The Role of Jets in Galactic Black-hole X-ray Binaries

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Introduction

- Jets have been observed from black-holes in X-ray binaries.
- The same from neutron-star binaries, but I will not discuss them.
- Steady jets are detected ONLY when the sources exhibit a HARD X-ray spectrum (hard state).
- No radio emission has been detected yet when the X-ray spectrum is soft (soft state).
- So, it is not crazy to say that, maybe, the jets are responsible for what we observe in the hard state.

- In my opinion, the jets from compact X-ray sources (neutron stars, black holes) have not been given proper attention.
- Most people treat jets in black-hole binaries as simply “fireworks”, which do nothing else but emit radio waves.
- The “party line” is that the hard X-rays are produced in a HOT STATIC CORONA near the black hole.
- NO ONE discusses what heats the corona or why it is static.

I hope to convince you that

- The jet is a central player in the observed phenomena and not simply an embellishment.

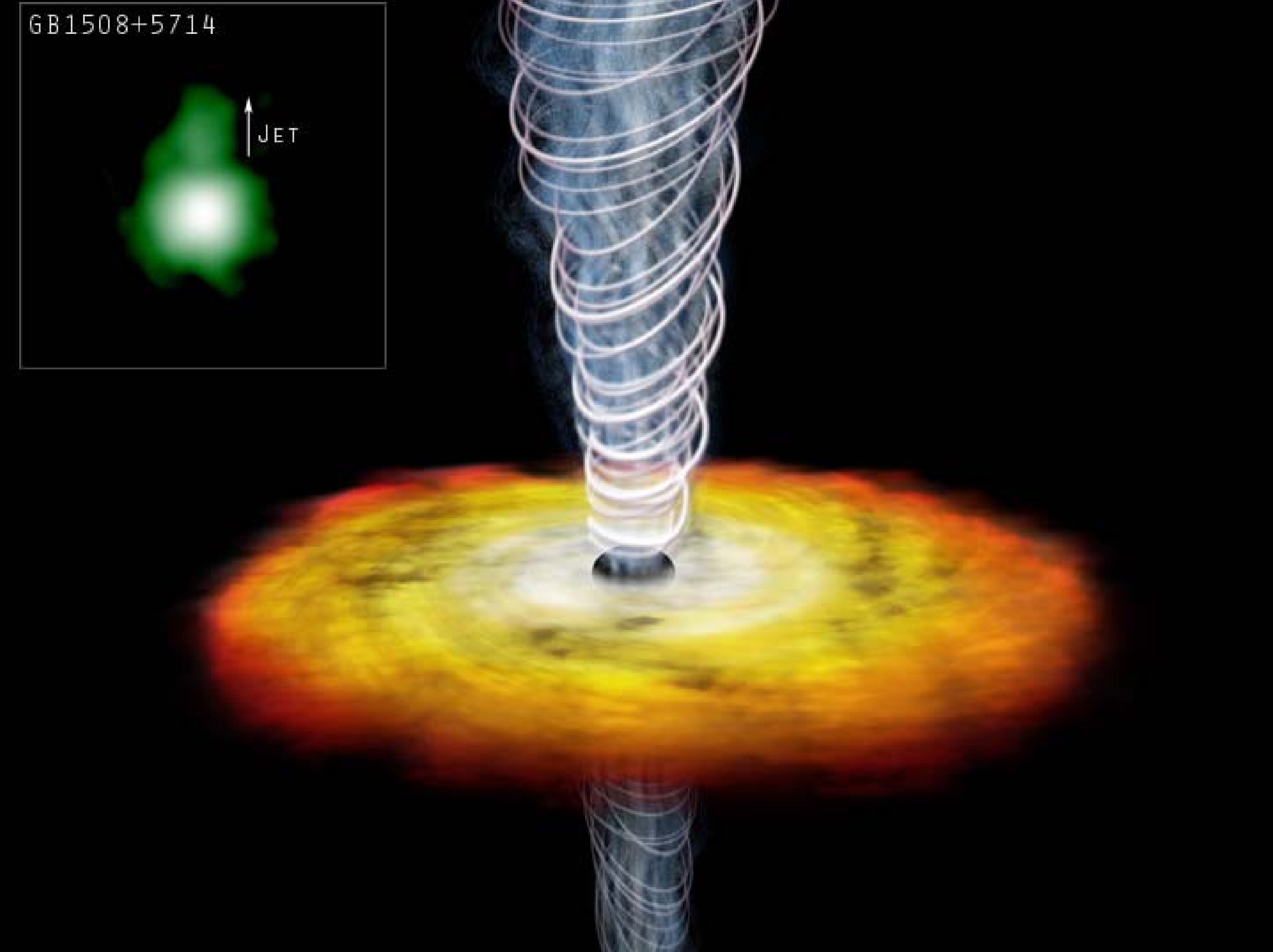
- In what follows, I will present the successes of the jet model that we have proposed.

The jet model

- In a series of four papers

  Reig, Kylafis, Giannios 2003, A&A
  Giannios, Kylafis, Psaltis 2004, A&A
  Giannios 2005, A&A
  Kylafis, Papadakis, Reig, Giannios, Pooley, 2008
  (astro-ph next week)

  we proposed a jet model that explains a number of observational facts, when the black-hole X-ray sources are in the HARD STATE (hard X-ray spectrum).


GB1508+5714
JET

Ingredients of the model

- The jet is semi-relativistic (v ~ 0.8 c). We have observational evidence for this.

- The density in the jet falls off inversely proportional to distance from the black hole. Such flows are allowed theoretically (Vlahakis & Koenigl).

- In the rest frame of the flow, there is a power-law distribution of electron γ’s (standard assumption for radio jets).

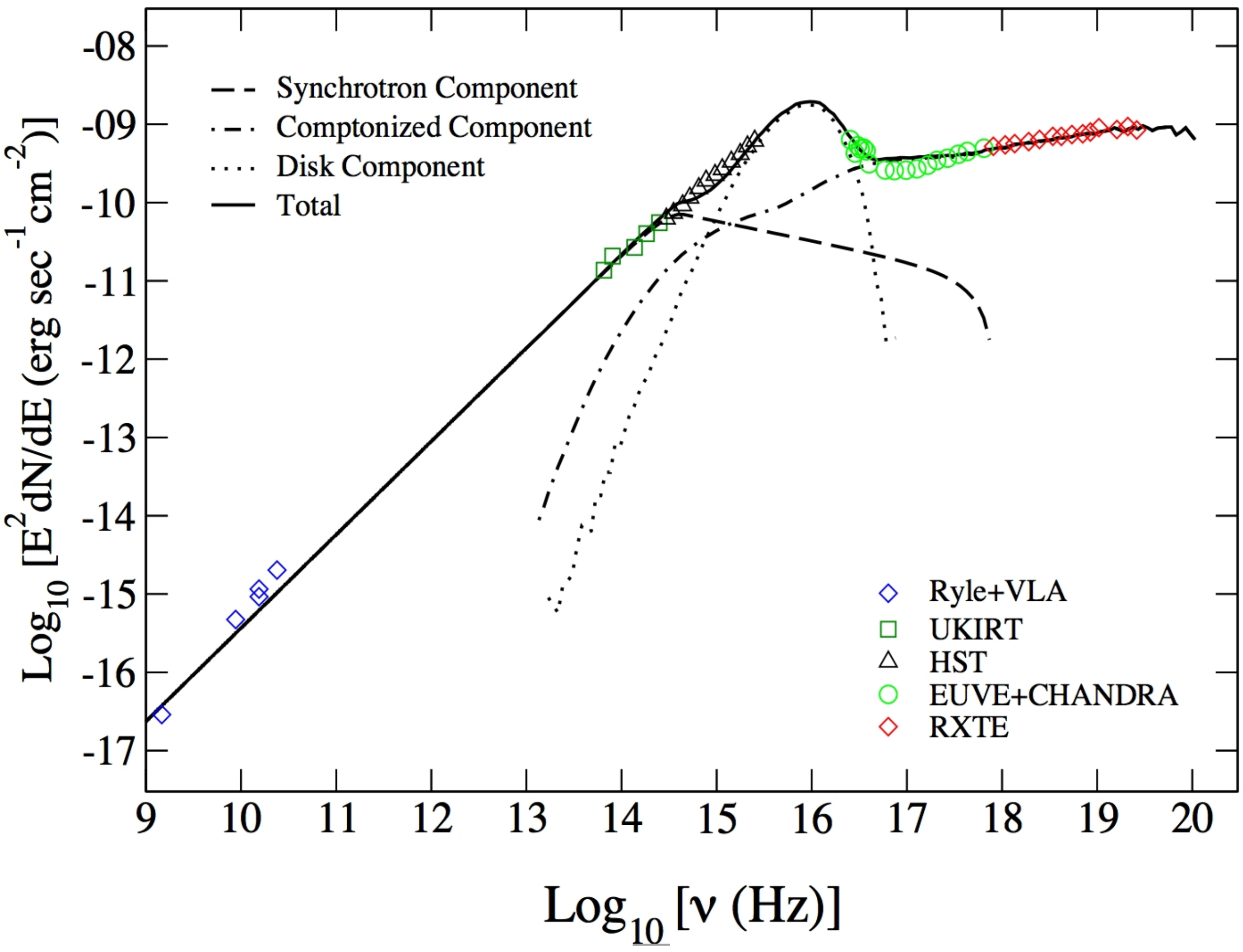
- Soft photons from the accretion disk get up-scattered in the jet and a power-law spectrum is produced in hard X-rays (photon number index Γ).

Observational facts

- ENERGY SPECTRUM

- Up to now, only for one source (XTE J 1118+480) we have simultaneous observations from radio to hard X-rays.

Giannios 2005, A&A



- Model and observations for XTE J 1118+480

Life is not so easy however ☹

- Impressive as the model fit may be, it DOES NOT constrain the model!
- Equally good fits to the data are produced by other models:

  Markoff, Falcke, Fender 2001, A&A

  Vadawale, Rao, Chakrabarti 2001, A&A

  Corbel & Fender 2002, ApJ

  Markoff et al. 2003, A&A

Let’s see why.

How can one produce a spectrum of the form $I(E) = E^{-\alpha}$? (α=Γ-1)

- Let's consider low-energy photons E_0, e.g. from the accretion disk.

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- Let’s consider low-energy photons E_0, e.g. from the accretion disk.
- Let $\lambda = \Delta E / E$ be the mean fractional increase of the photon energy per scattering. Then

$$E_1 = E_0 + \Delta E_0 = E_0(1 + \Delta E_0 / E_0) = E_0(1+\lambda)$$

$$E_2 = E_1 + \Delta E_1 = E_1(1 + \Delta E_1 / E_1) = E_1(1+\lambda) = E_0(1+\lambda)^2$$

…

$$E_n = E_0(1+\lambda)^n \qquad (1)$$

- If p is the probability for a photon to be scattered once, then the intensity of photons scattered n times is

$$I_n \sim p^n \quad (2)$$

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- Solving equation (1) for n and substituting into (2) we obtain

$$I(E) \sim (E/E_0)^{-\alpha}$$

where $\alpha = \ln(1/p)/\ln(1+\lambda)$

Therefore …

- The energy spectrum alone CANNOT constrain the model.

Time lag between hard and soft X-rays

- It has been observed (Nowak et al. 1999; Ford et al. 1999) that the hard X-rays (say 8 -14 keV)

  LAG the soft X-rays (say 2 - 4 keV).

- This is expected in models where Compton up-scattering of soft photons takes place.

- However, the observed time-lag is a function of Fourier frequency!!!

- That's strange! Why should the light-travel time of a photon care about the variability of the source?

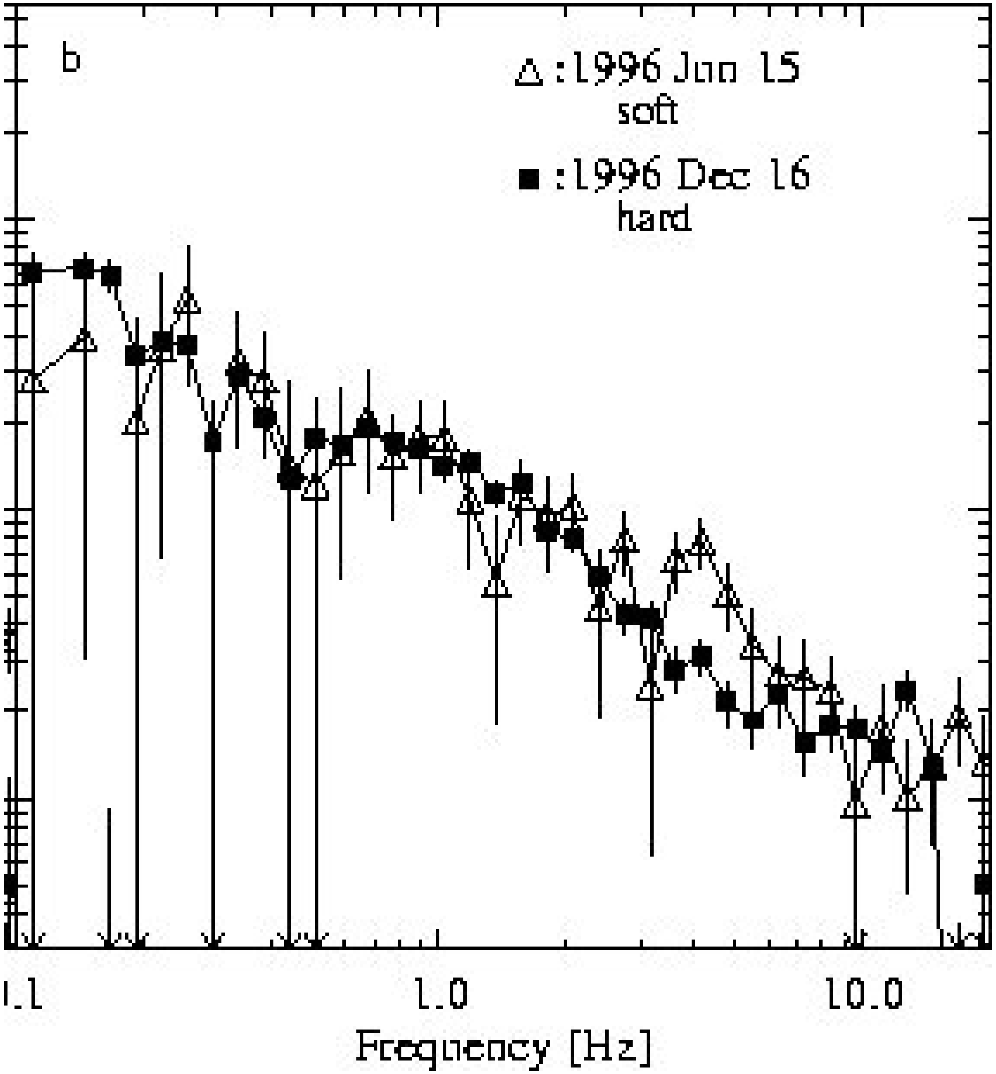
Time lag between hard and soft X-rays

- For Cyg X-1,

$$t_{lag} \propto \nu^{-\beta}, \beta \approx 0.7$$

Time lag vs Fourier frequency

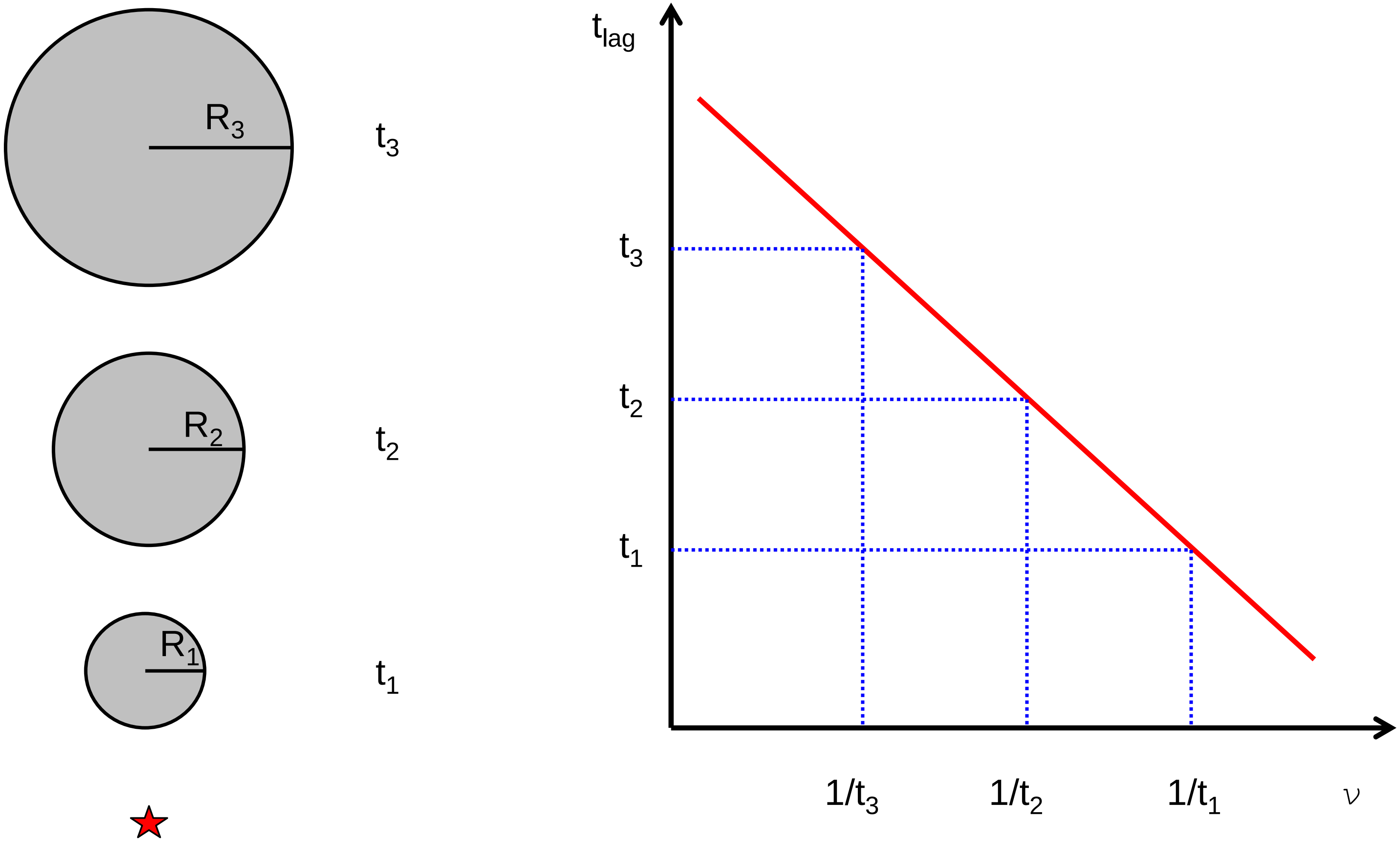
time lag



Compton scattering acts like a filter

- It cuts off the high frequencies.
- If (period of variability) < (time lag), the variability is washed out.
- Therefore, frequencies > 1/(time lag) are not observed.

Schematic picture of our jet



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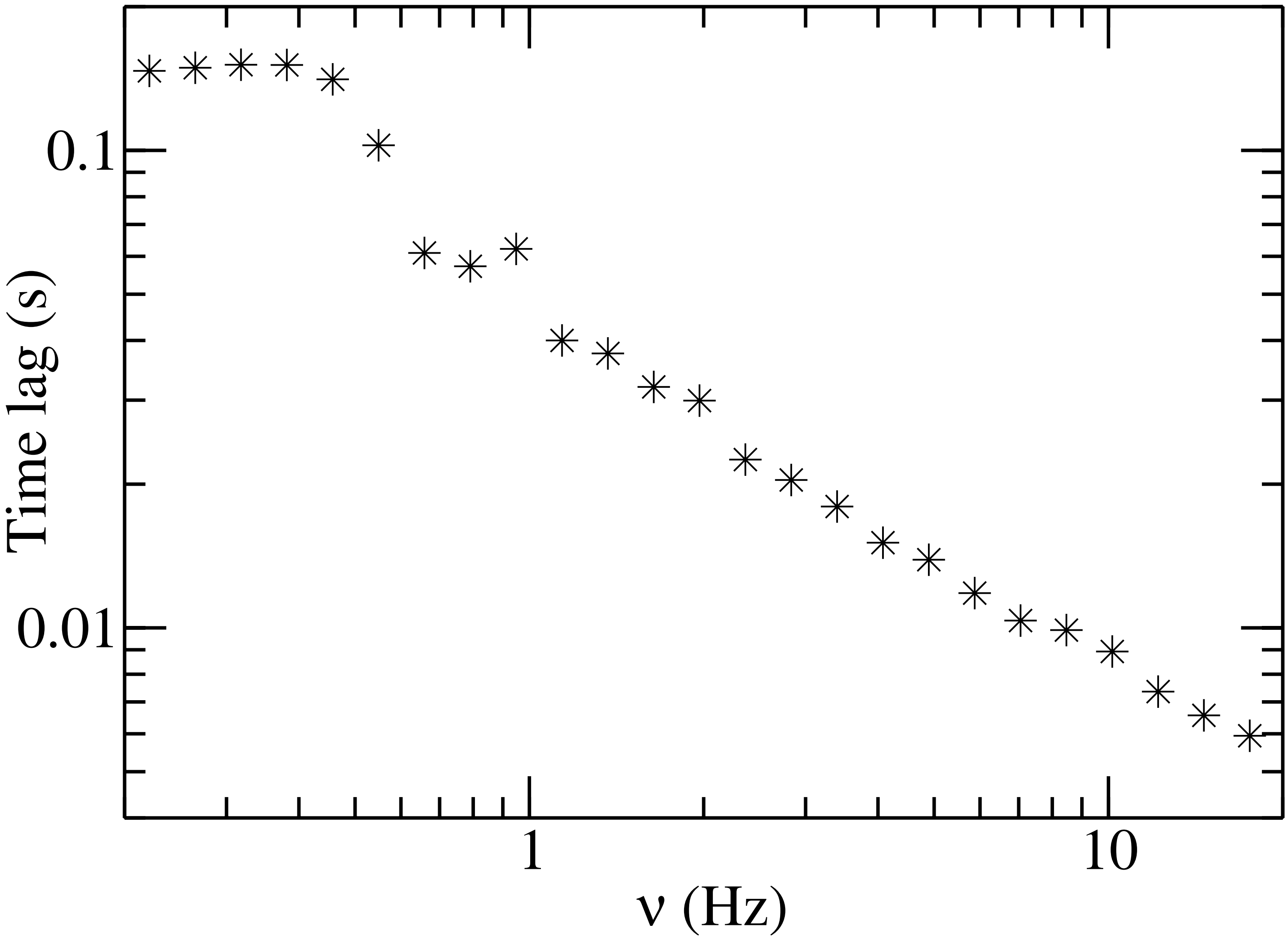


Other models

- Constraining as it is, the time lag vs Fourier frequency relation has been explained by other models also:

Poutanen & Fabian 1999, MNRAS
Kotov, Churazov, Gilfanov 2001, MNRAS
Koerding & Falcke 2004, A&A

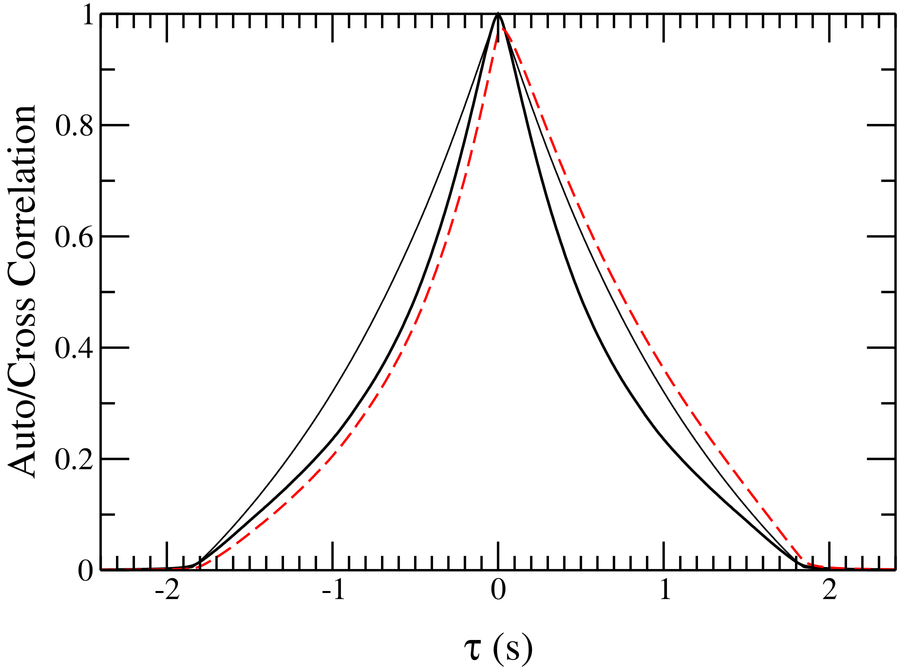
Therefore, even more constraints are needed.

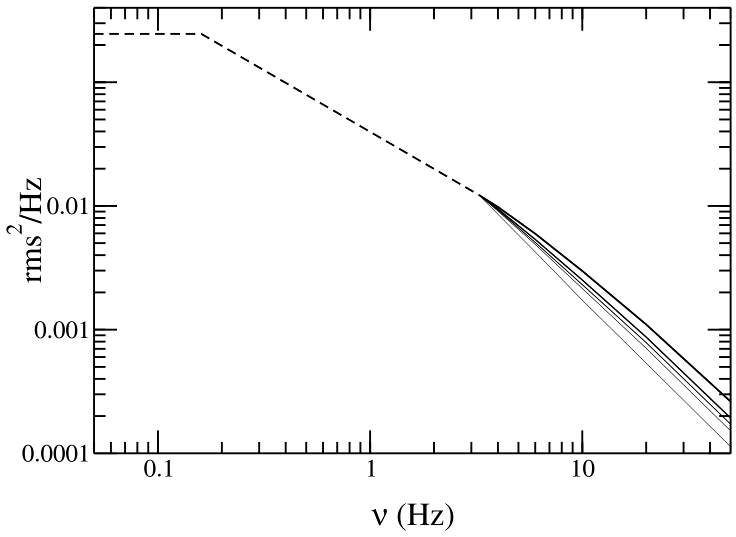
Another observational constraint

- The light curve of the hard photons is narrower than that of the soft photons. Strange!!!

- To quantify this we say that the width of the autocorrelation function of the light curves of Cyg X-1 decreases with increasing photon energy (Maccarone et al. 2000).

- Equivalent to this is the observation that the high-frequency power spectrum flattens with increasing photon energy (Nowak et al. 1999).


Auto/Cross Correlation
1
0.8
0.6
0.4
0.2
0
-2
-1
0
1
2
τ (s)


rms²/Hz
0.01
0.001
0.0001
0.1
1
10
ν (Hz)

Model explanation

- Our jet model explains these observations (Giannios, Kylafis, Psaltis 2004, A&A).
- The harder photons are kicked mainly in the forward direction (direction of the flow) and have a light-curve that is NARROWER than that of the softer photons.
- No other model explains this. In particular, a static corona cannot explain it.
- Let’s look now at other observational constraints.

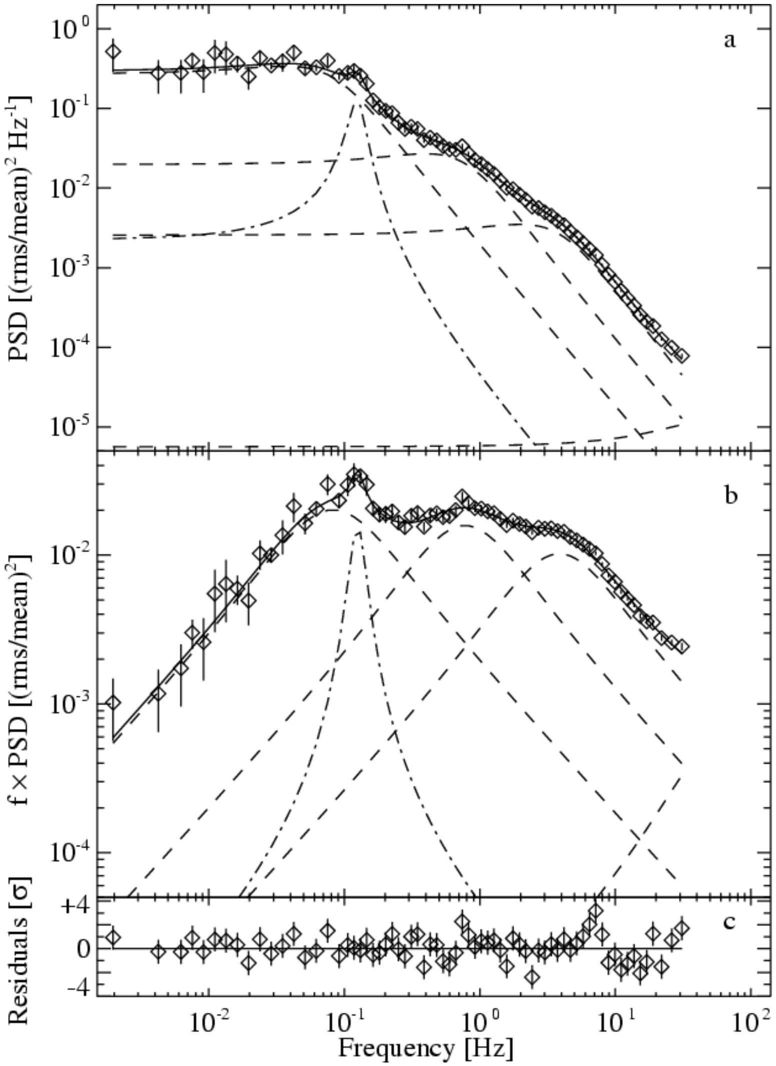
More observational constraints

- The long-term variability of Cyg X-1 has been studied by Pottschmidt et al. (2003), A&A.
- When the source was in the hard state, the study revealed a number of very stringent constraints.
- These are:

Pottschmidt et al. (2003), A&A

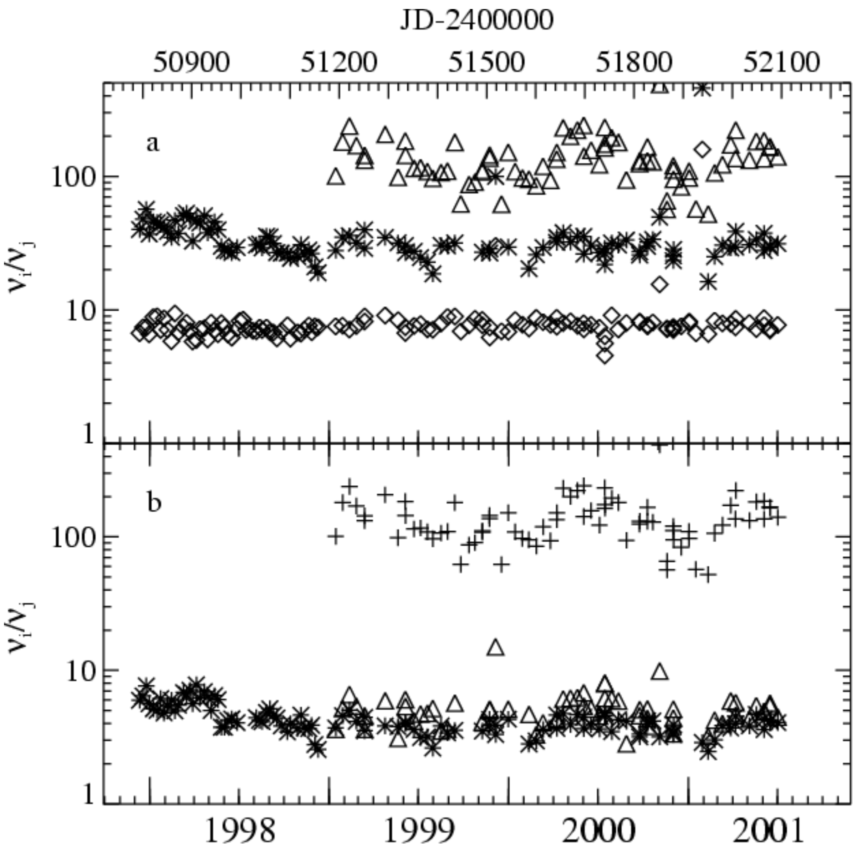
- The power spectrum of Cyg X-1 was fitted with four broad Lorentzian profiles that have peak frequencies

$$\nu_1, \nu_2, \nu_3, \nu_4$$



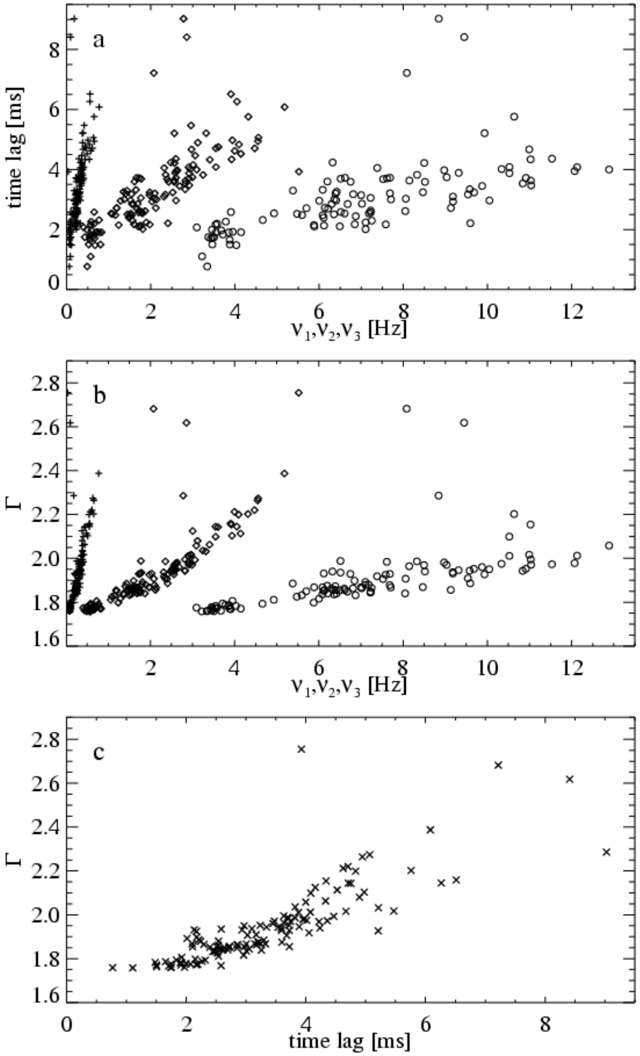
Pottschmidt et al. (2003), A&A

- The ratios of the peak frequencies are CONSTANT!!!



Pottschmidt et al. (2003), A&A

- Very stringent correlations:



Our jet model

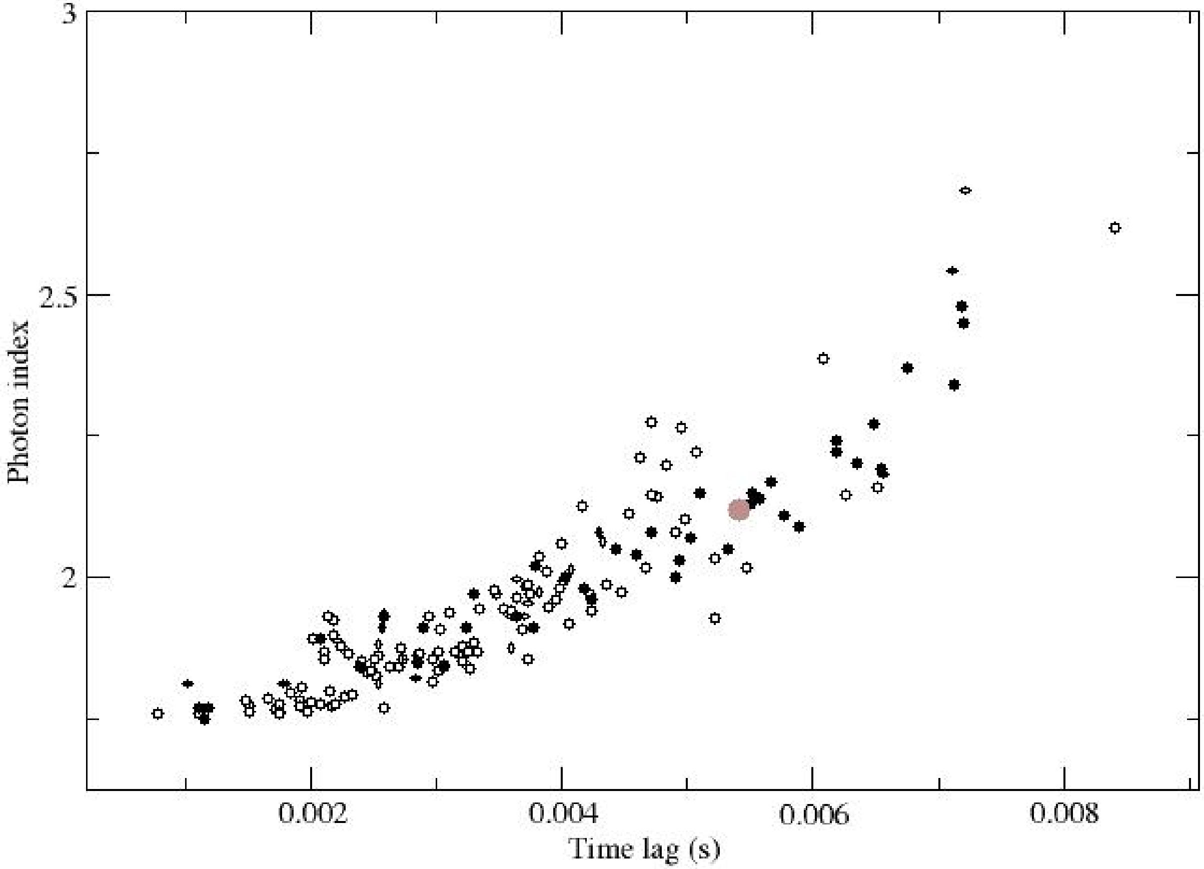
- Question: Can we explain these correlations by simply varying the parameters of our model around their typical values?

- The answer is YES!   (else I would not pose the question ☺).

- To change Γ, we varied the density (or equivalently the optical depth). To change the time lag, we varied the size (the radius of the base of the jet).

- We were thus able to reproduce the Gamma - <timelag> correlation.

Gamma vs. <timelag>



Identification of the Lorentzian peak frequencies.

- Using just the density and the radius at the base of the jet, can we think of a combination that has the dimensions of frequency (inverse timescale)?

Identification of the Lorentzian peak frequencies.

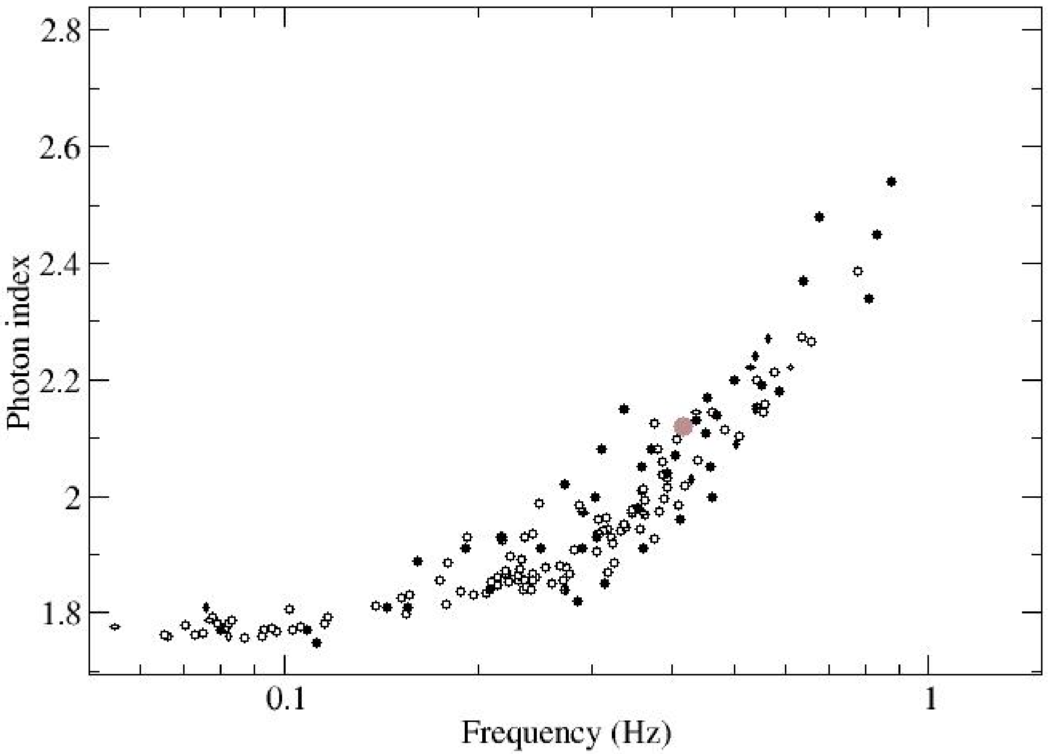
- The only inverse timescale that I can think of is

$$\frac{\dot{M}_{outflow}}{M_{available\ \ for\ outflow}}$$

Identification of the Lorentzian peak frequencies

$$\frac{\dot{M}_o}{M_o} = \frac{\pi R_0^2 n_0 u_{flow}}{M_o} = C R_0^2 n_0 \propto \nu_1$$

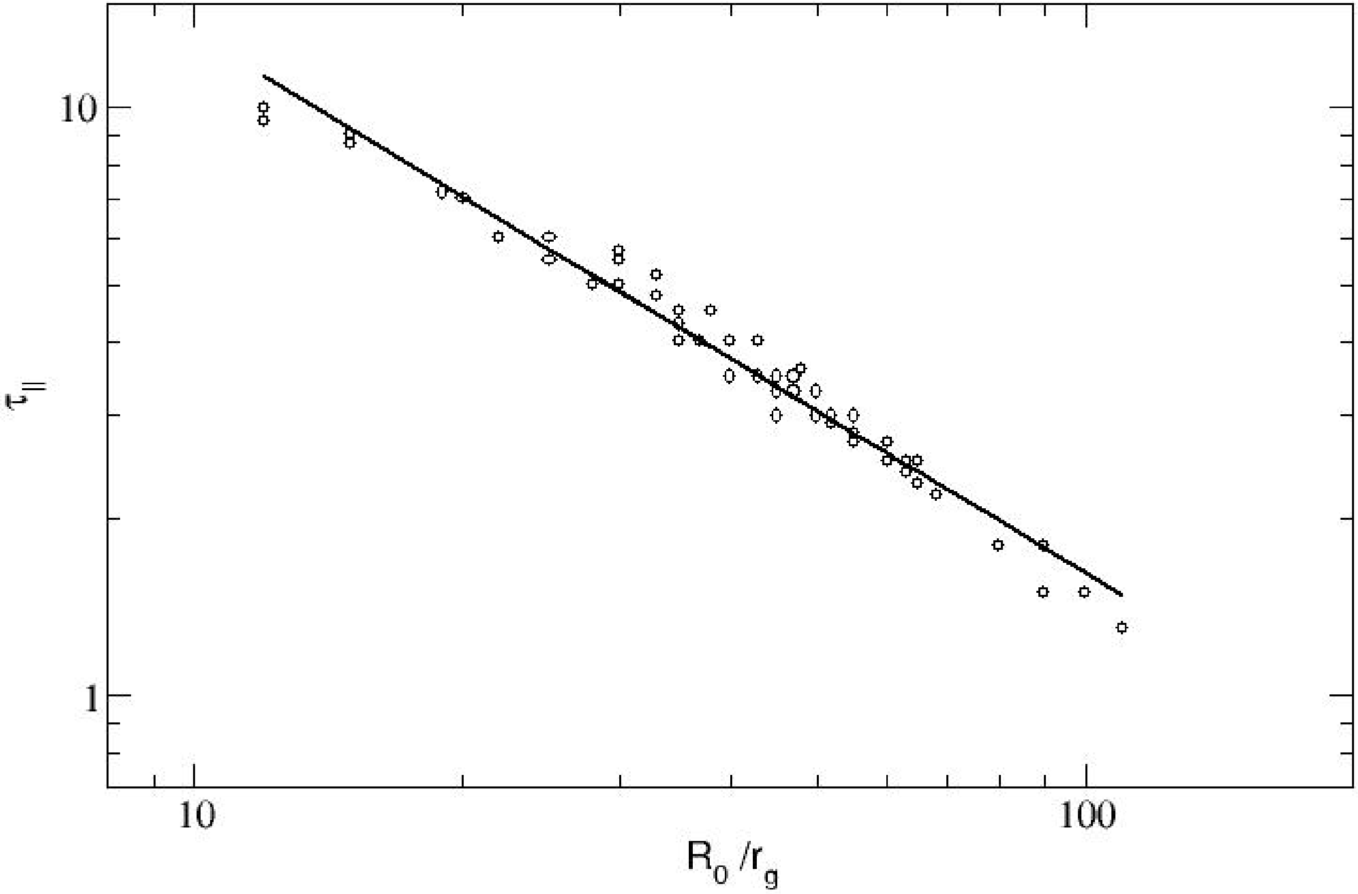
Gamma vs. peak frequency 1



An important relation

- The values of the density and the radius of the jet at its base, that we used in the previous correlations, are correlated !!!

Density vs. Radius at base of jet



Therefore,

$$\frac{\dot{M}_o}{M_o} \propto \frac{R_0^2 n_0}{M_o} \propto \frac{R_0}{M_o} \propto R_0$$

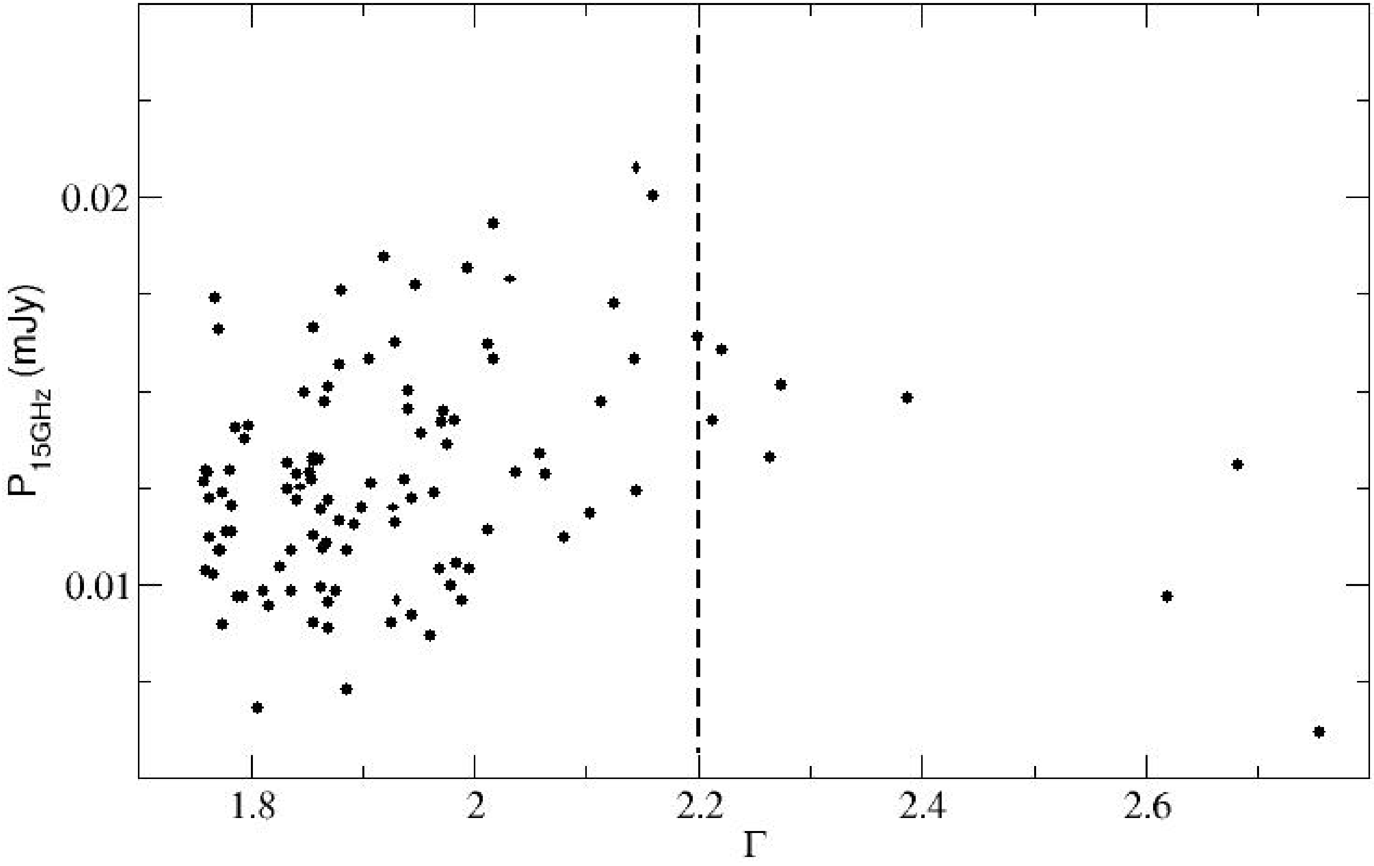
Summary

- If our model has anything to do with reality, it forces us to think that, the characteristic frequencies of variation **increase** with radius.
- This is not what we normally think.
- The "party line" is that the frequencies of variability **decrease** with radius (e.g. QPOs as Keplerian frequencies).
- Let's push the jet model further!

Additional constraint

- Our jet model predicts a positive correlation between radio flux and Γ.
- Such a correlation has not been seen or proposed before.
- In Cyg X-1 we have found this correlation. It is not very tight, but it is certain (Kendall's tau=0.21, i.e., probability < 0.2% that there is no correlation).

Radio flux vs Gamma



In closing,

I feel that our jet model may indeed have something to do with reality.

Therefore, I suggest that

we abandon the "static corona" models,

that teach us nothing,

and take a closer look at jets!

Happy JeTseTting !!!