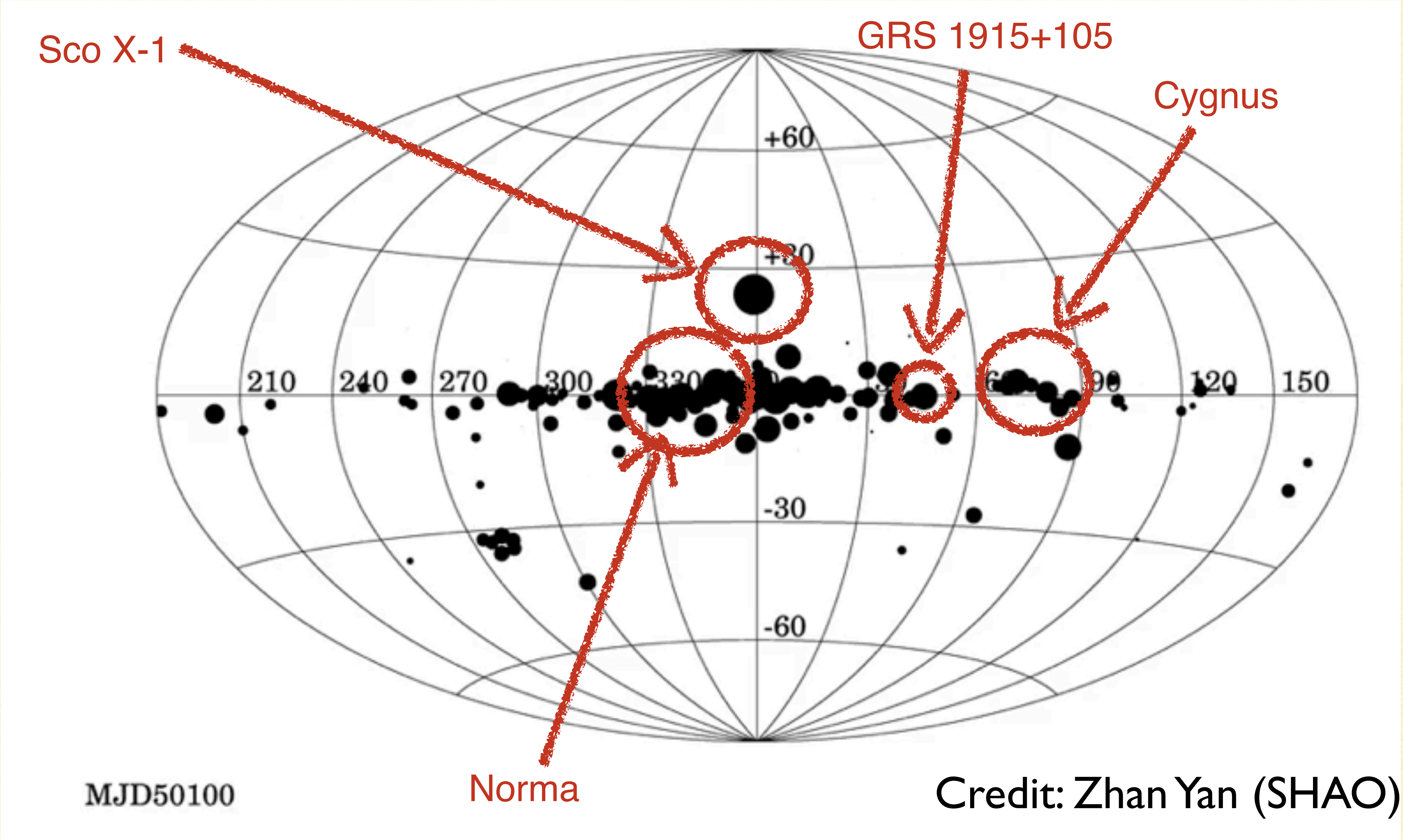


THE X-RAY SKY: VIOLENT & VARIABLE



RXTE/ASM: 16 years all sky monitoring of the X-ray sky

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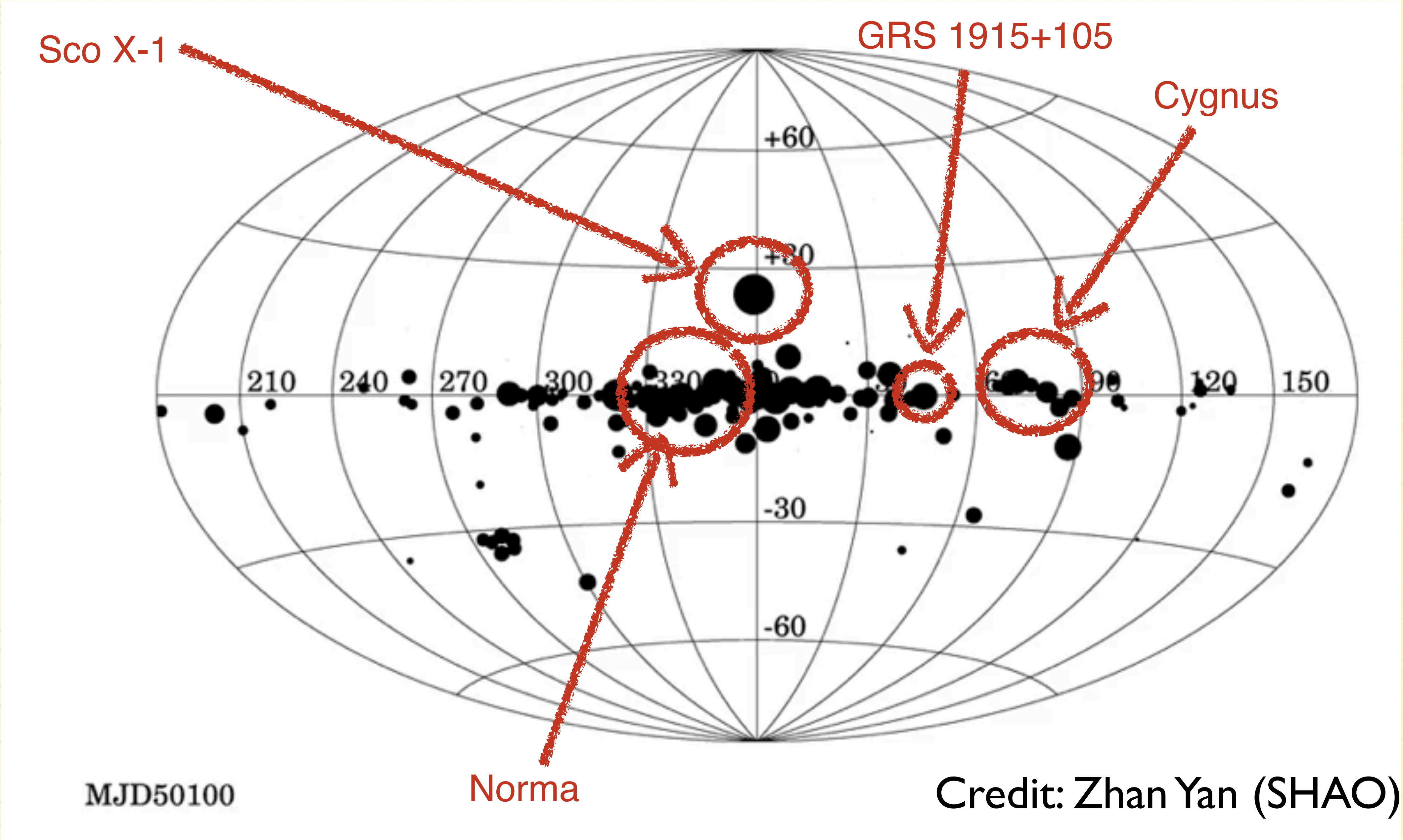


RXTE/ASM: 16 years all sky monitoring of the X-ray sky

X-RAY VARIABILITY: EXPECTED

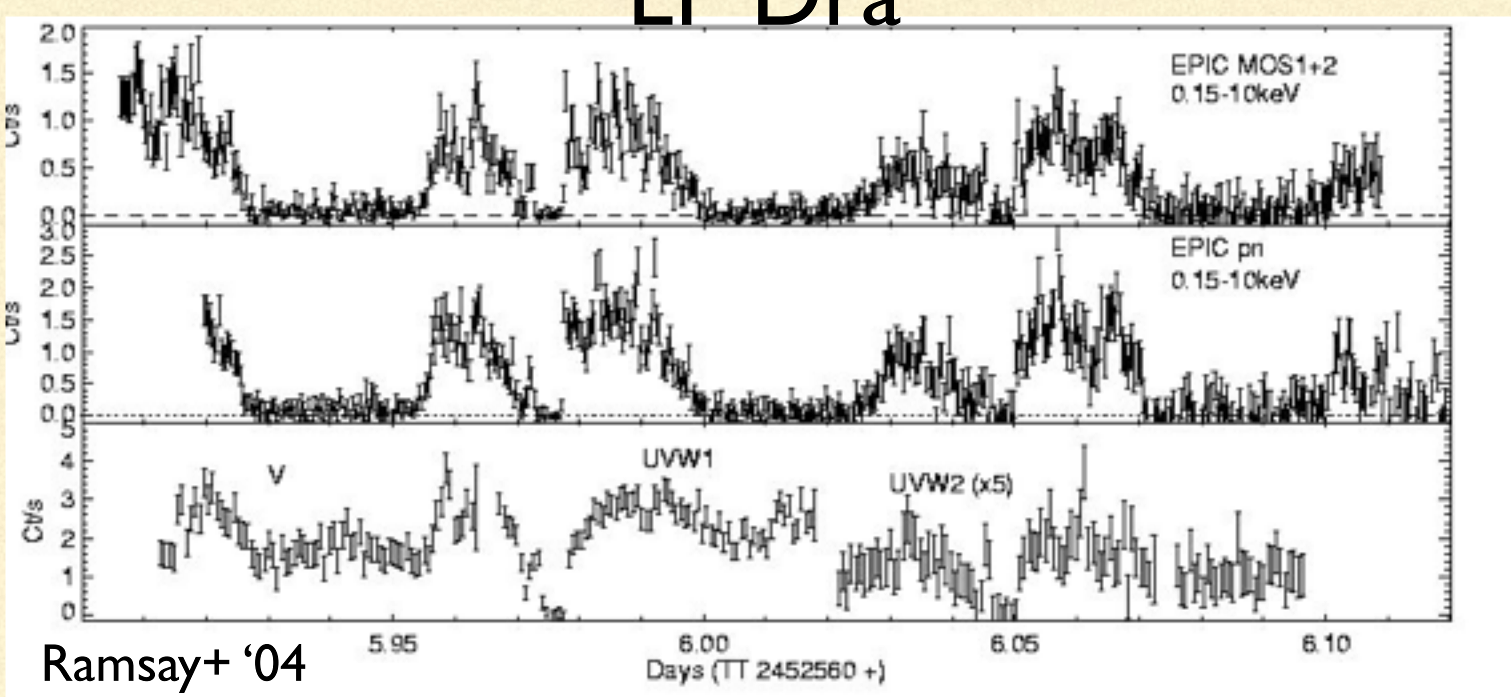
$$\tau_{\rm dyn,Kepler} \sim \sqrt{\frac{r^3}{GM_{OC}}} \qquad \tau_{\rm dyn,Kepler} \sim 2\ {\rm ms}(1\ {\rm M}_\odot, 100\ {\rm km})$$

$$1\ {\rm hr} \lesssim {\rm P}_{\rm orb} \lesssim 100\ {\rm j}$$

$$\text{Spin of neutron stars}: 1\ {\rm ms} \lesssim P \lesssim 1{\rm hr}$$

Variability can be expected just because of natural periods in systems

EP Dra



Ramsay+ '04

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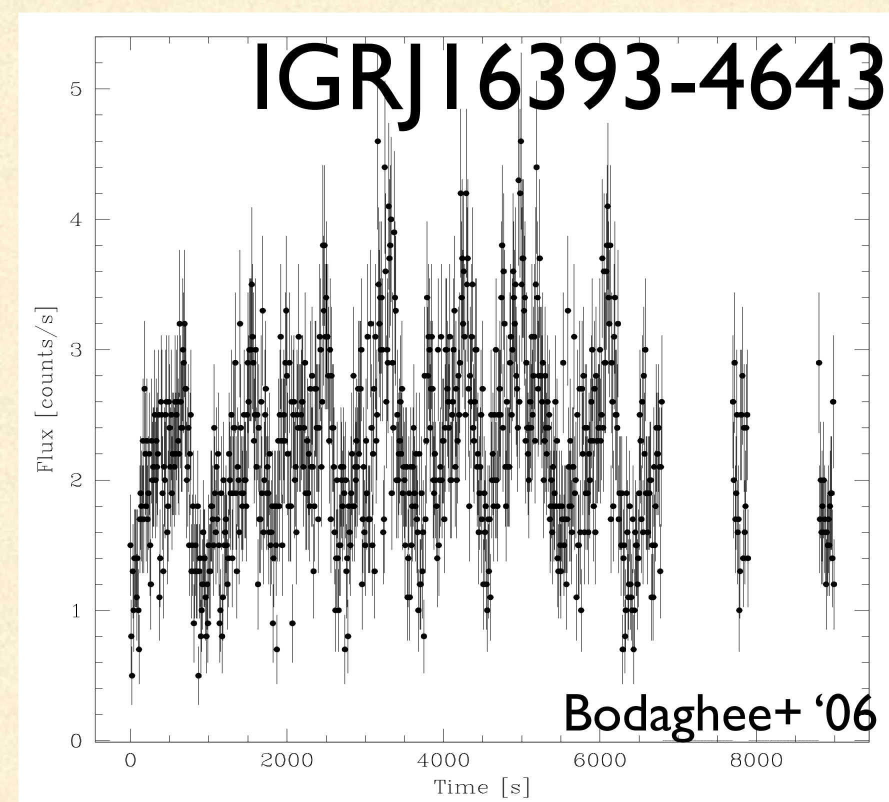
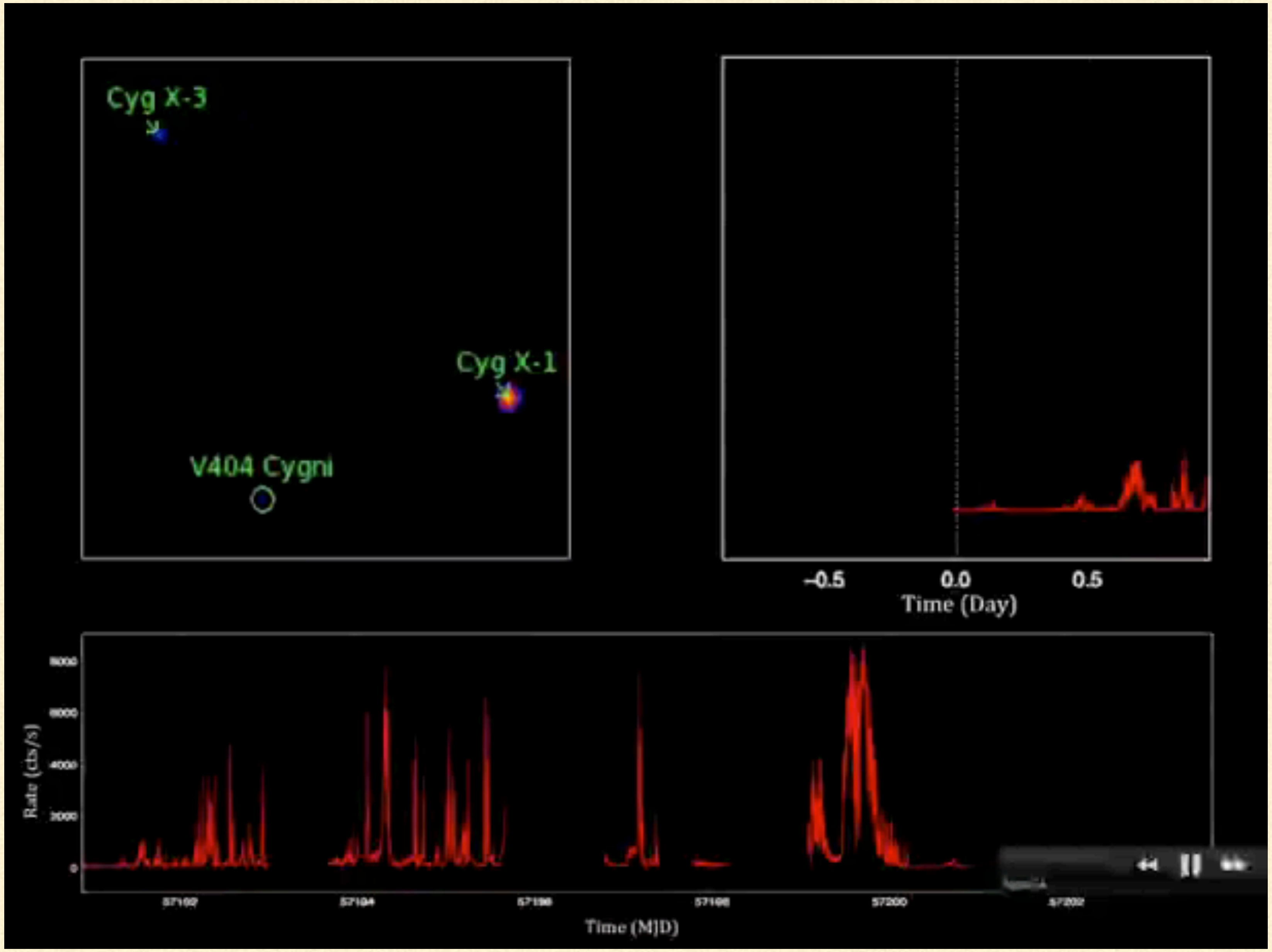


Bodaghee+ '06

NOT ALWAYS THAT SIMPLE

V404 Cygni:

- ~10 sol M black hole
- 6.2 d orbital period
- Dormant for 30 years



(Extreme) Variability obvious
No evident recurrent pattern
No links with 'natural' periods

Origin?
How can it be probed ?

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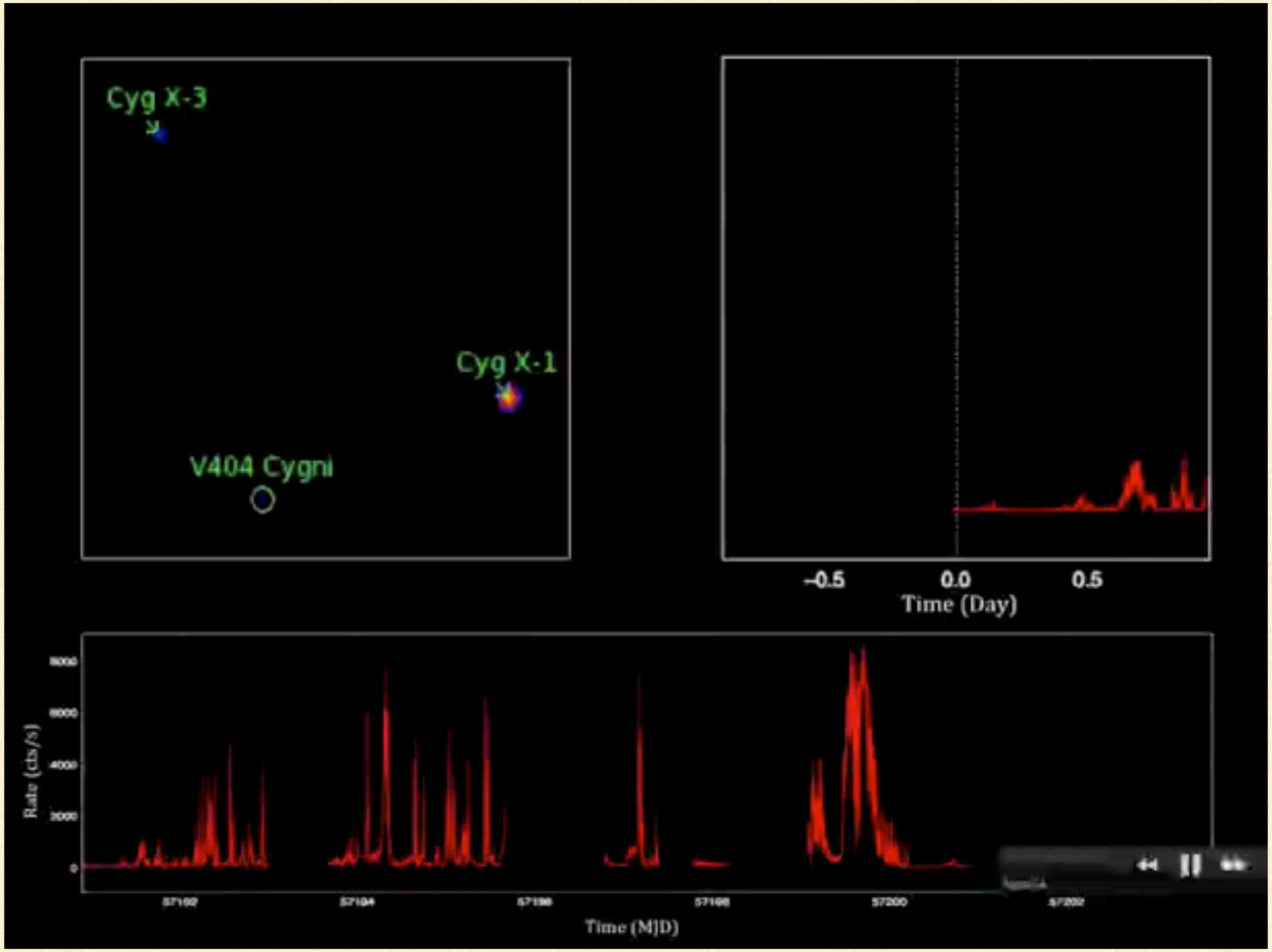

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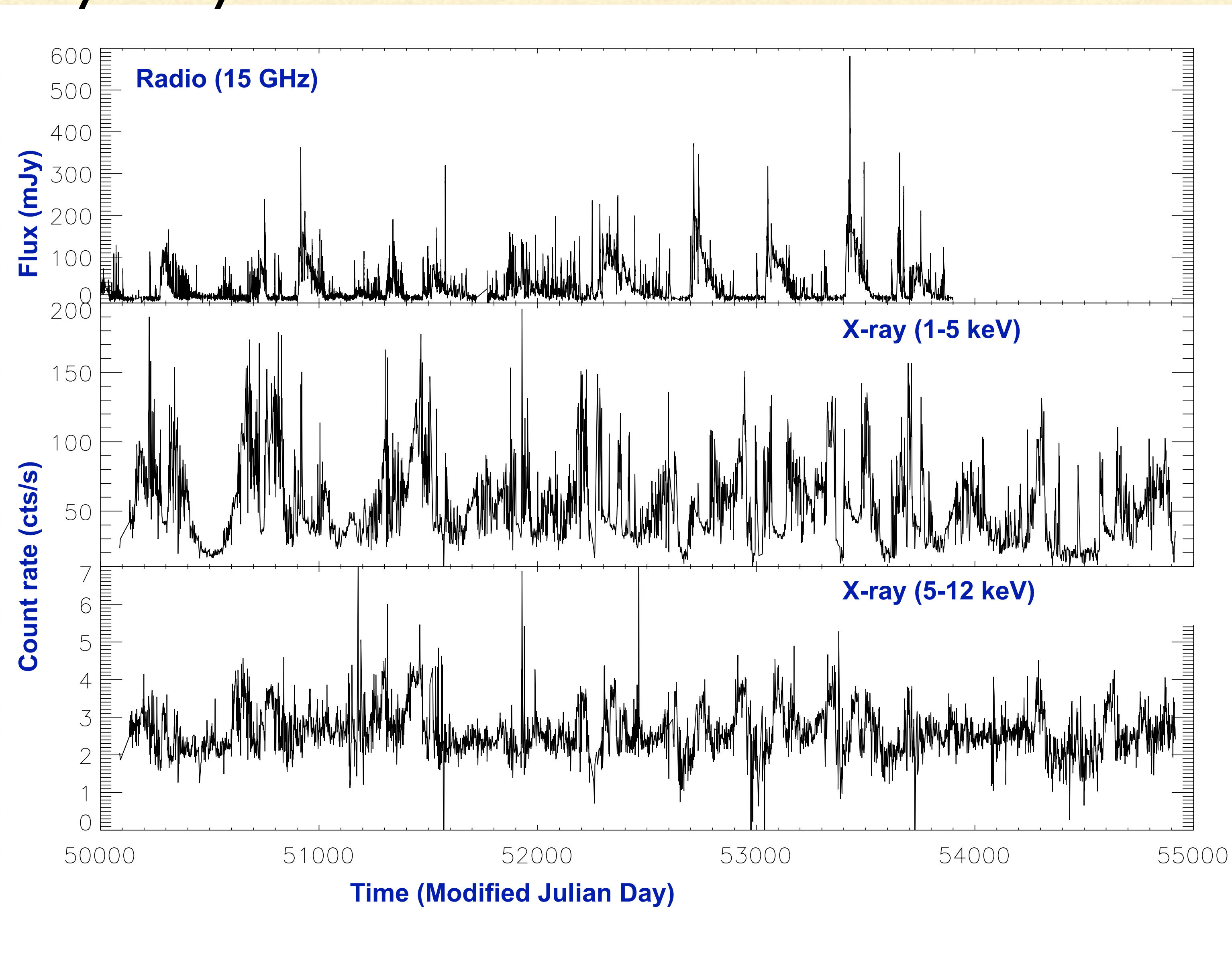
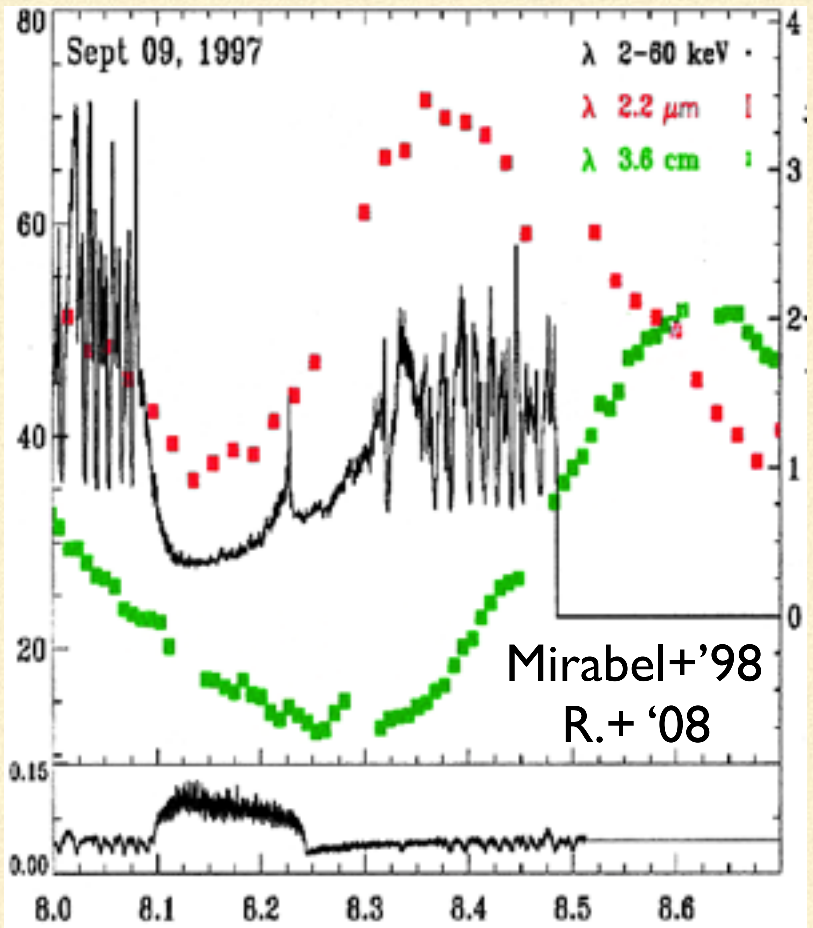
MULTI-WAVELENGTH VARIABILITY

Days to years



Seconds to hours

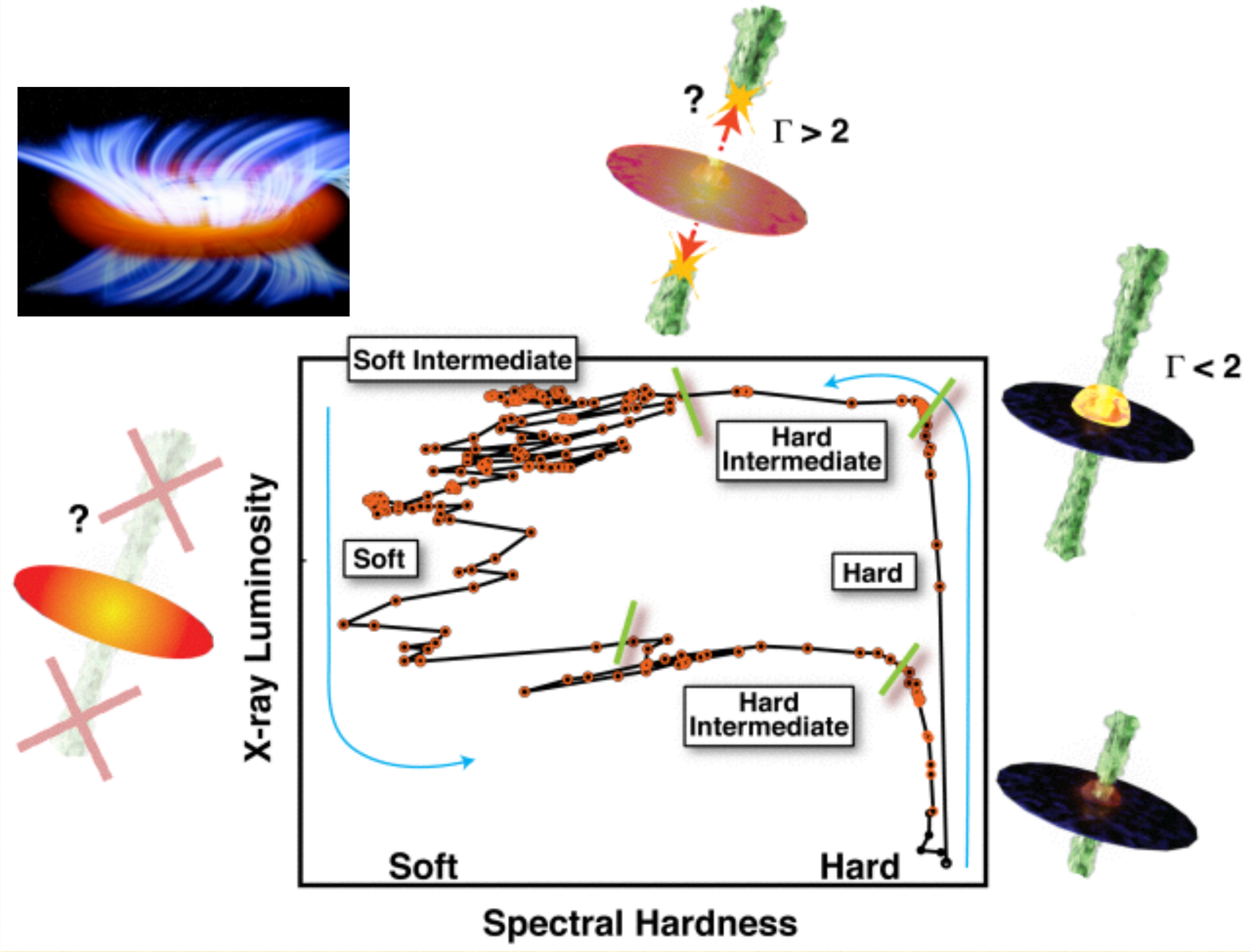


X-rays (accretion, disc) lead variability
=>Jet in response to accretion inst.
=>Jet matter from inner flow
=>Jet energised by inner flow/BH

=> Lags give constraints on :
=>Causal relationship
=>Geometries
=>Distances
(see G. Ponti's talk)

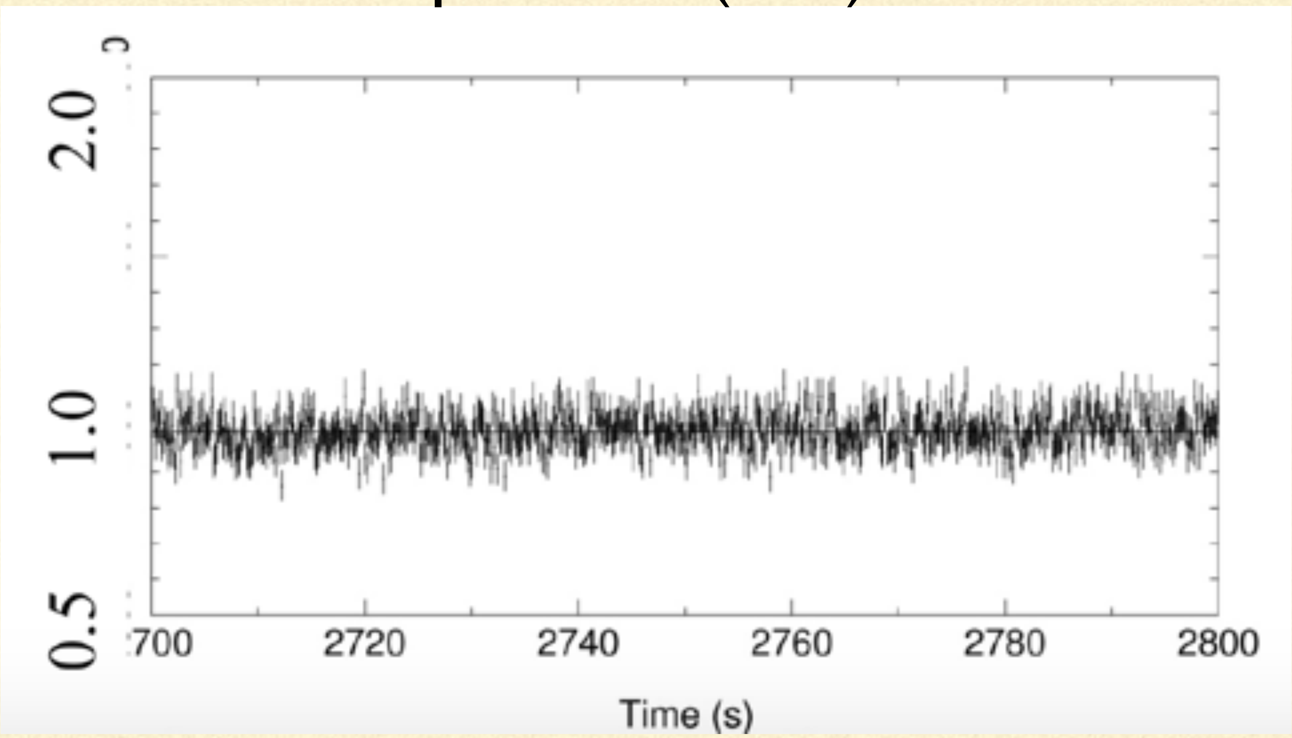
Physical mechanism yet to be discovered

UNDERSTANDING OF THE LONG TERM EVOLUTION

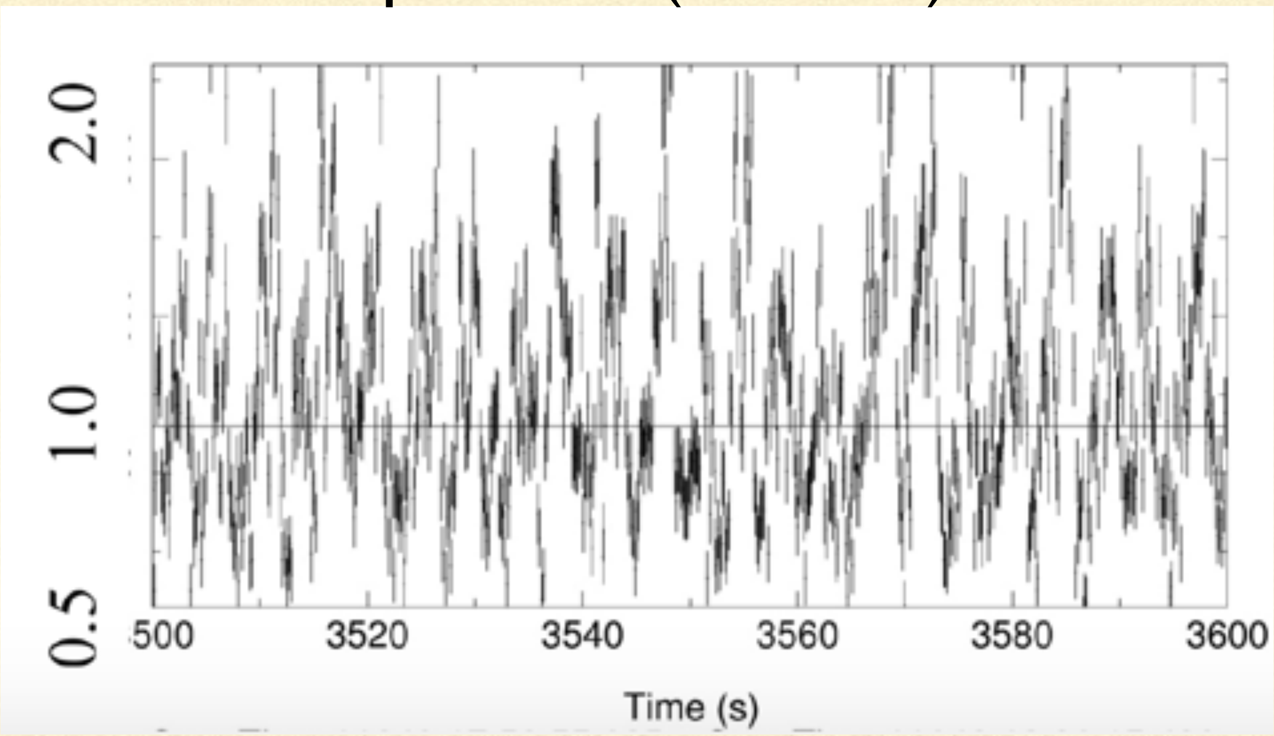


TO GO FURTHER SUB-SECOND VARIABILITY

Soft spectrum (disc)



Hard spectrum ('corona')



Variability clear in some cases
Periodic fluctuations?
Relation with spectral state?
Origin and link with disc/jet?

We first need to quantify, characterize, and understand the rapid variability ?

FOURIER ANALYSIS

- Fourier transform = decomposition of signal into sine waves

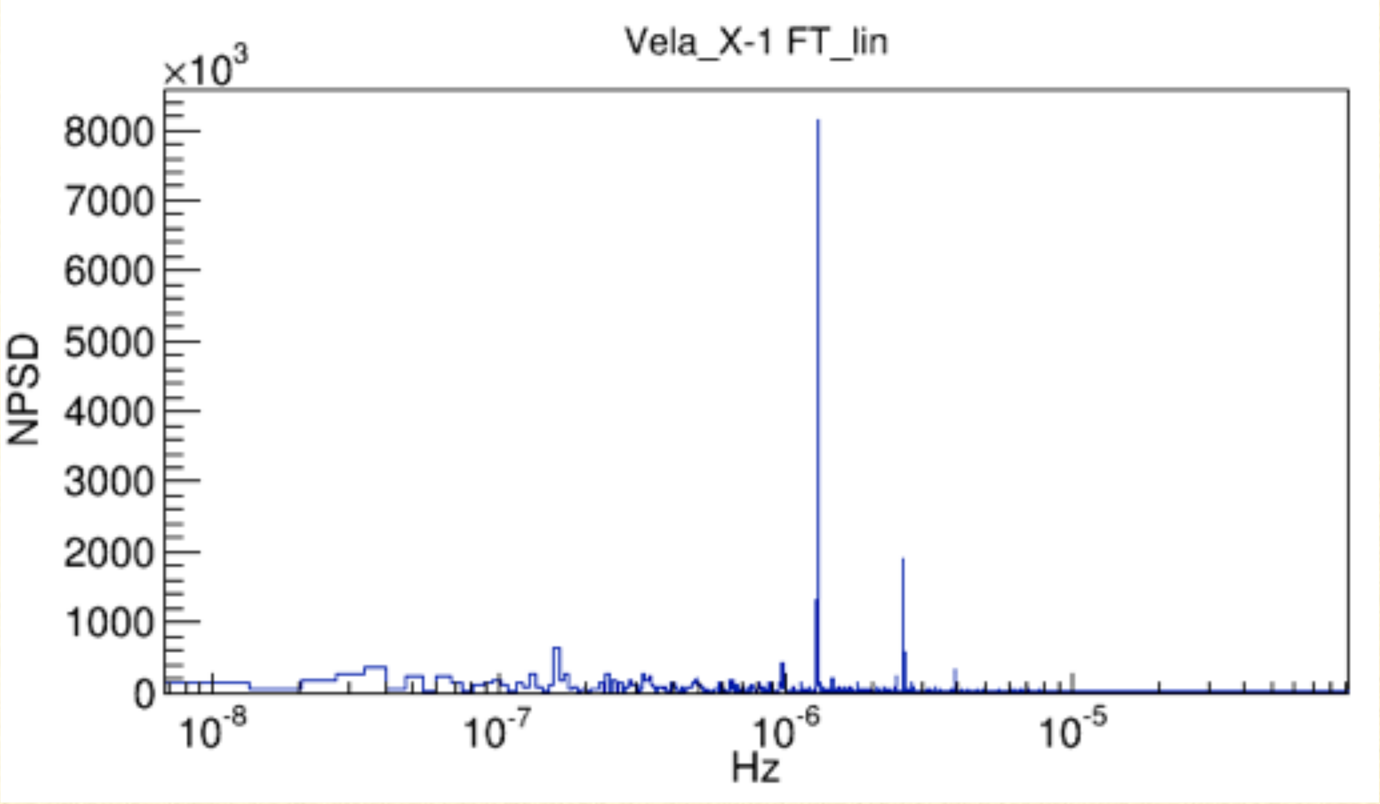
$$L(t) = \frac{1}{N} \sum_{j=\frac{-N}{2}}^{\frac{N}{2}-1} a_j e^{-i2\pi\omega_j t}$$

Signal is discrete/binned

$$L_k = \frac{1}{N} \sum_{j=-\frac{N}{2}}^{\frac{N}{2}-1} a_j e^{-i2\pi\omega_j t_k} \quad k = 0, .., N$$

  - With aj is the Fourier coef. of pulsation ωj : represent the correlation of L(t) with modulation with pulsation ωj

=> aj high <=> signal with strong period at ωj



$$\nu_{min} = \delta\nu = \frac{1}{T}$$

$$\nu_{max} = \frac{1}{2 \times \delta t} = \frac{N}{2T}$$

IN PRACTICE « POWER SPECTRA »

- We use the Leahy normalisation (such that WN power has a level of 2):

$$P_j = \frac{2}{N_{tot}} |a_j|^2$$

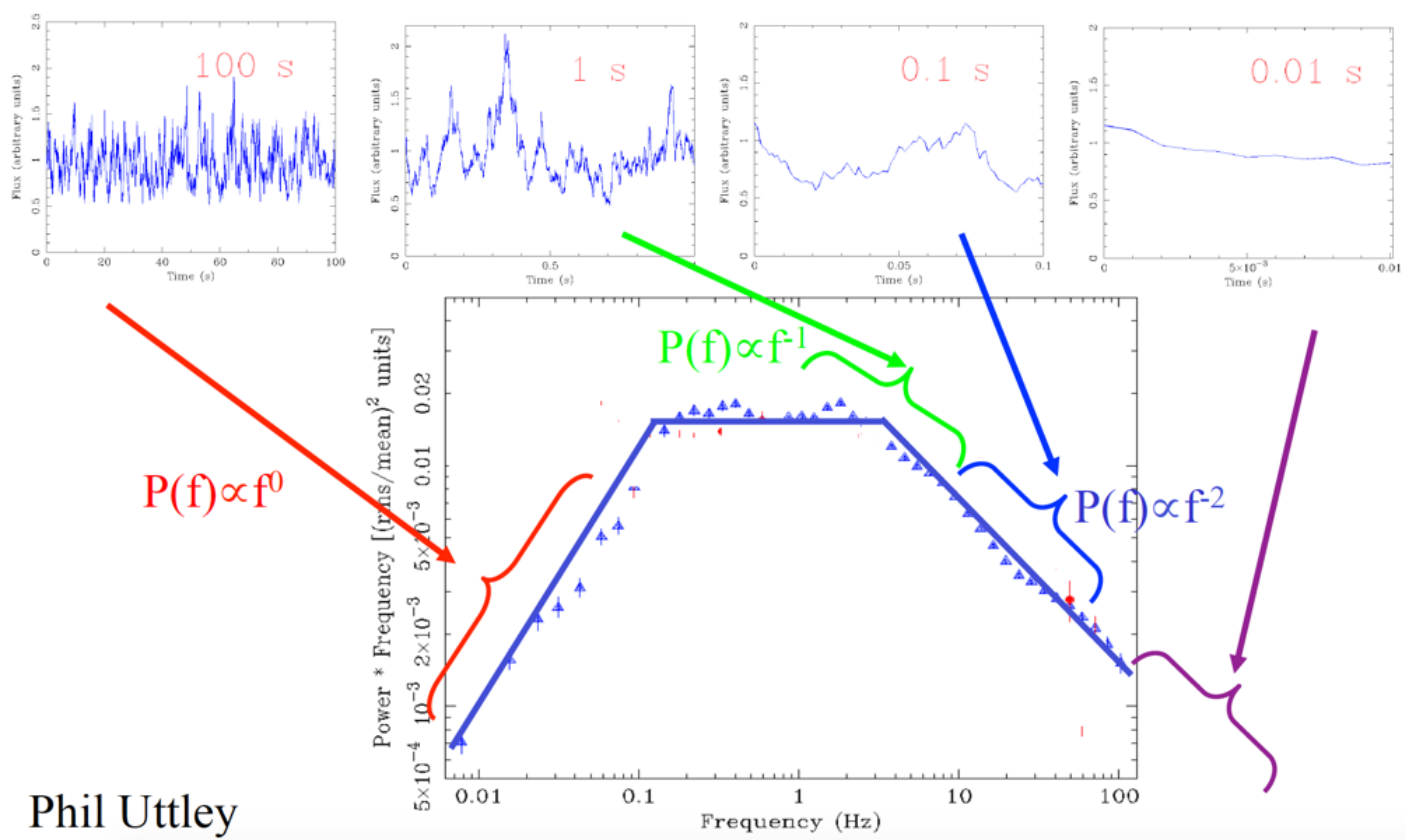
$$Var(L_k) = \frac{1}{N} \sum_{j=-\frac{N}{2}, j\neq 0}^{\frac{N}{2}-1} |a_j|^2$$

- Variance is the sum of powers :

$$Var(L_k) = \frac{\sum_k L_k}{N} \left(\sum_{j=1}^{N/2-1} P_j + 0.5 P_{\frac{N}{2}} \right)$$

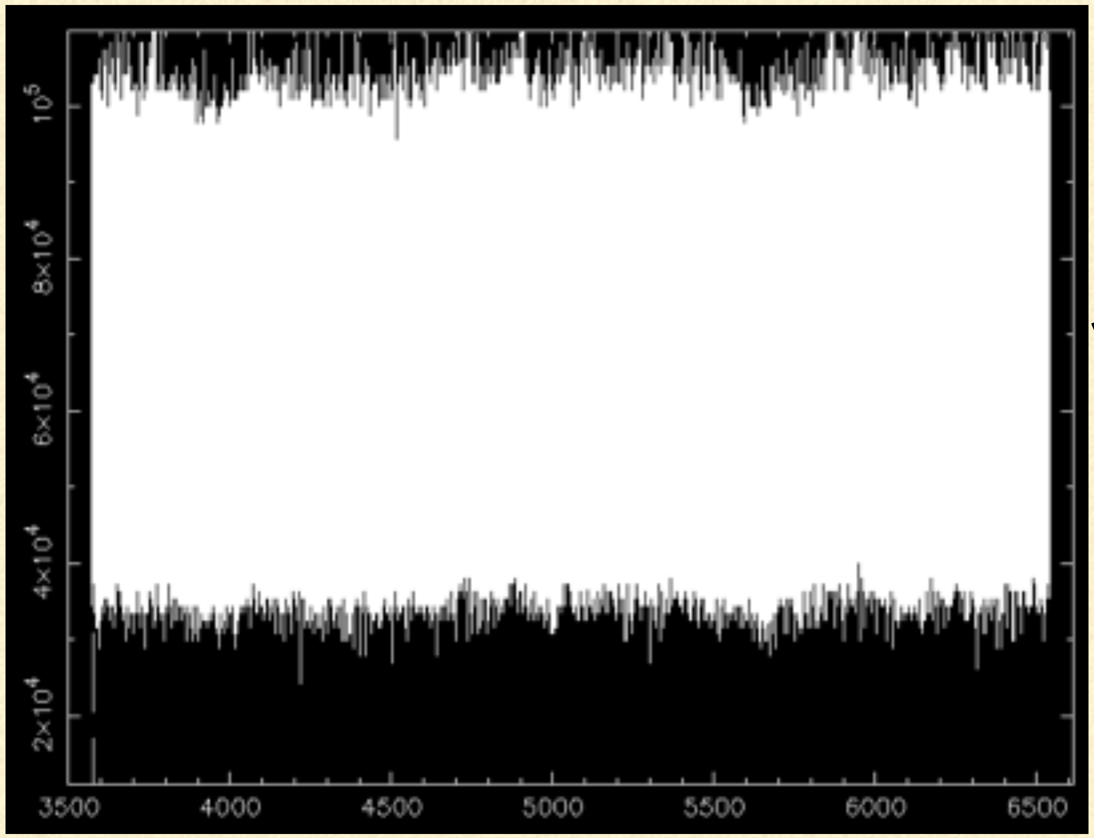
- Power density gives power per unit frequency => the integral of the power spectrum is the sum of power: equivalent to measuring the variance of signal

GRAPHICALLY

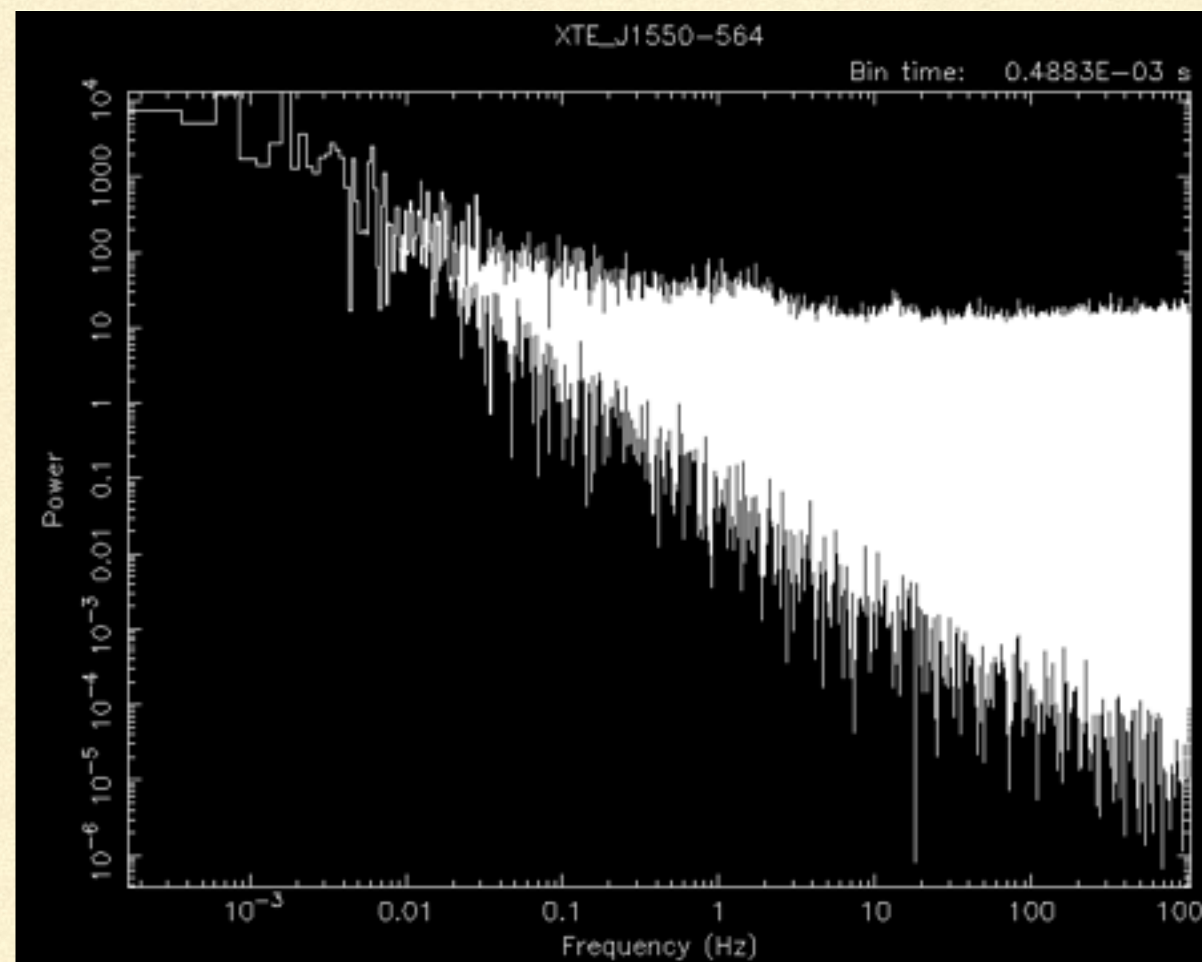


Phil Uttley

OBSERVATIONS



- High frequencies <=> high resolution
- Large photon stat. <=> large collecting area
  - => RXTE ~6600 cm2 (1996-2011)
  - => Astrosat 8000 cm2 (launched 2015)



IN PRACTICE (2)

Sum the N Poisson PDS => Gaussian with mean 2N and σ=2/N

⇨ Divide in shorter intervals
Calculates the indiv. PDS
Average PDS (such that poisson level =2)

Significance of feature with HWHM $\Delta\nu$ and power r is:

$$n_\sigma = 0.5 \times r_s^2 \sqrt{(\frac{T}{\Delta\nu})} \frac{S^2}{S+B}$$

T is total duration (mean count rate is N/T) , S is source net signal, B is background

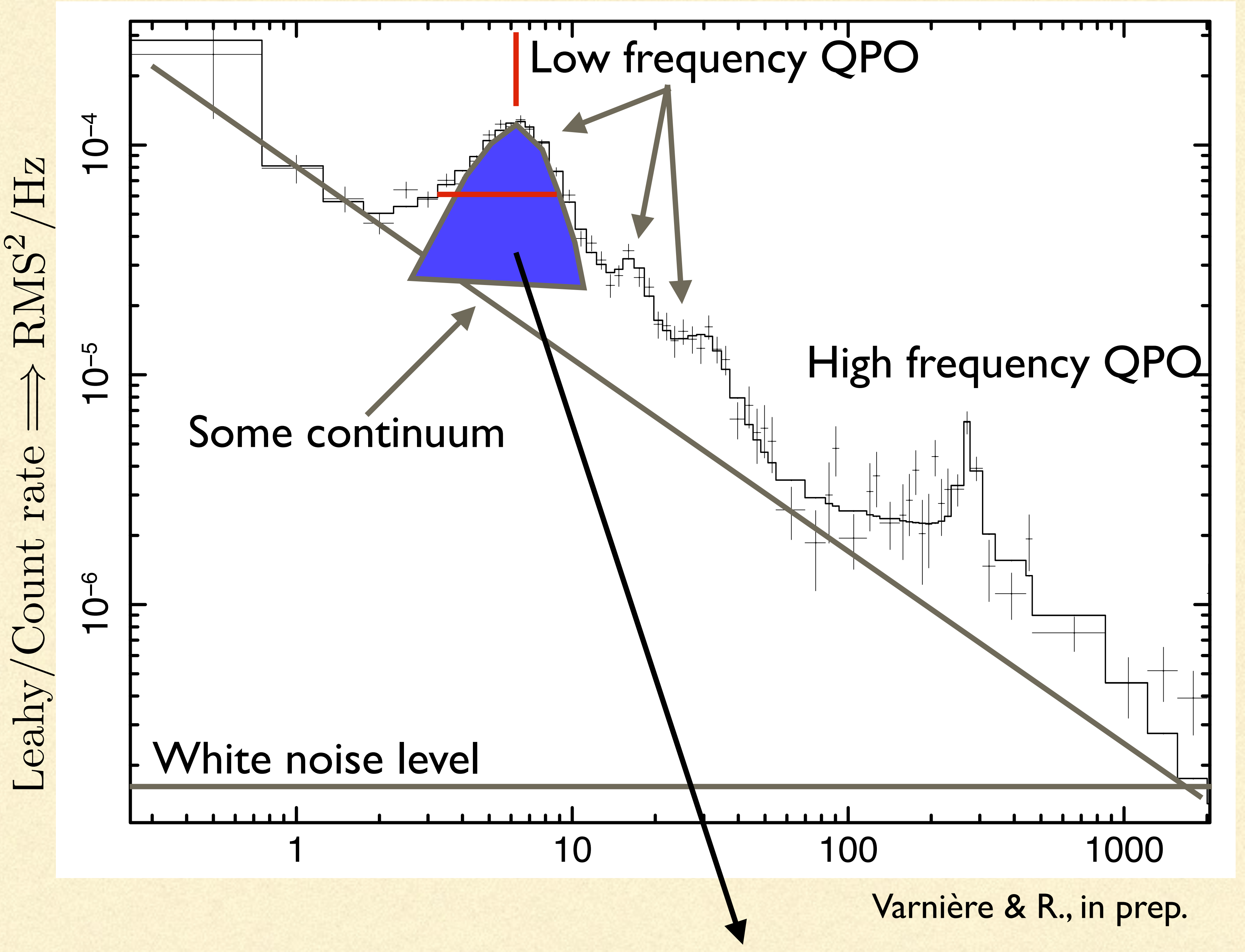
WITH APPROPRIATE CHOICE

ν in Hz

FWHM (or σ) in Hz

Power in % RMS

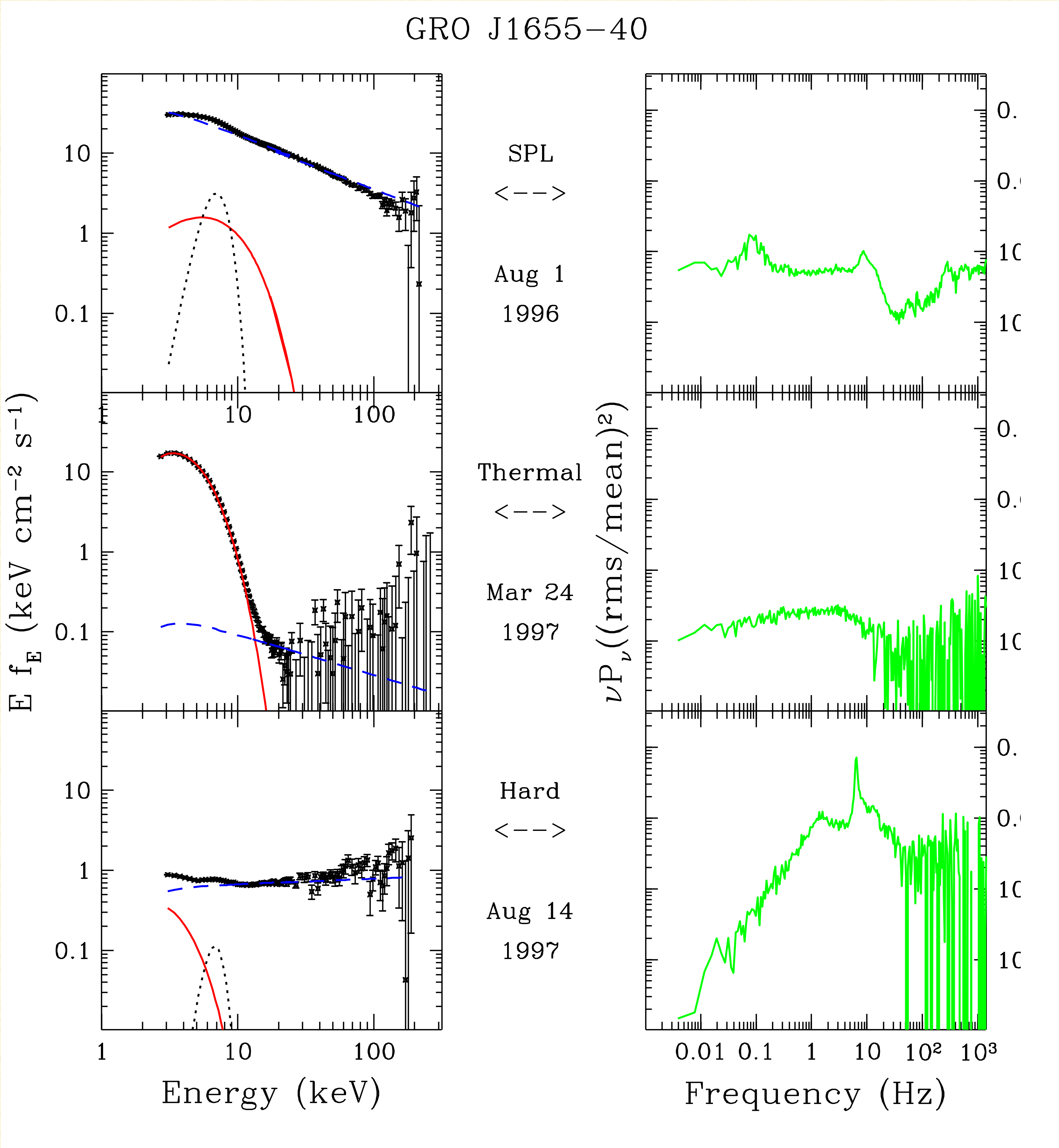
QPO <=> Q=ν/σ>2 ie peaked, signal has certain coherence



Varnière & R., in prep.

$$\text{Power}[\nu 1, \nu 2] = \sqrt{\int_{\nu 1}^{\nu 2} PDS(\nu) d\nu}$$

VARIABILITY QPOS AND SPECTRAL STATES



Remillard & McClintock '06

Complex broad band shape a few %
LF and HF QPOs (~1%)

Weak variability $dP \propto \nu^{-\Gamma} d\nu$
noQPOs $\Gamma \sim 1$

« Flat top » broad band shape:

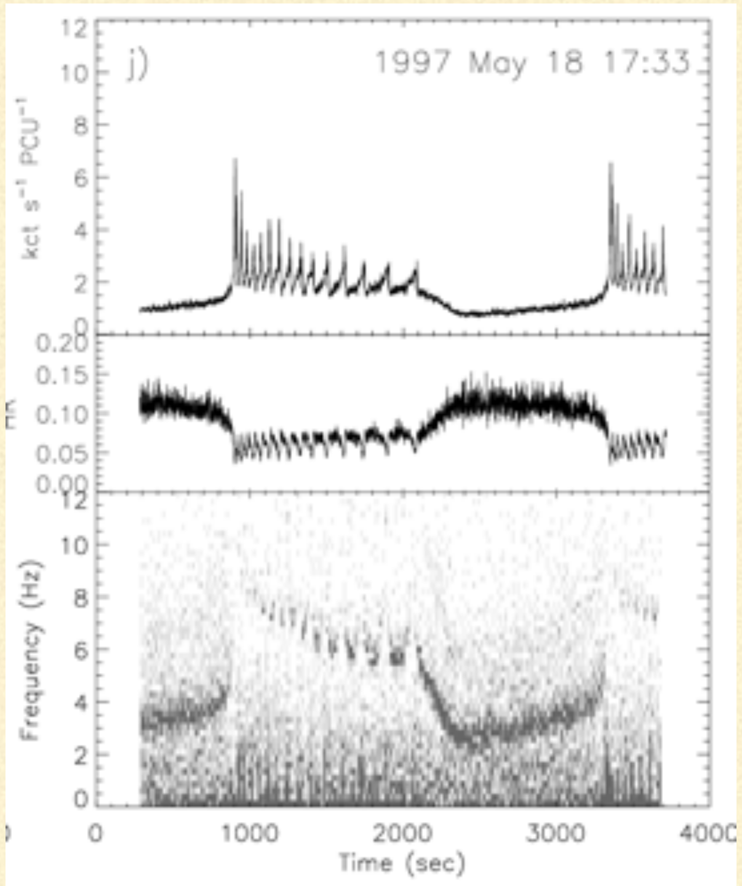
$P \sim \text{cte} \; \nu < \nu_{\text{break}}$

$dP \propto \nu^{-\Gamma} d\nu \quad \nu > \nu_{\text{break}}; \Gamma > 1$

Strong variability (10-40%)
LFQPO (10-20%)

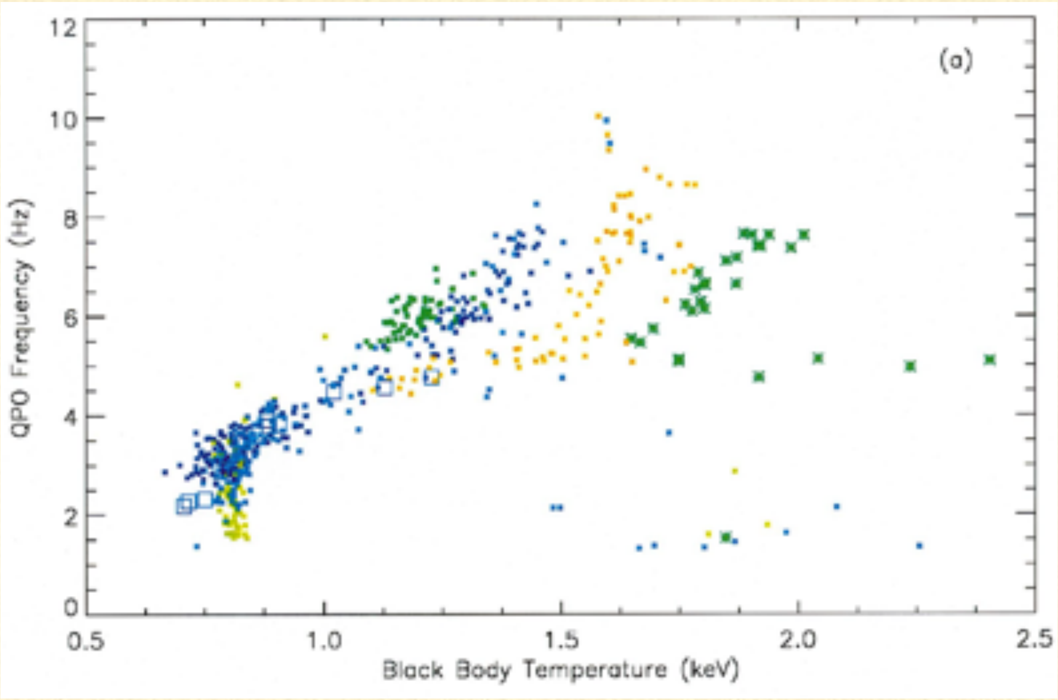
LFQPOS ORIGINATE FROM DISC…..

Frequency vs Hardness and (soft) Flux



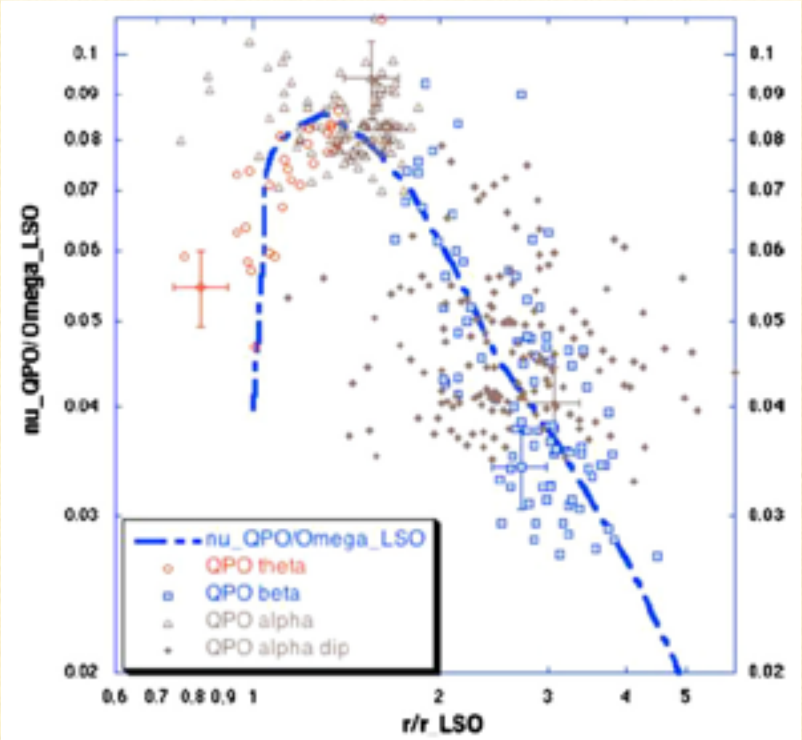
Muno+ '01, R.+'04

Frequency vs Disc Temp.



Muno+ '01

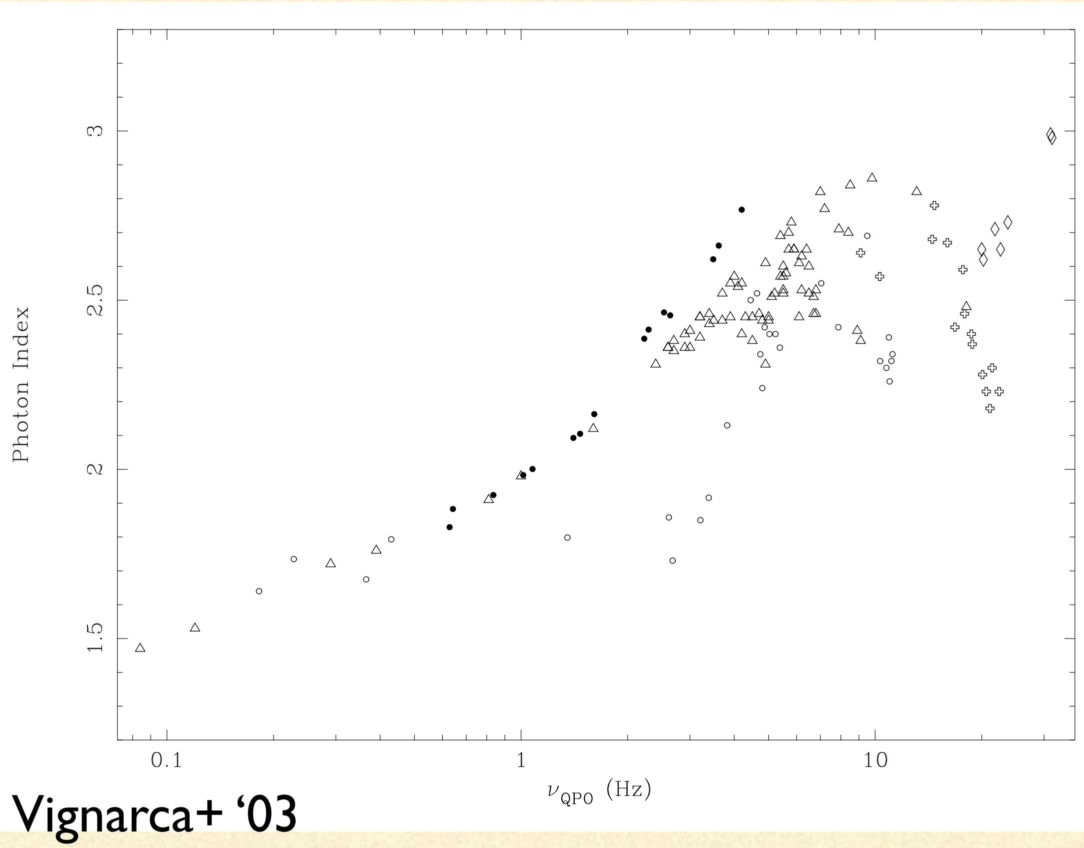
Frequency vs Disc Radius



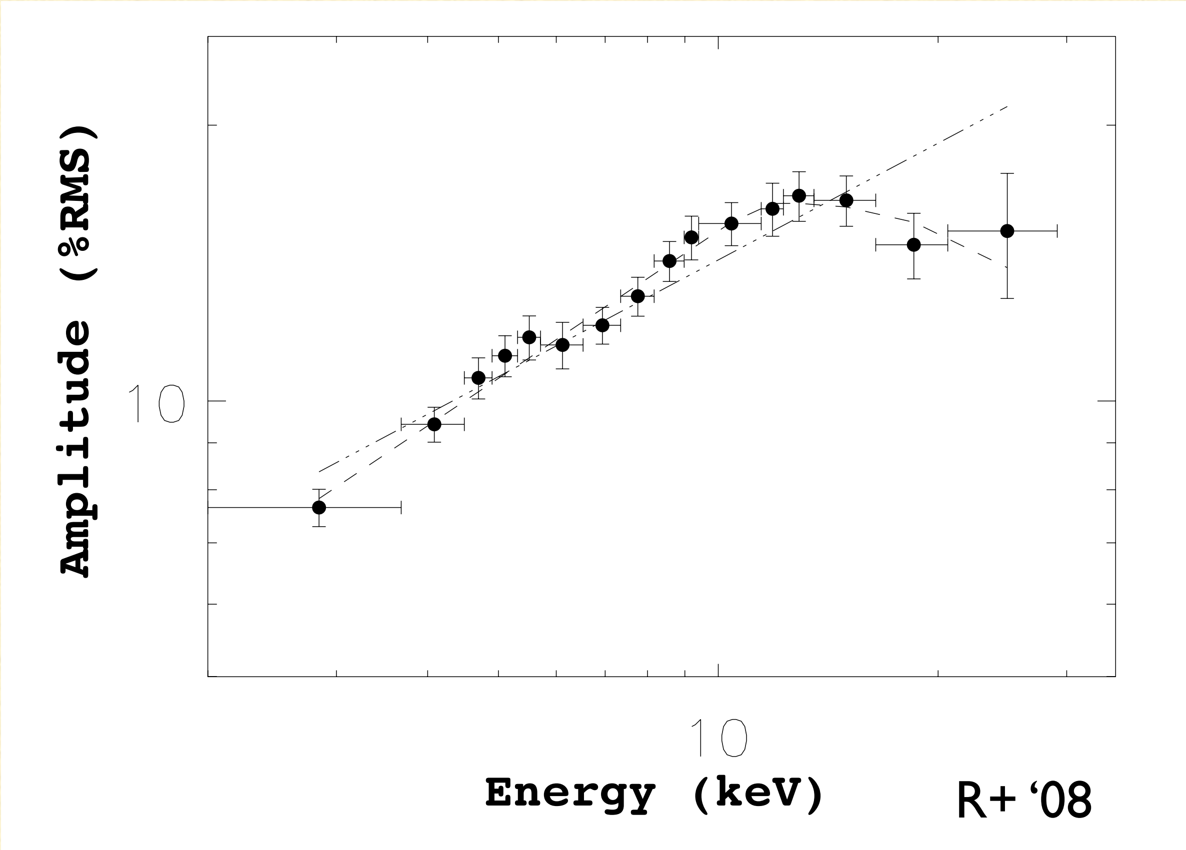
Mikles+ '09, R.+'02

…… OR CORONA/JET?

Frequency vs Corona slope



QPOs have hard spectra



Possible link to mechanism giving rise to ejections

CONCLUSIONS

- Spectral analysis gives a static picture of physics
- Accreting sources are highly variable on very different time scales
- Variability is complex, with broad band « noise » and (quasi)periodic pulsations
- Fourier analysis permits to dig into the properties of variable accretion flows :
  - Link of variability with accretion states indicates complex phenomena
  - Models of accretion/ejection cannot ignore the dynamical properties!
  - Fast variability has to be considered in the picture