Radiation processes and models

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irap

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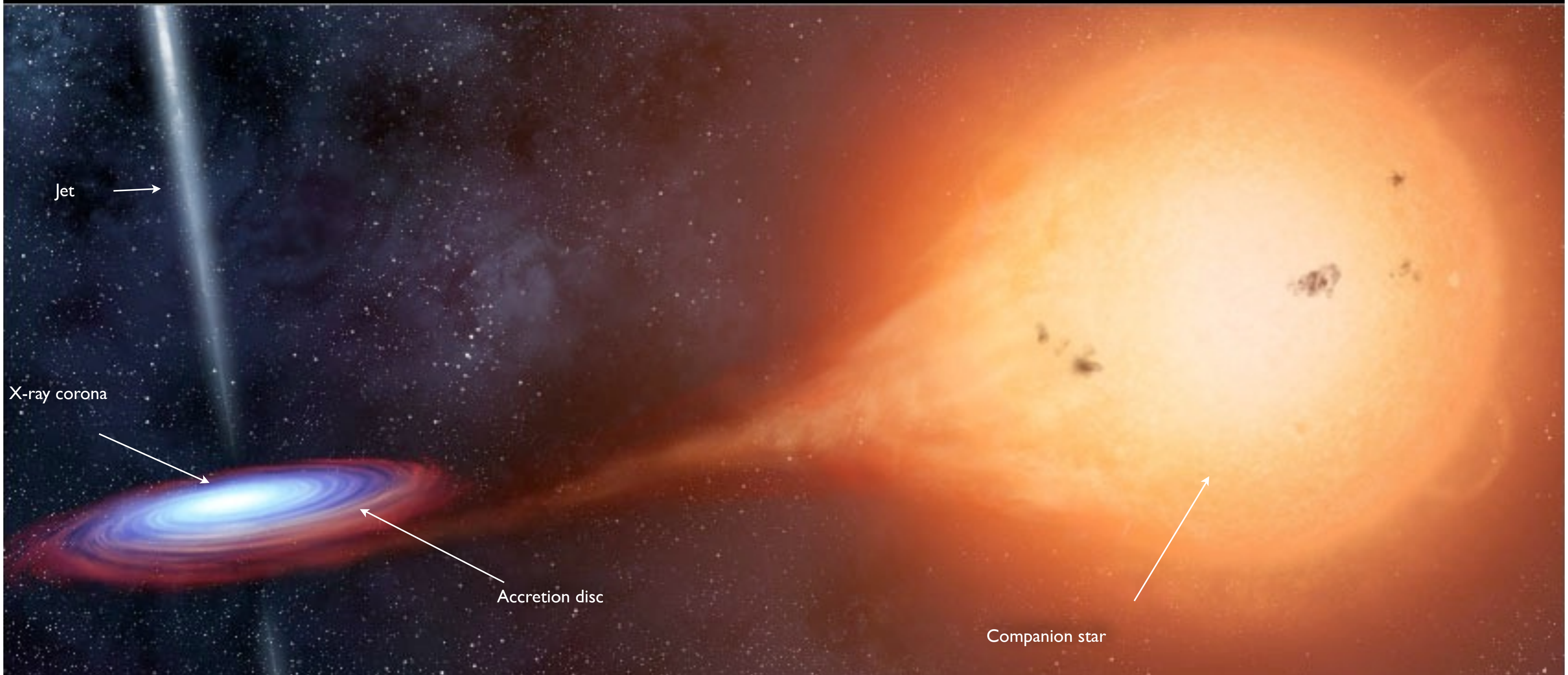
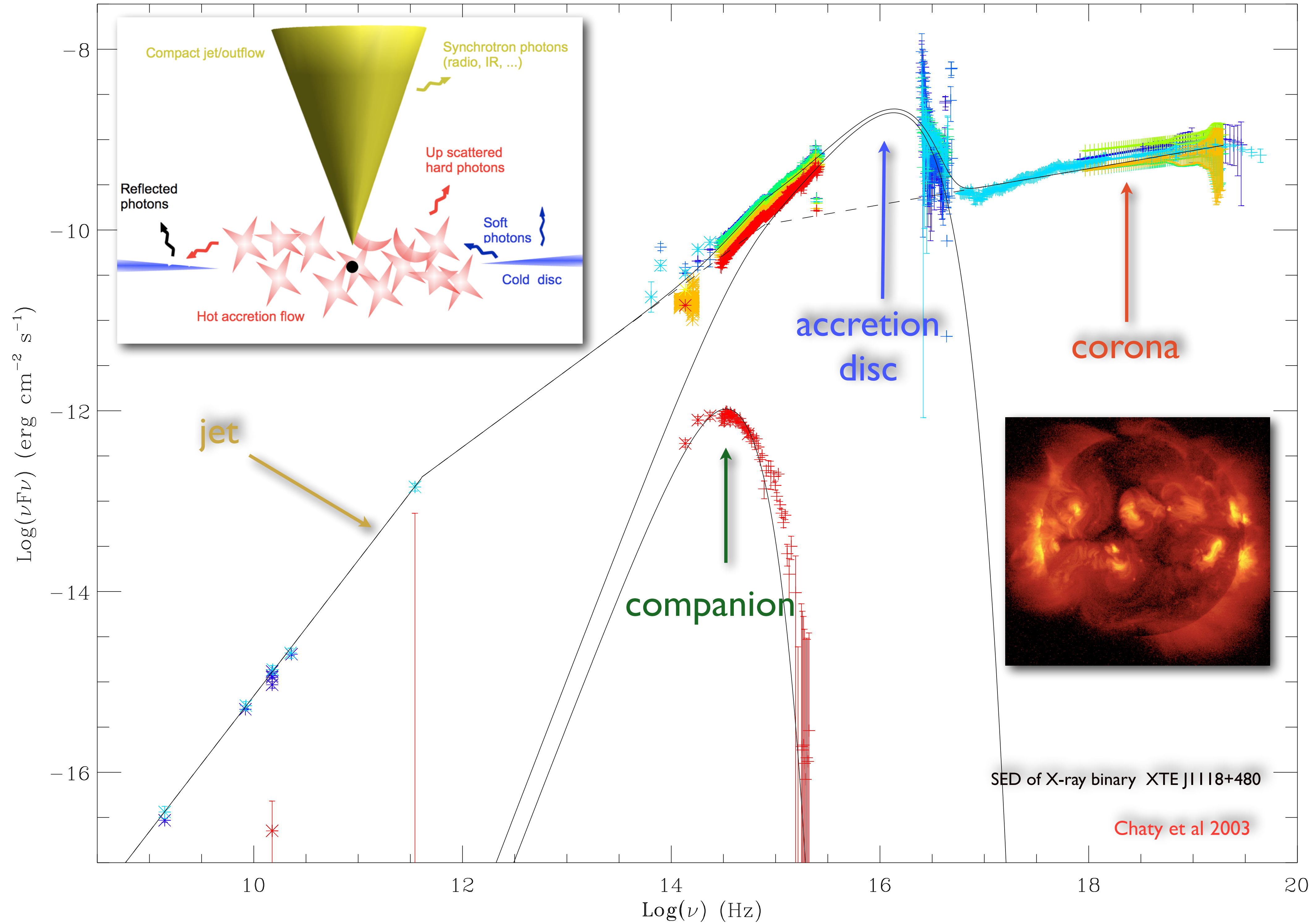
- **Lesson 1: Introduction to compact object physics**
- **Lesson 2: Radiation processes**
- **Lesson 3: Models for accreting black hole binaries: accretion flows**
- **Lesson 4: Models for accreting black hole binaries: compact jets**

CHAOS

Models for the multi wavelength emission of black hole binaries: Jets



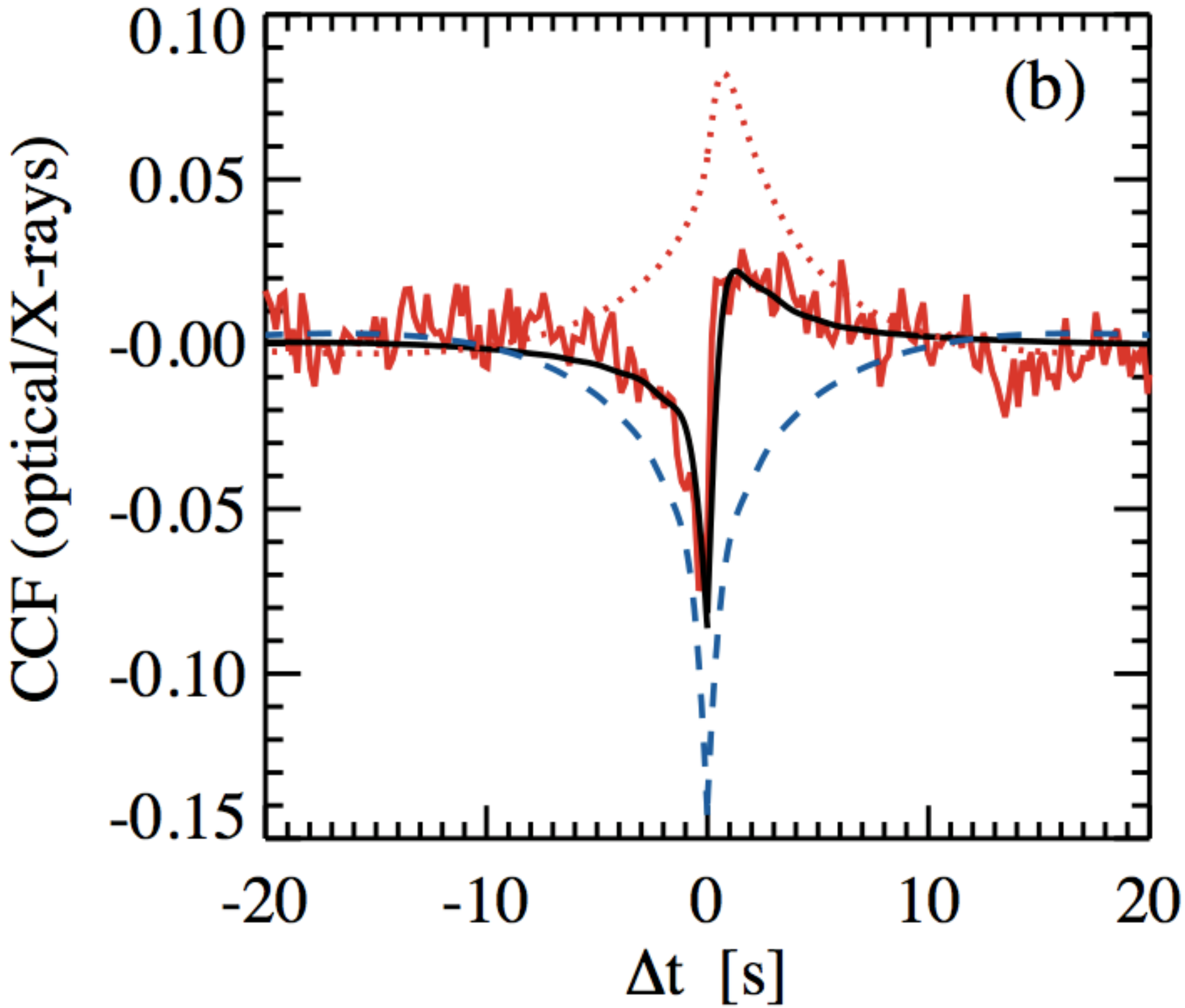


Compact jet/outflow
Synchrotron photons (radio, IR, ...)
Up scattered hard photons
Reflected photons
Soft photons
Cold disc
Hot accretion flow
accretion disc
corona
jet
companion
SED of X-ray binary XTE J1118+480
Chaty et al 2003
Log(νFν) (erg cm−2 s−1)
Log(ν) (Hz)

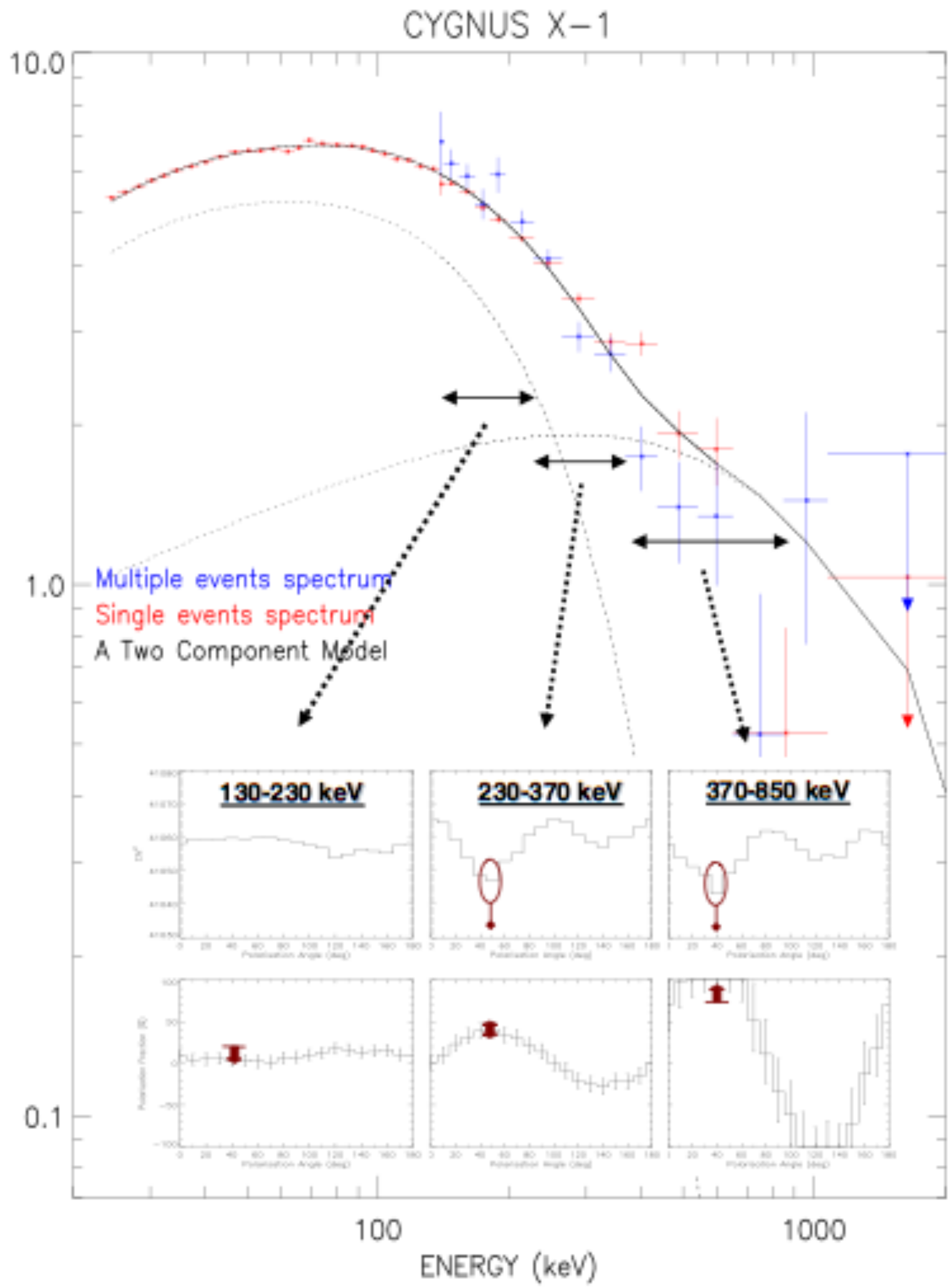
Recap from lesson 3

- Truncated disc model+ a precessing hot flow with non-thermal electrons reproduces many of the spectral and observed properties of BH binaries

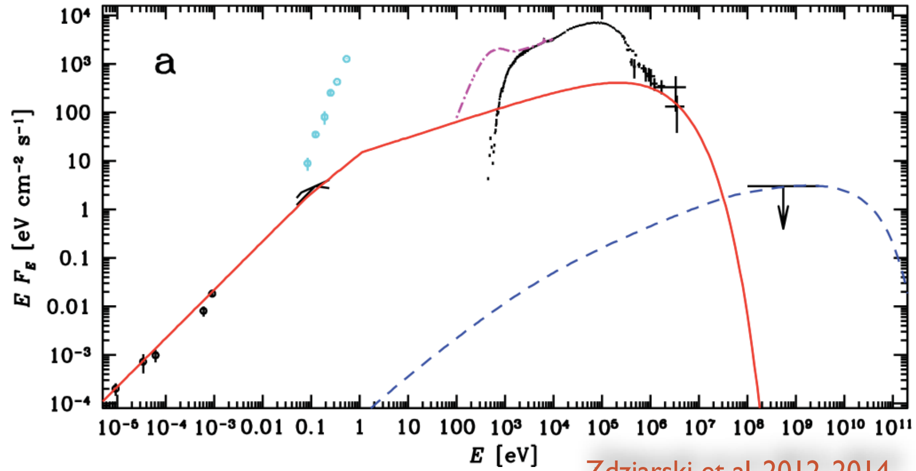
- Correlated optical/X-ray variability of swift J1753.5-0127



INTEGRAL detects polarization in Cyg X-1



- ~70 % polarization above 300 keV
- Jet contribution in soft gamma-rays ?



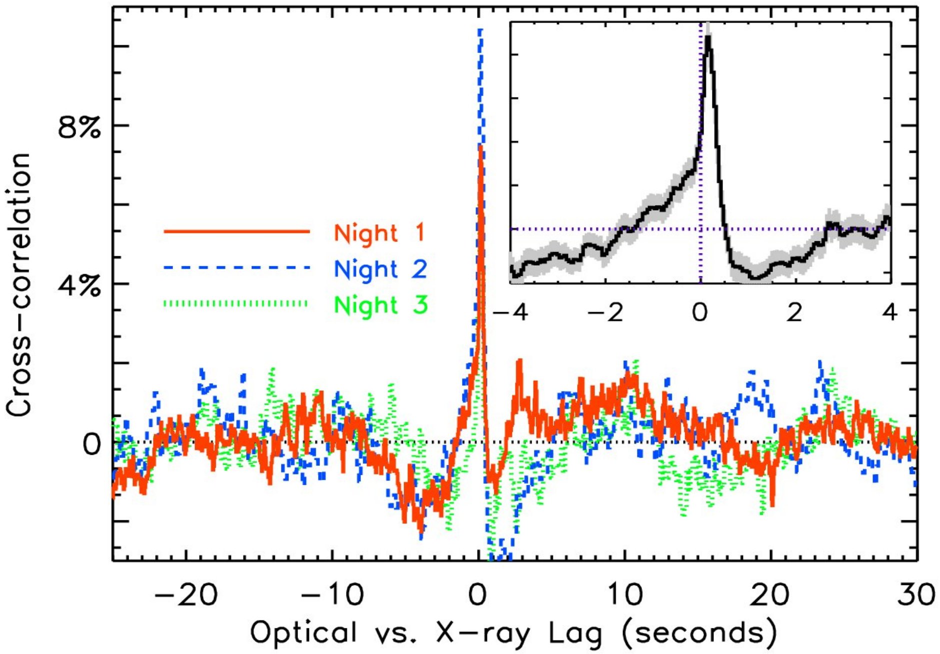
Zdziarski et al. 2012, 2014

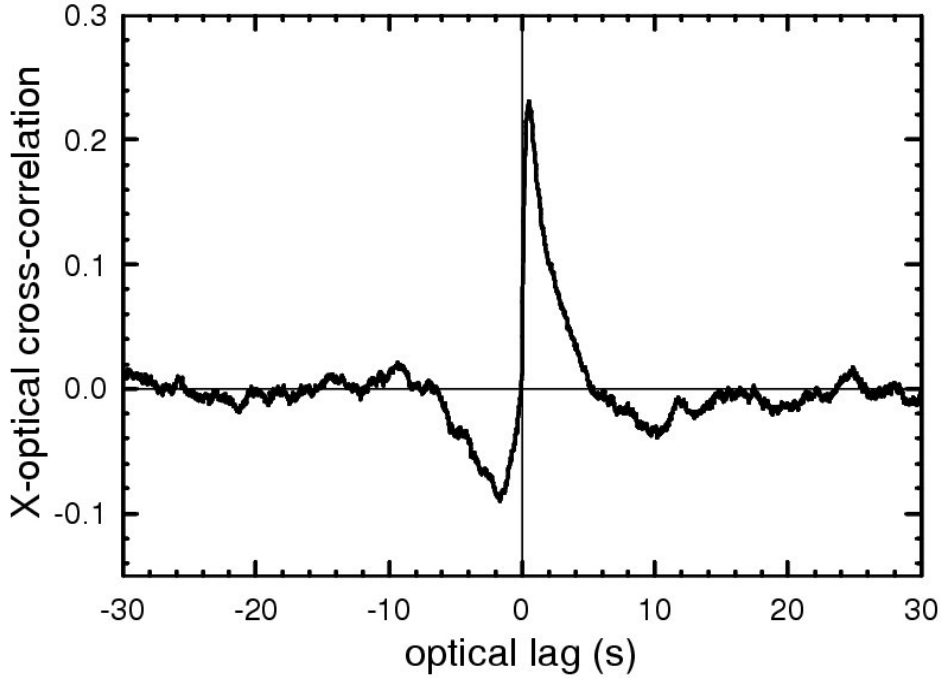
The minimum indicates the polarisation angle for each energy range. No prefered value at low energy, but high energy values are in agreement.

The red arrows indicate the best estimate of the polarisation fraction. It increases with energy.

Laurent et al. 2011 (IBIS), Jourdain et al. 2011, 2012 (SPI)

Other observed Opt/X-ray cross correlation functions





GX 339-4

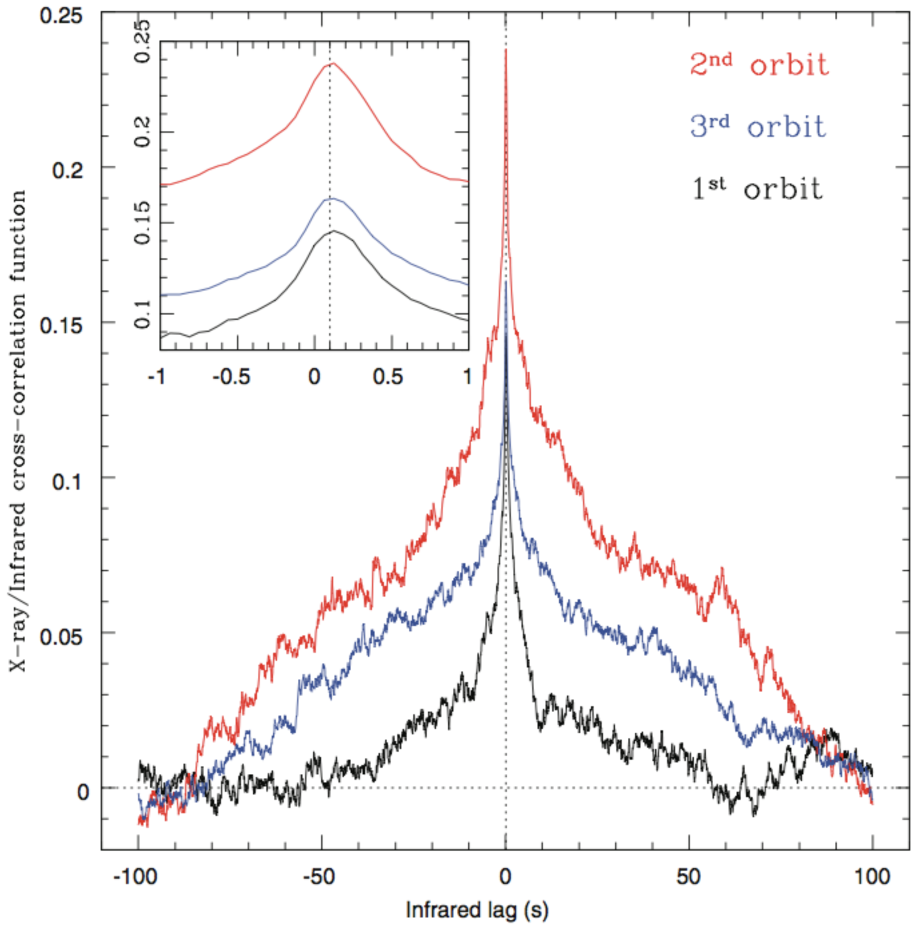
Gandhi+08, 10

XTE J1118+480:
Kanbach+01,
Hynes+03

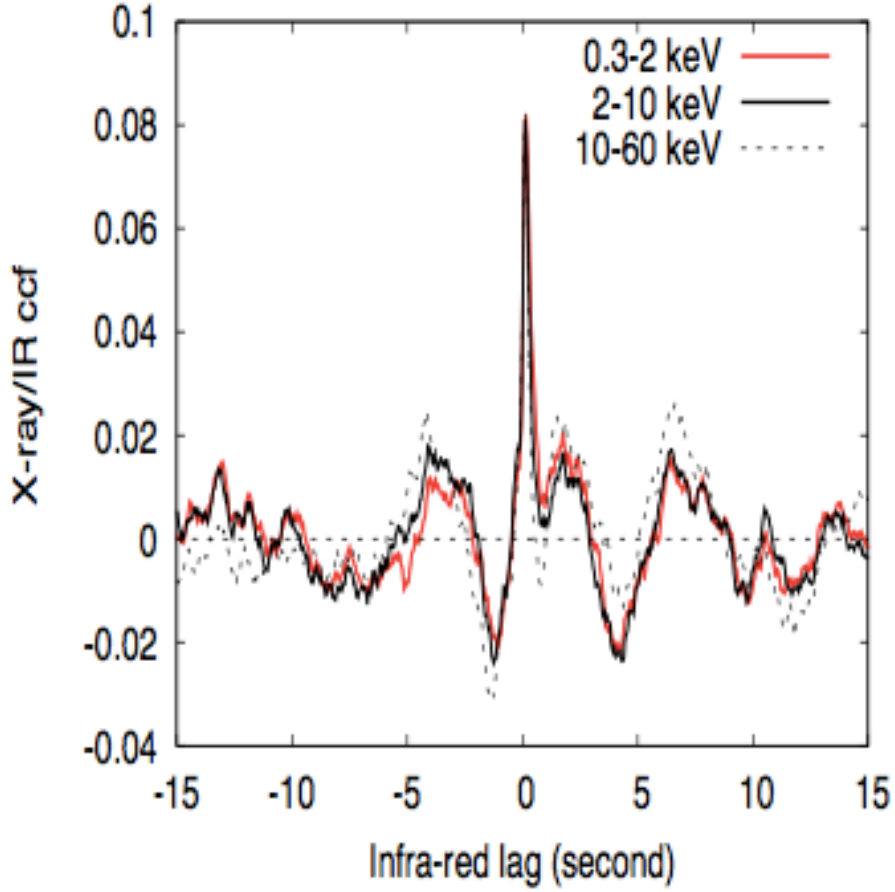
P. Gandhi

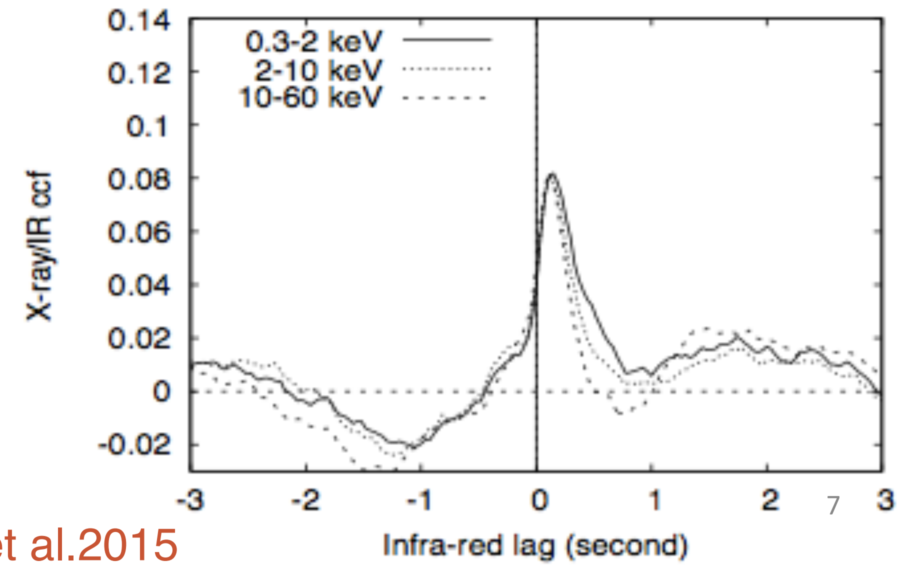
Observed Infrared/X-ray cross correlation functions

GX 339-4



Casella et al. 2010

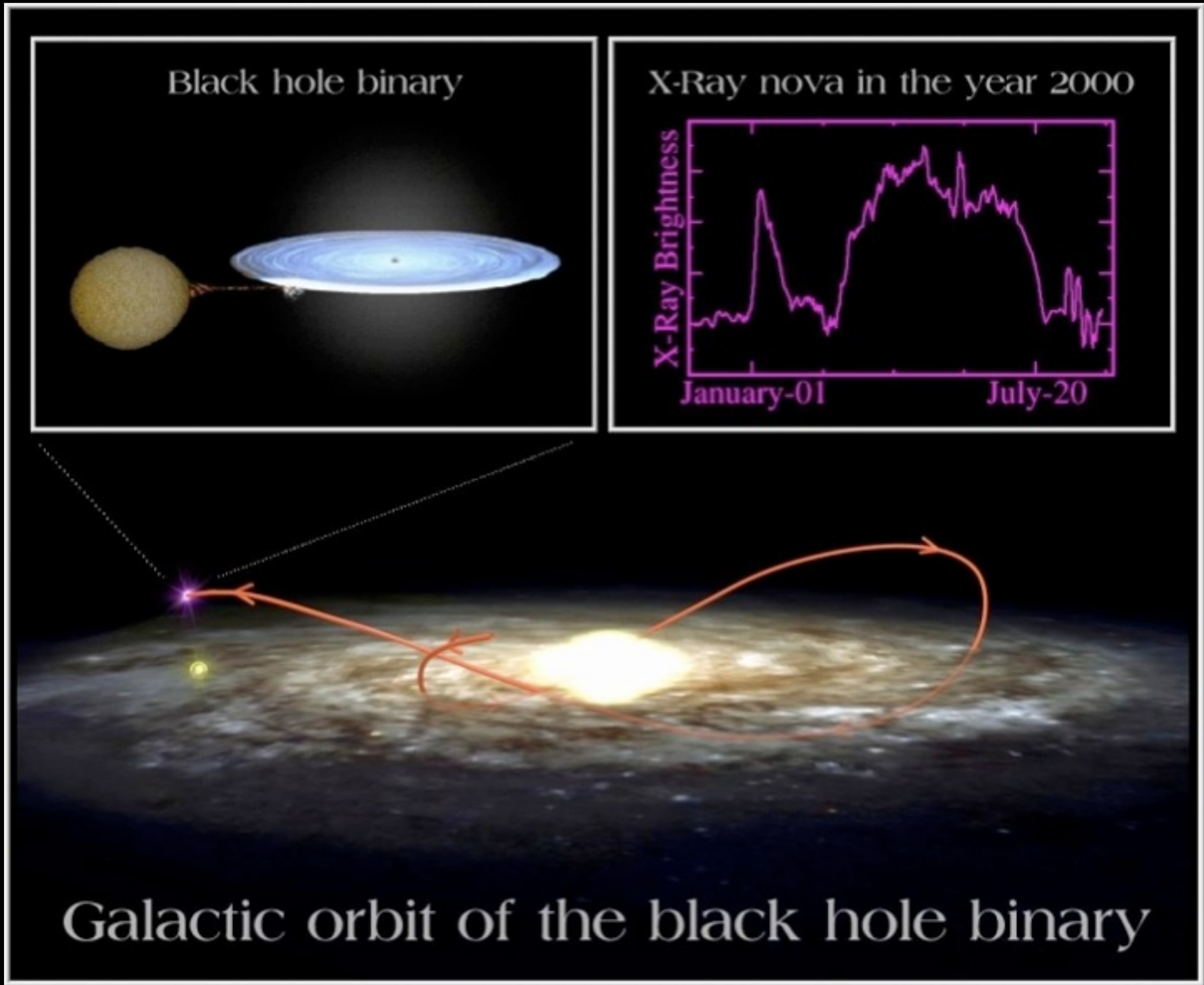




Kalamkar et al.2015

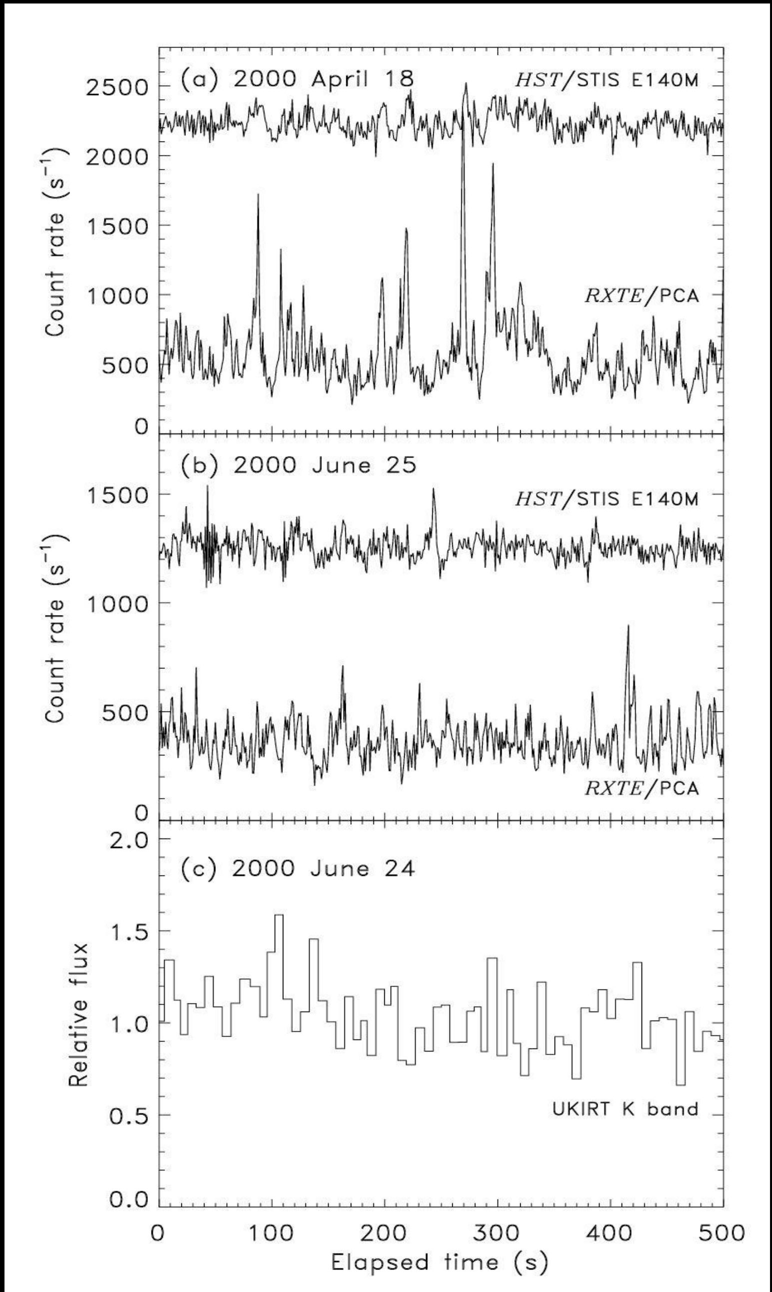
- Jet variability ?

The case of XTEJ1118+480

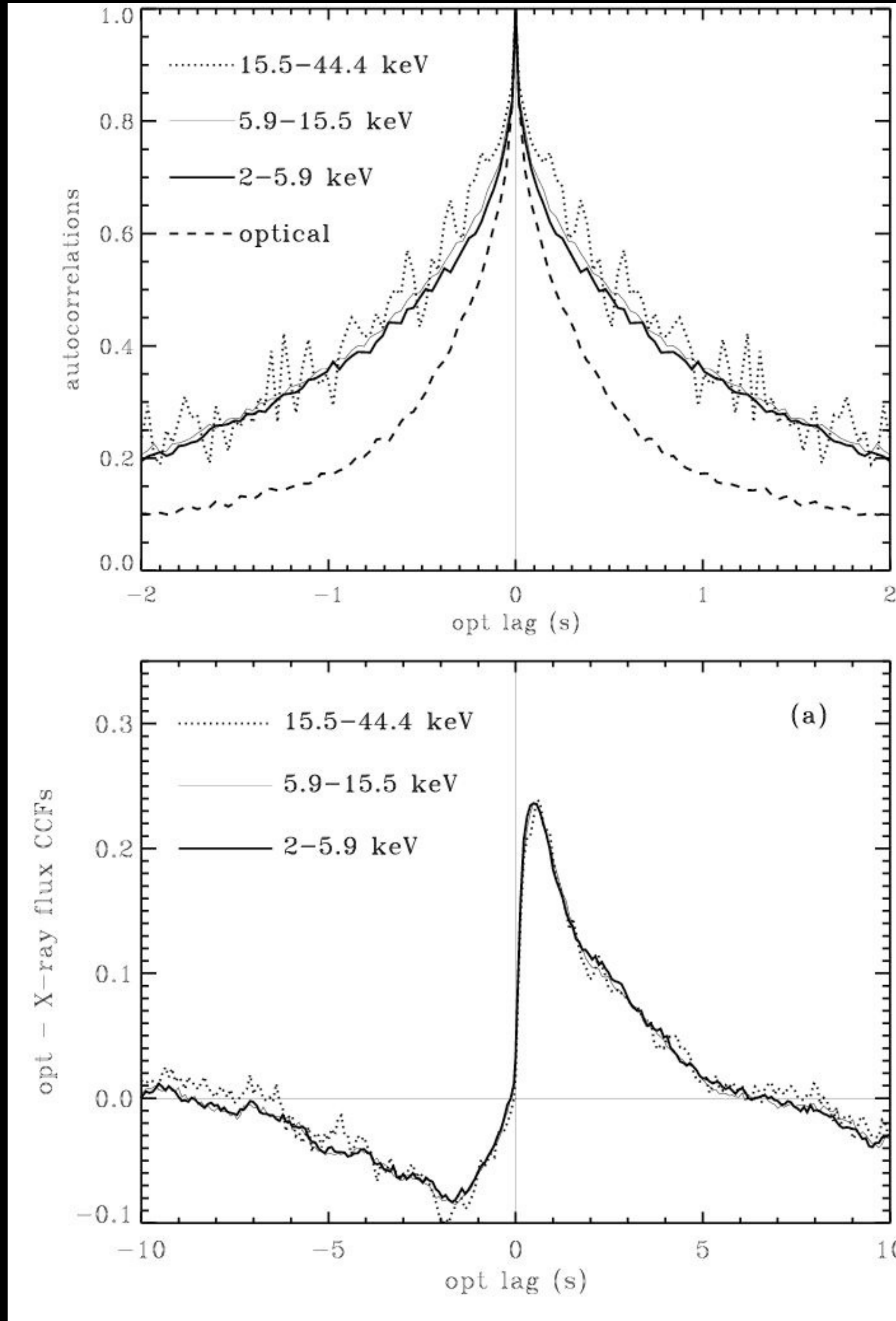


The case of XTEJ1118+480

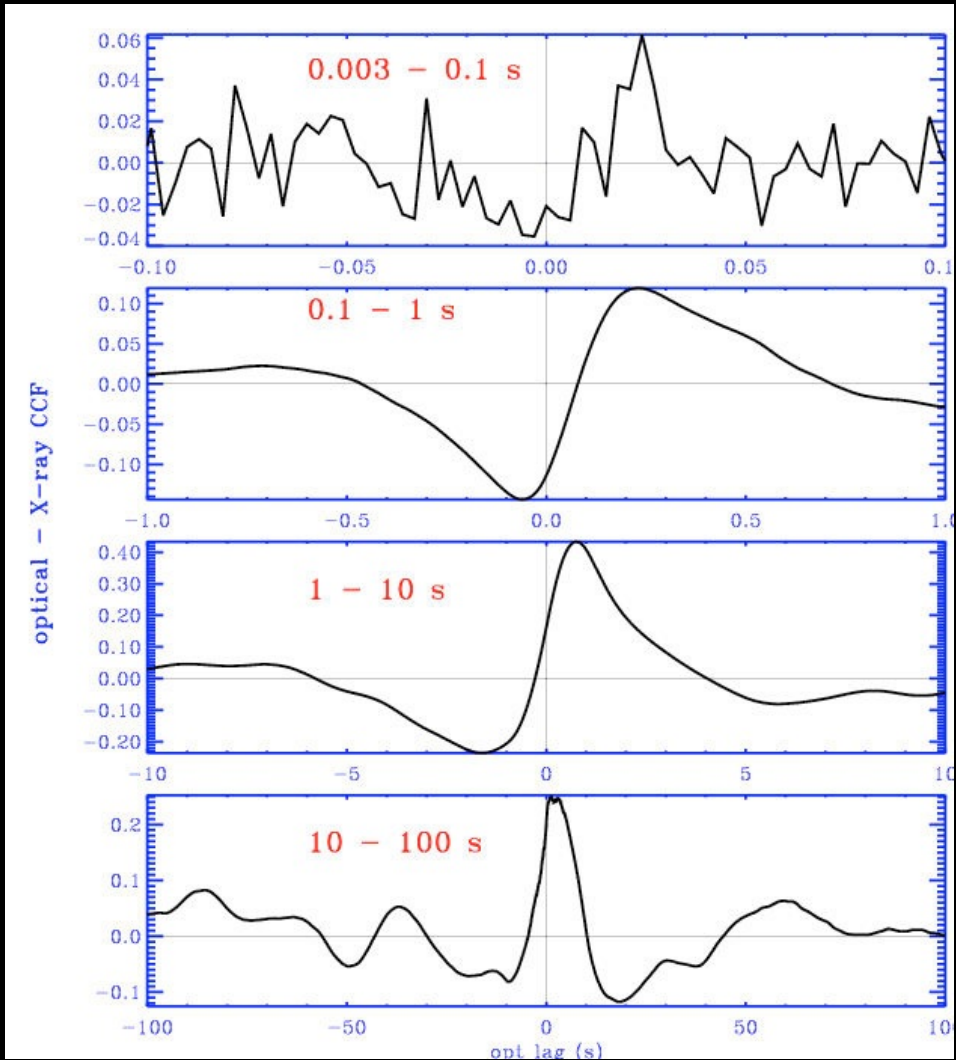
X-ray, UV, optical and IR flickering



Hynes et al. 2003



Dependence of the CCF on the time-scale of the fluctuations



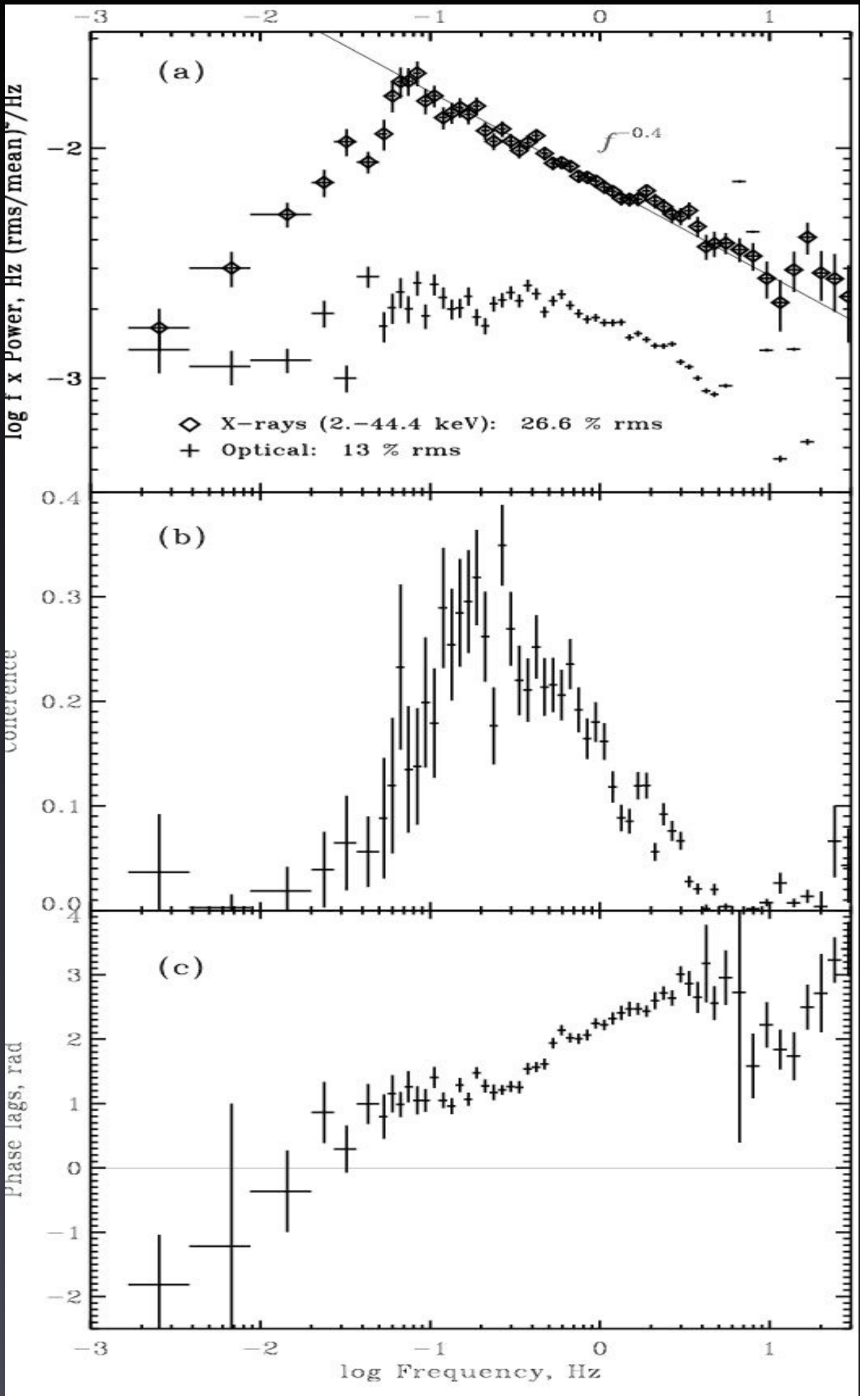
(from Malzac et al., A&A, 2003)

Light curves filtered to keep only fluctuations of specified time-scales

⇒ Nearly scale-invariant CCF

⇒ The optical lag does depend on time-scale

Fourier Analysis



X-ray power spectrum typical of low/hard state sources

Optical varies on shorter time-scales than X-rays

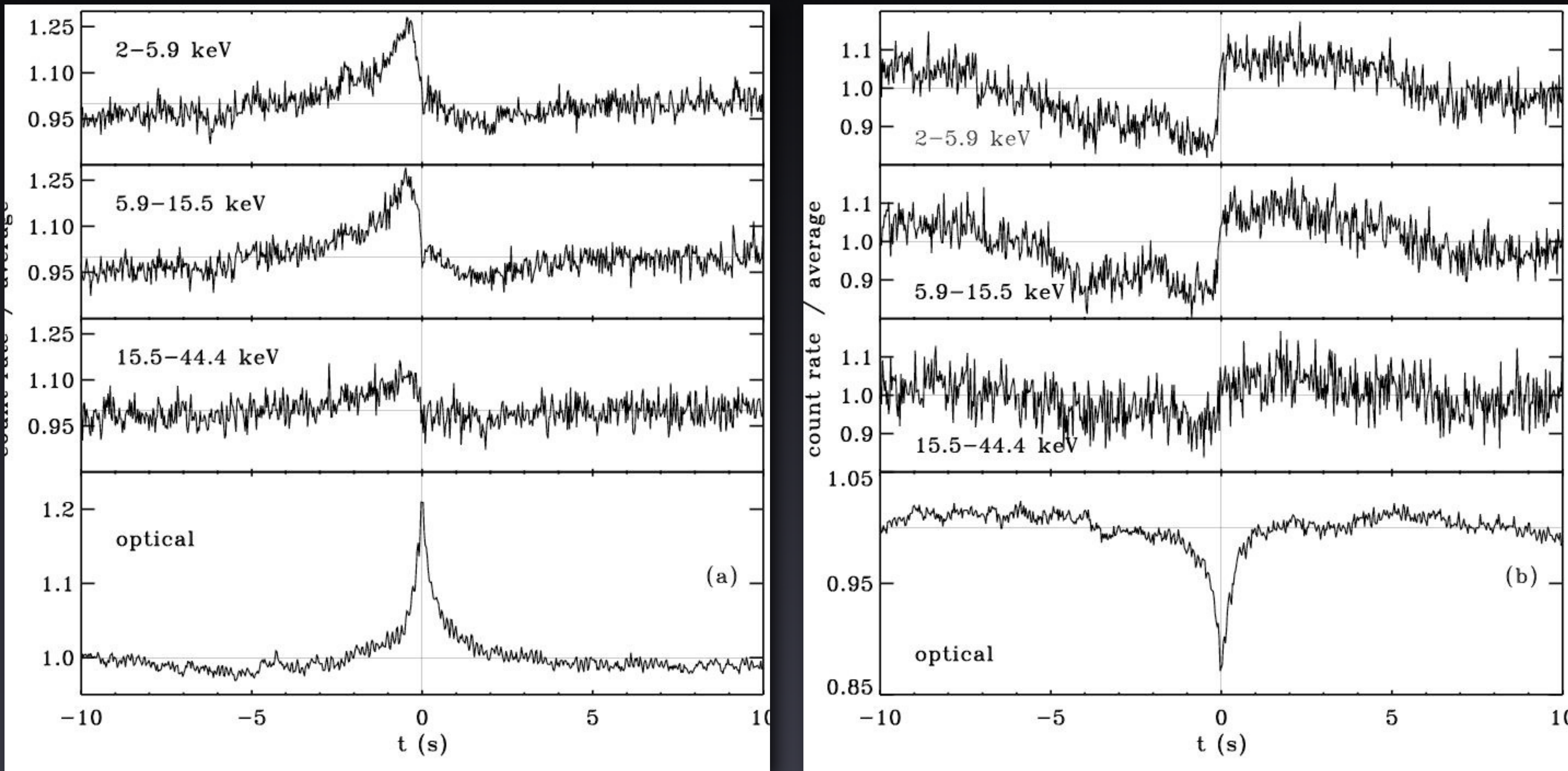
Coherence spectrum:
Opt and X-rays
correlated for 1 to 10 sec fluctuations

Opt. Phase lag $\phi = 2\pi f \Delta t \sim \pi/2$

$$\Rightarrow Opt \propto -\frac{dX}{dt}$$

(Malzac et al. A&A 2003)

Event superposition analysis

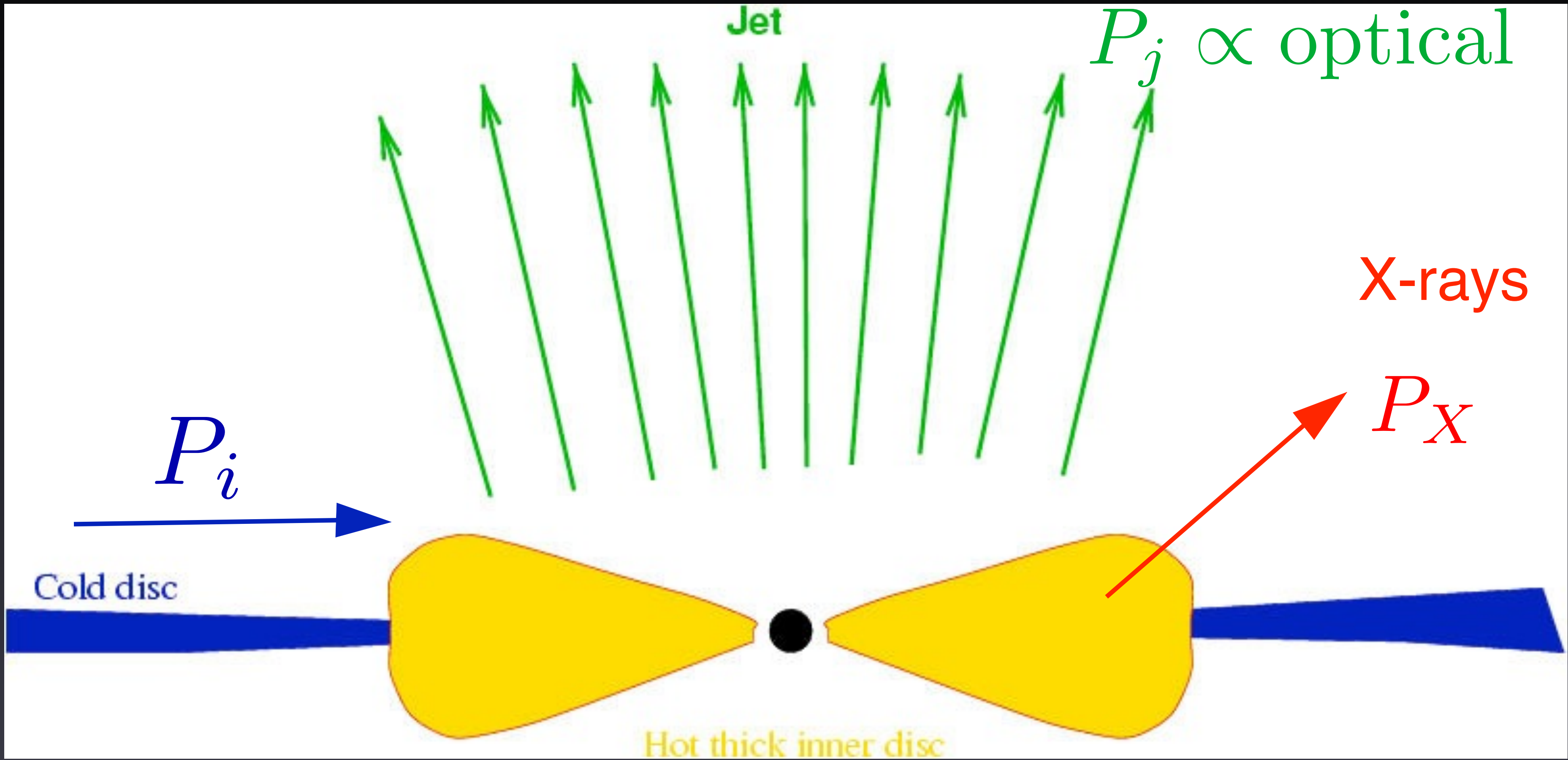


$$\Rightarrow Opt \propto -\frac{dX}{dt}$$

(Malzac et al. 2003)

A signature of jet disc coupling ?

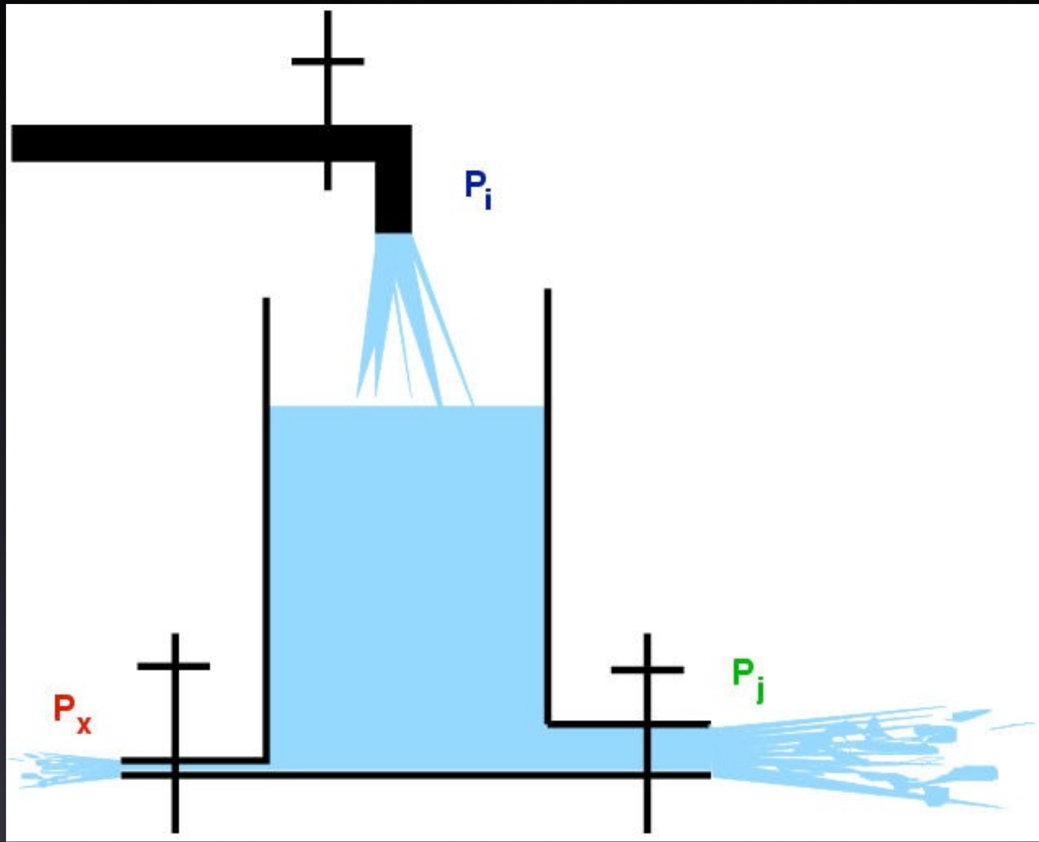
Jet corona coupling through common energy reservoir



Assume accretion energy is stored in the accretion flow
A fraction is dissipated into the corona the rest is used to power the jet.

Jet corona coupling through common energy reservoir

A simple analogue:



taps controlled by a stochastic process

If $P_j > P_X$ then $P_X \propto E \propto -\int_{-\infty}^{t} P_j dt \Leftrightarrow P_j \propto -\frac{P_X}{dt}$

⇒ behaviour of XTE J1118+480

Malzac, Merloni & Fabian, MNRAS, 2004

Time dependent model

- On short time-scales the system is out of equilibrium:

$$\dot{E} = P_{\rm i}(t) - K_{\rm j}(t)E(t) - K_{\rm x}(t)E(t)$$

→ we impose independent random fluctuations of P_i, K_x and K_j and then solve the equation for E(t)

- We then generate synthetic light curves assuming:

$$X(t) \propto P_{\rm x} = K_{\rm x}(t)E(t)$$

$$Opt(t) \propto P_{\rm j}(t-\Delta) = K_{\rm j}(t-\Delta)E(t-\Delta)$$

Travel time from the disc to the jet optical photo-sphere

⇒Time delay $\Delta \sim 0.05 \quad {\rm s}$

- Main parameters:

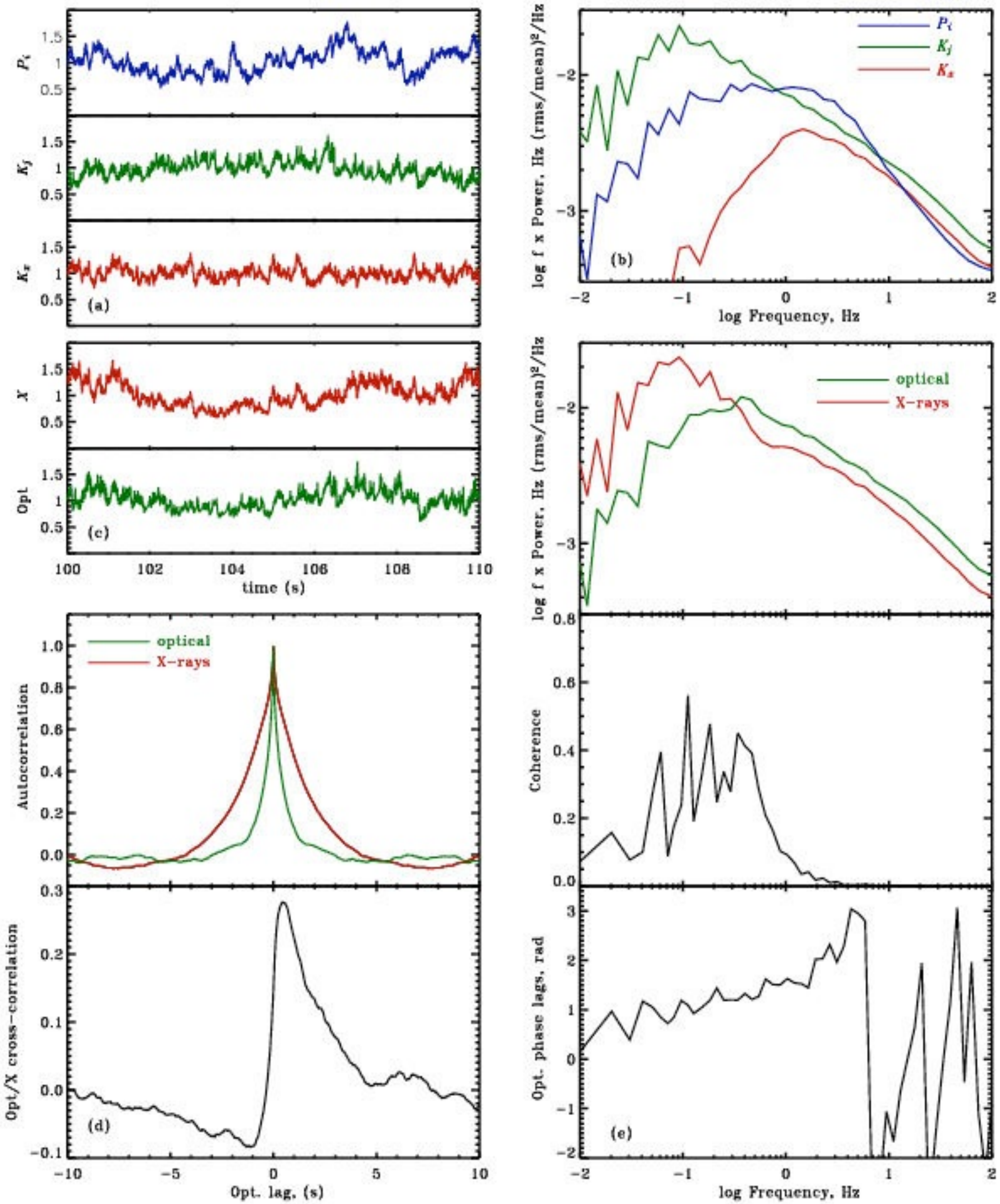
Dissipation time of the energy reservoir: $T_{dis} = \left[K_X + K_j\right]^{-1}$

Fraction of the power dissipated into the X-rays: $f_X = K_X T_{dis}$

Time dependent model

$$f_X = 0.1$$

$$T_{dis} = 0.5\,\mathrm{s}$$



(Malzac, Merloni & Fabian, MNRAS, 2004)

Energy Reservoir Model

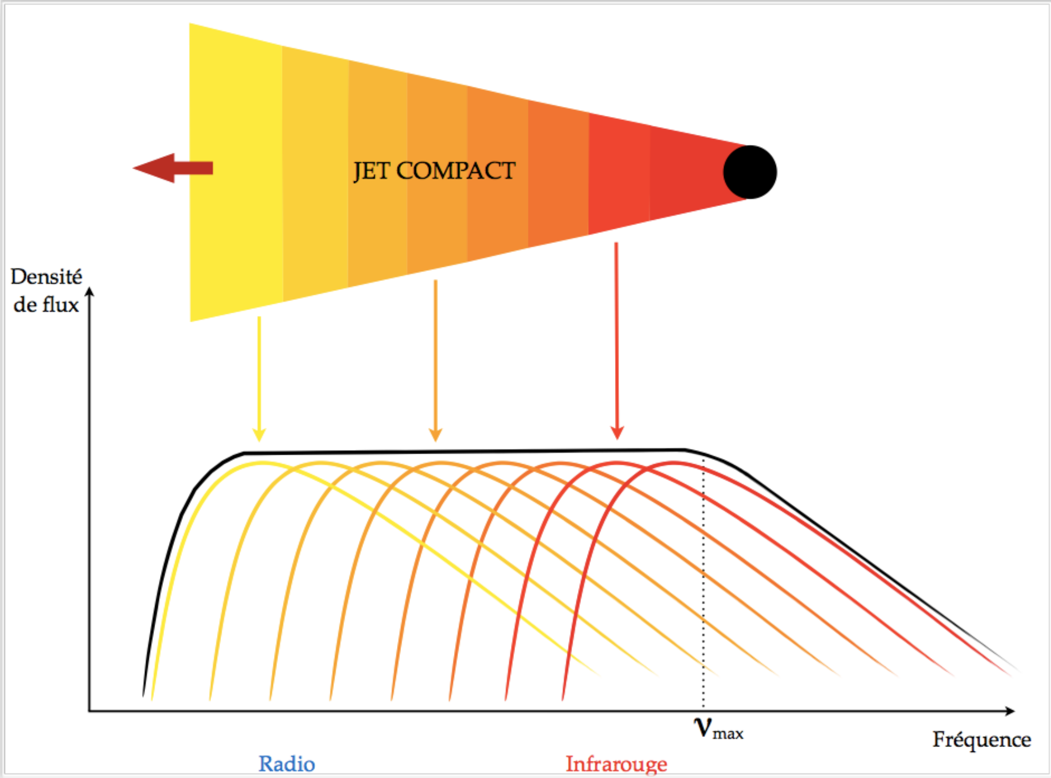
- Jet/disc coupling through a common energy reservoir can explain the complex behaviour of XTE J1118+480.

- Toy model: need to take into account more realistic jet physics

- Suggests that simultaneous IR/optical/X-ray can unveils the dynamics of accretion/ejection coupling at the shortest times scales.

(From Malzac, Merloni & Fabian, MNRAS, 2004)

Standard conical jet emission model (Blandford & Koenigl 1979) erved



(M. Coriat)

- Synchrotron radiation from a population of relativistic leptons travelling down the jet

$$n_e(\gamma_e) \propto \gamma_e^{-p}$$

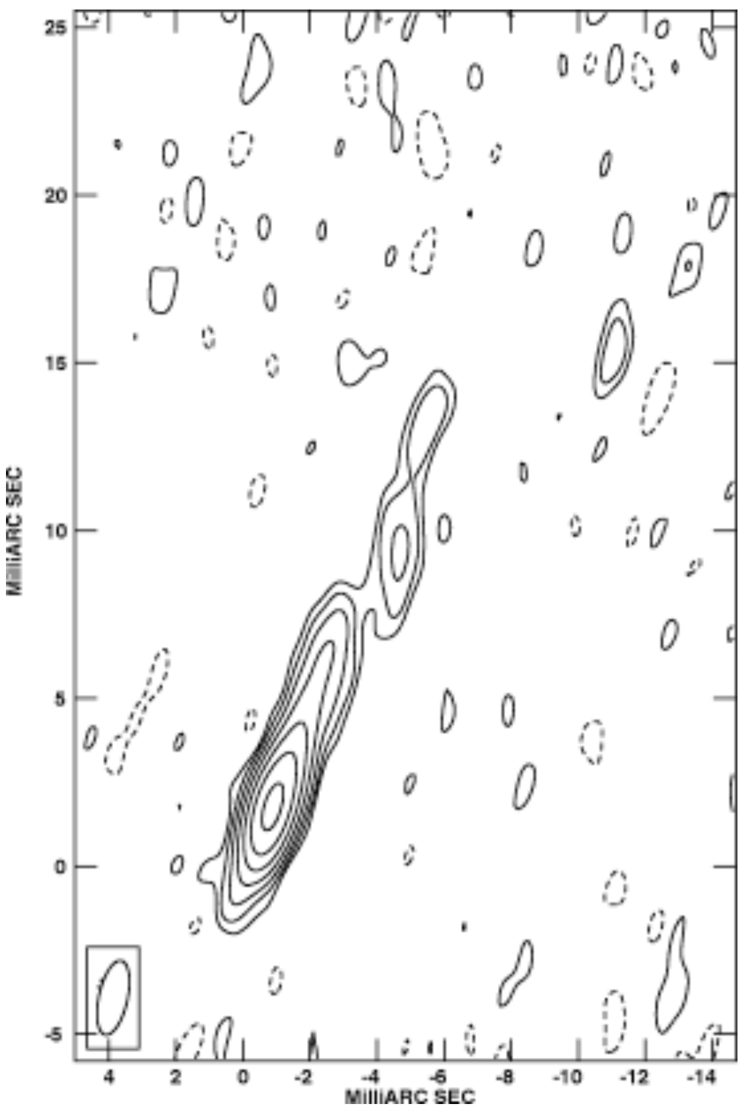
- Energy losses neglected ⇒ constant specific internal energy:

$$\tilde{\epsilon}(z) = \tilde{\epsilon}_0 \;\; \Rightarrow \;\; B^2 \propto n \propto E_{\rm int} \propto V^{-1} \propto r^{-2} \propto z^{-2}$$

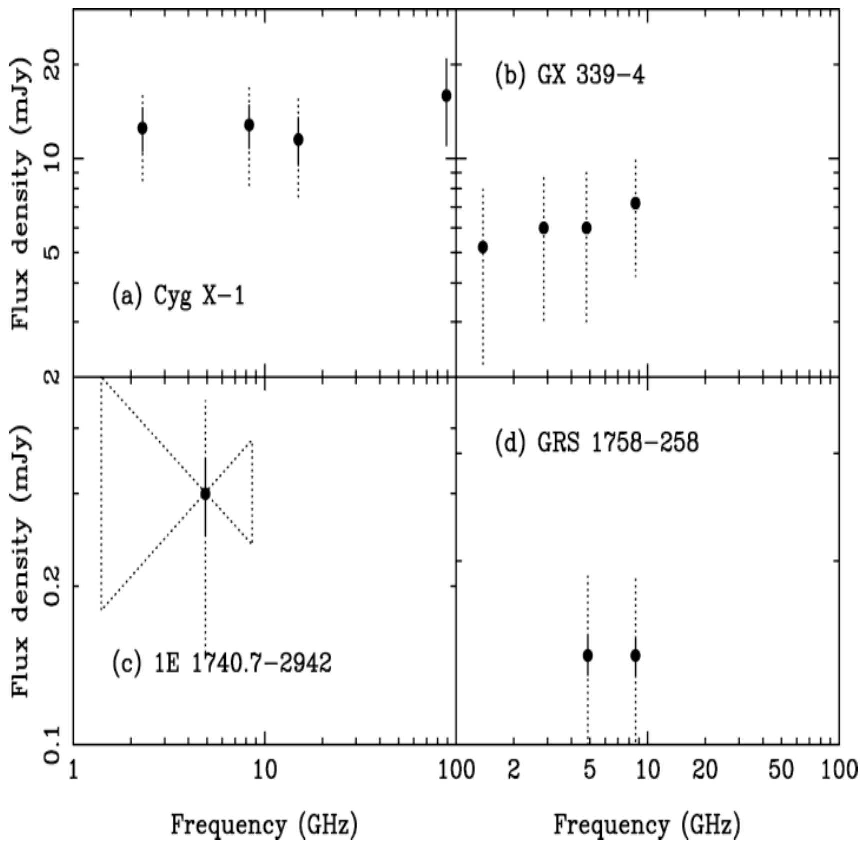
$$F_\nu \propto \nu^\alpha \;\; \Rightarrow \alpha_{\rm thick} = 0$$

$$\alpha_{\rm thin} = \frac{1-p}{2}$$

Evidence for compact radio jets in the hard state

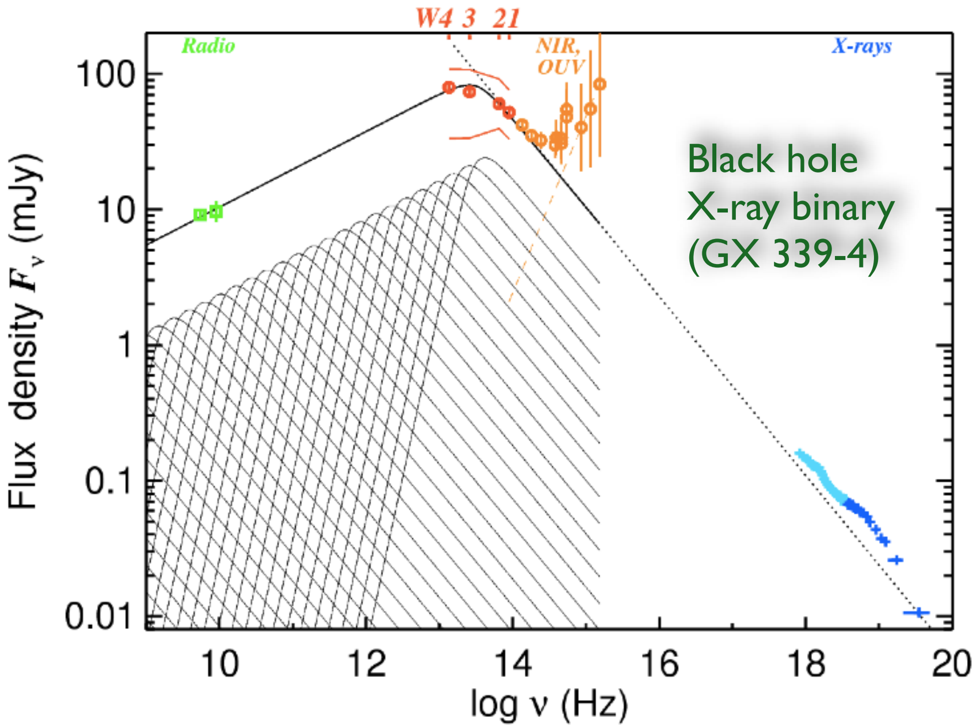


Cygnus X-1
(Stirling et al. 2001)



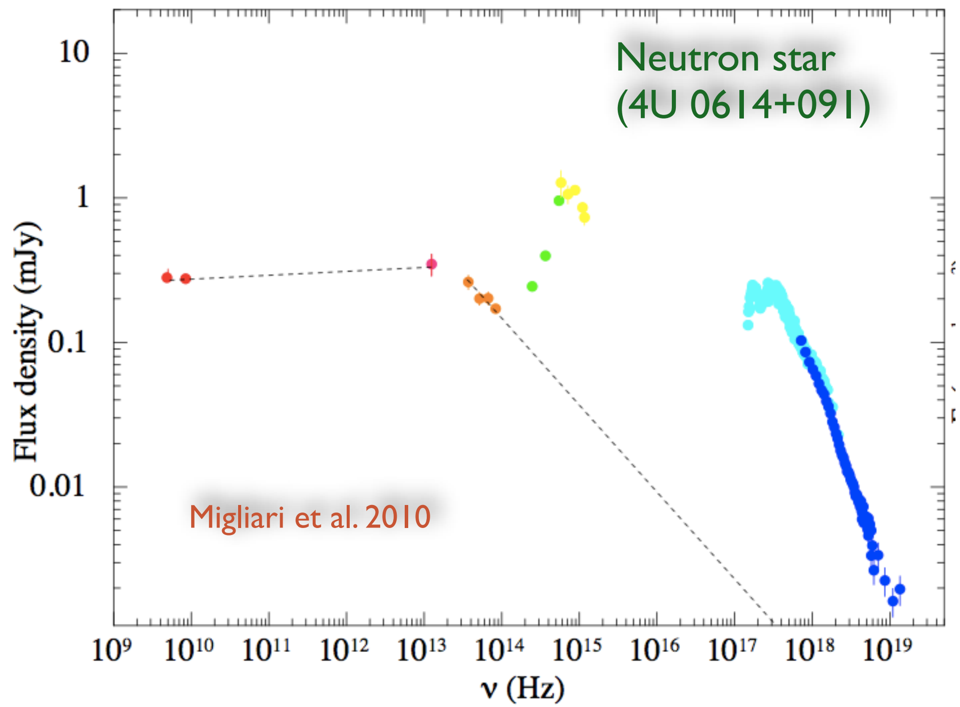
Flat/inverted radio spectra
(Fender 2001)

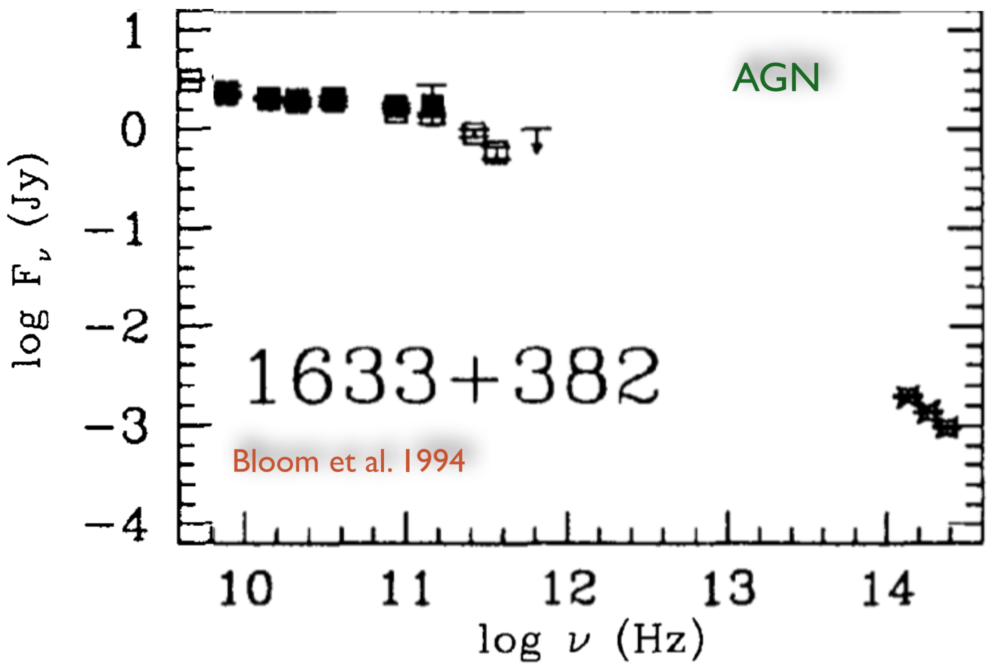
Observed Spectral Energy Distribution of Compact Jets



Gandhi et al. 2011

see also Corbel & Fender 2002, Chaty et al. 2011; Rahoui et al 2012; Russell et al. 2013...



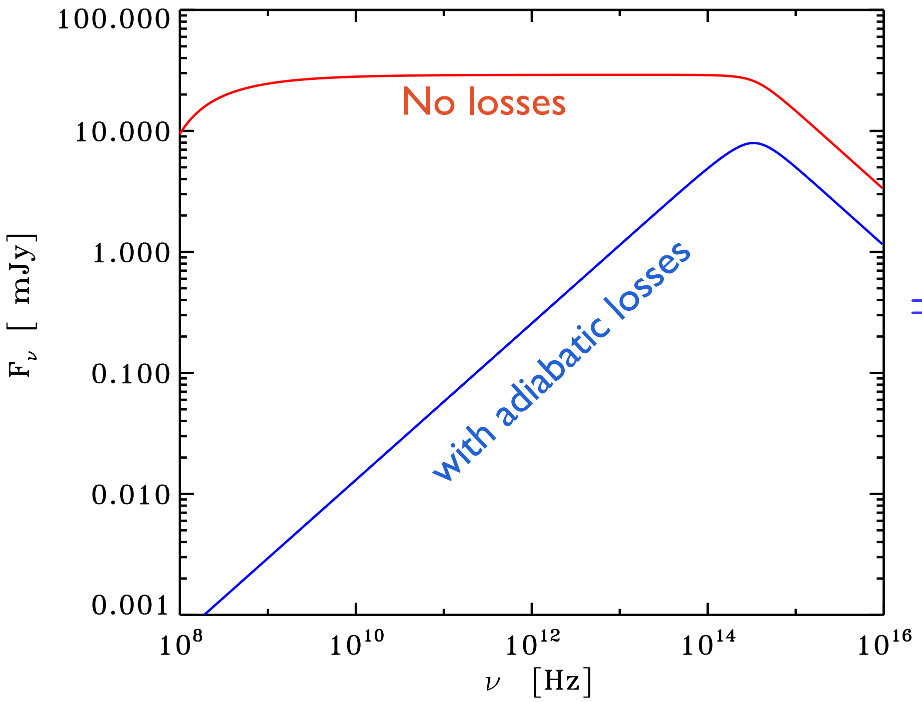


What about adiabatic expansion losses ?

Pressure work against external medium as flow expands in conical geometry

$$d\tilde{W} = Pd\tilde{V} = (\gamma_a - 1)m\tilde{\epsilon}\frac{d\tilde{V}}{\tilde{V}} \simeq \frac{2m\tilde{\epsilon}}{3}\frac{dR}{R}$$

$\Rightarrow$ Specific internal energy decreases: $\tilde{\epsilon} \propto R^{-2/3} \propto z^{-2/3}$

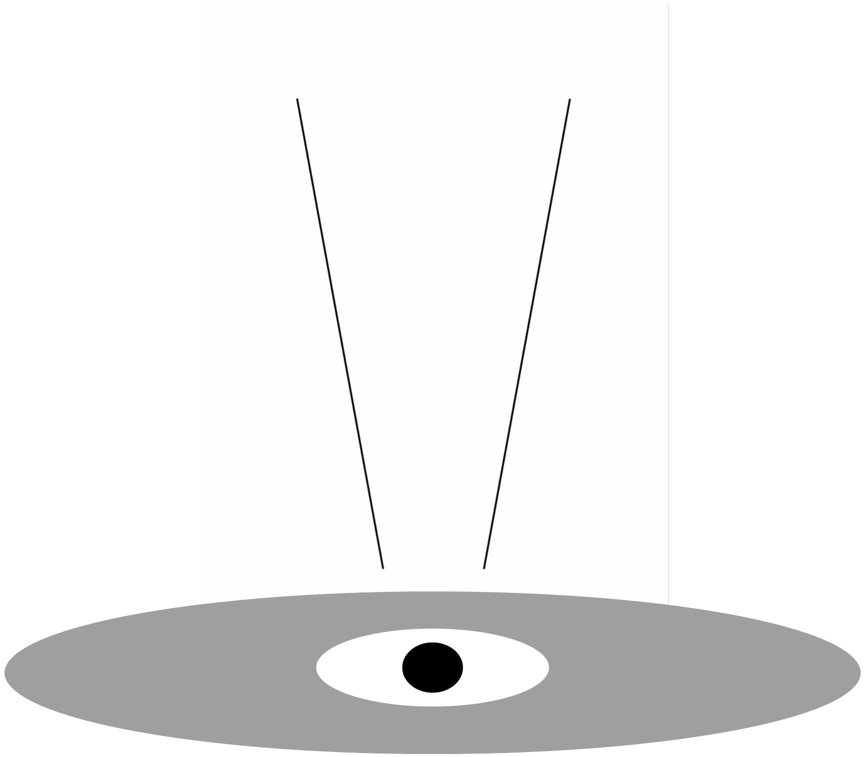


$$\Rightarrow \alpha_{\rm thick} = \frac{2p+13}{4p+18} \simeq 0.65$$

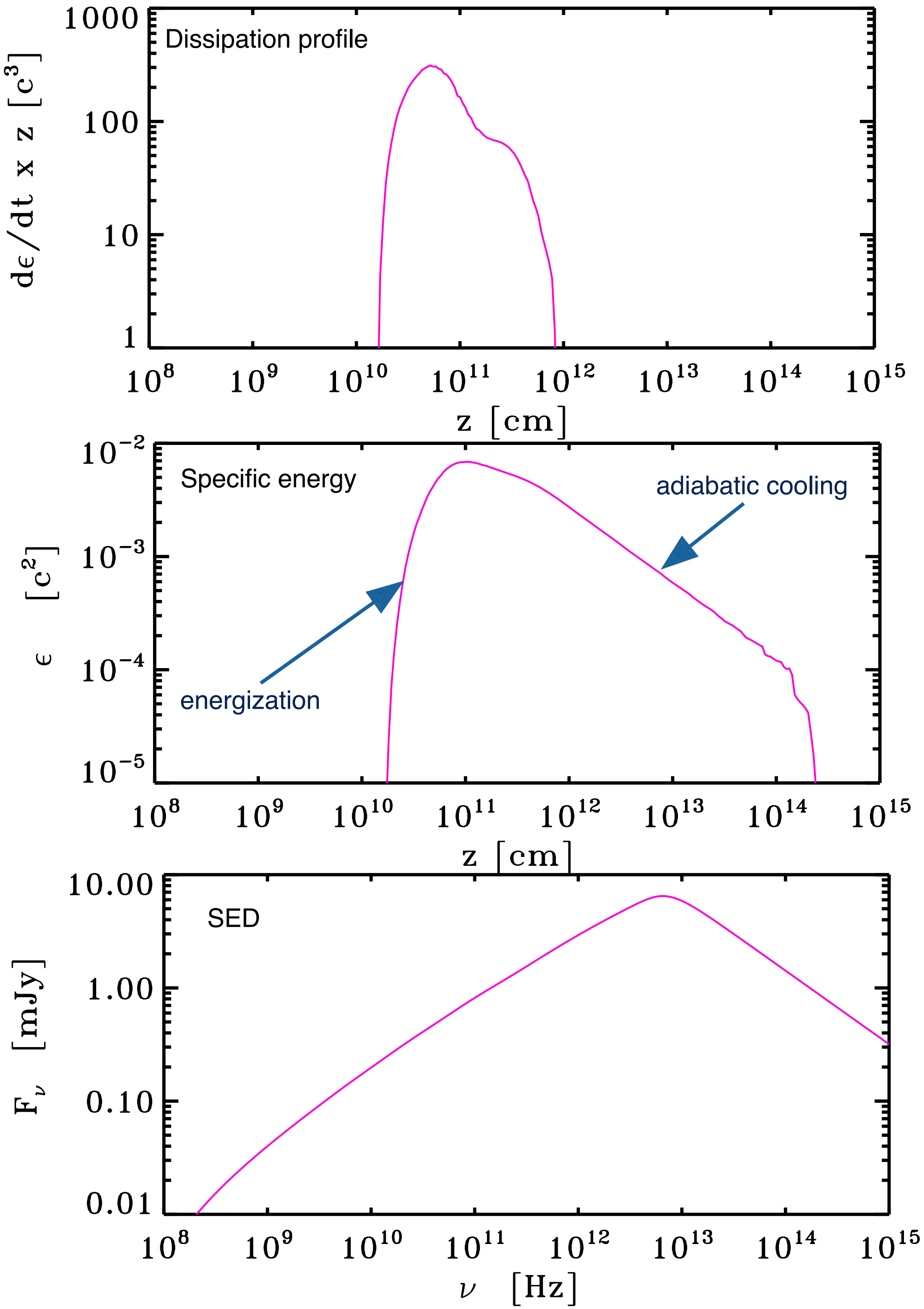
Spectrum is strongly inverted : need to compensate for losses

Internal shock model

- Jet= ‘shells‘ ejected a time intervals ~ t_{dyn} with randomly variable Lorentz factors
- Faster shells catch up will slower shells and collide
- Shocks, particle acceleration, and emission of synchrotron radiation
- Hierarchical merging process



Response to sinusoidal fluctuations of jet Lorentz factor



$$\Gamma_t(t) = \Gamma + \sqrt{2}\Gamma_{\rm rms} \sin\left(2\pi f_i t\right)$$

$$\Gamma = 2 \qquad \Gamma_{\rm rms} = 0.3$$

$$f_i = 1/T_i = 1\mathrm{Hz}$$

➡Localised dissipation at distance:

$$z_d \simeq \frac{\Gamma^3 \beta^3 c T_i}{4\Gamma_{\rm rms}}$$

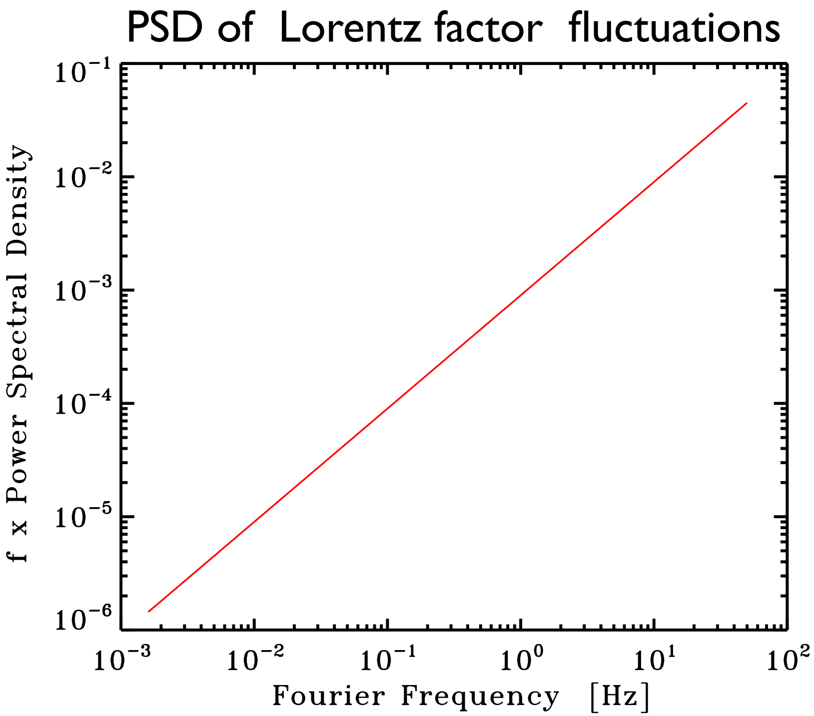
➡ Fluctuations of smaller amplitudes and longer time-scales merge (and dissipate) at larger distances

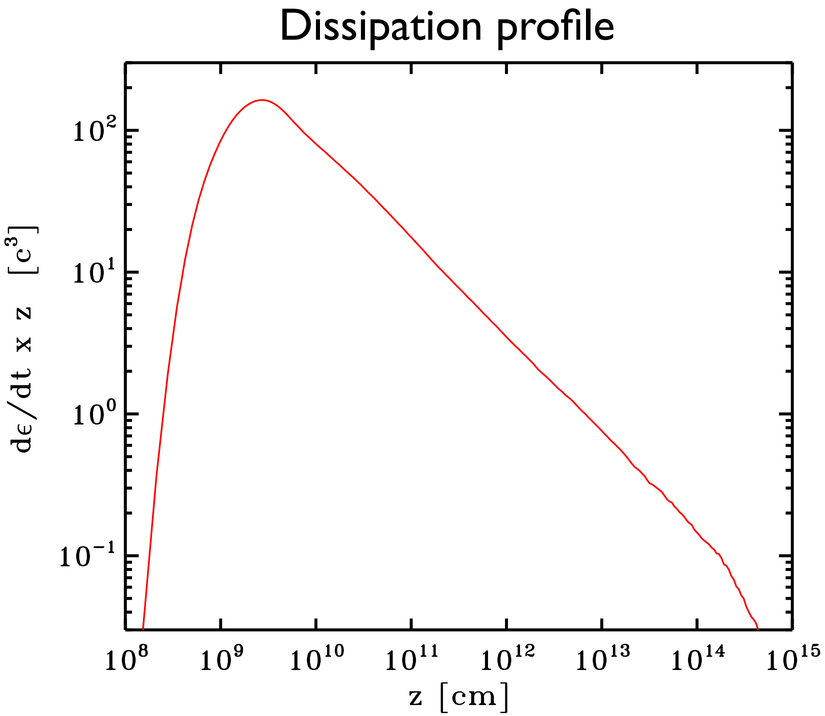
Only one time-scale and amplitude:

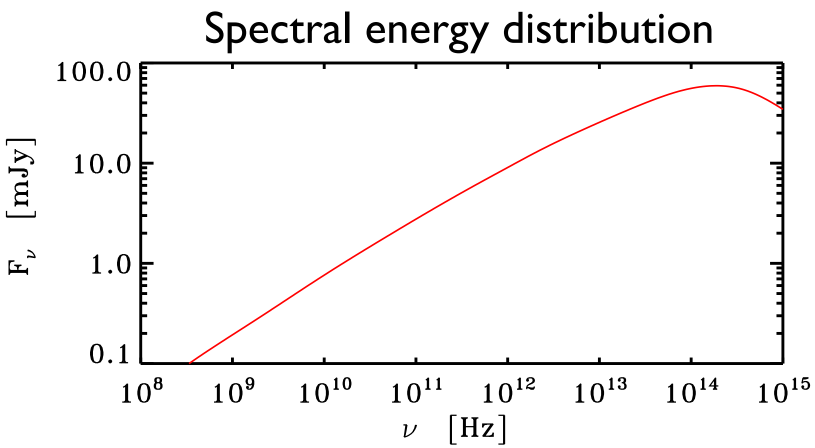
➡ Dissipation in a narrow range of distances and then cooling

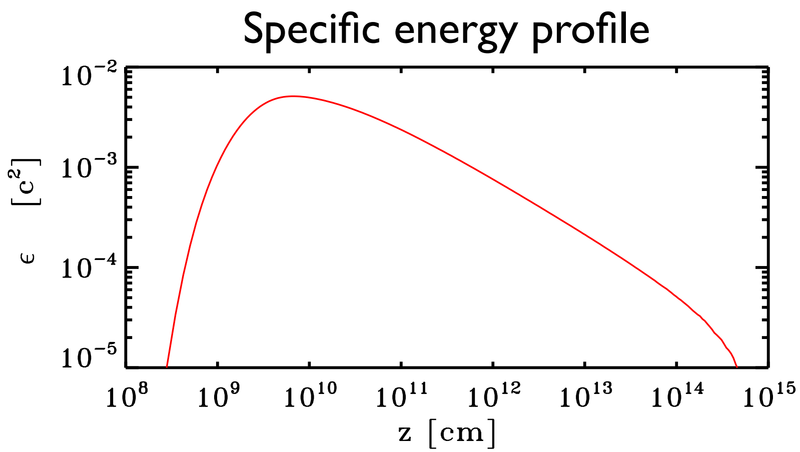
➡ Similar to one-zone acceleration model

Response to white noise fluctuations







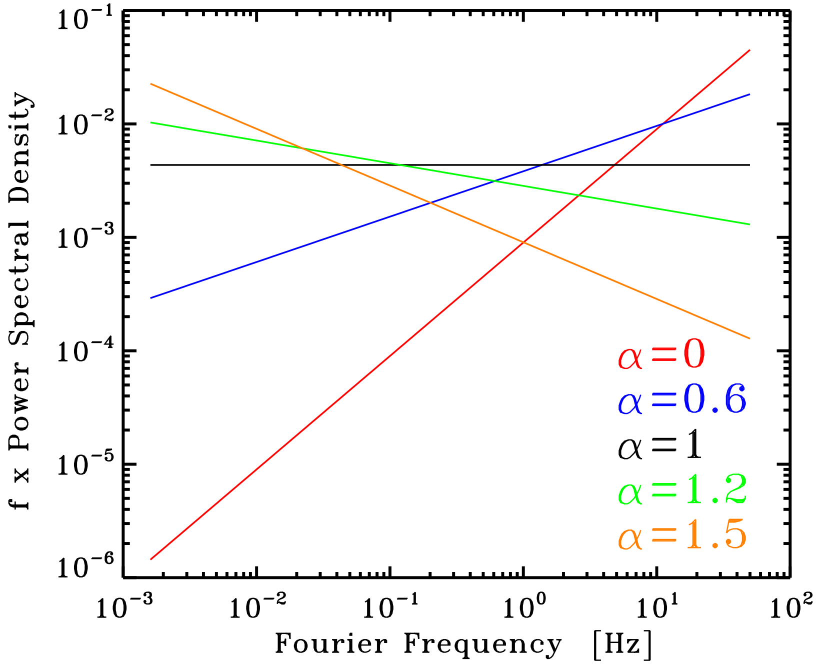


$$\Rightarrow \alpha_{\rm thick} = \frac{2p+13}{4p+18} \sim 0.65$$

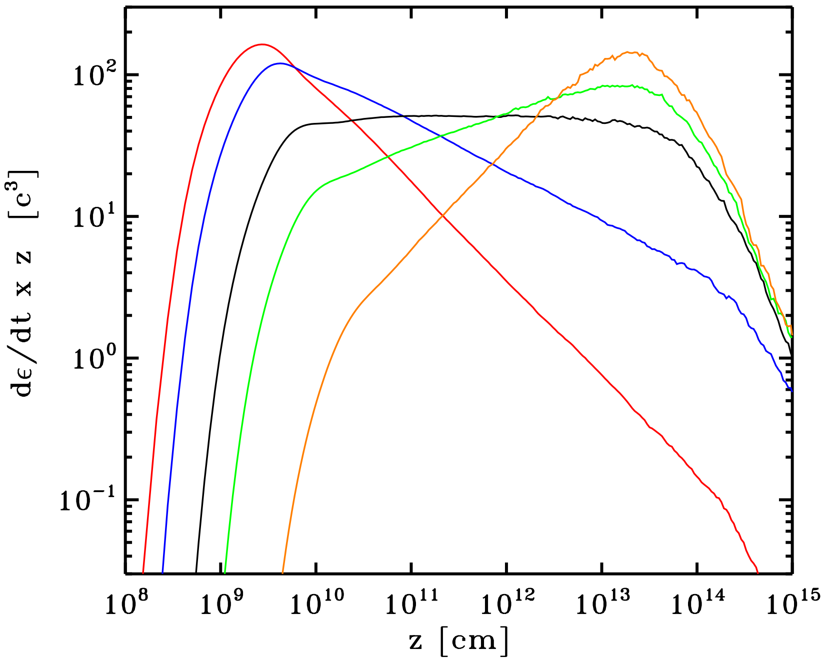
$$\tilde{\epsilon} \propto z^{-2/3}$$

$$P(f) \propto f^{-\alpha}$$

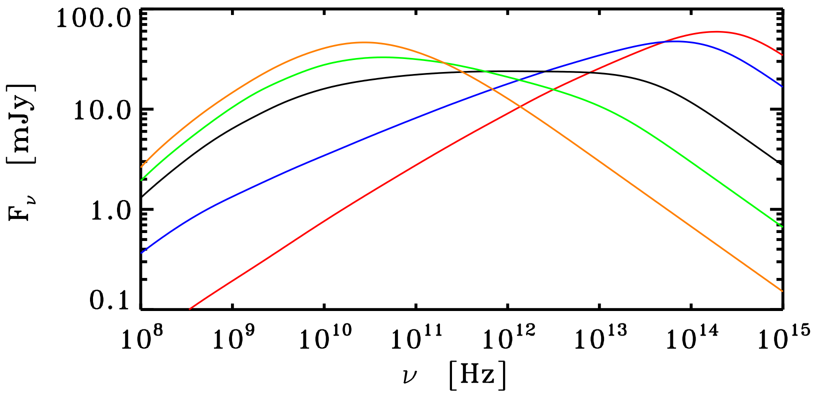
PSD of Lorentz factor fluctuations



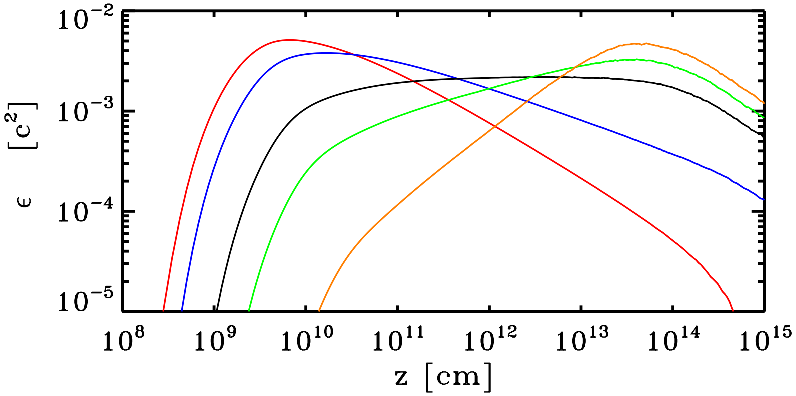
Dissipation profile



Spectral energy distribution



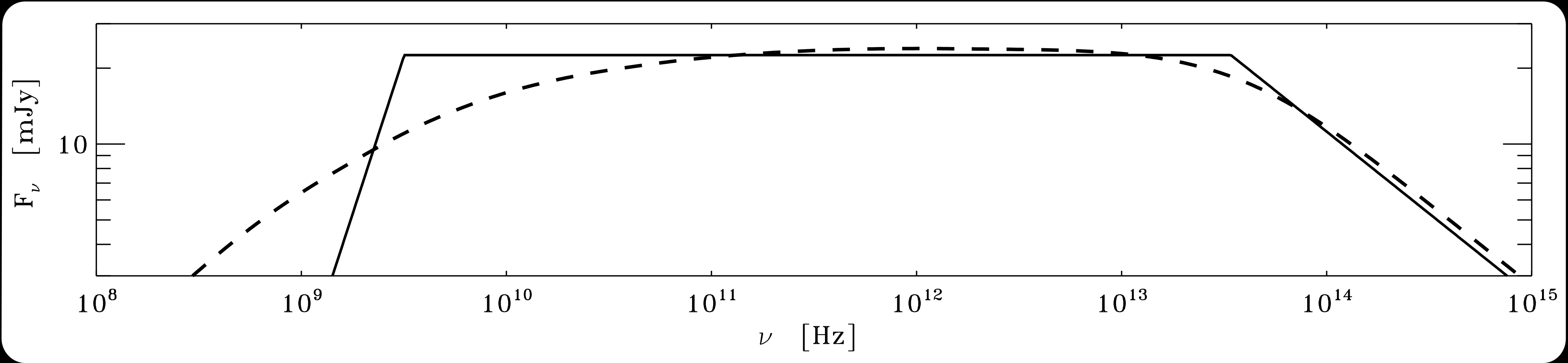
Specific energy profile



$$\Rightarrow \alpha_{\mathrm{thick}} = \frac{(2p+13)(1-\alpha)}{4p+18-\alpha(10+2p)}$$

$$\tilde{\epsilon} \propto z^{-\frac{2(1-\alpha)}{3-\alpha}}$$

Application to black hole binaries

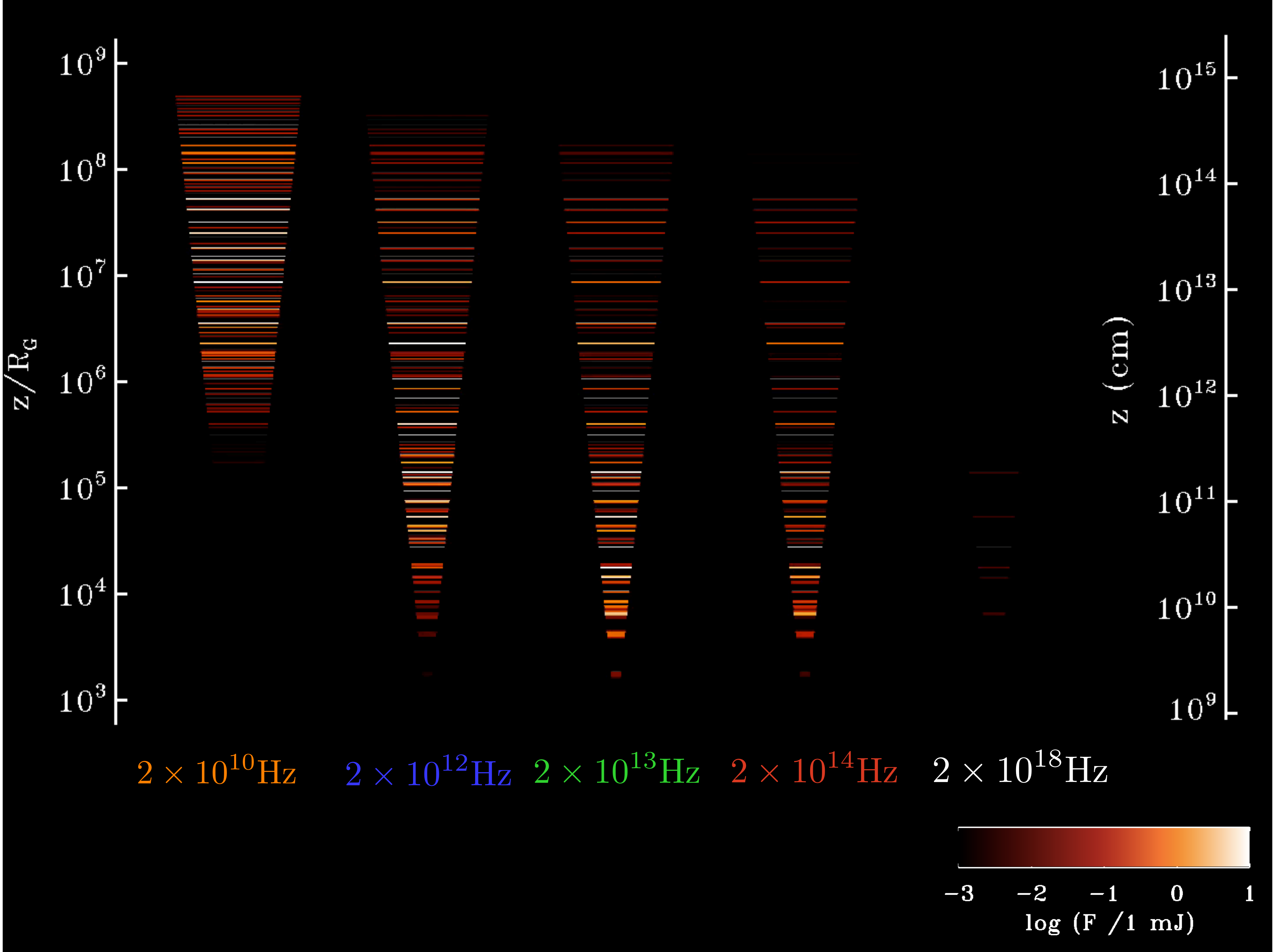


$P(f) \propto 1/f$ for $10^{-3} < f < 50$ Hz   rms = 30%

$P_{kin} = 0.01 L_{\rm E}$, $\Gamma = 2$ $\phi_j = 1^o$ + equipartition

- Base of emitting region: $z_0 \sim 10^{10}\rm cm$
- Magnetic field at base: $B_0 \sim 10^4$ G
- Flux of flat component: $F_{v0} \simeq 84 \frac{\delta^2}{D^2_{\rm kpc}}$ mJ
- High frequency break: $\nu_T \simeq 2 \times 10^{13}\rm Hz$
- Low frequency break: $\nu_s \simeq 1\,\rm GHz$

Malzac 2013

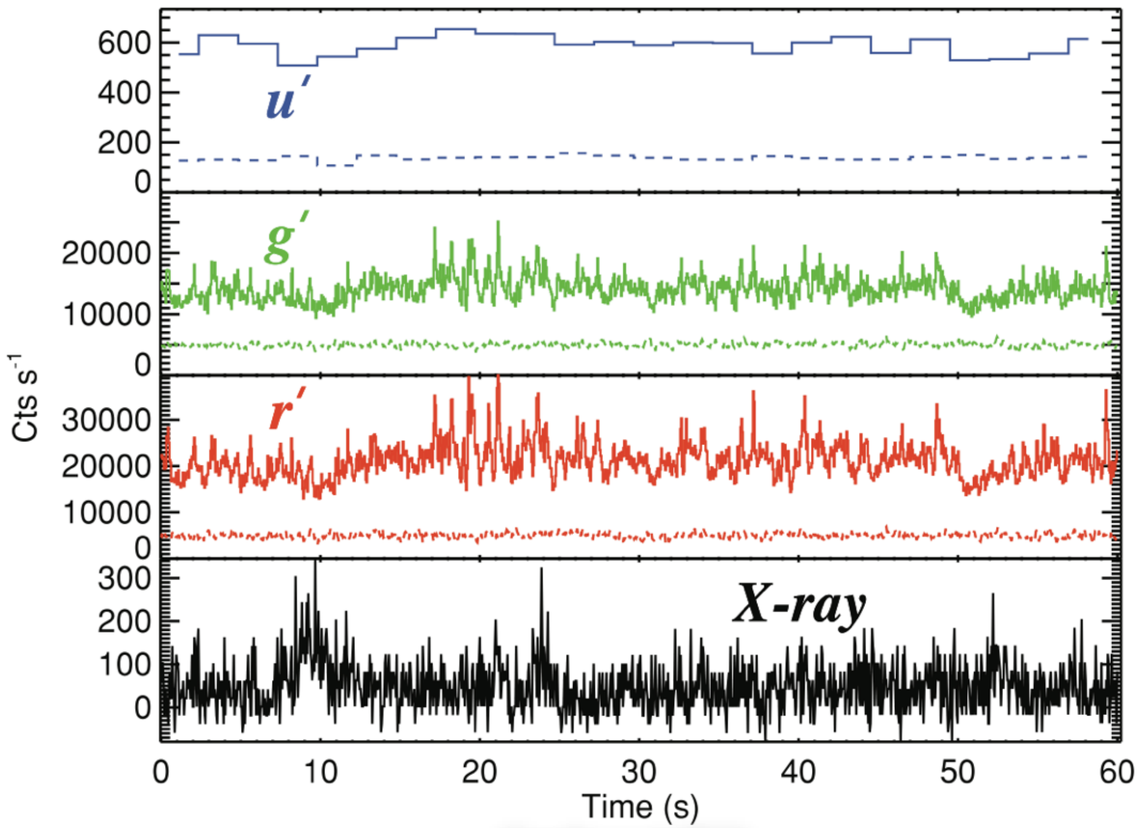


z/R_G
10^9
10^8
10^7
10^6
10^5
10^4
10^3
z (cm)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^9
2×10^{10}Hz
2×10^{12}Hz
2×10^{13}Hz
2×10^{14}Hz
2×10^{18}Hz
−3
−2
−1
0
1
log (F /1 mJ)

Fast Jet Variability

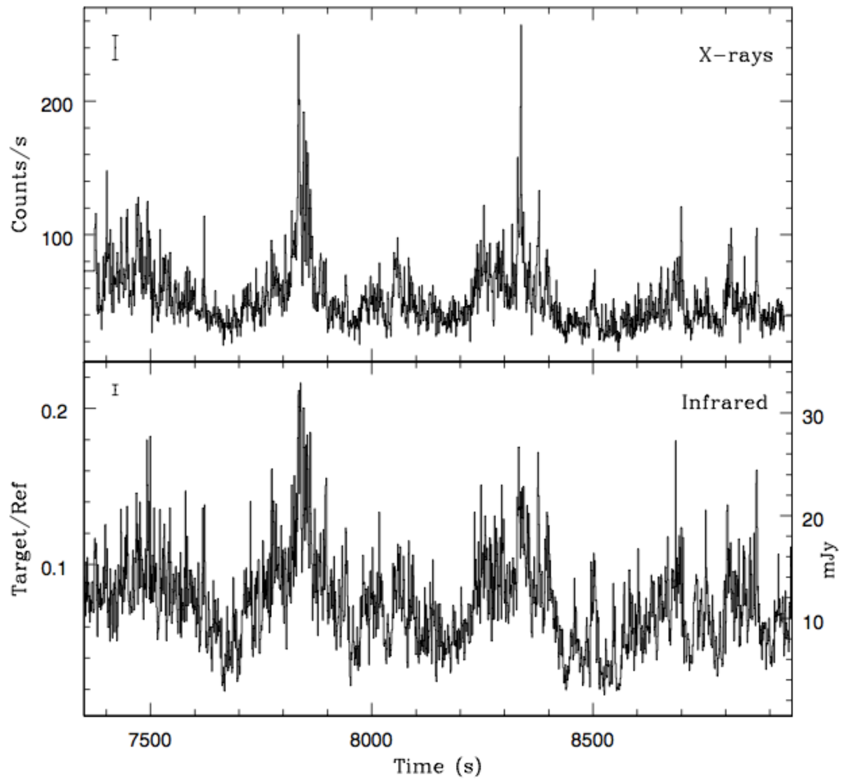
Observations of GX 339-4

Optical



Gandhi et al. 2010

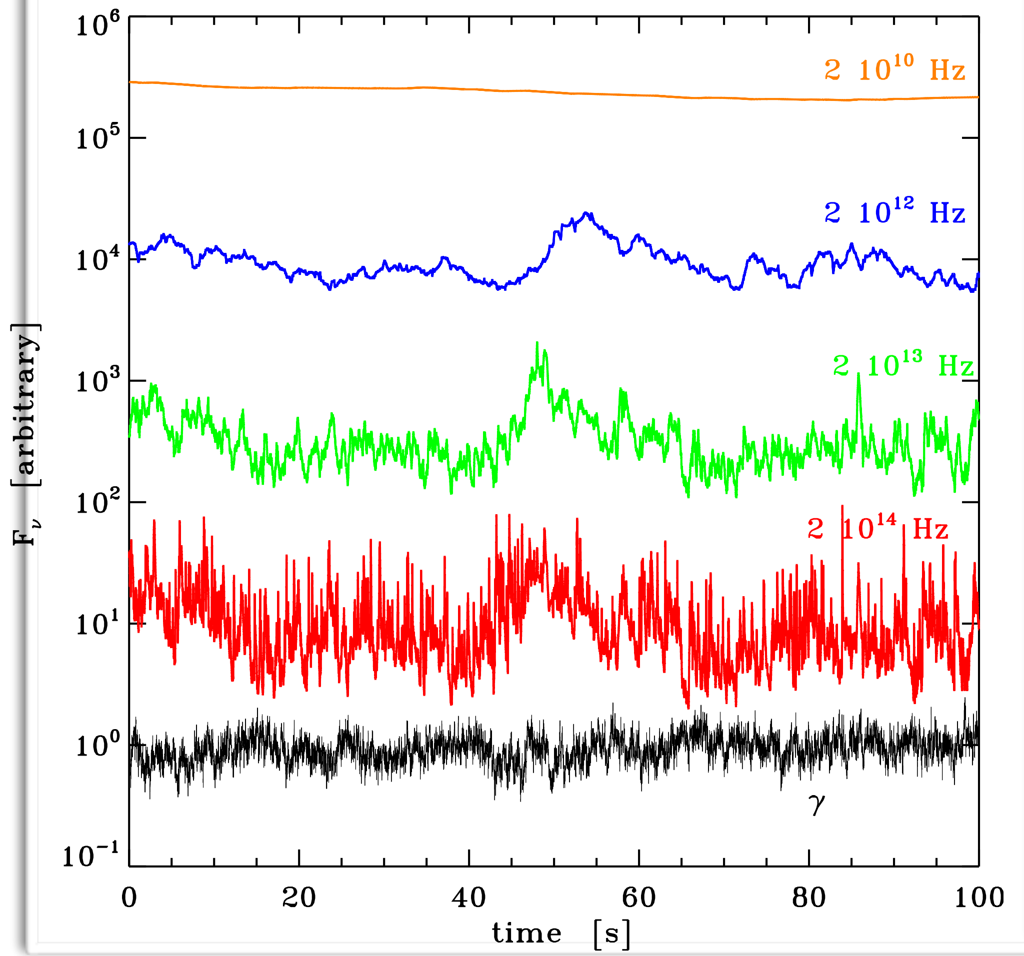
Infrared

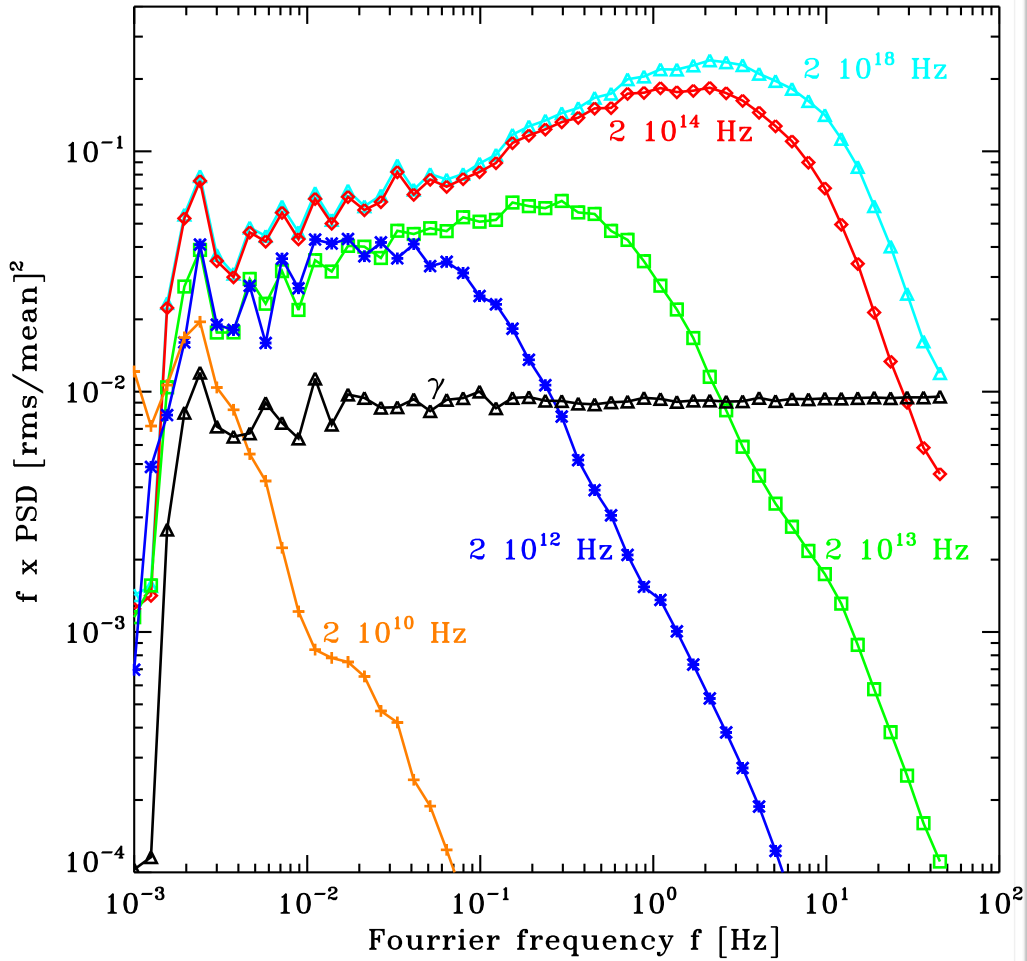


Casella et al. 2010

Fast Jet Variability

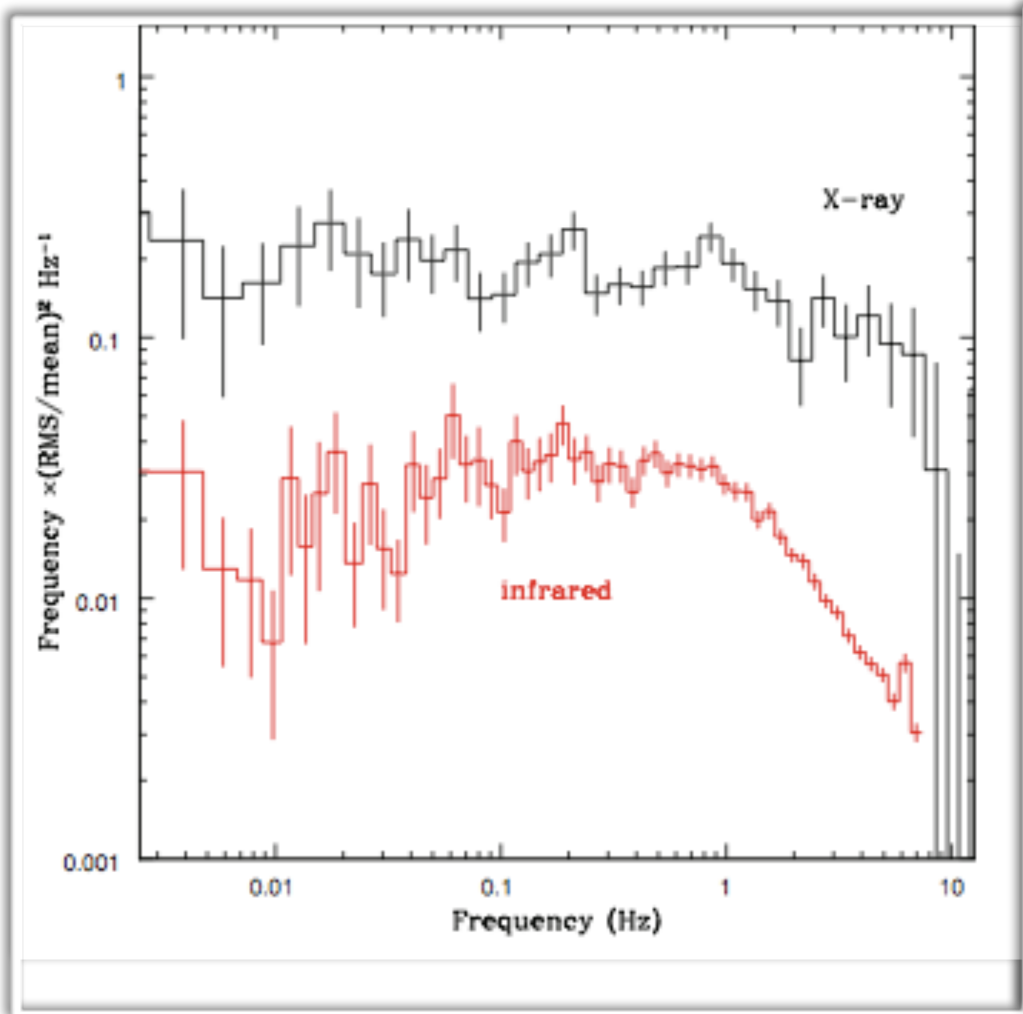
Model

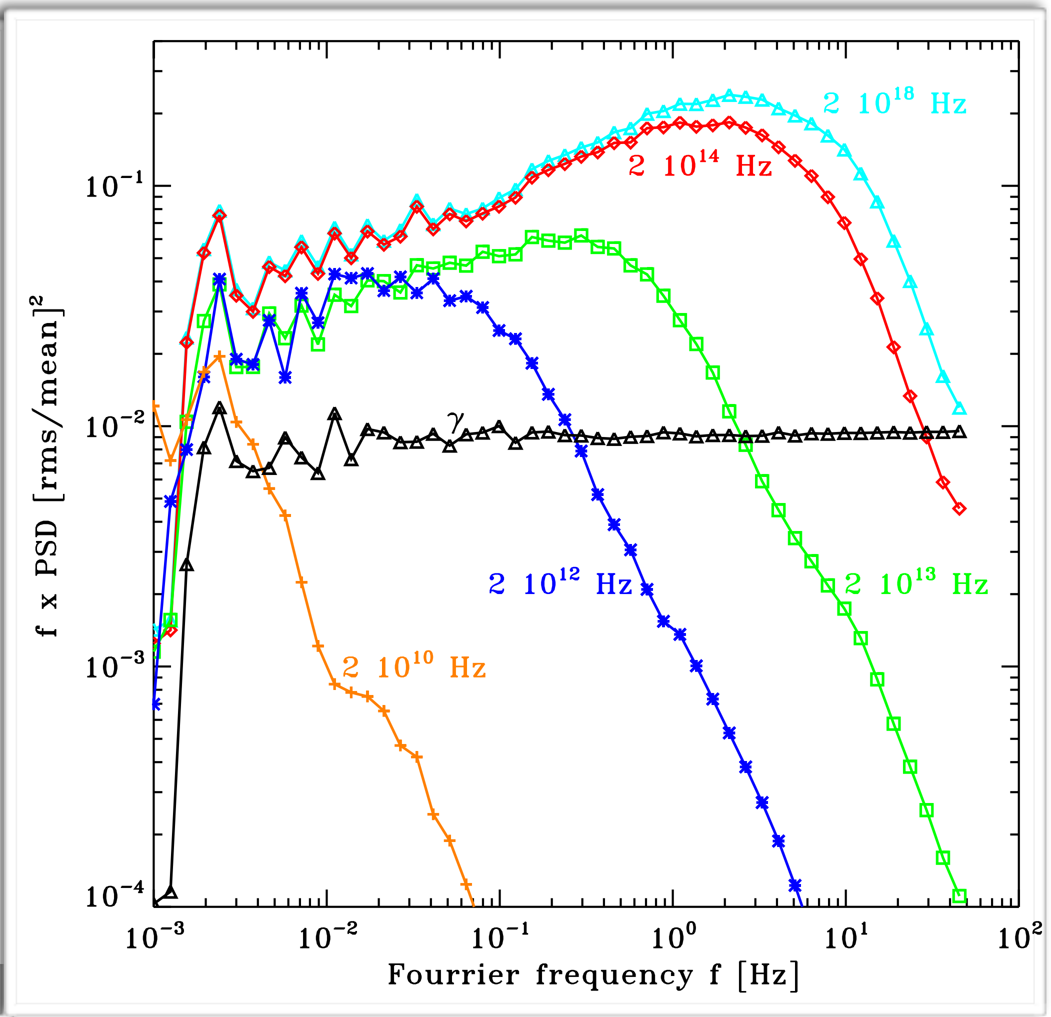




Malzac, MNRAS, 2014

Fast Jet Variability



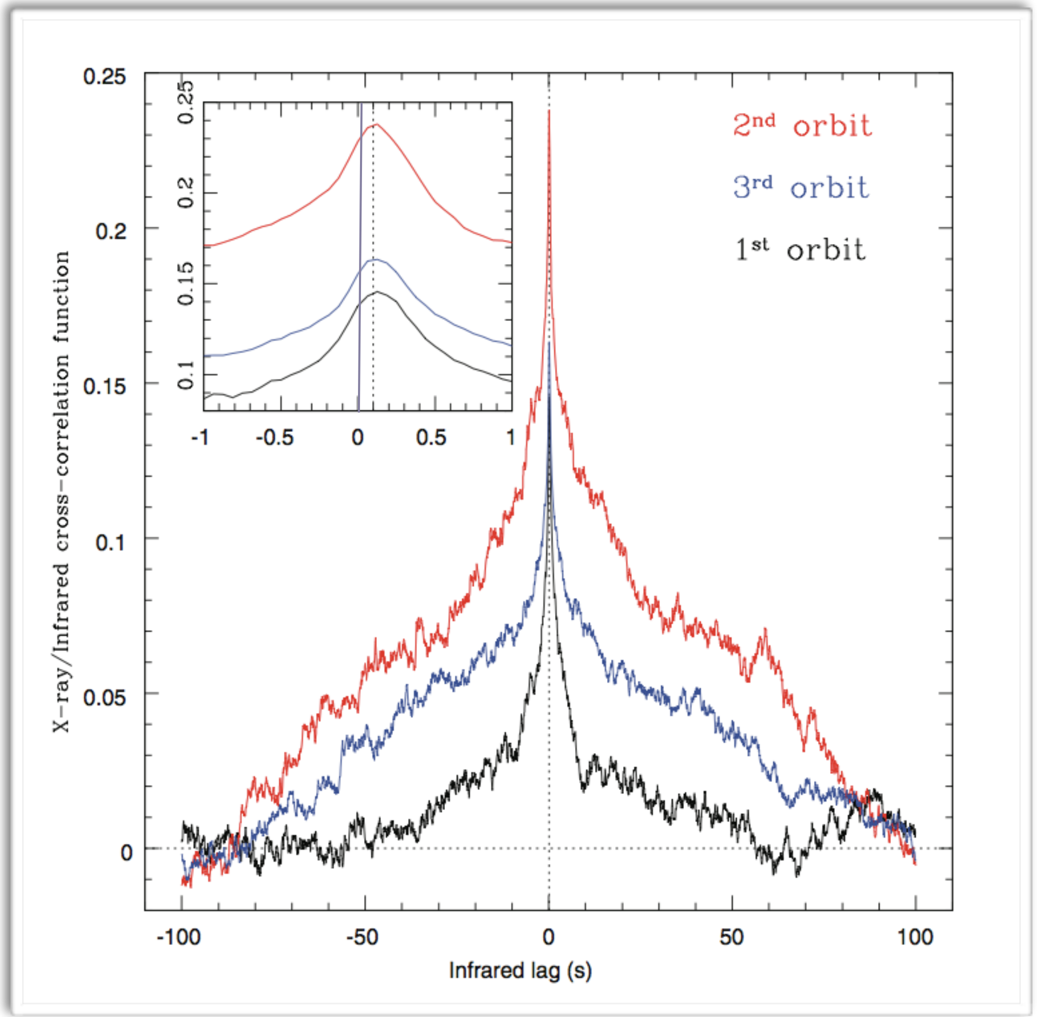


Casella et al. 2010

Malzac, 2014

IR /X-ray correlation

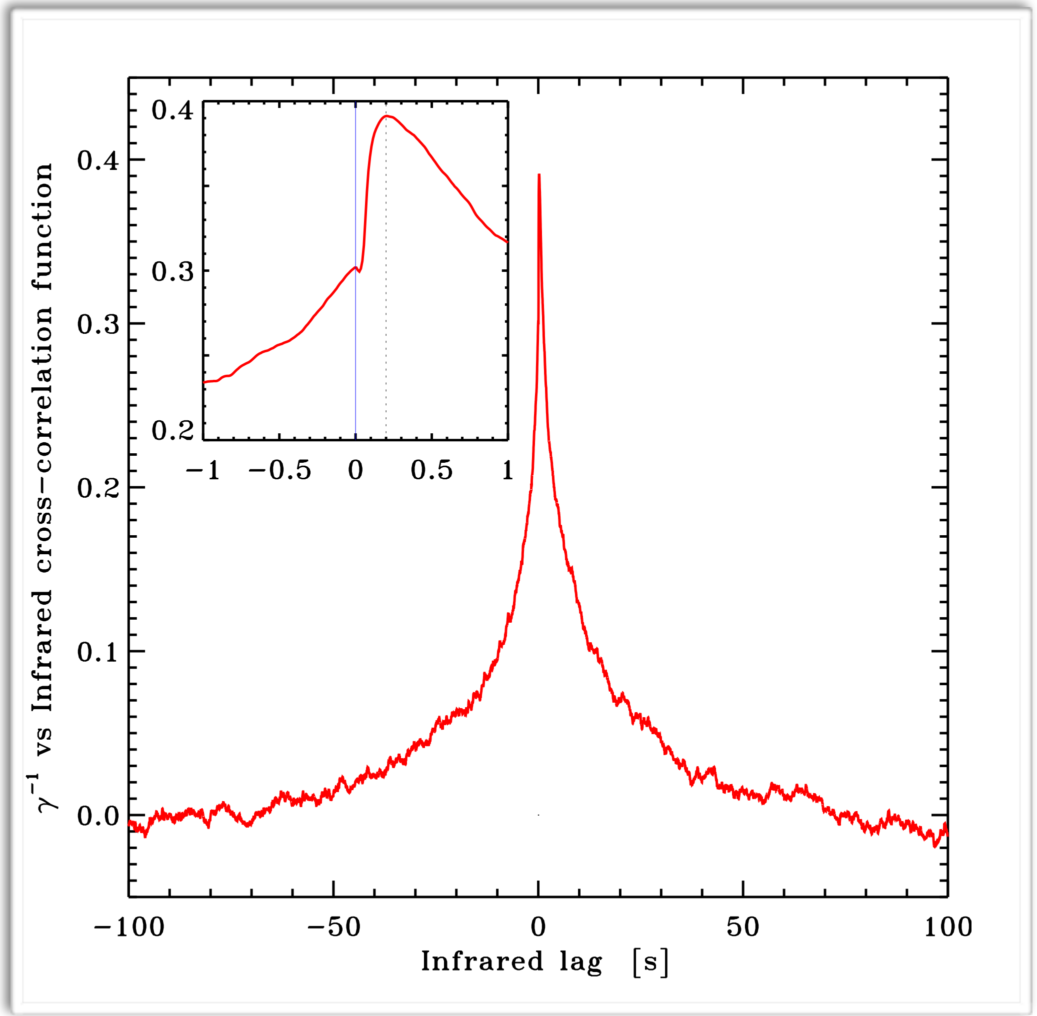
Observations



GX 339-4

Casella et al. 2010

Simulation



Assuming X-ray flux $\propto 1/\Gamma$

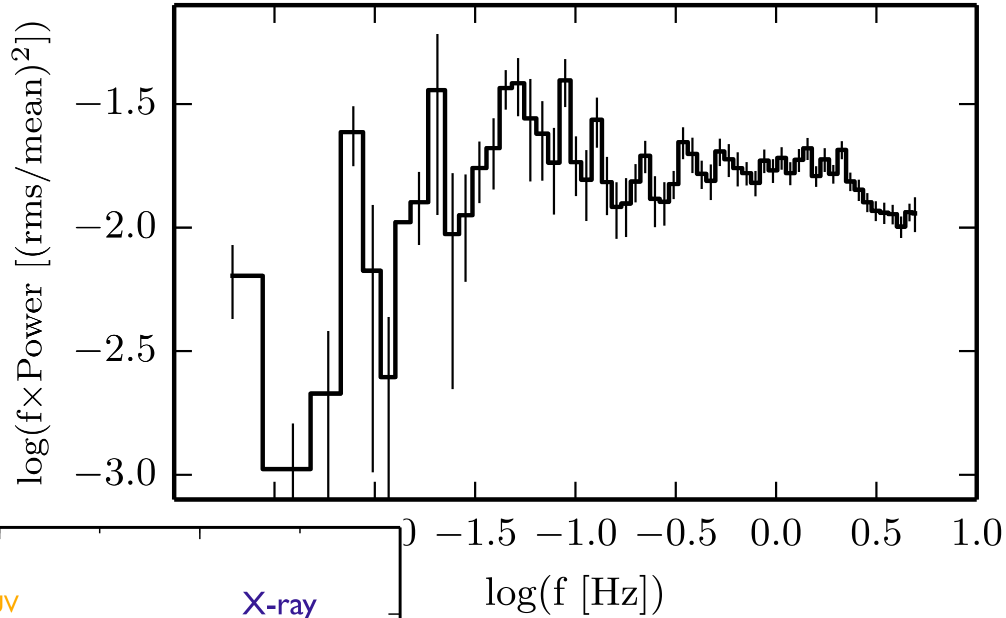
Malzac 2014

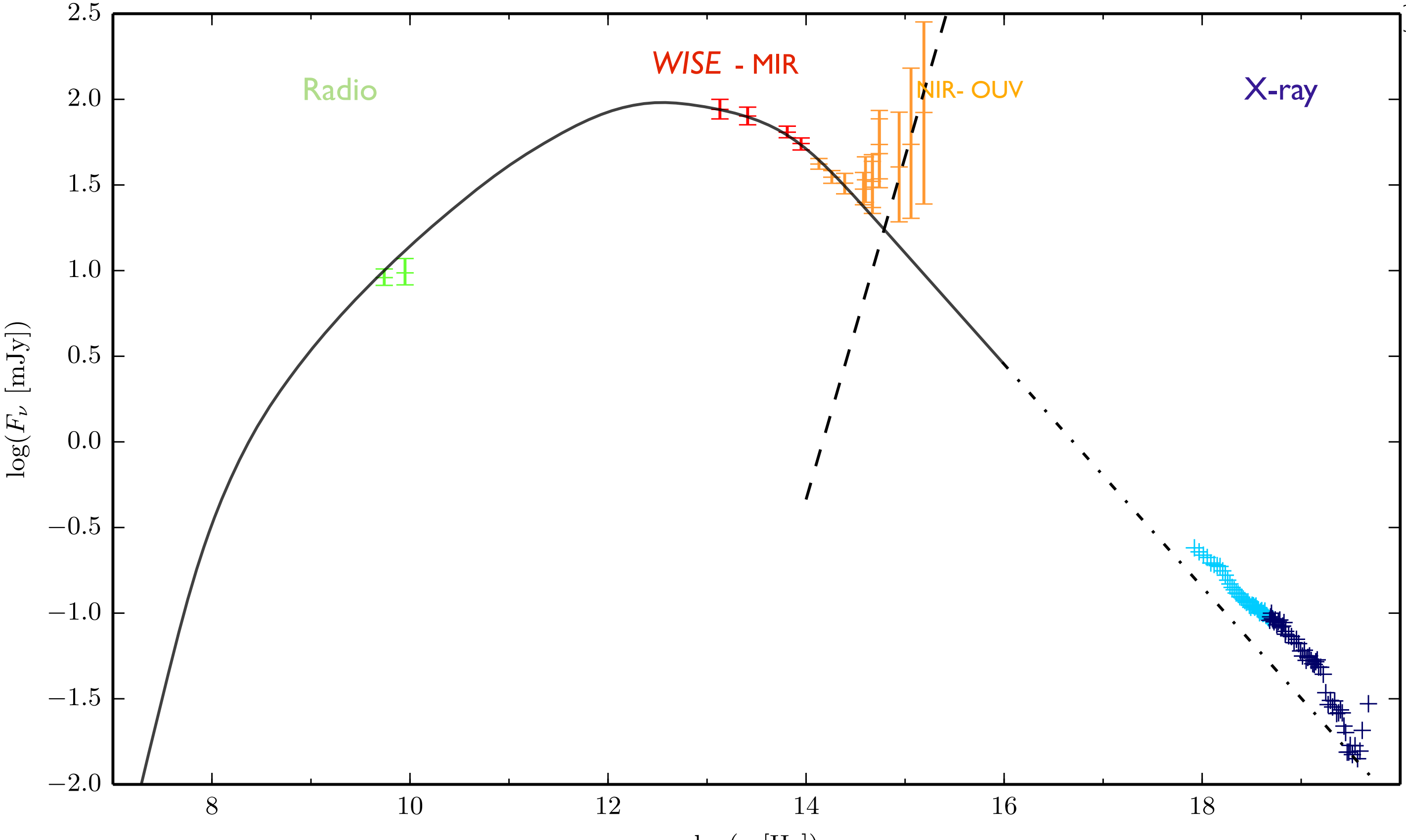
Why flicker noise fluctuations ?

- If jet driven by accretion flow: jet fluctuations should 'look like' that of the accretion flow
- Accretion disks may produce 1/f noise (Lyubarskii 1997; King et al. 2004; Mayer & Pringle 2006…)
- Jet Lorentz factor PDS expected to be similar to X-ray PDS

- Jet Lorentz factor fluctuations driven by accretion flow variability which is best traced by X-ray light curves

Fourrier PDS of X-ray light curve
=
Power spectrum of Lorentz factor fluctuation





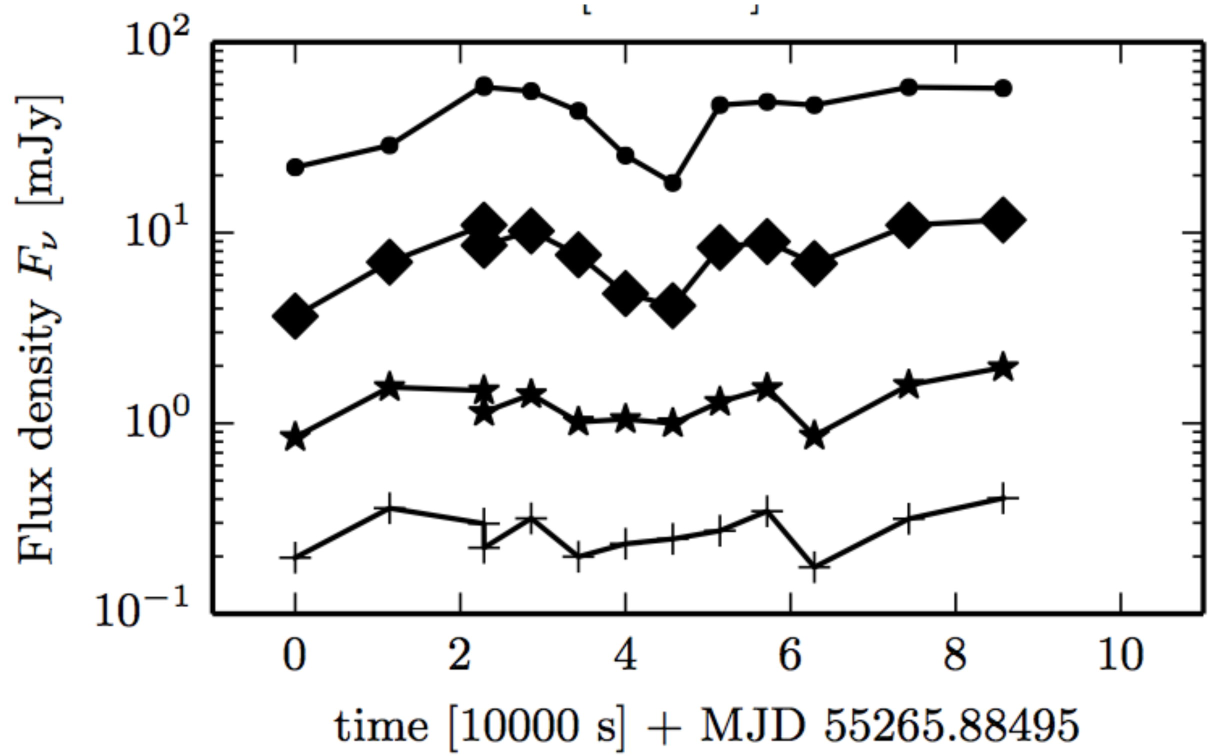
Jet SED

Drappeau, et al. MNRAS, 2015

Observation

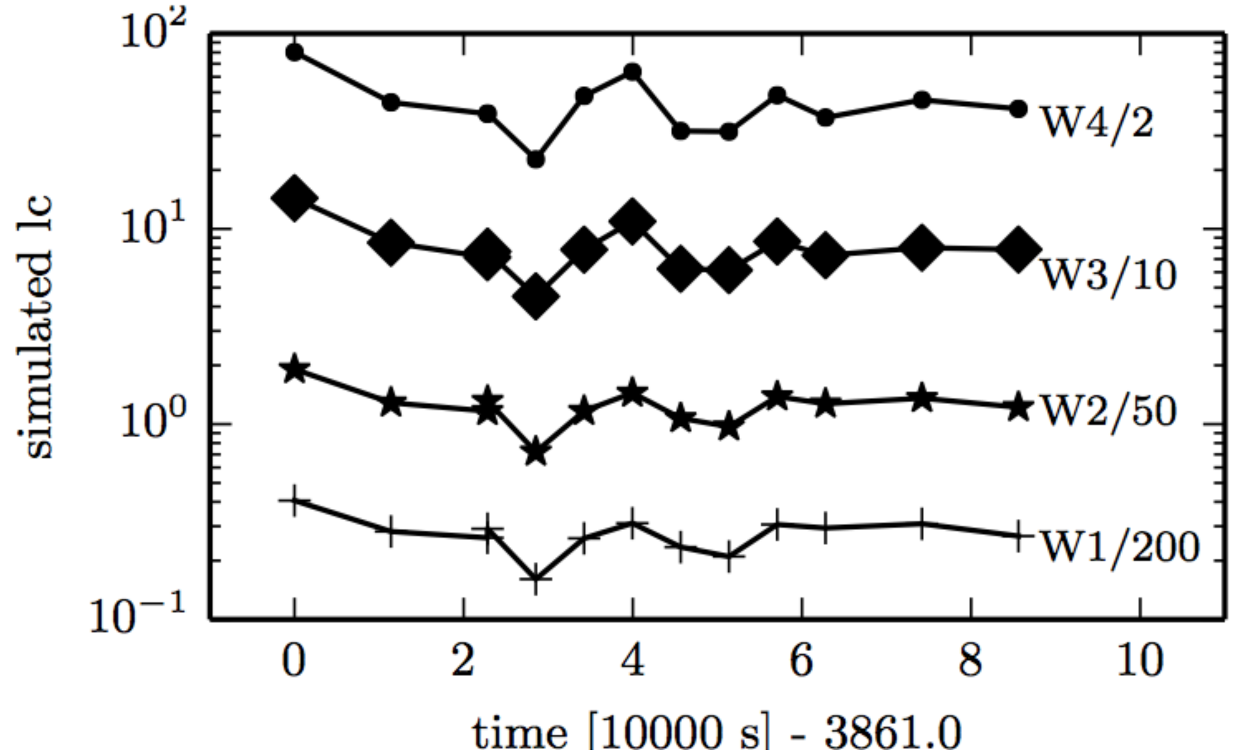
Observed IR light curves

(Gandhi et al. 2011)



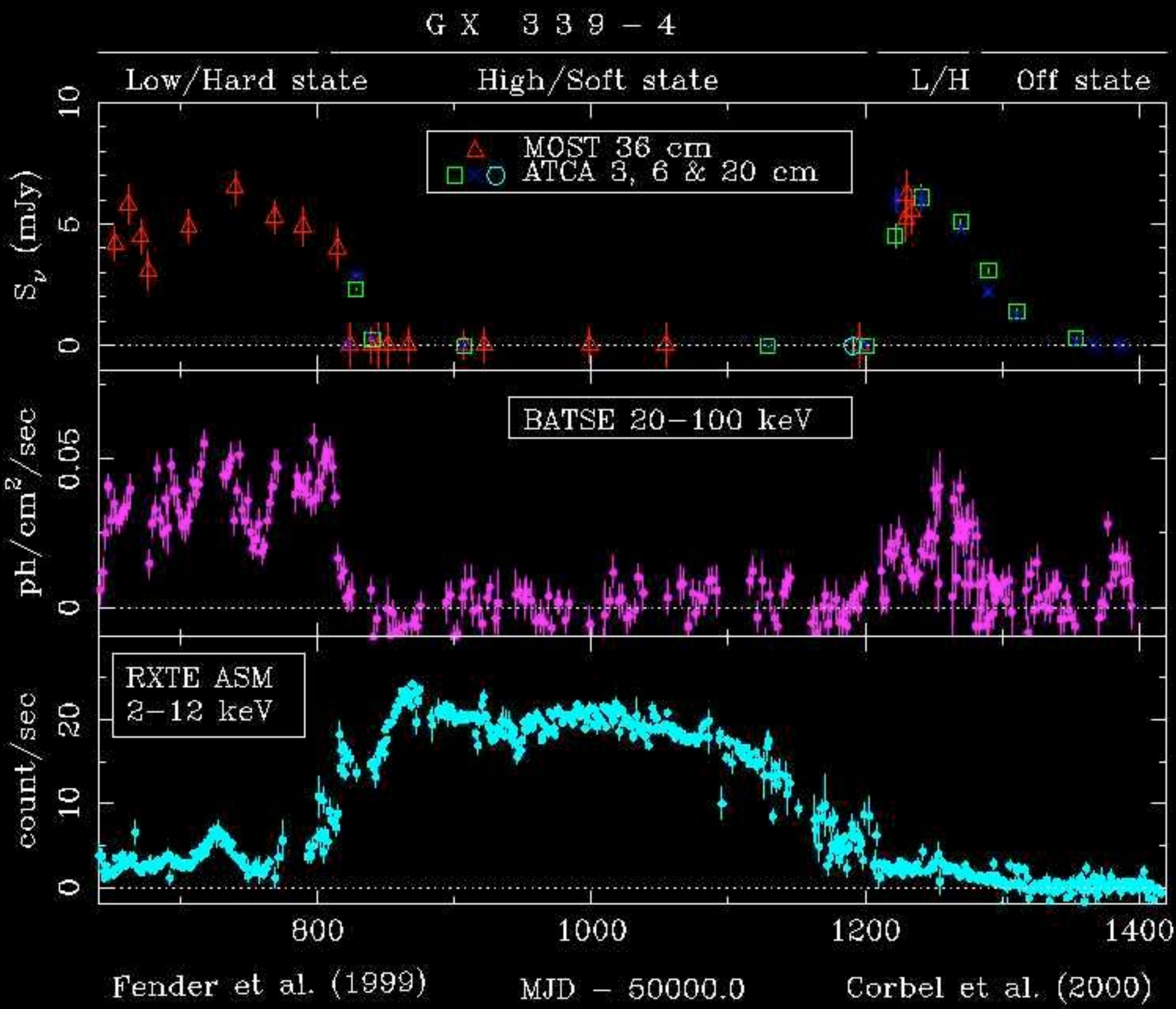
Simulation

Sample simulated light curves



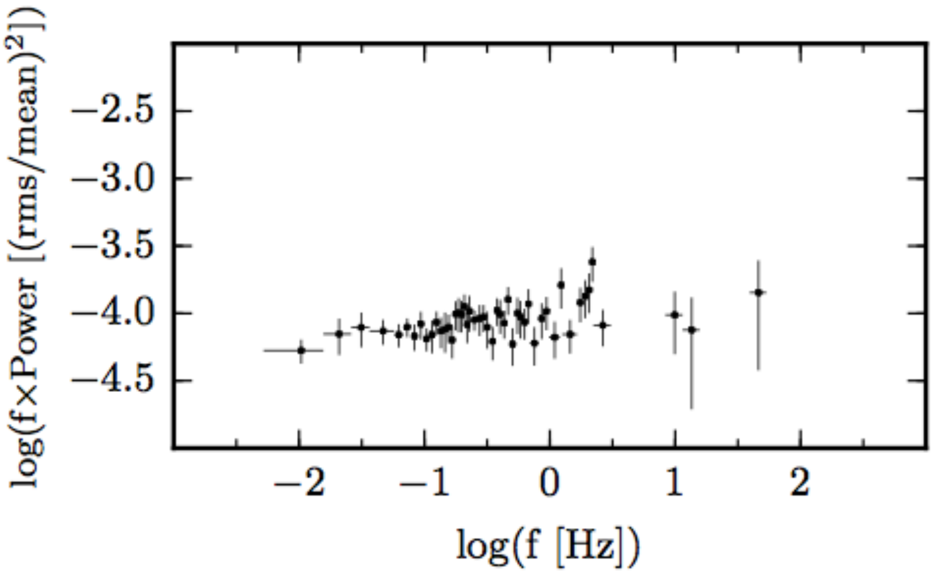
Drappeau, et al. MNRAS, 2015

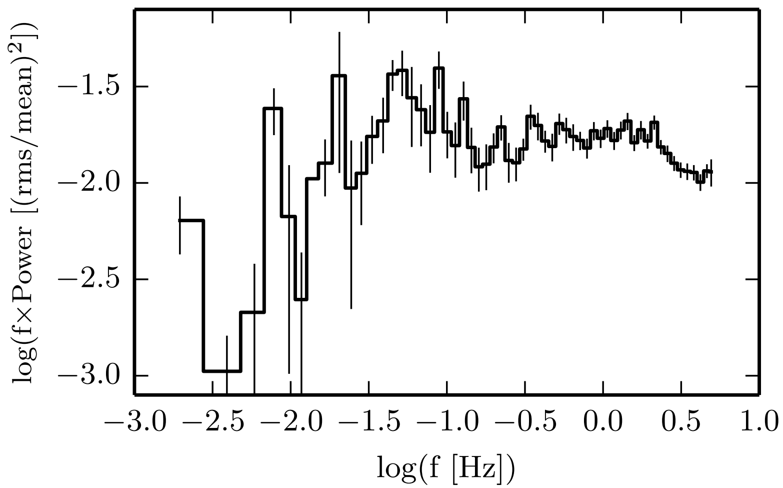
X-ray/Radio correlations



⇒ Jet quenched in the high soft state

A dark jet in the soft state ?



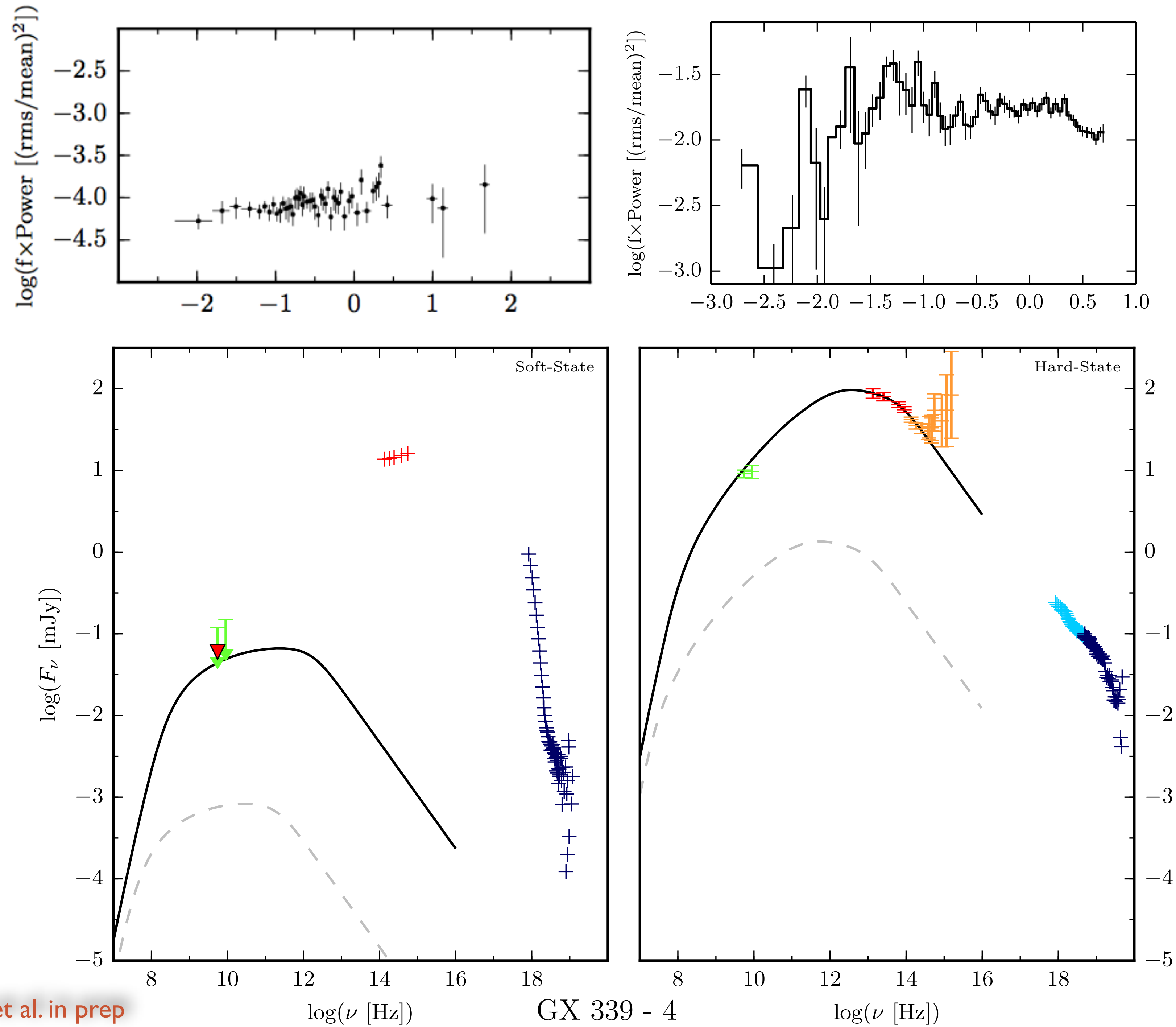


- Jet luminosity very sensitive to rms amplitude of fluctuations

- Disappearance of the jet in soft state associated to drop in X-ray variability ??

- Jet with same kinetic power as in hard state but radiatively inefficient ??

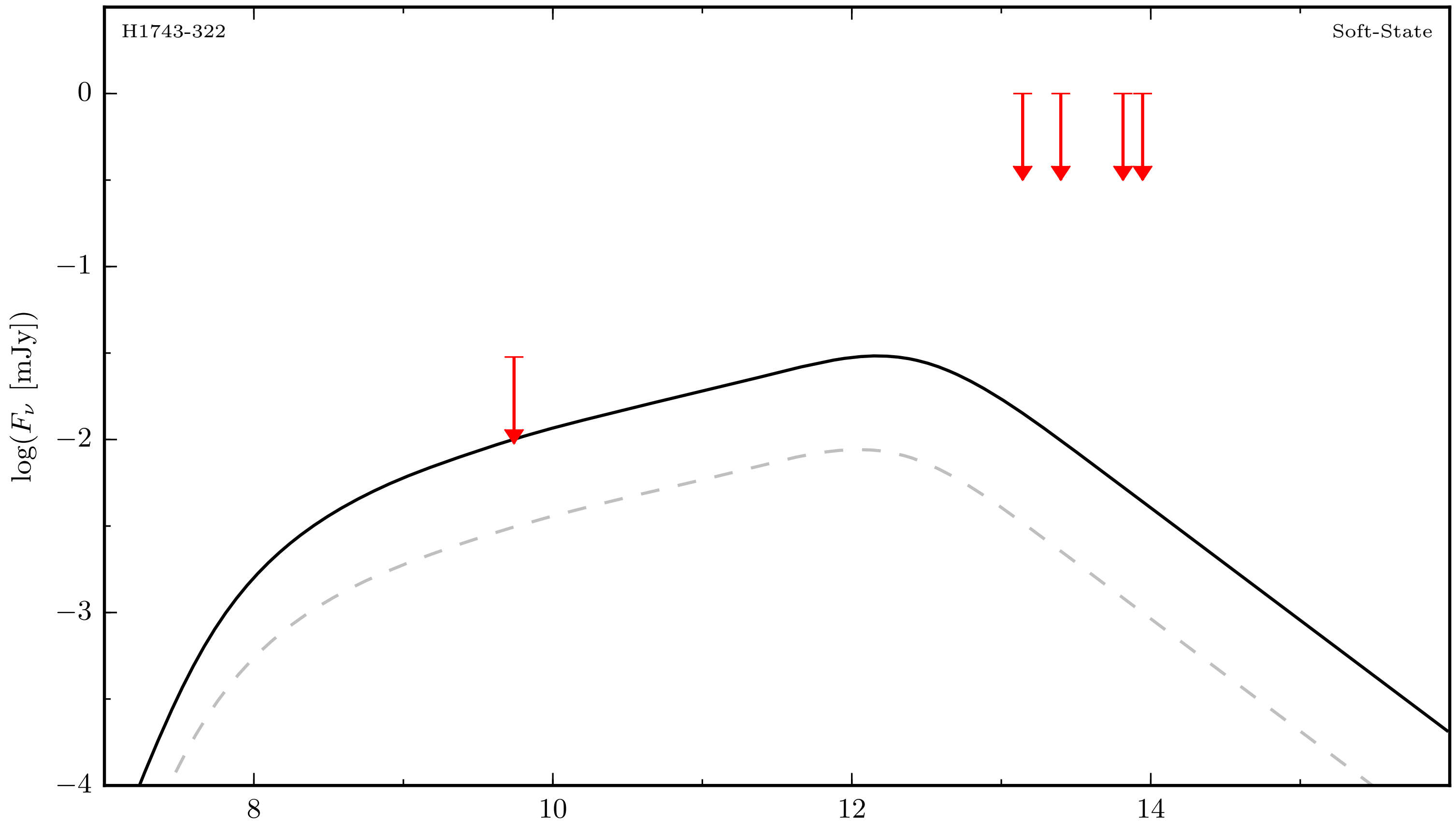
A dark jet in the soft state ?

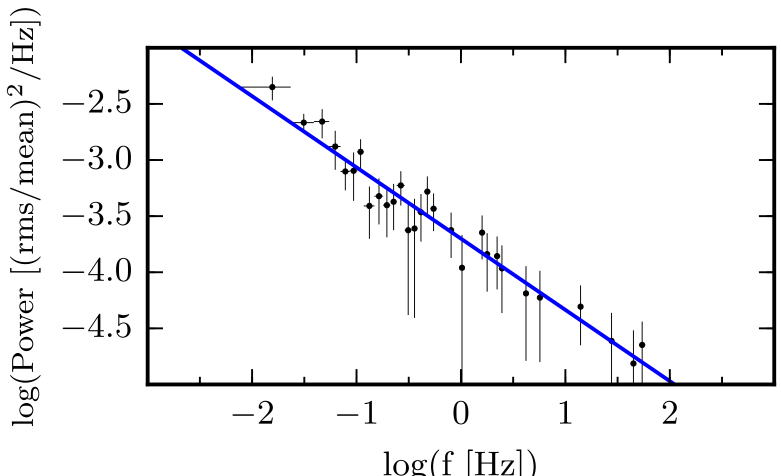


Drappeau et al. in prep

GX 339 - 4

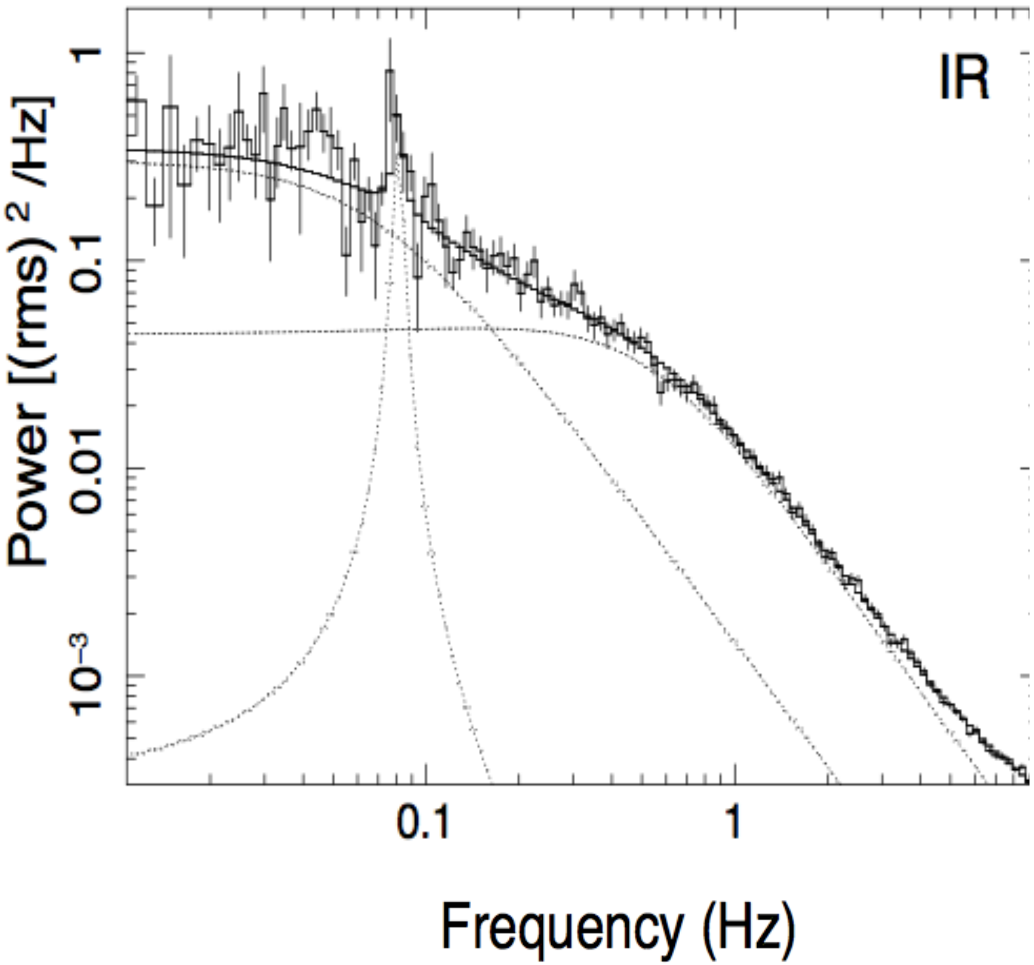
Soft state of H1743-322

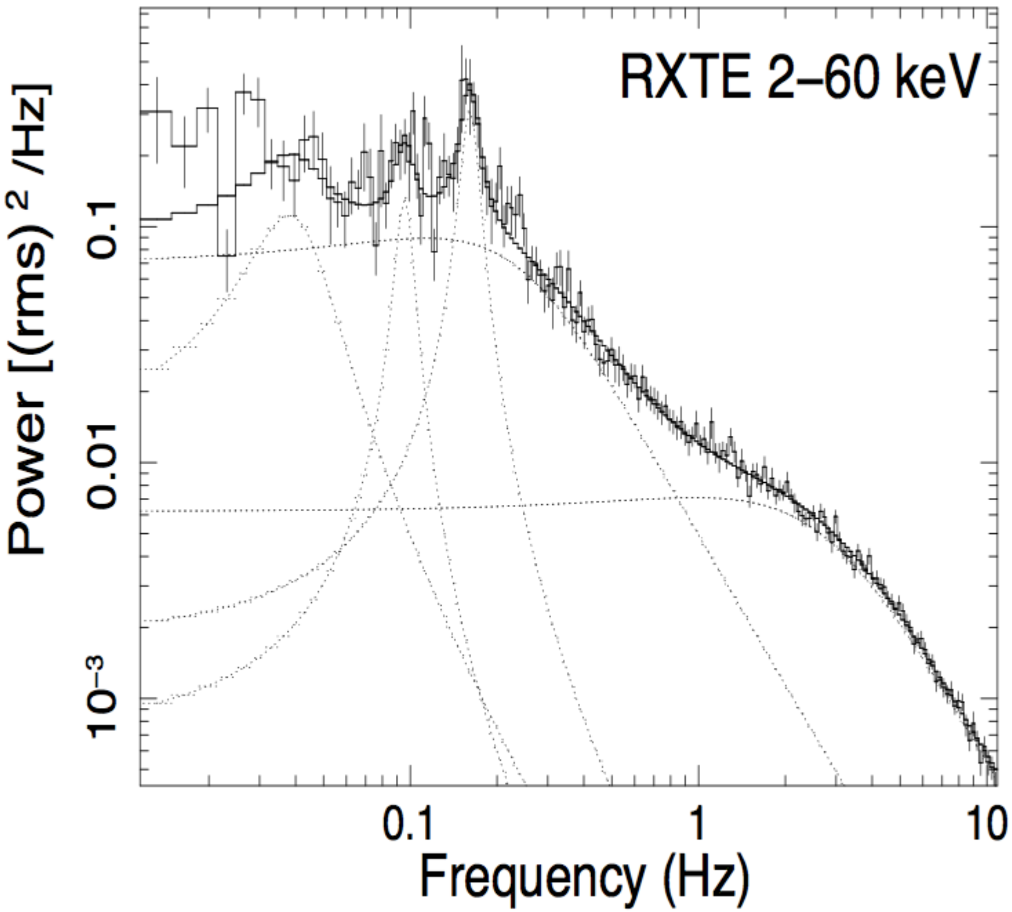




Drappeau et al. in prep

New fast IR timing data of GX 339-4: First QPO detected in Infrared

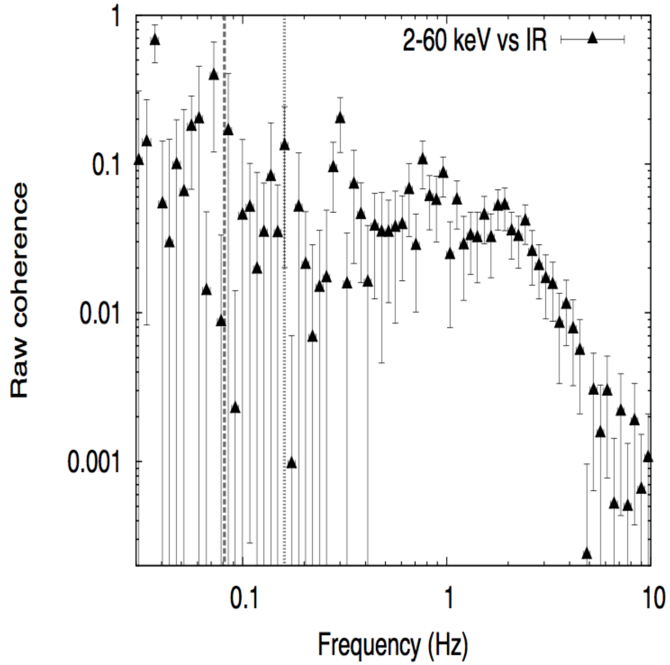


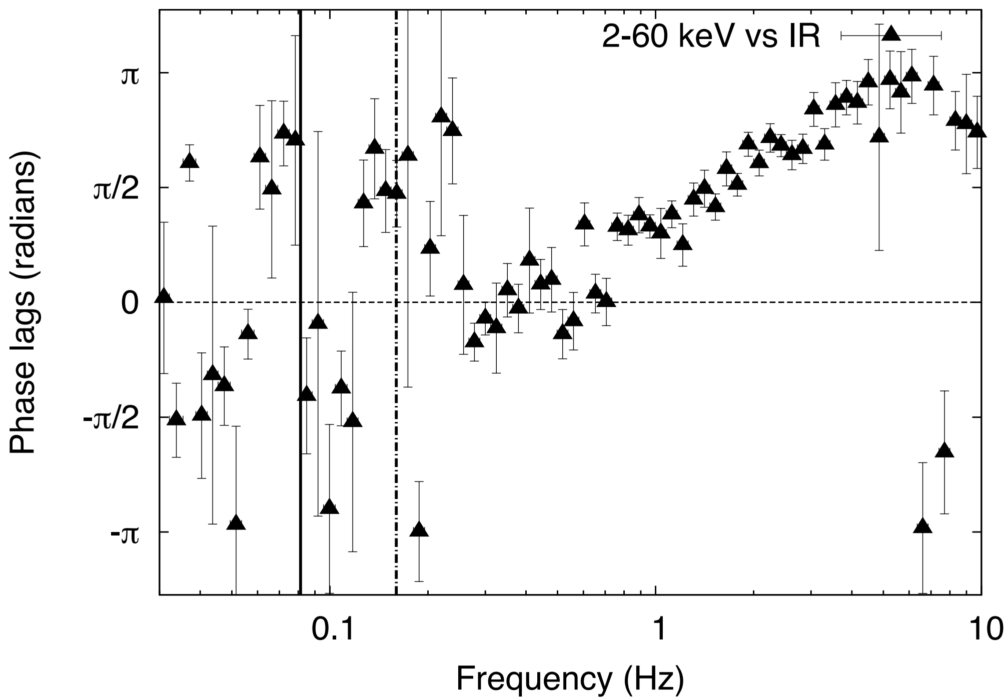


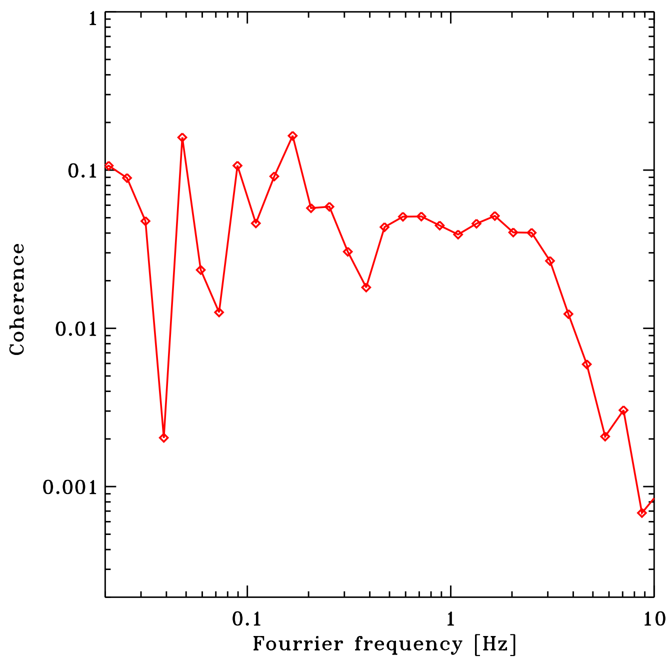
Kalamkar et al. submitted

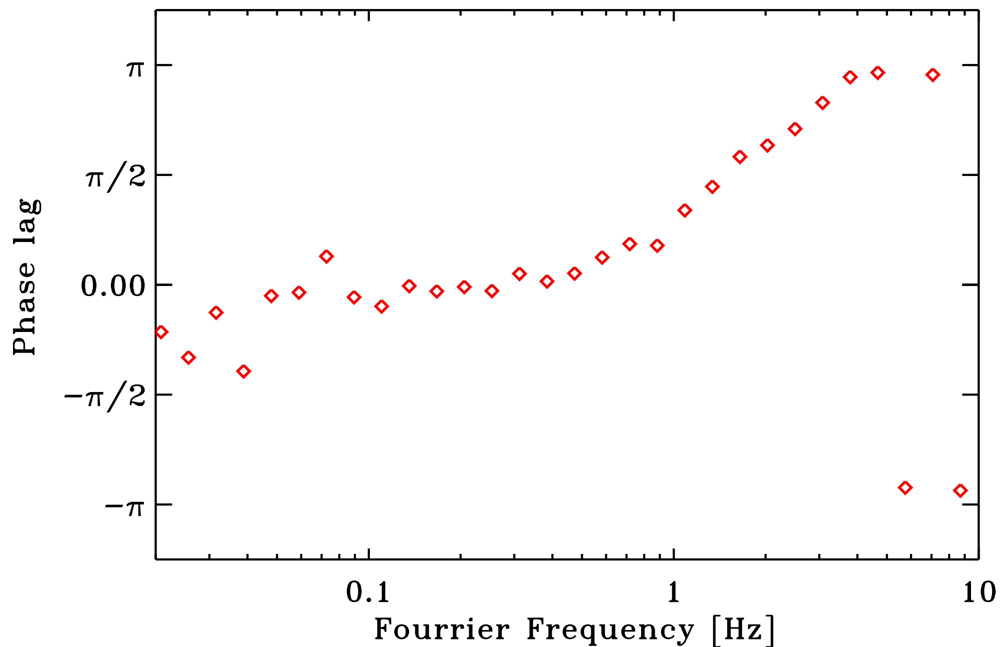
IR /X-ray correlations

Preliminary comparisons to IS model









Optical/IR QPOs from jet precession

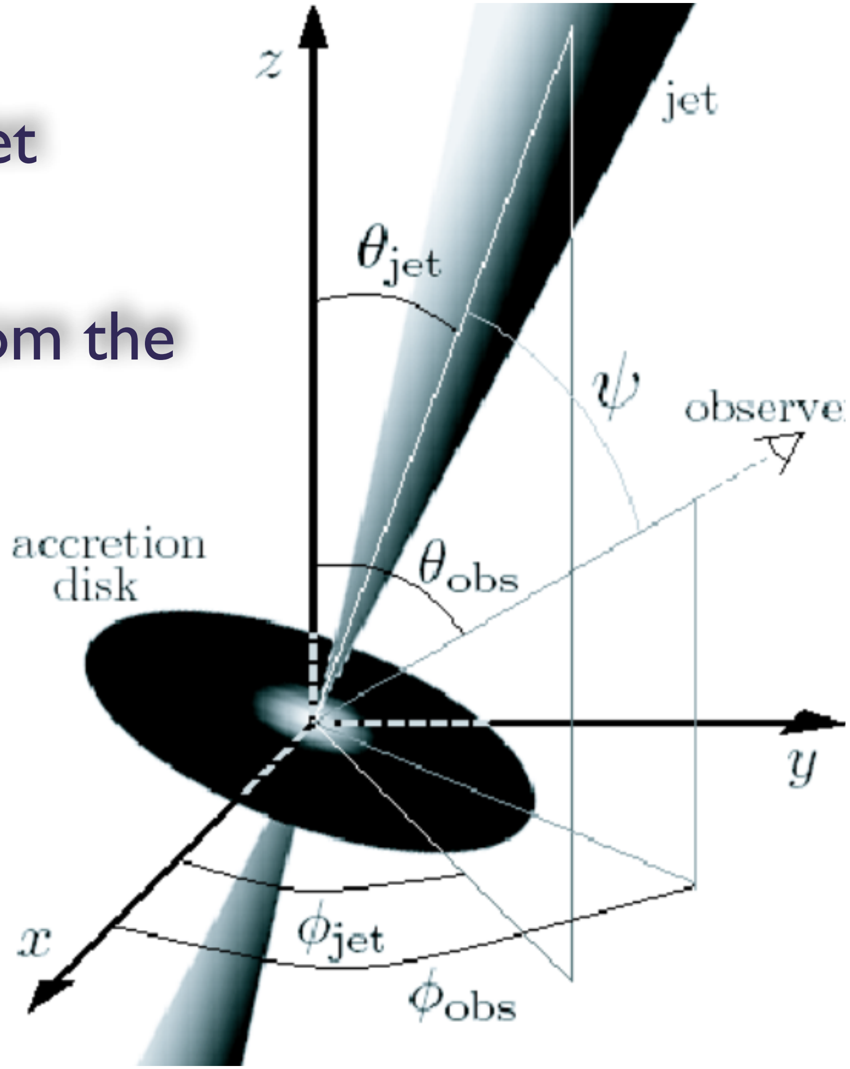
- If jet launched by the accretion flow, jet precesses with the hot flow

➡ modulation of synchrotron emission from the jet

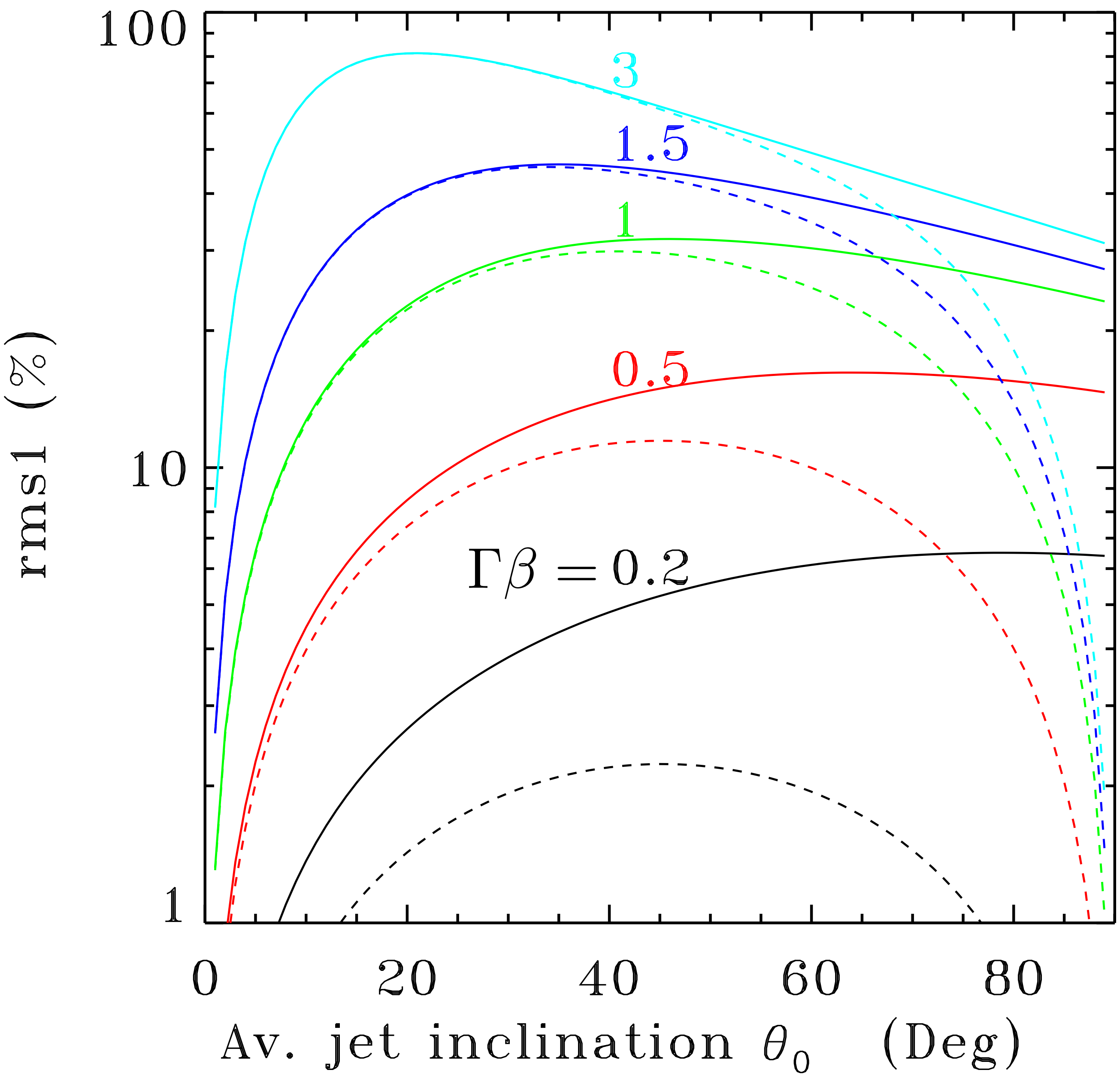
- For a relativistic jets emitting in the optically thin regime, anisotropy is dominated by relativistic Doppler boosting:

$$F_{\nu,\mathrm{obs}} \propto \delta^{2-\alpha}$$

$$\delta = \left[\Gamma\left(1 - \beta\cos\theta\right)\right]^{-1}$$

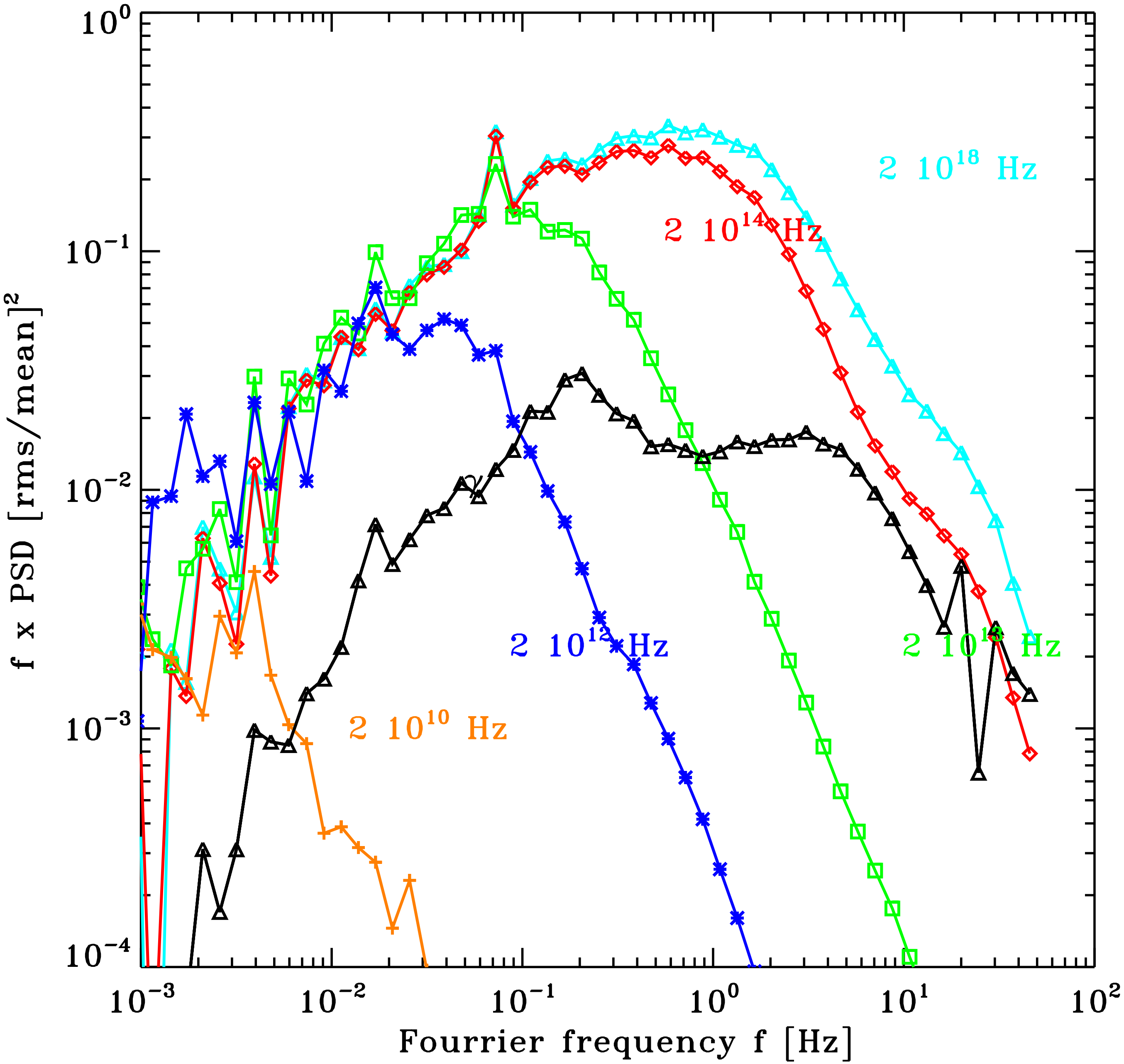


Optical/IR QPOs from jet precession



Kalamkar et al. 2015, Malzac et al. in prep

Optical/IR QPOs from jet precession



Conclusions

- Internal shock model predict strong, frequency dependent, variability similar to that observed.
- Possible connection between X-ray POWER spectrum
  and Radio-IR PHOTON spectrum.
- Comparisons to data suggest at least part of the IR and optical variability produced in the jet
- Opt/IR/X-ray correlations can unveil the dynamics of accretion and ejection physics (energy reservoir ?) More observations needed!!
- Need to combine accretion flow and jet models.