# Spectral and timing modelling of accreting black hole binaries

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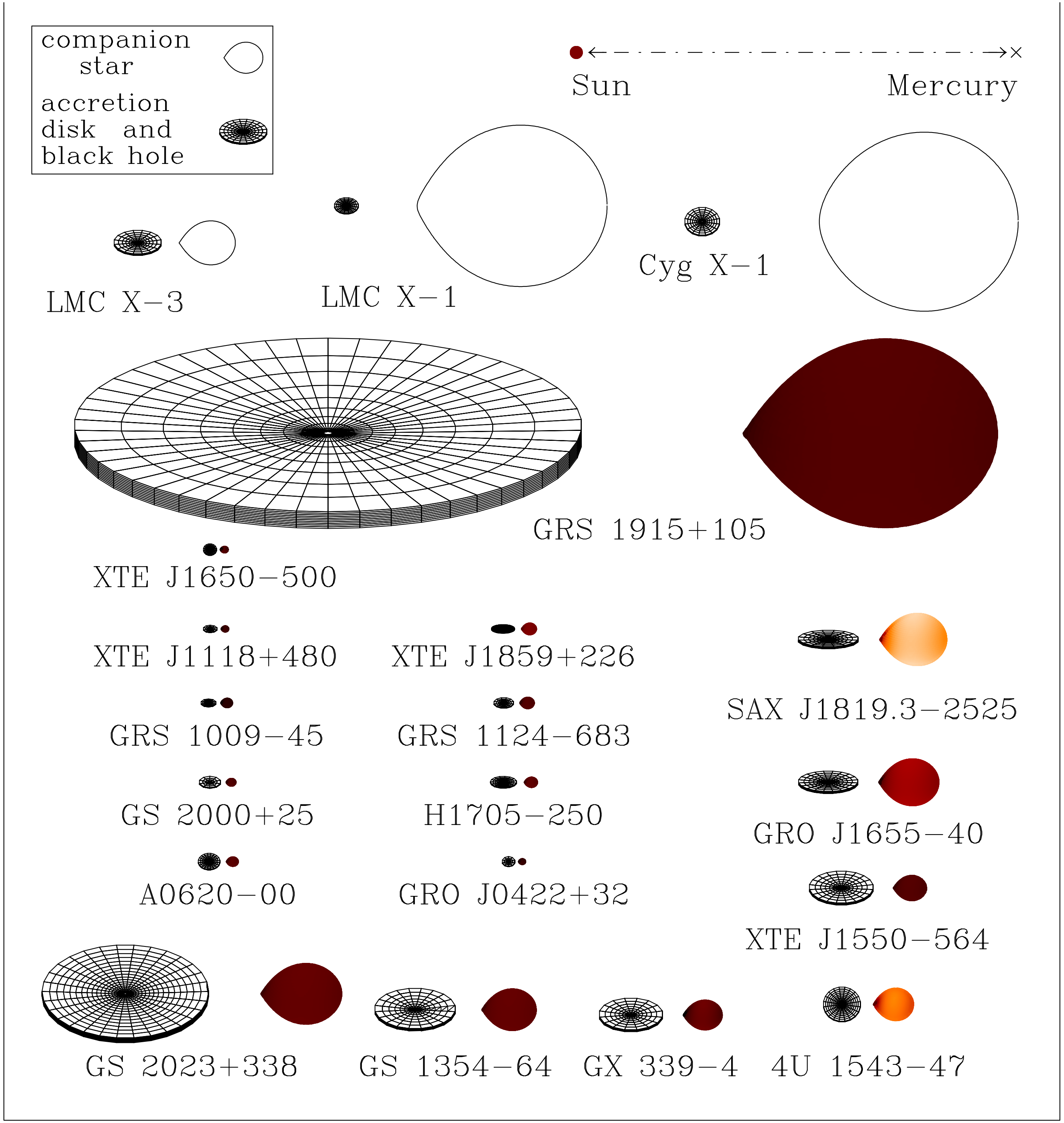
KITP, 7 Mar 2017

# Outline

- General properties
- Spectra: radio to X-rays
- Short-term variability in optical and X-rays:
  - Aperiodic
  - QPOs
- Long-term behaviour




P: 3h – 33d

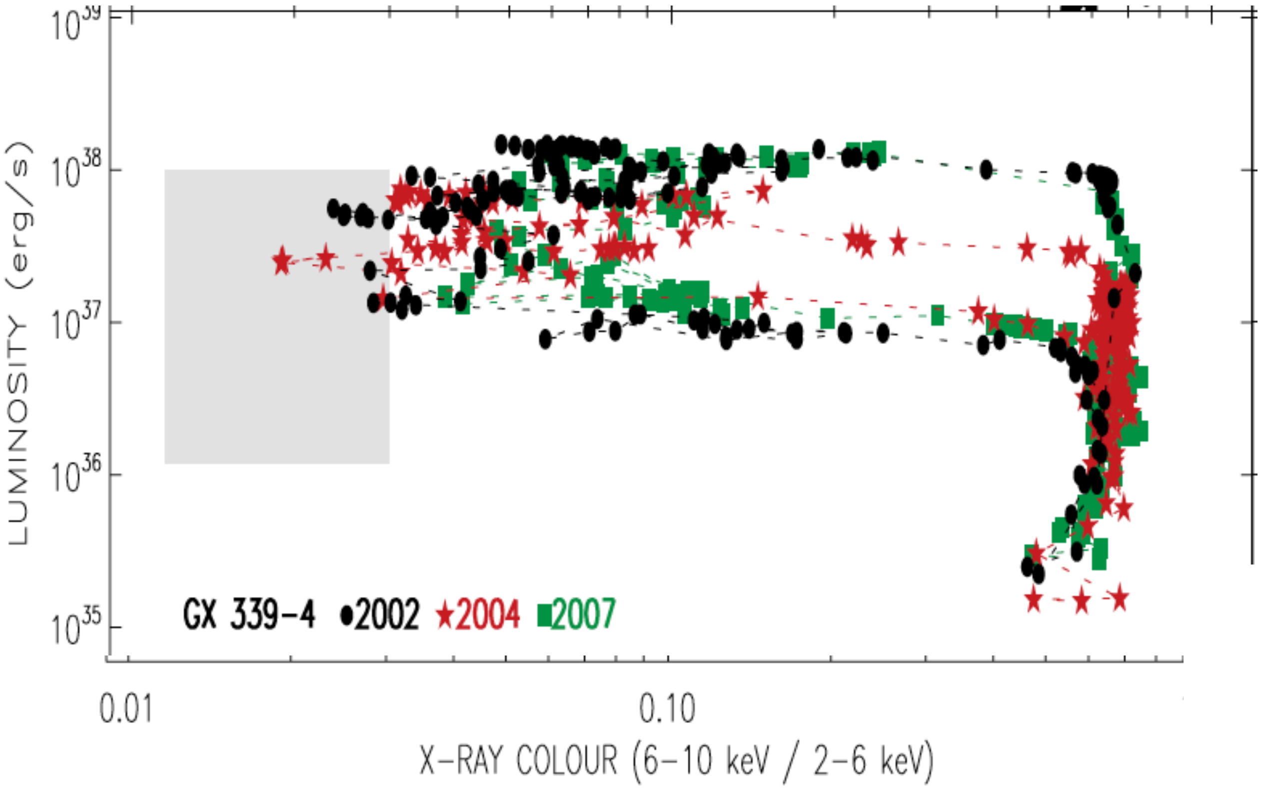
25 confirmed BHs

$M_{BH}$: $3M_{Sun}$ – $15M_{Sun}$

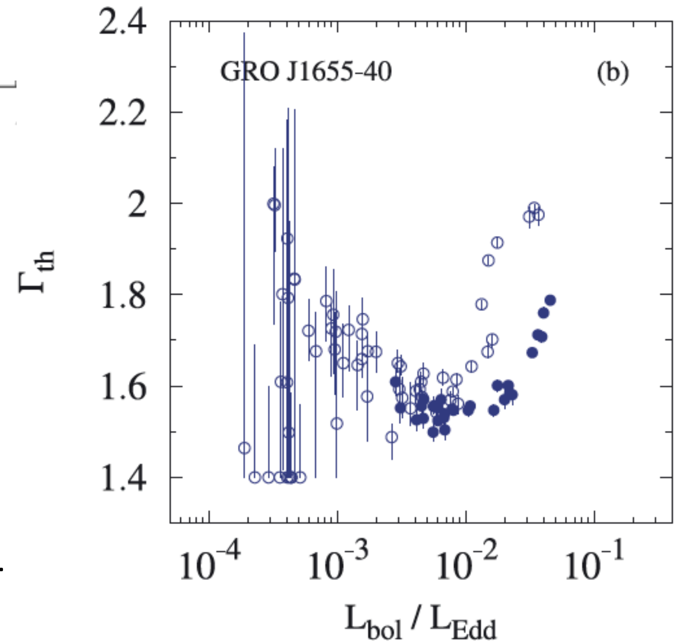
By J. Orosz (http://mintaka.sdsu.edu/faculty/orosz/web/)

# I: Spectra

# Outburst, q-diagram

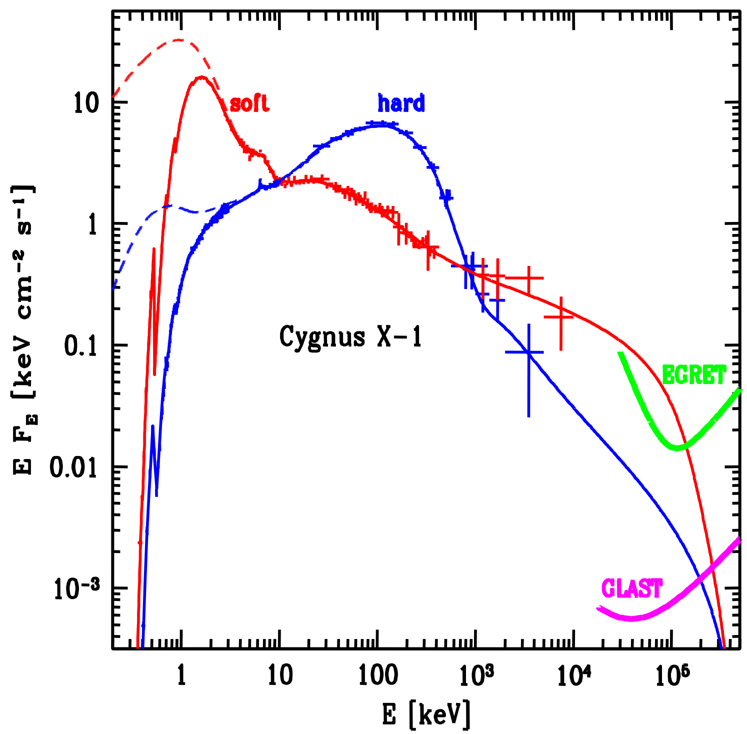



Munoz-Darias et al. 2013




Sobolewska et al. 2011

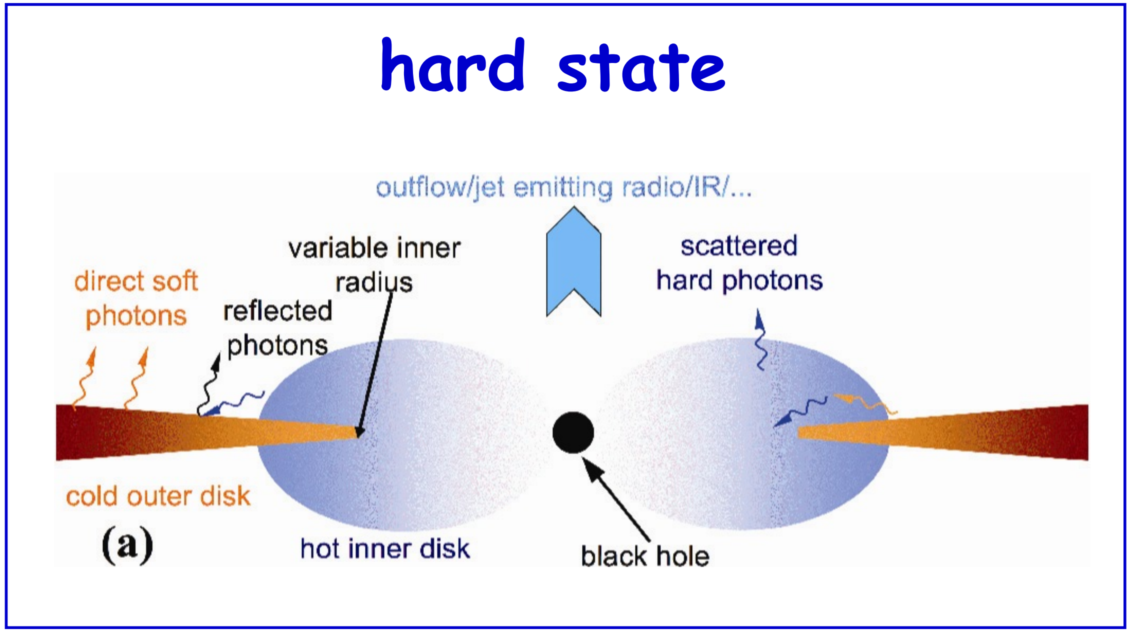
# X-ray spectra and geometry

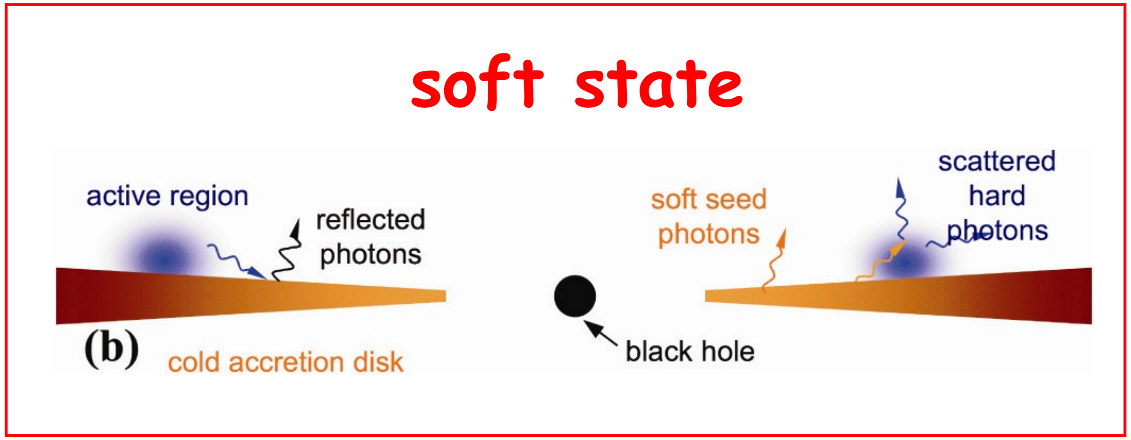



Hard state - standard cold outer disc + hot inner flow

100 keV cut-off

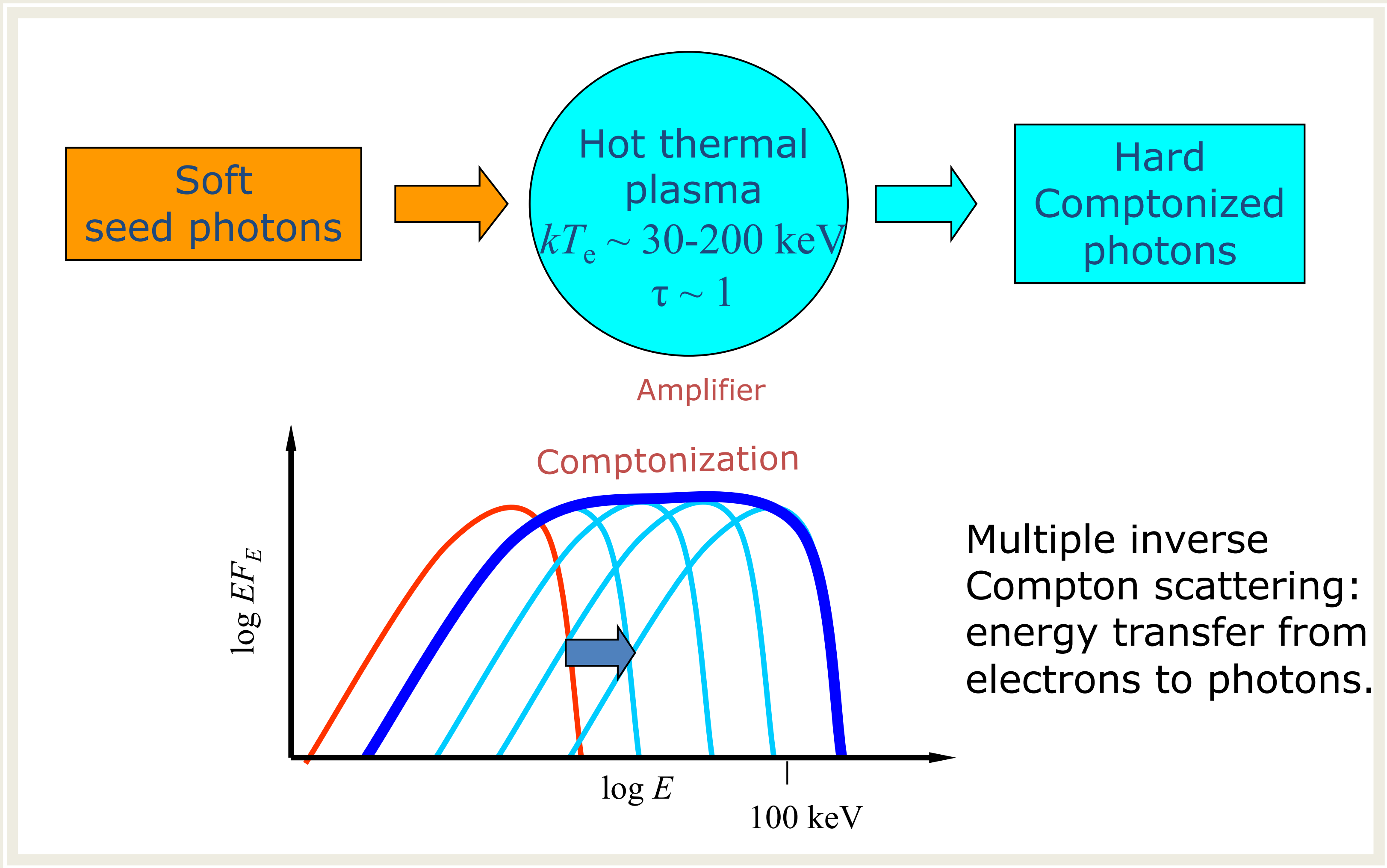
Soft state - standard accretion disc (< 1keV), plus corona



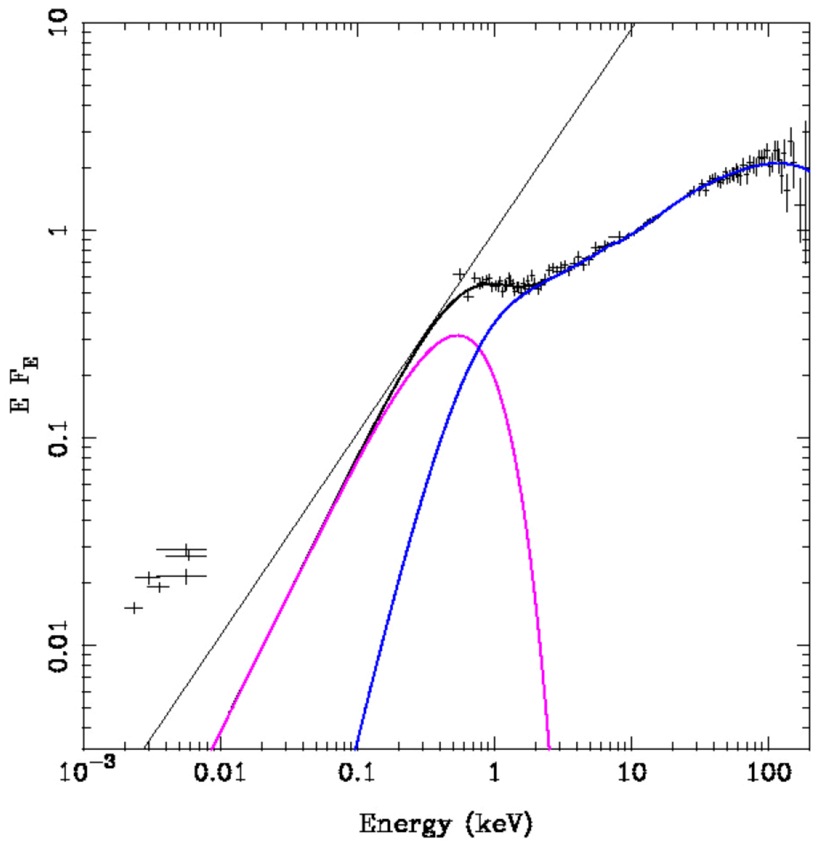

Zdziarski & Gierlinski, 2004

# X-ray spectra and geometry



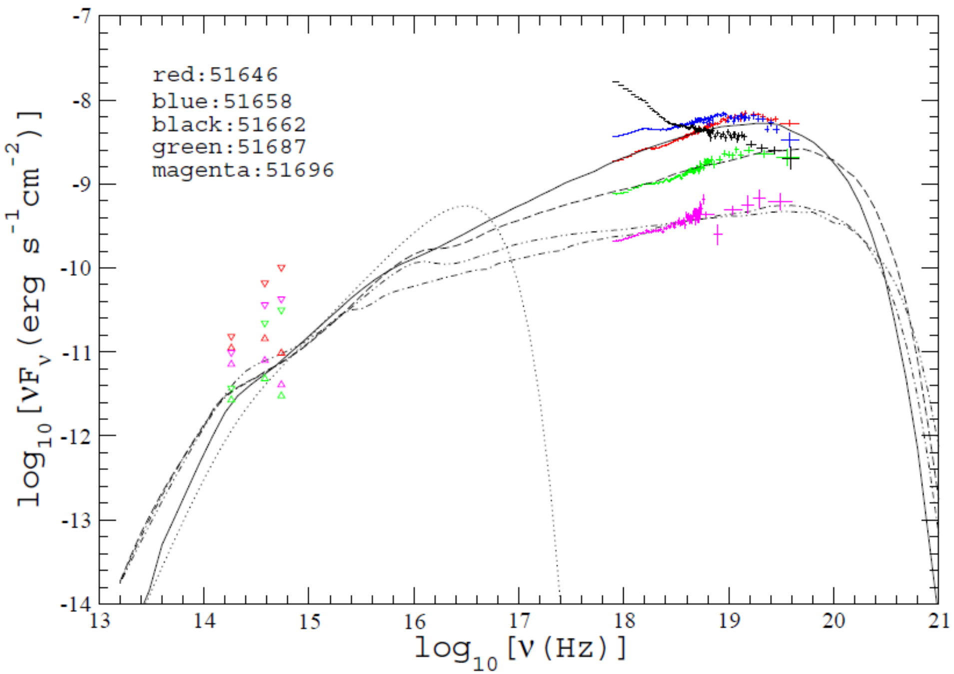
# Thermal Comptonization in the hard state: what is the source of seed photons?

**Thin accretion disc**



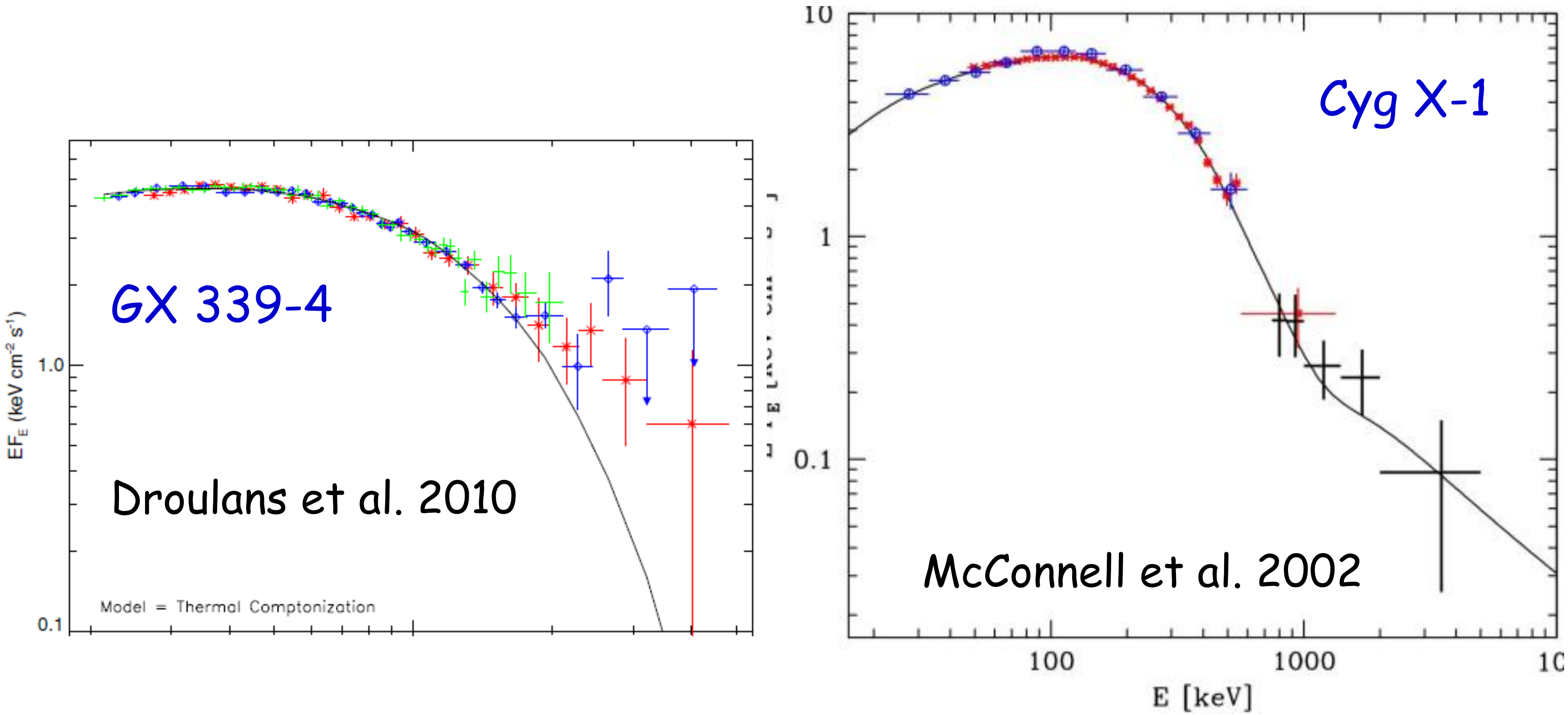

Chiang et al. 2010

**Thermal synchrotron**




Yuan et al. 2007

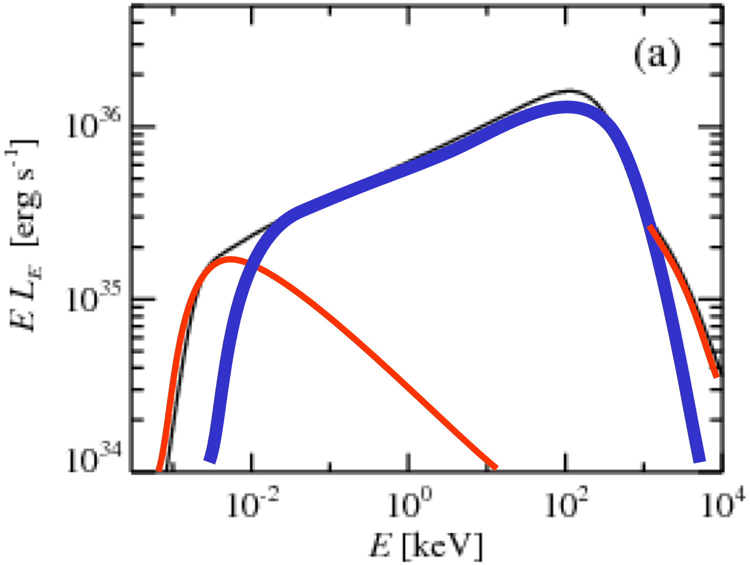
# Thermal Comptonization in the hard state: what is the source of seed photons?

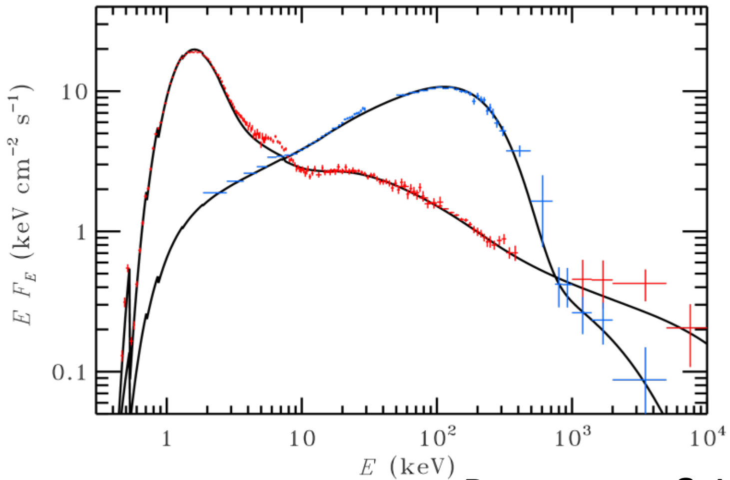



A weak non-thermal tail is present

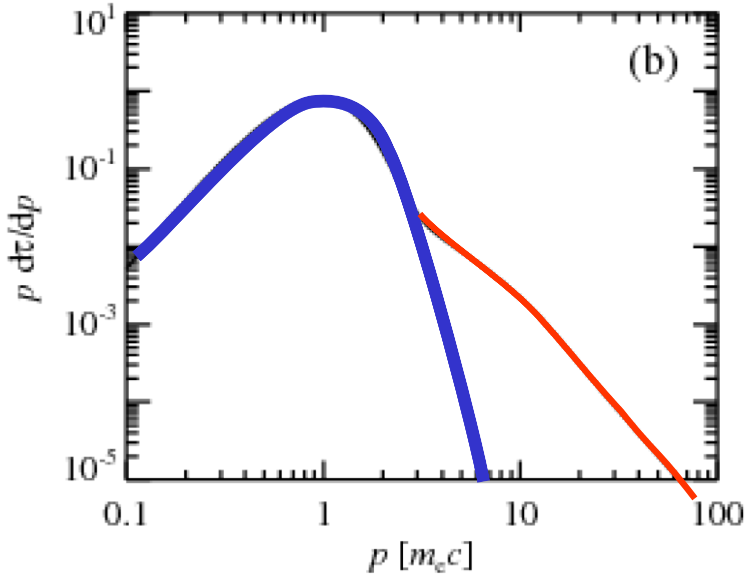
Huge increase in synchrotron luminosity (Wardzinski & Zdziarski 2001)

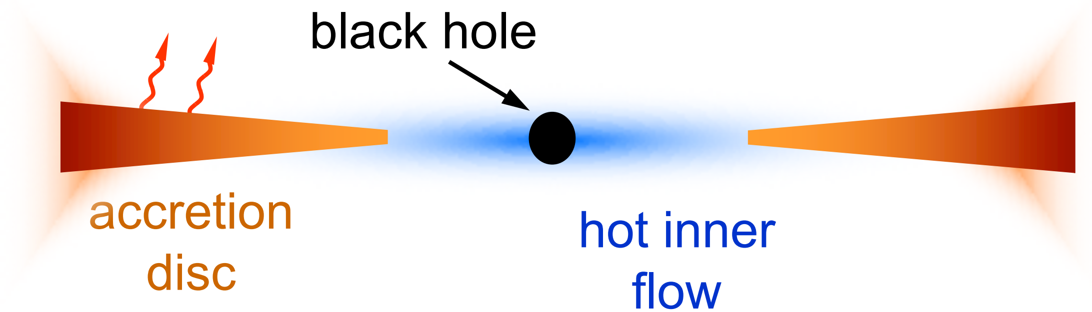
# Synchrotron Self-Compton (SSC) mechanism in hybrid plasma




Poutanen & Vurm 2009

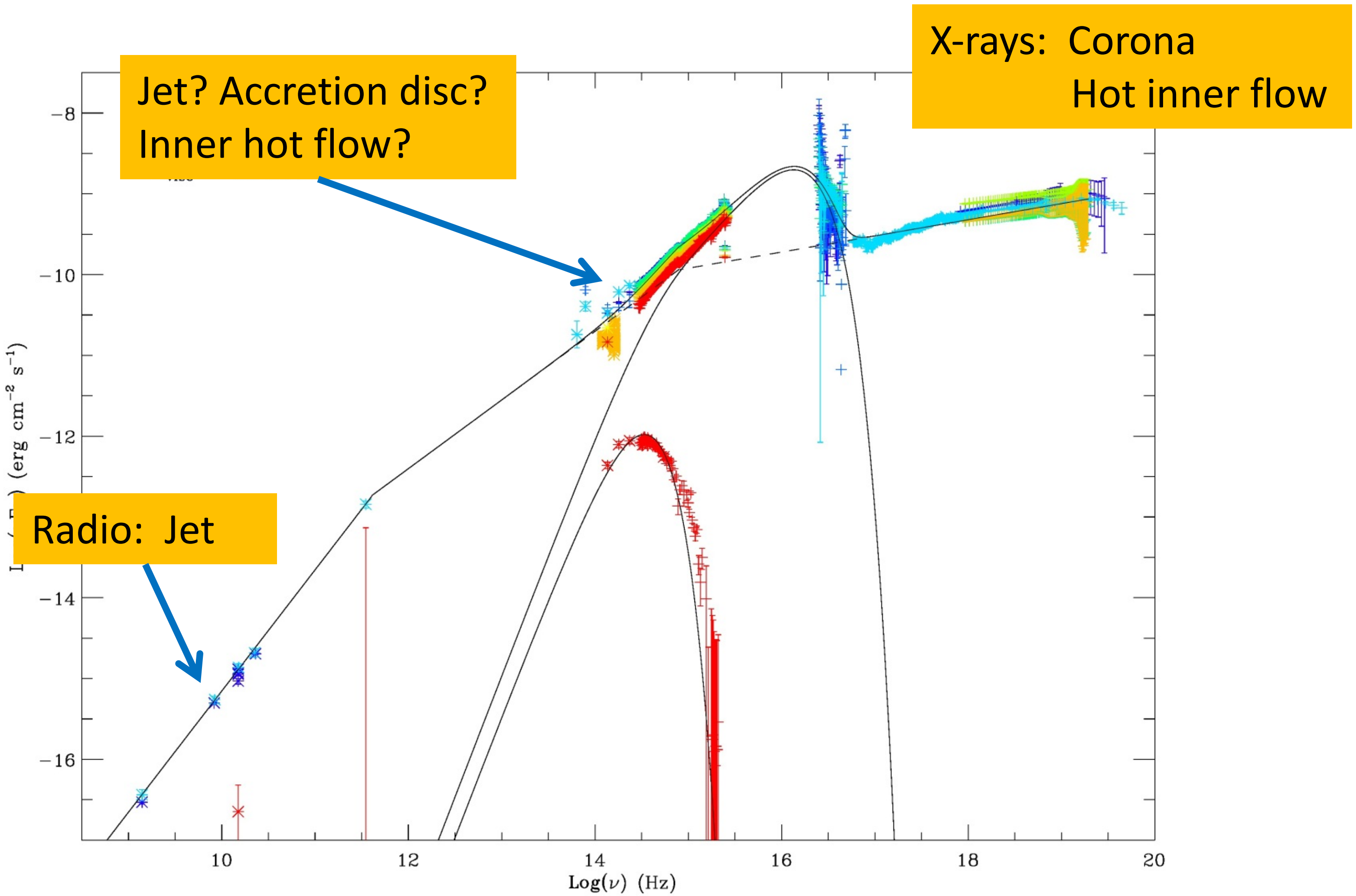



$R = 9 \times 10^7\,\mathrm{cm} \qquad \tau = 1.0 \qquad B = 3 \times 10^5\,\mathrm{G}$

$L = 10^{37}\,\mathrm{erg\,s^{-1}}$

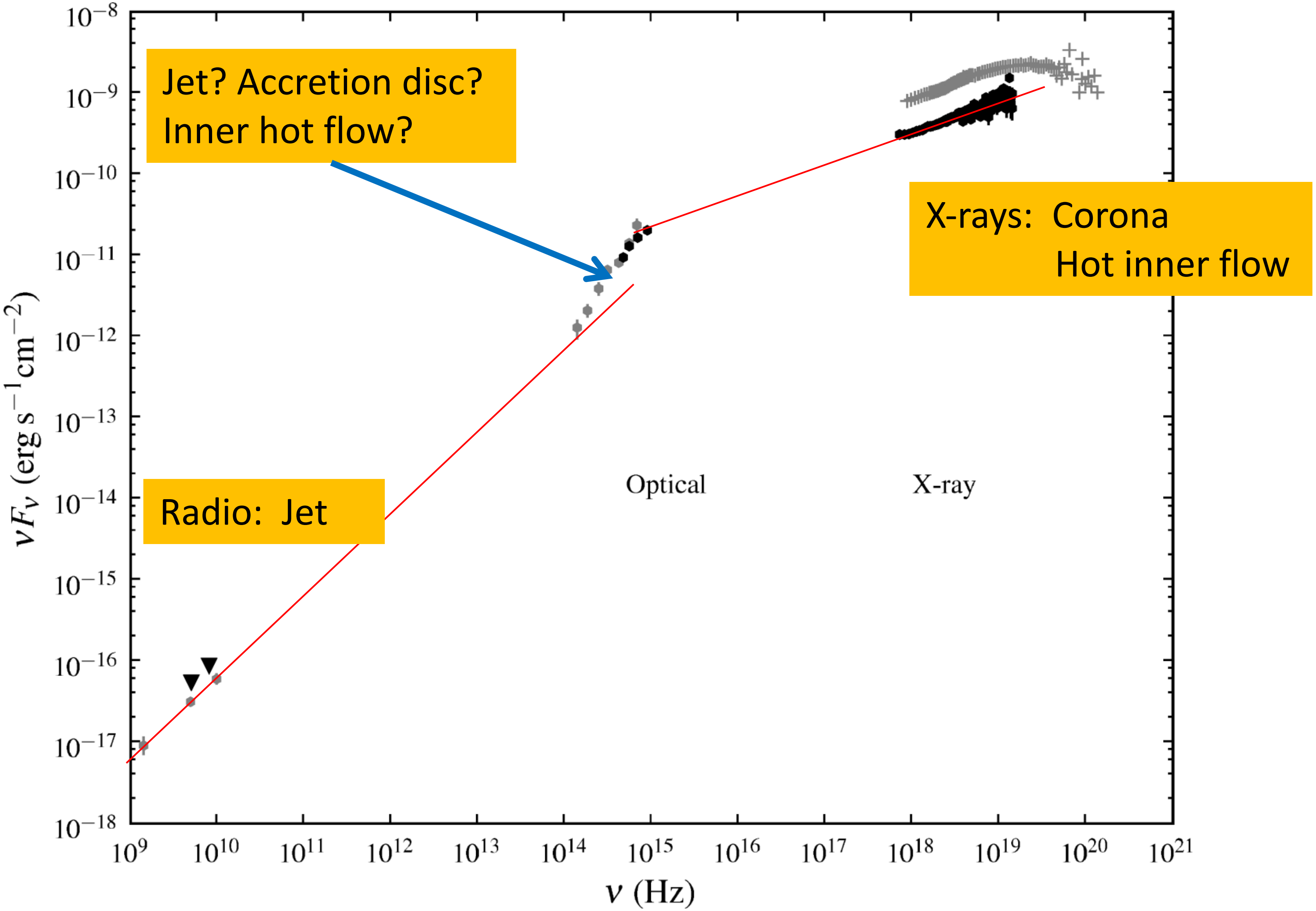
# Broadband spectra of LMXBs




XTE J1118+480

Chaty et al. 2003

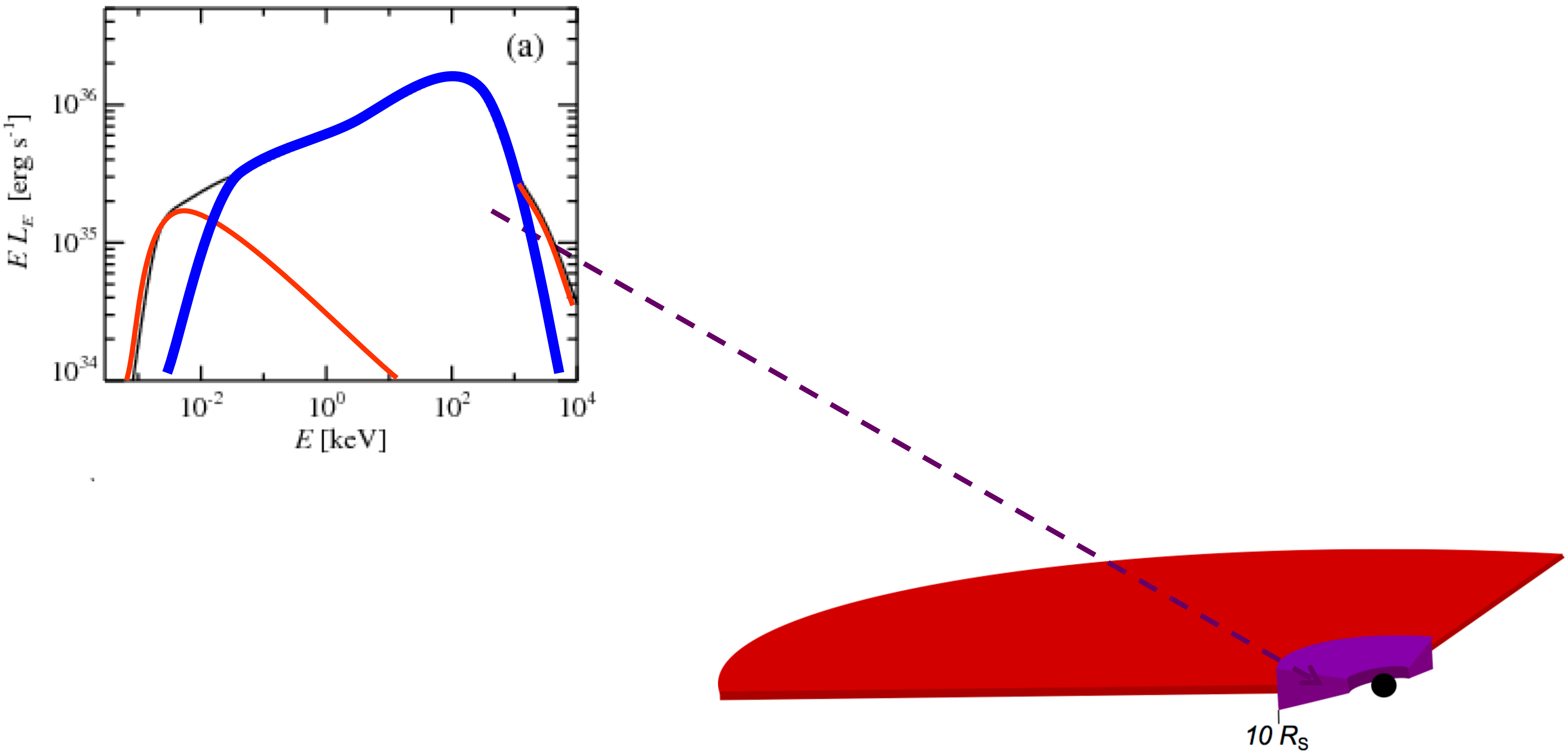
# Broadband spectra of LMXBs



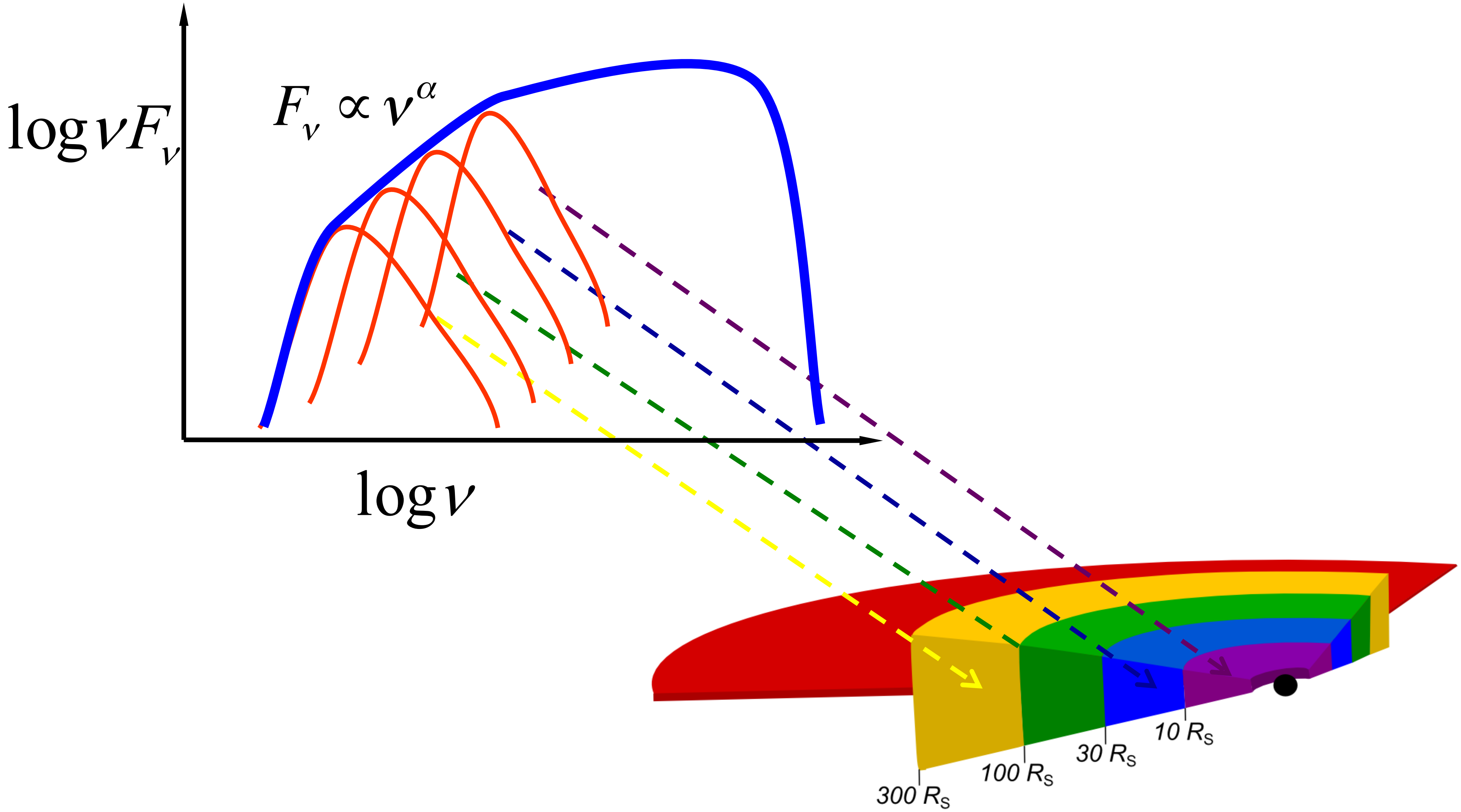

Durant et al. 2009

Swift J1753.5-0127

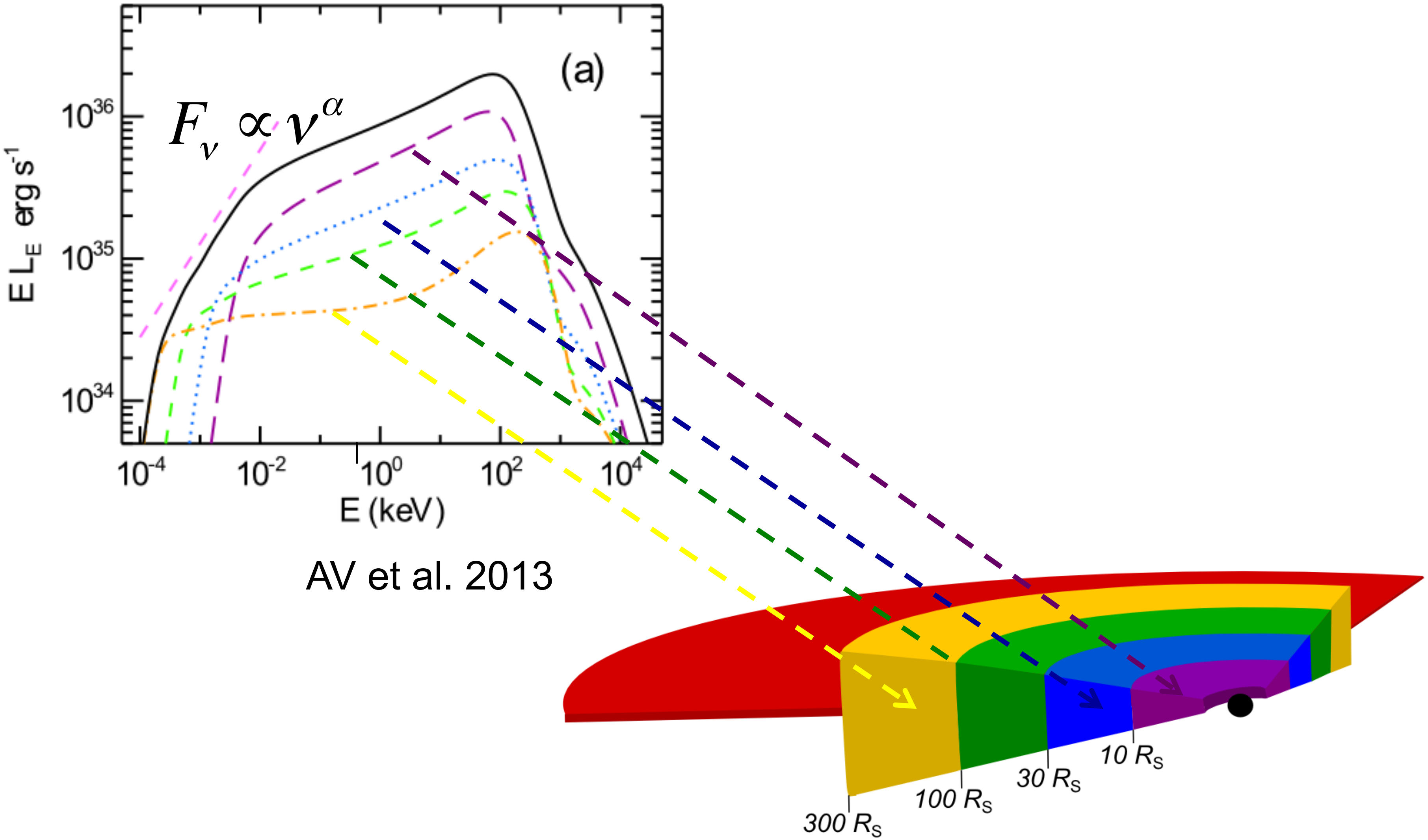
# Homogeneous accretion flow



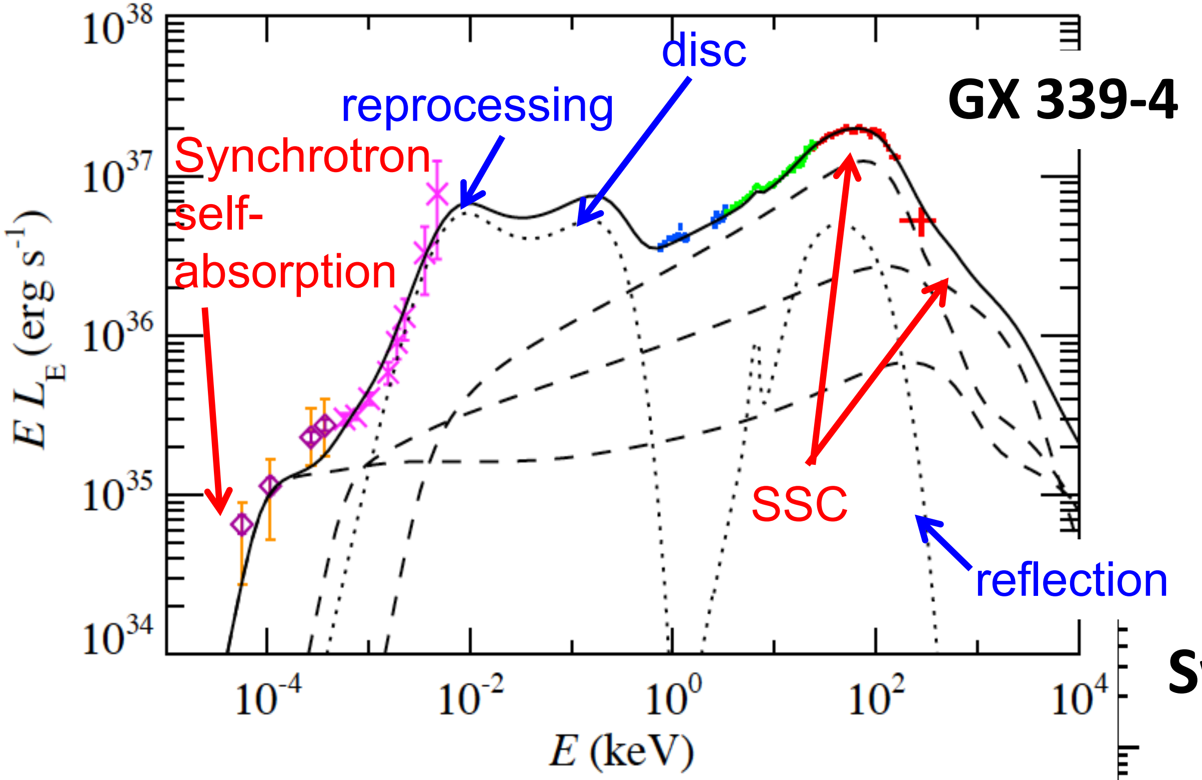
# Inhomogeneous accretion flow

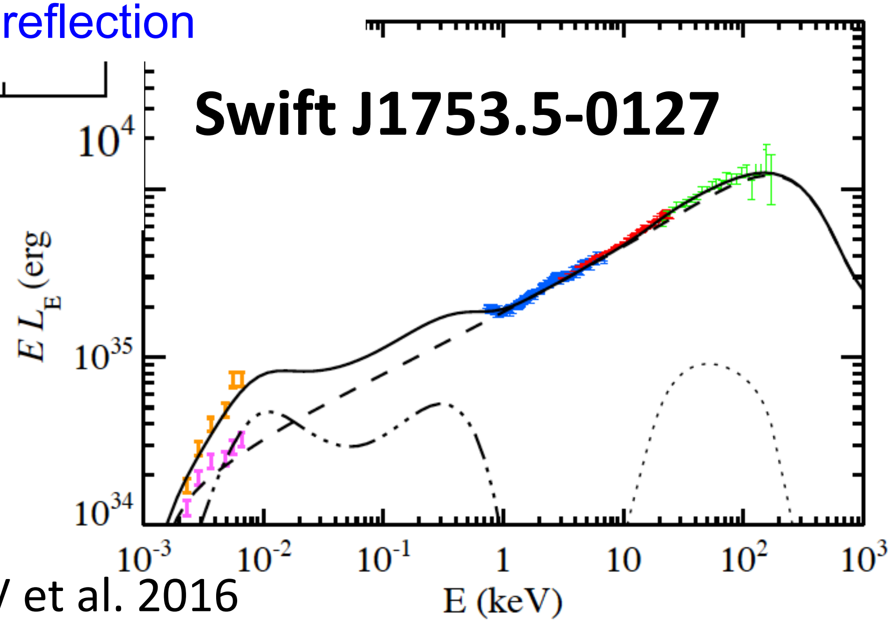


# Inhomogeneous accretion flow



# Broad-band spectrum from extended hot accretion flow

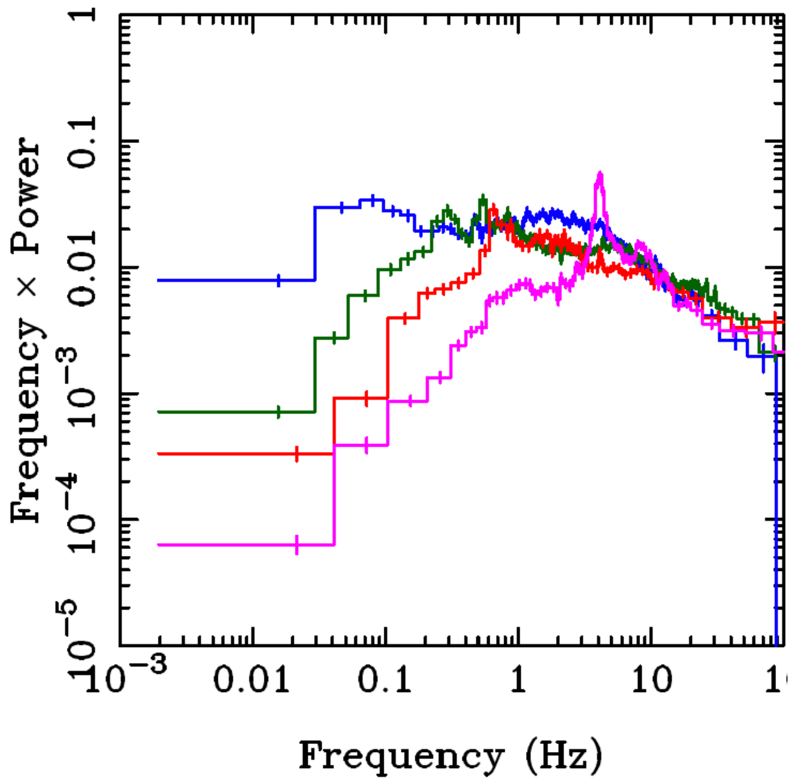


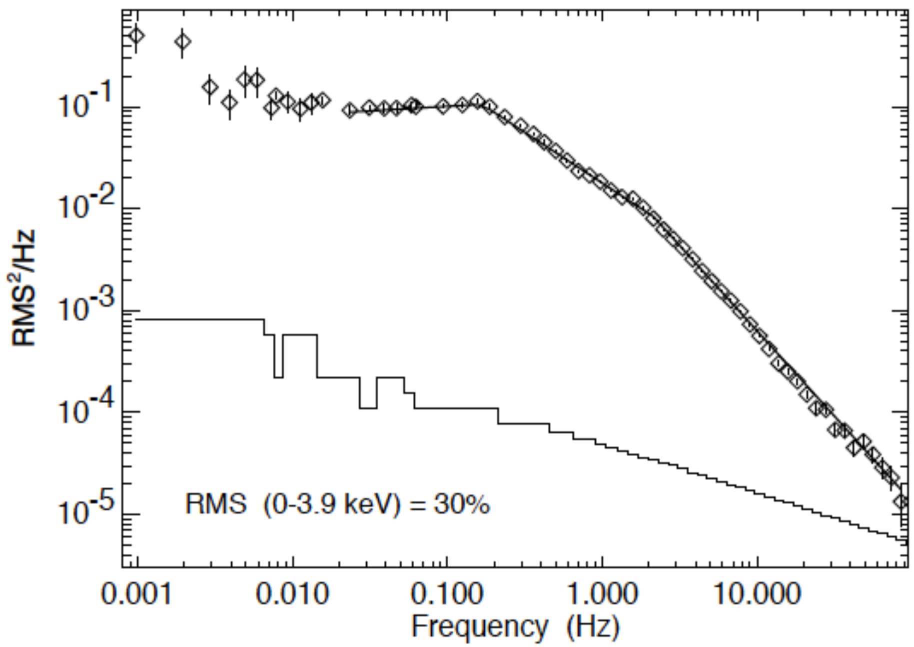

Kajava, AV et al. 2016

# II: Aperiodic variability

# Propagating fluctuations

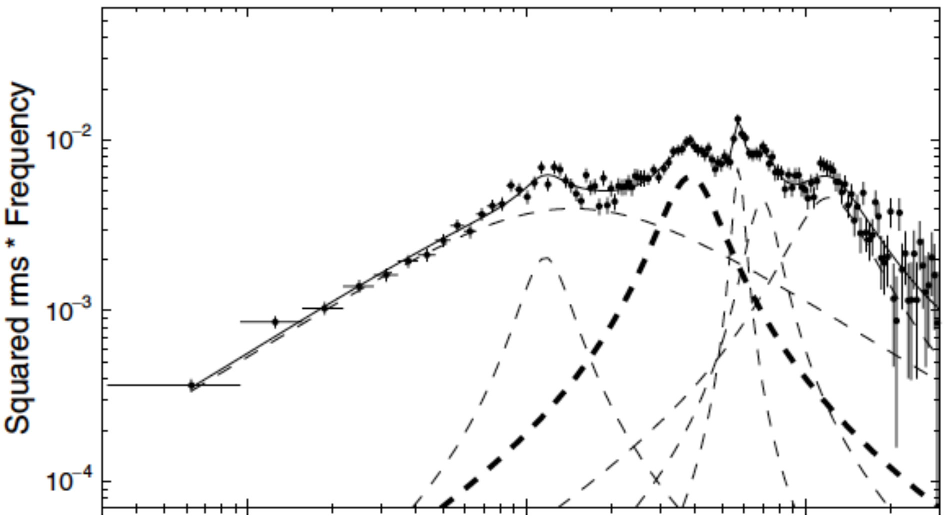



Done et al. 2007

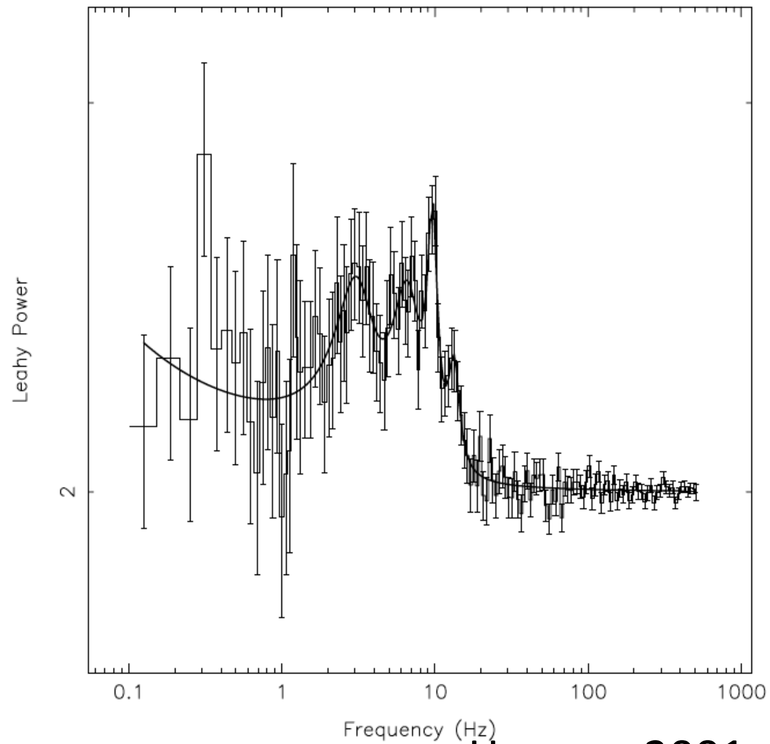



Nowak et al. 1999

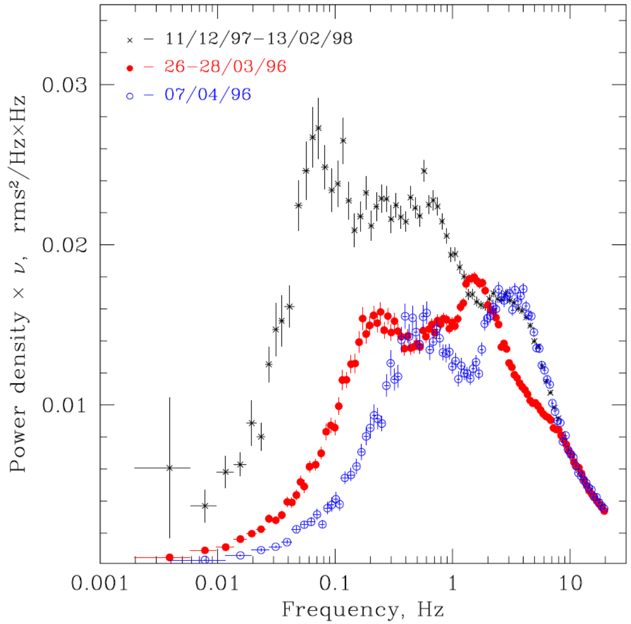
# Multi-peak power spectra…




Belloni+2006

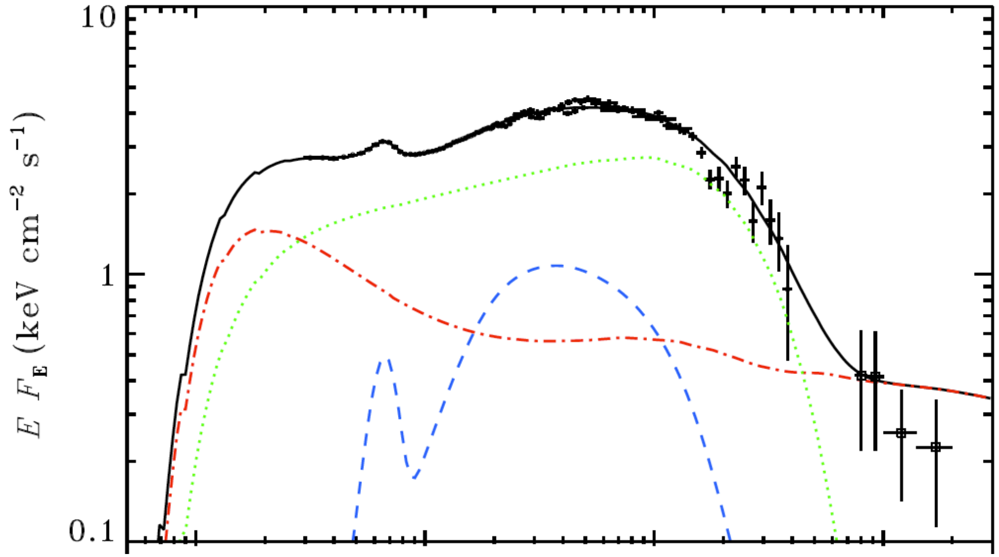



Homan+2001

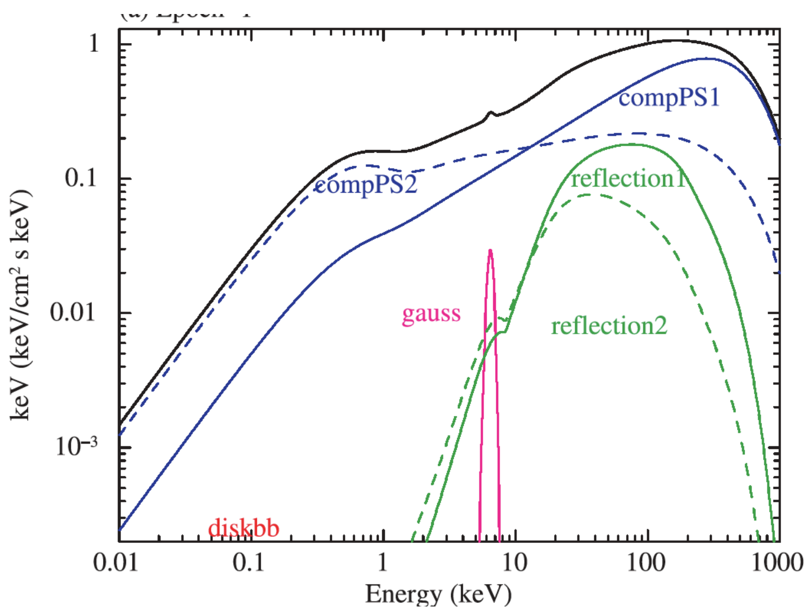



Gilfanov+1999

# …and two components in X-rays

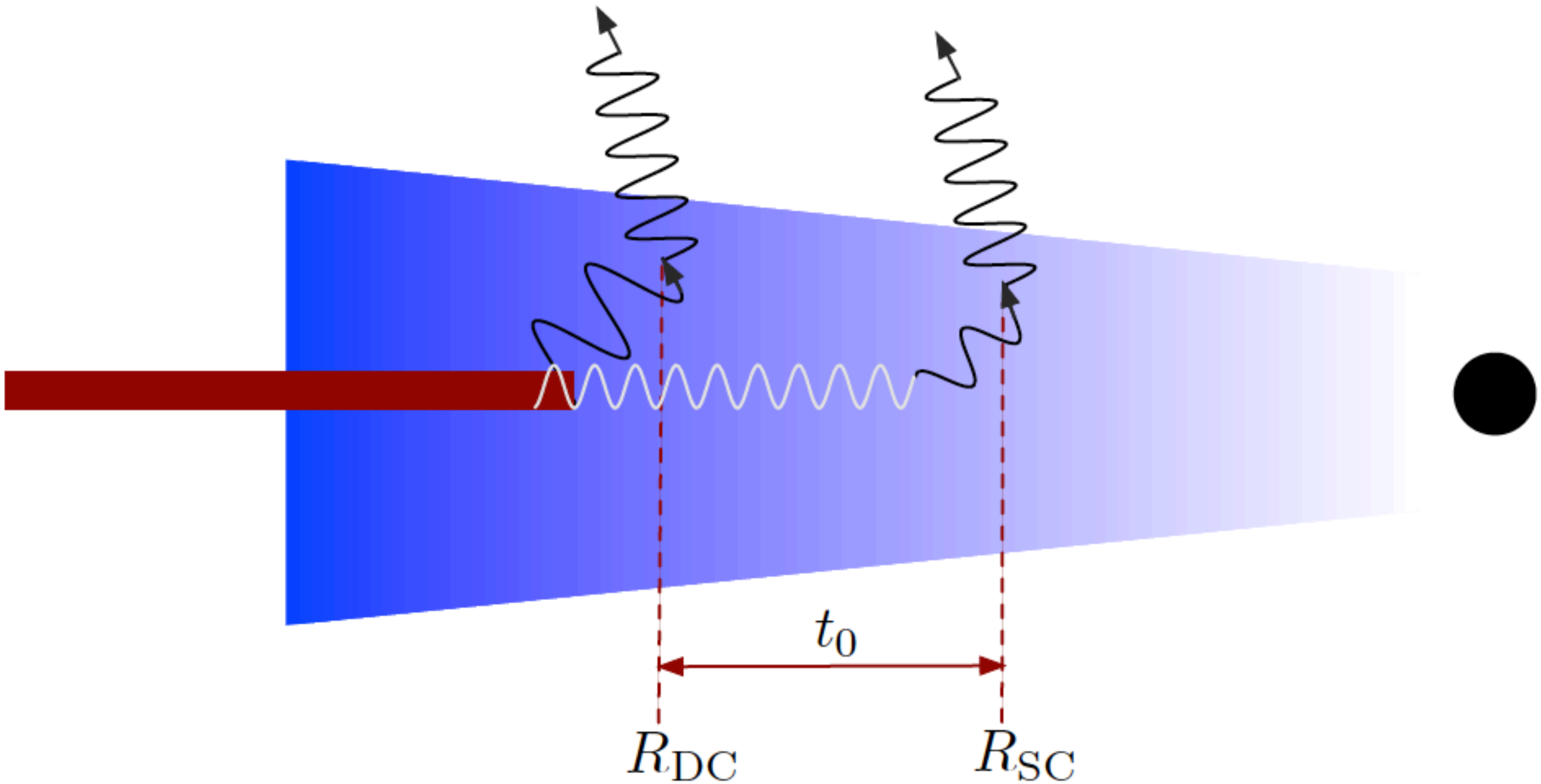



Ibragimov+2005



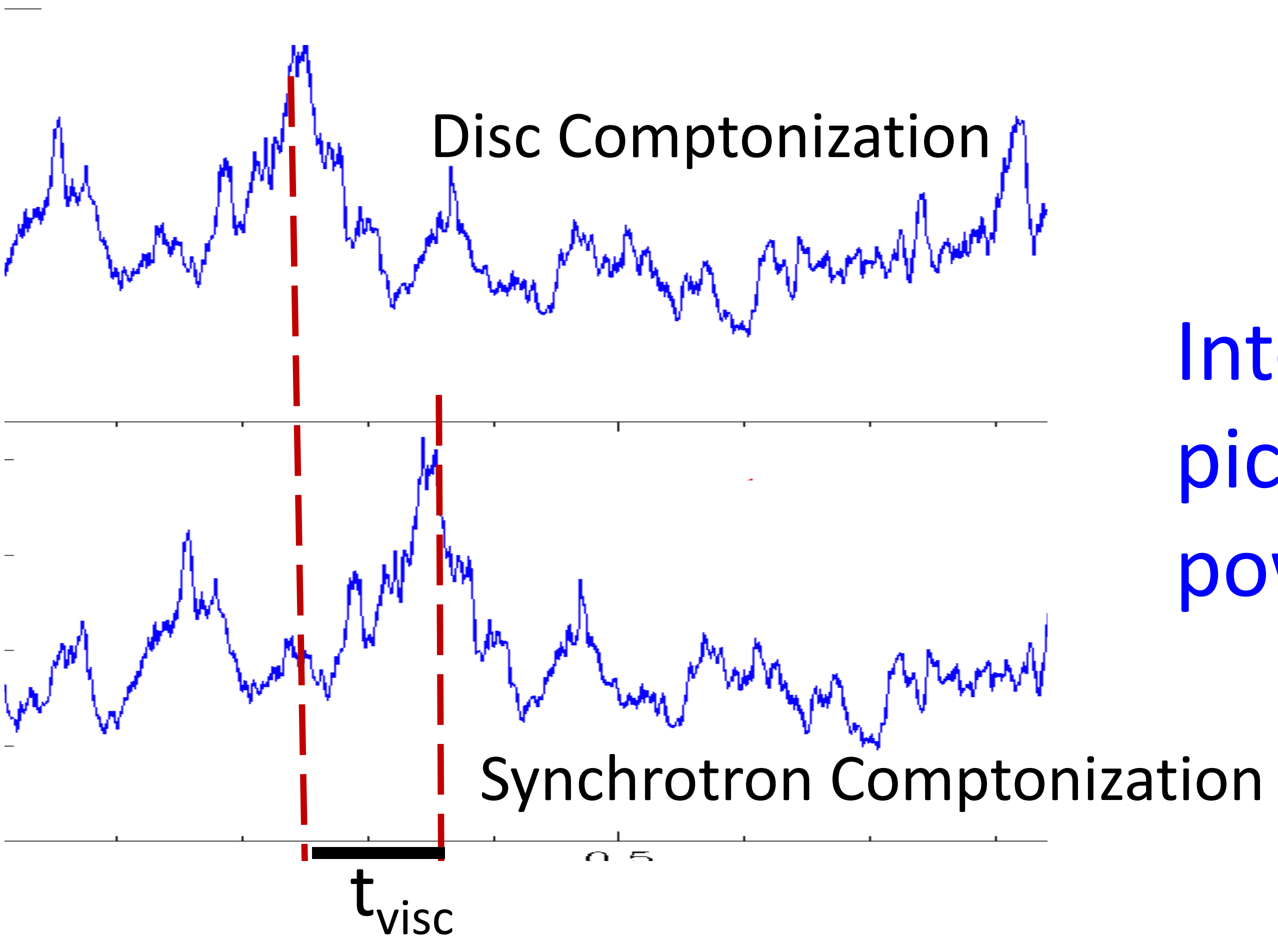

Shidatsu+2011

# Interference of two components




AV16

# Interference of two components

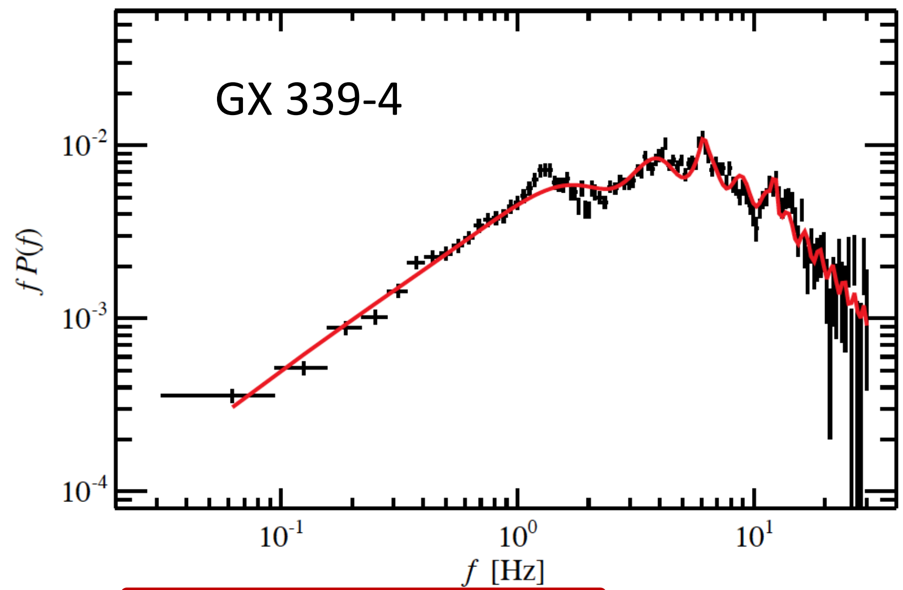


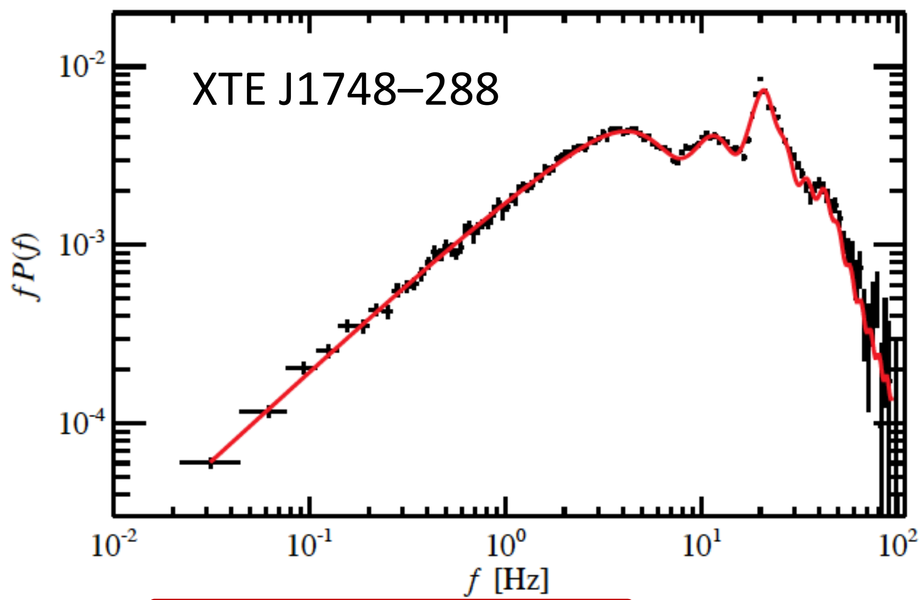

Interference picture in the power spectrum

$$P(f)=X^2_{DC}+X^2_{SC}\pm 2X_{DC}X_{SC}\cos(2\pi f t_{visc})$$

# Interference of two components

$$\alpha\left(\frac{H}{R}\right)^2 = \frac{0.05}{t_{\rm visc}}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{R}{50R_{\rm S}}\right)^{3/2}$$



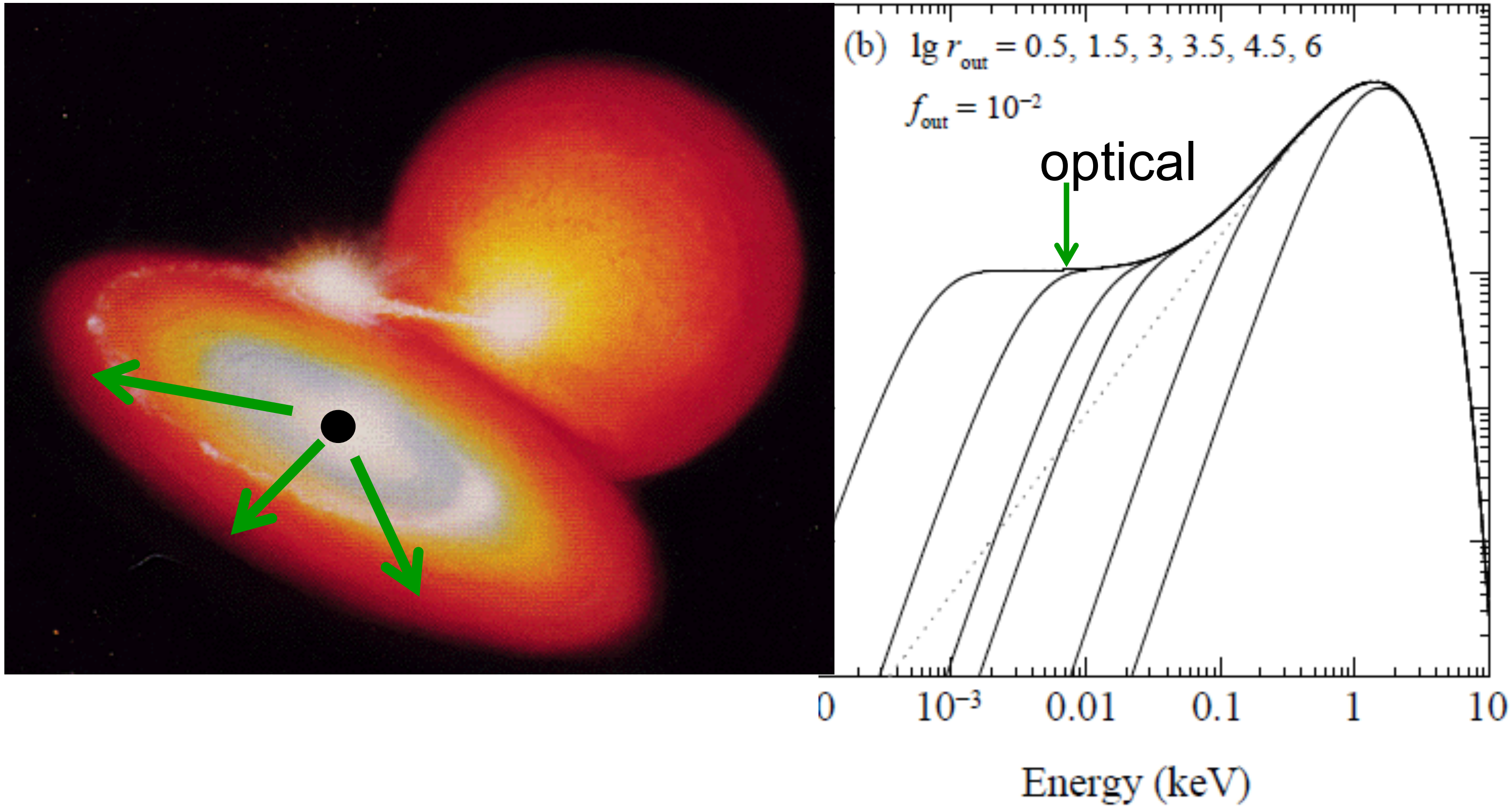




$0.01<\alpha<0.5$
$H/R>0.2$

$0.03<\alpha<0.7$
$H/R>0.3$

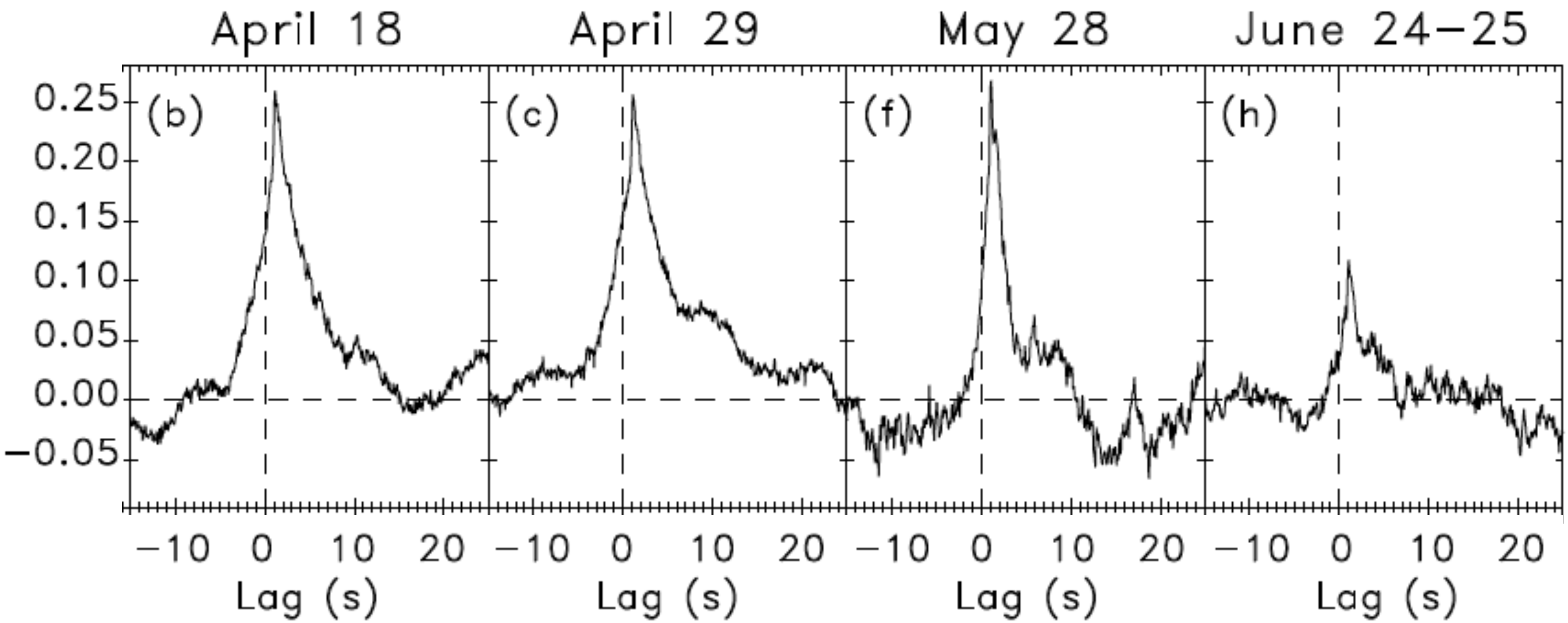
AV16

# Irradiated discs




Gierlinski et al. 2009

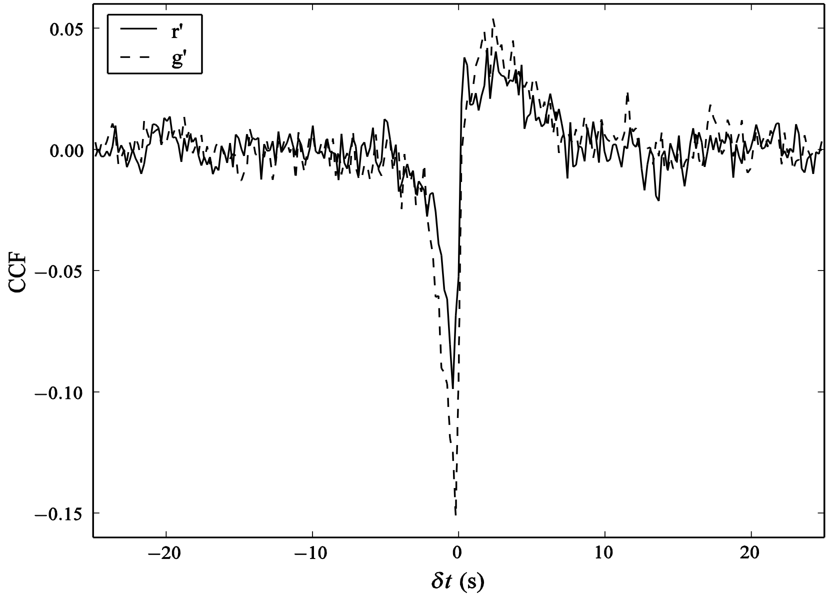
# UV/X-ray cross-correlation



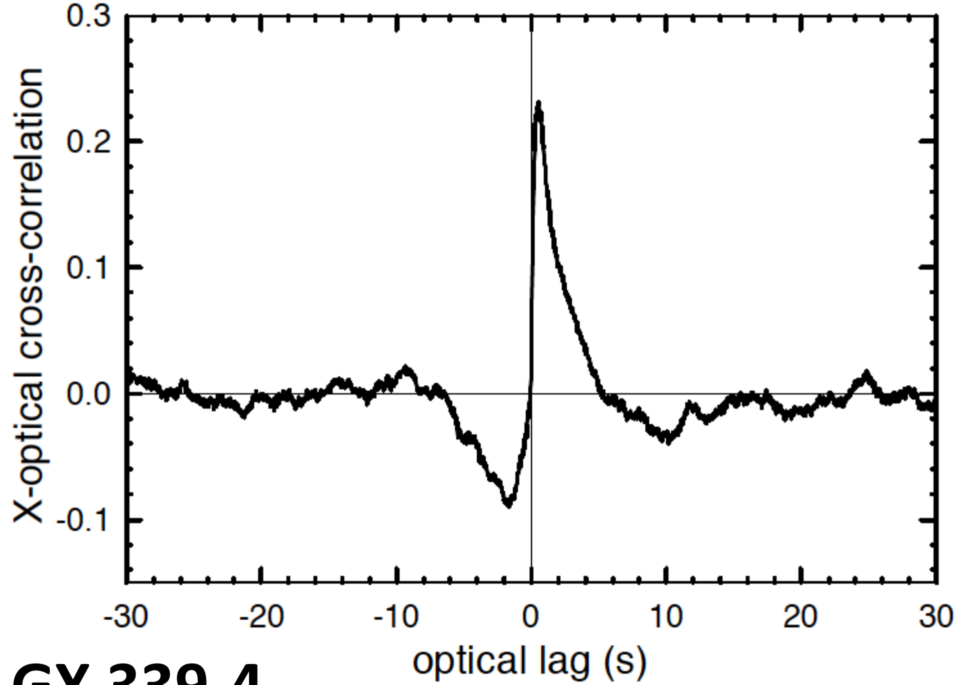

**XTE J1118+480**

Hynes et al. 2003

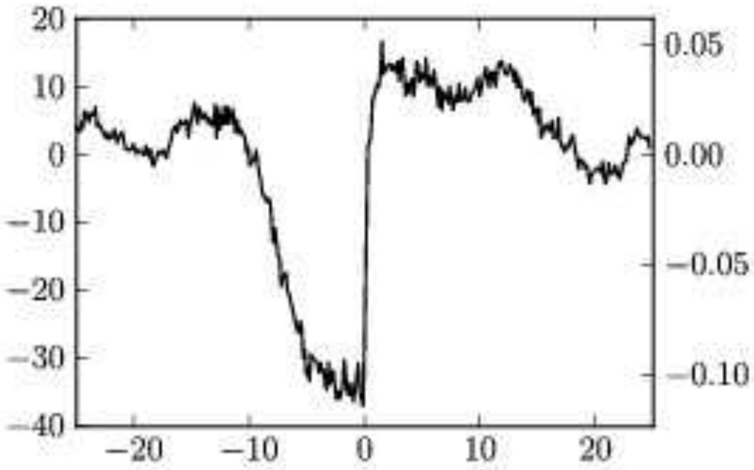
# Optical/X-ray cross-correlation



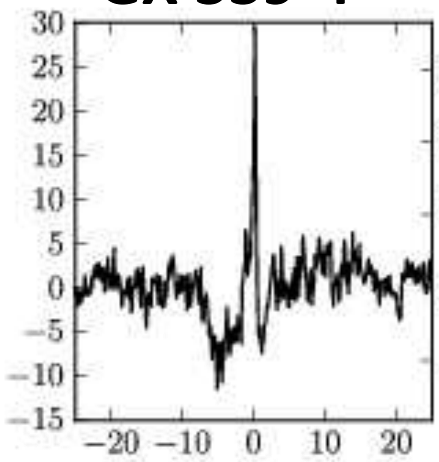

**XTE J1118+480**




**SWIFT J1753.5-0127**

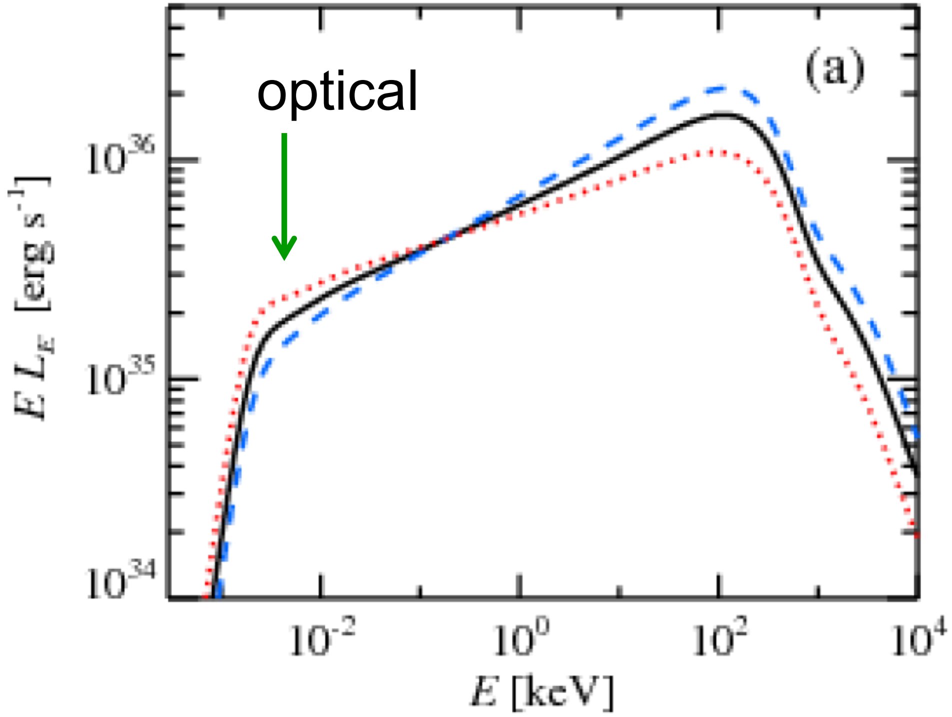



**GX 339-4**




Kanbach et al. 2001
Gandhi et al. 2008, 2010
Durant et al. 2008, 2011

# SSC mechanism in hybrid plasma




$$R \propto \dot{m}^{-4/3}$$

$$L \propto \dot{m}$$

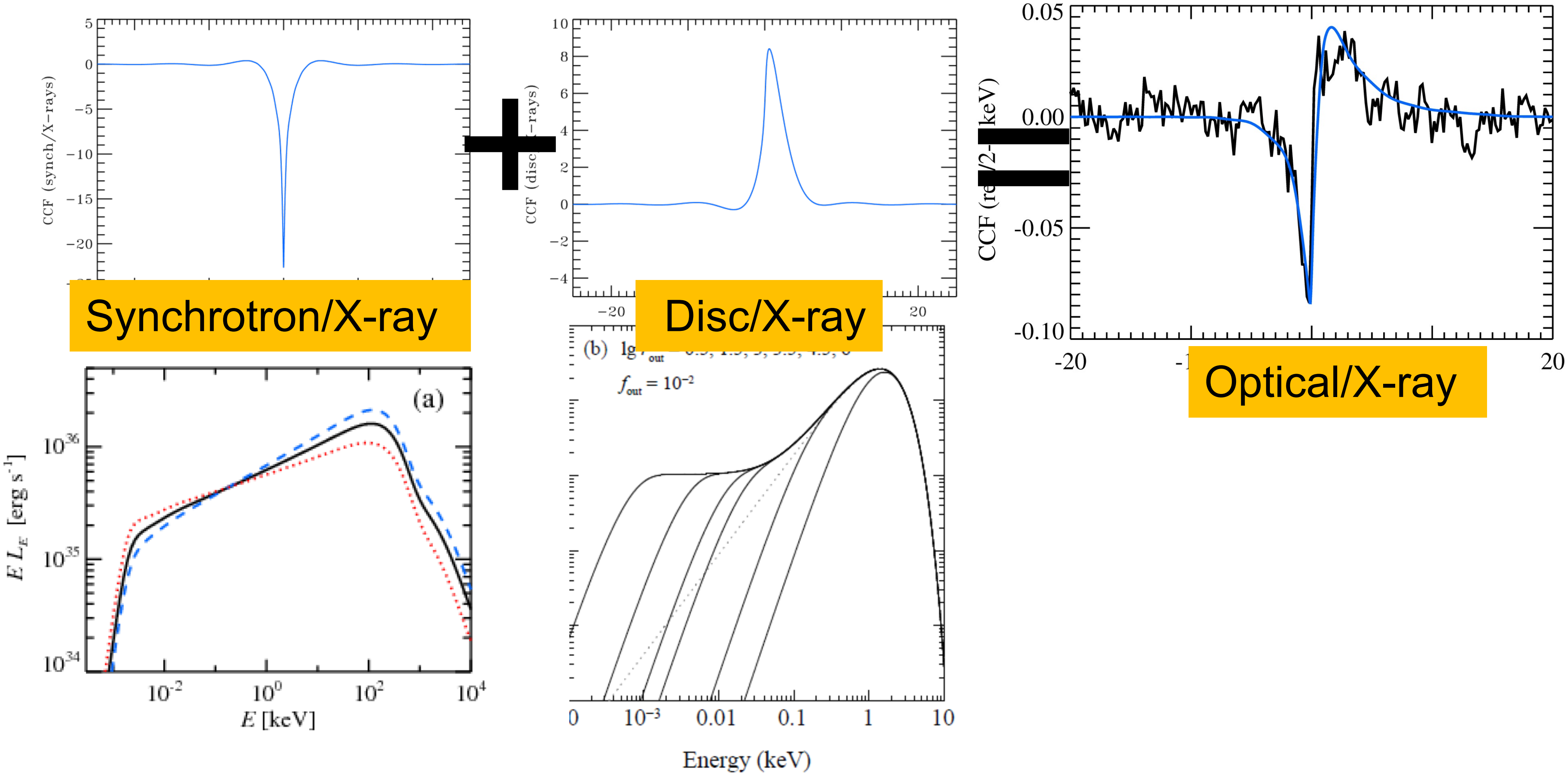
$$\tau \propto \dot{m}$$

$$B = const$$

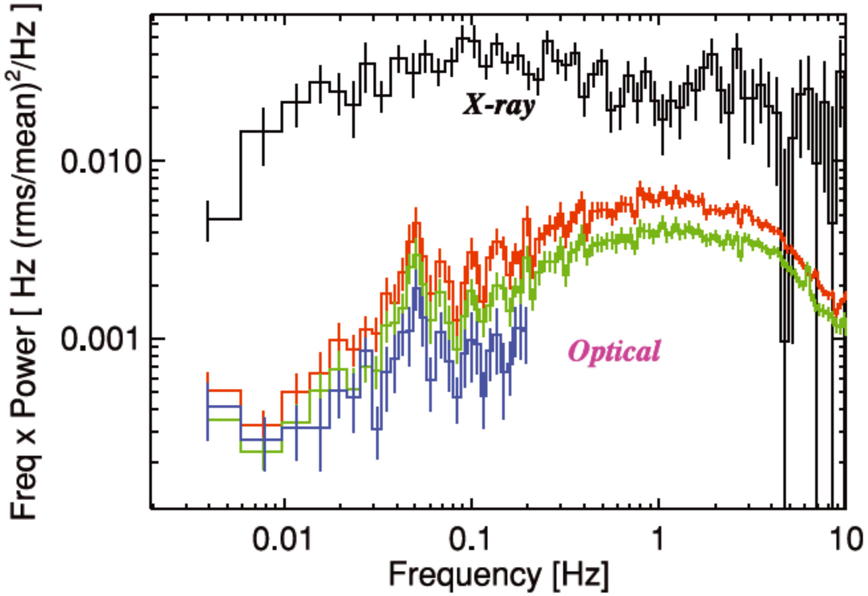
AV et al. 2011

The optical and X-ray fluxes are anticorrelated

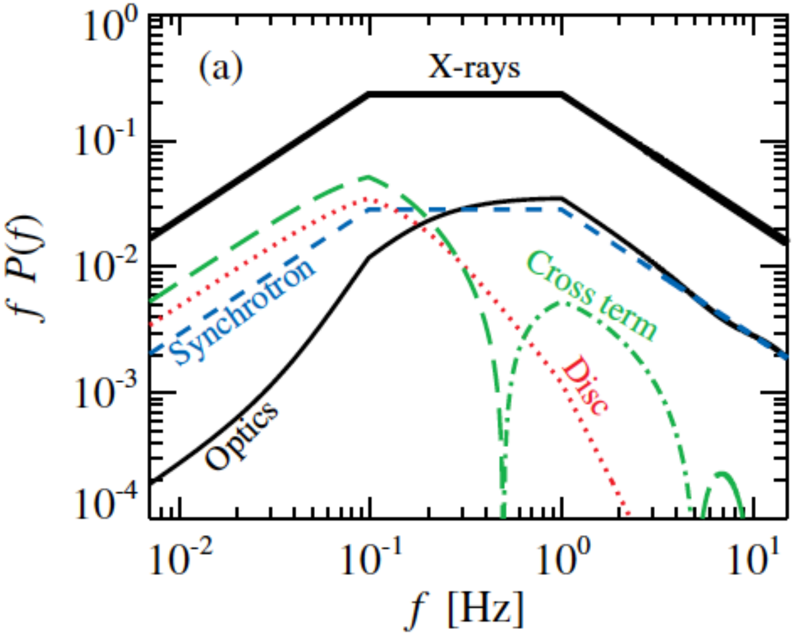
# Optical/X-ray cross-correlation



# Optical and X-ray PSDs




Gandhi et al. 2010

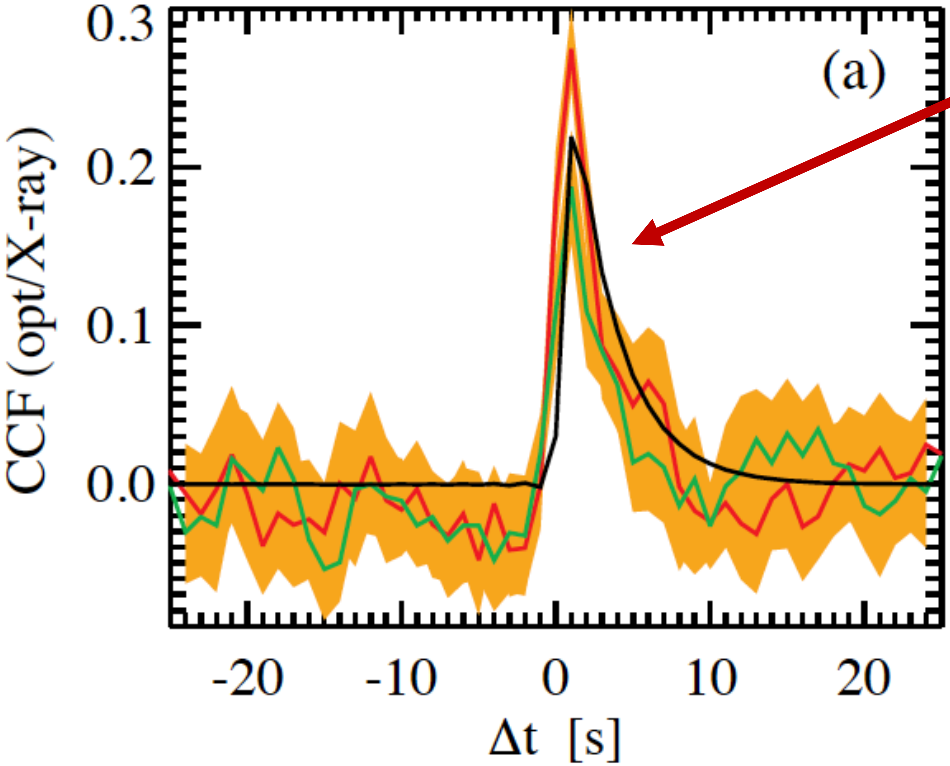



AV et al 2011

Optical PSD peaks at higher, relative to X-rays, frequencies because of the presence of two components

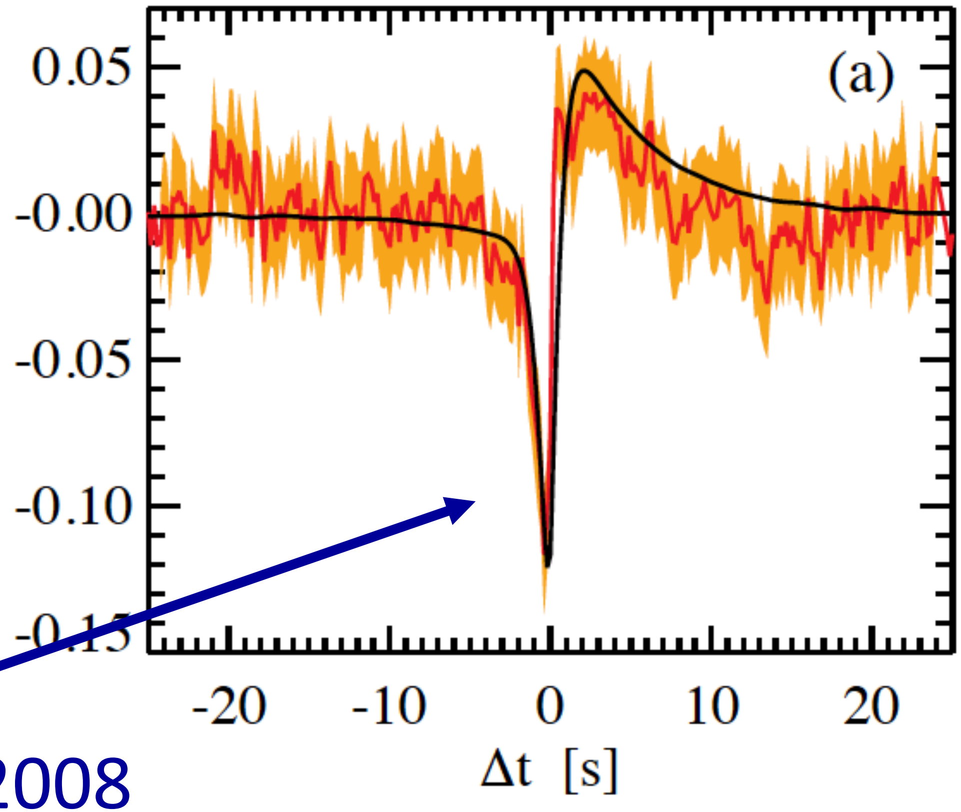
$$P_{\rm O}(f) \propto P_{\rm X}(f)\left\{1 + r_{\rm ds}^2\,|R(f)|^2 - 2r_{\rm ds}{\rm Re}\,[R(f)]\right\}$$

# Outburst decline – changing CCF




Outburst peak, Jul 2005

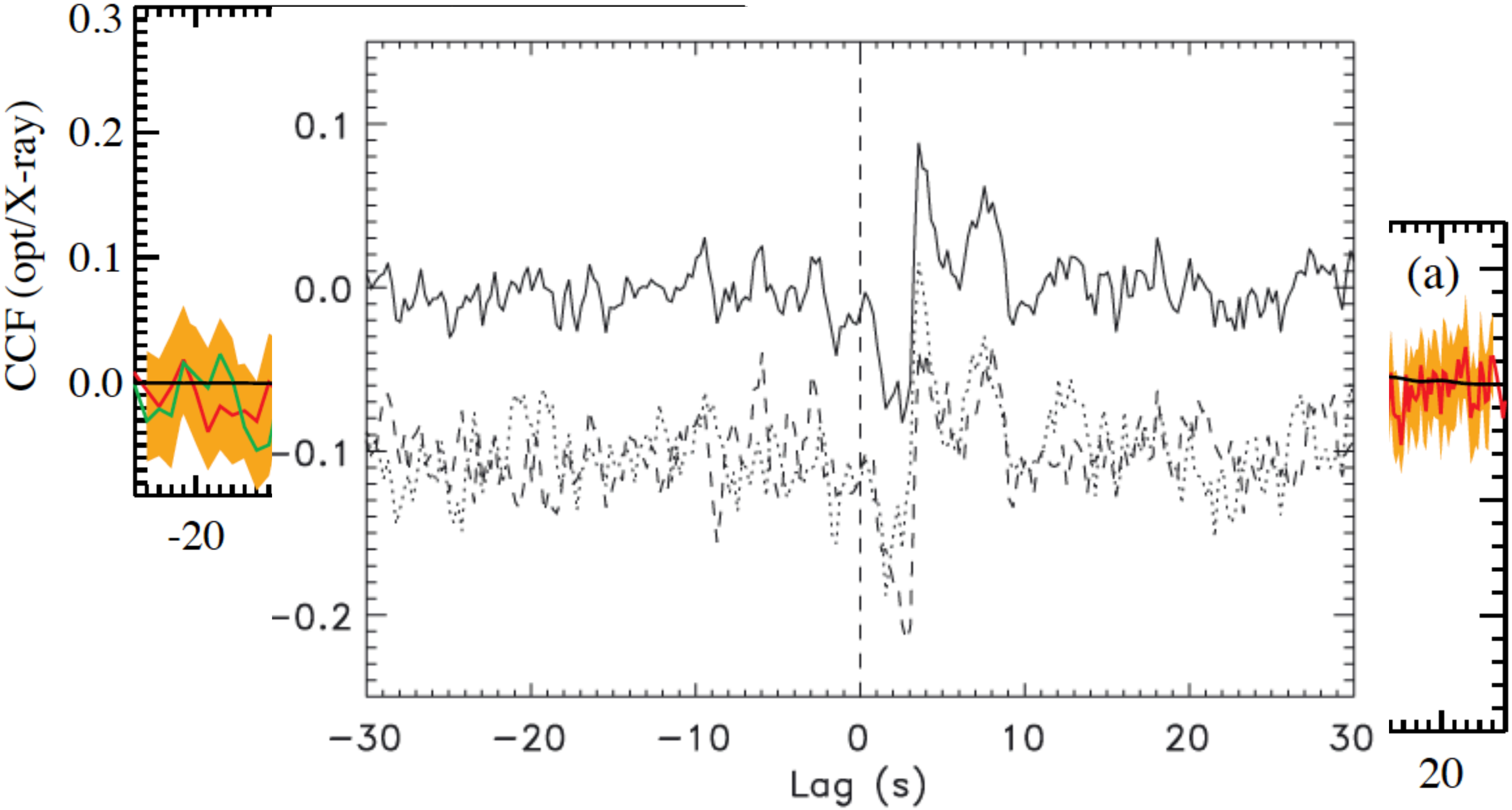
**SWIFT J1753.5-0127**




Outburst tail, 2008

AV et al. 2016

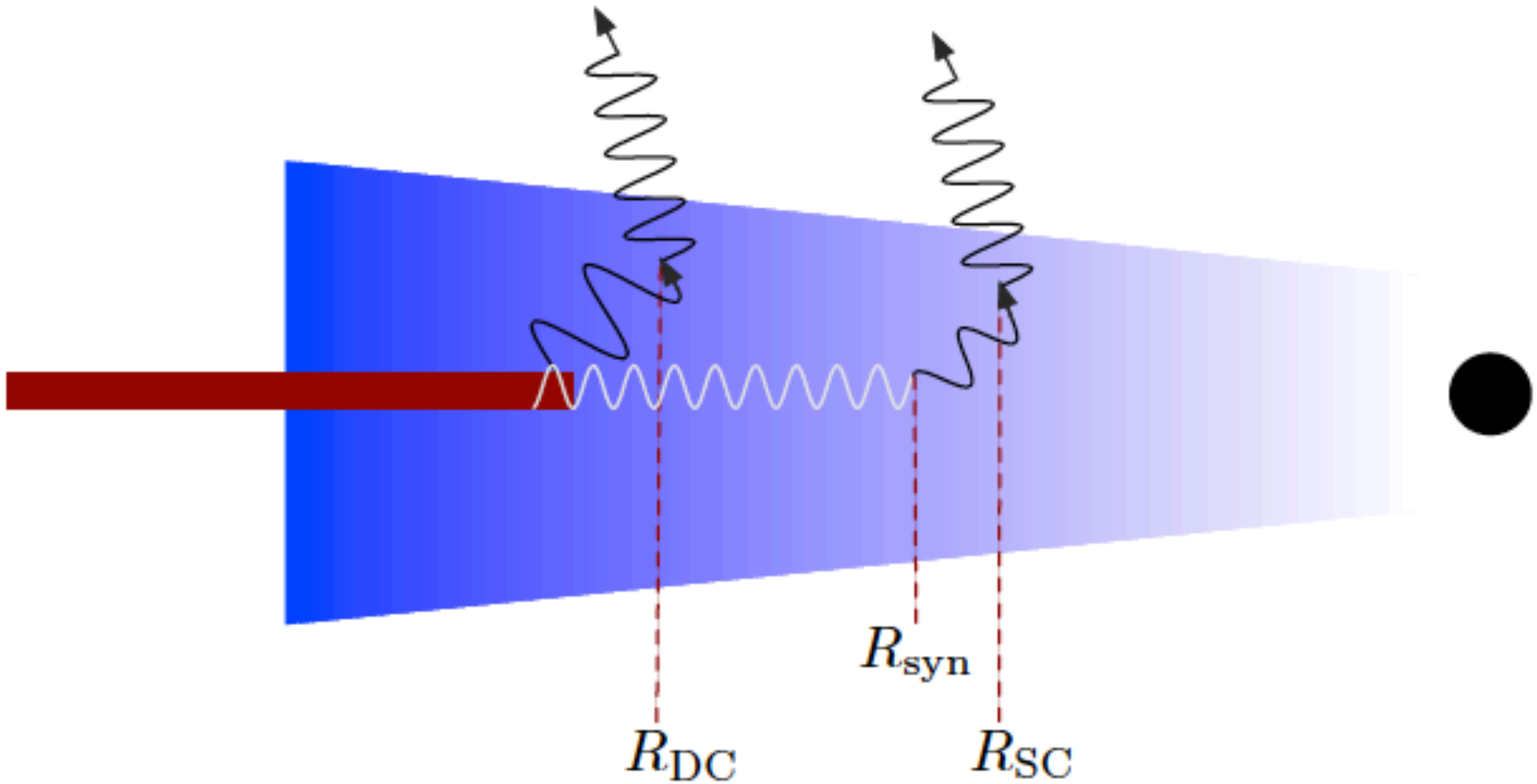
# Outburst decline – changing CCF



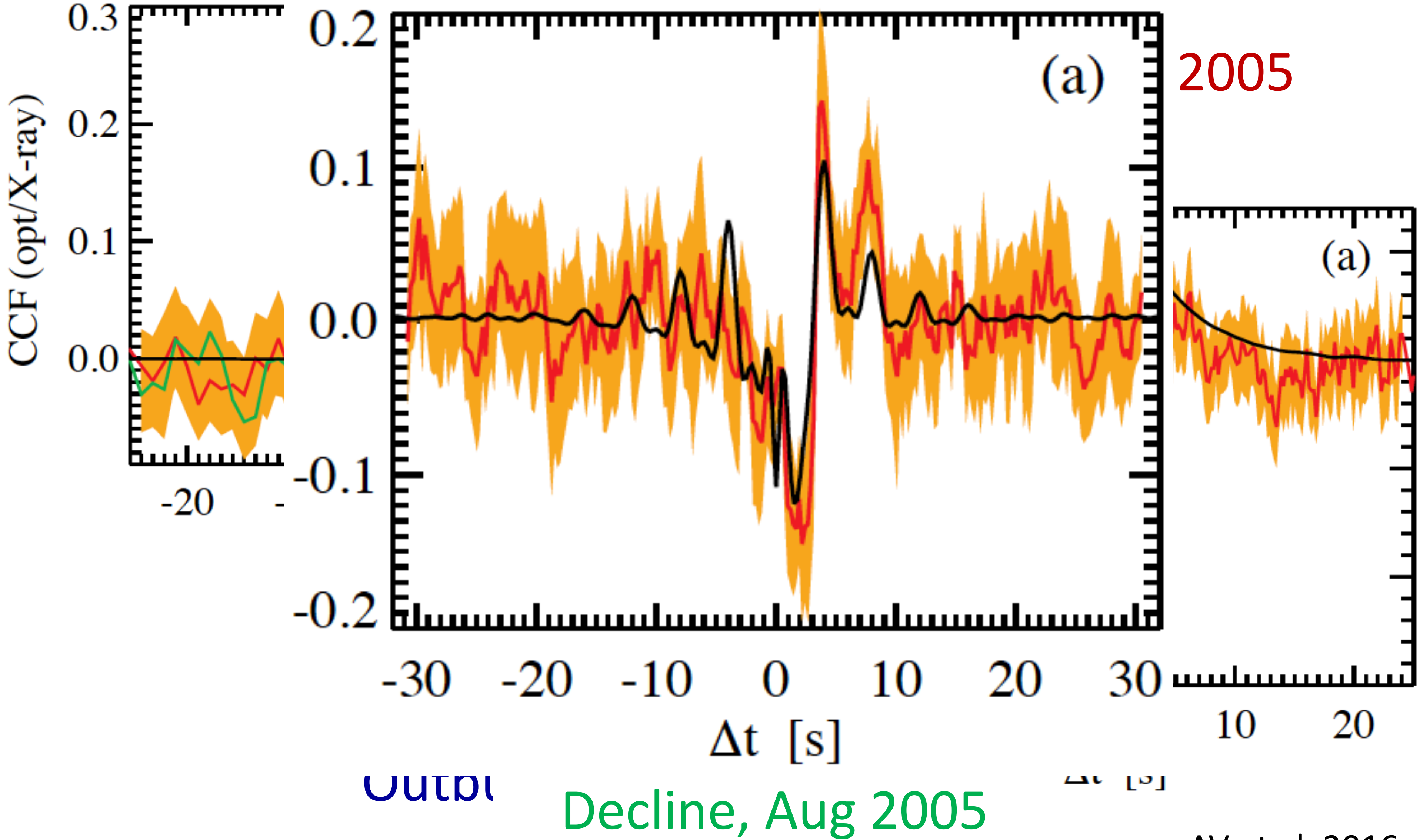

Decline, Aug 2005

Hynes+09

# Outburst decline – changing CCF



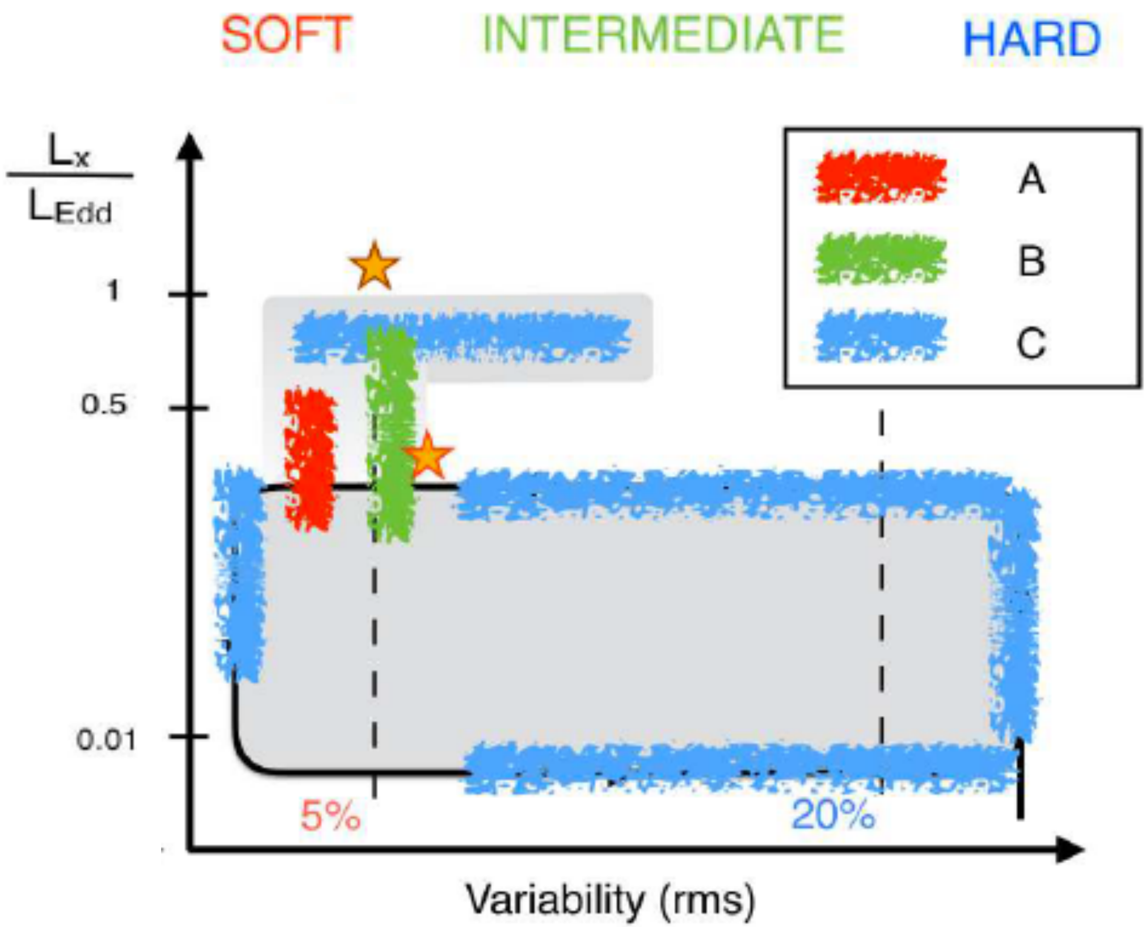
# Outburst decline – changing CCF

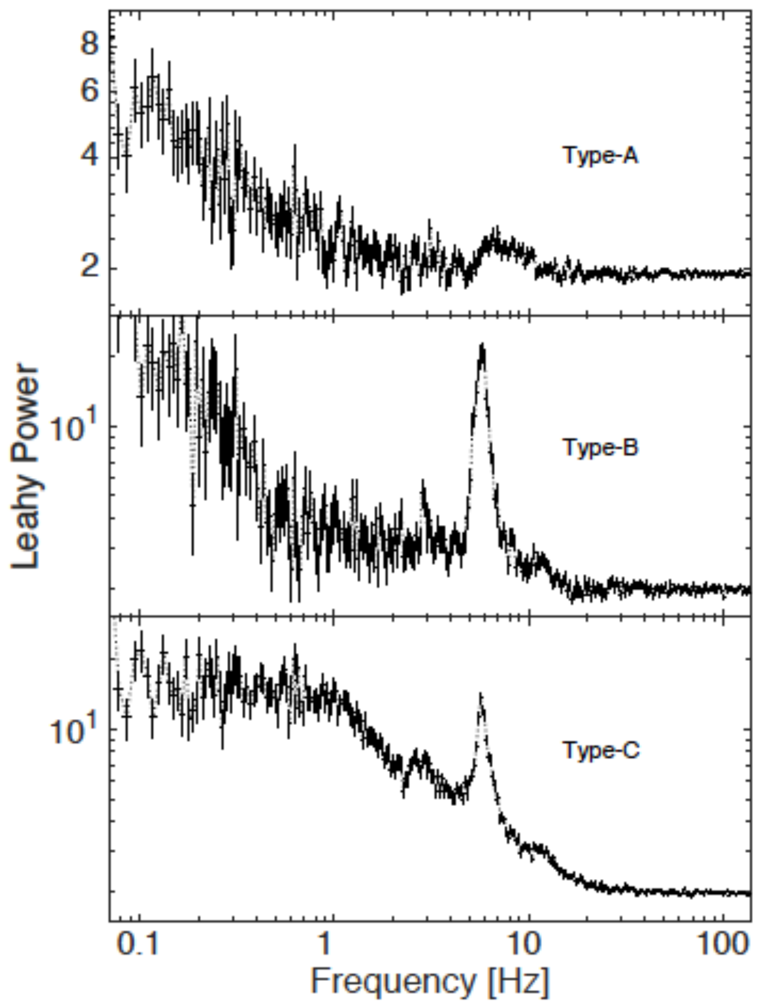



AV et al. 2016

# III: Quasi-periodic oscillations

# ABC of QPOs

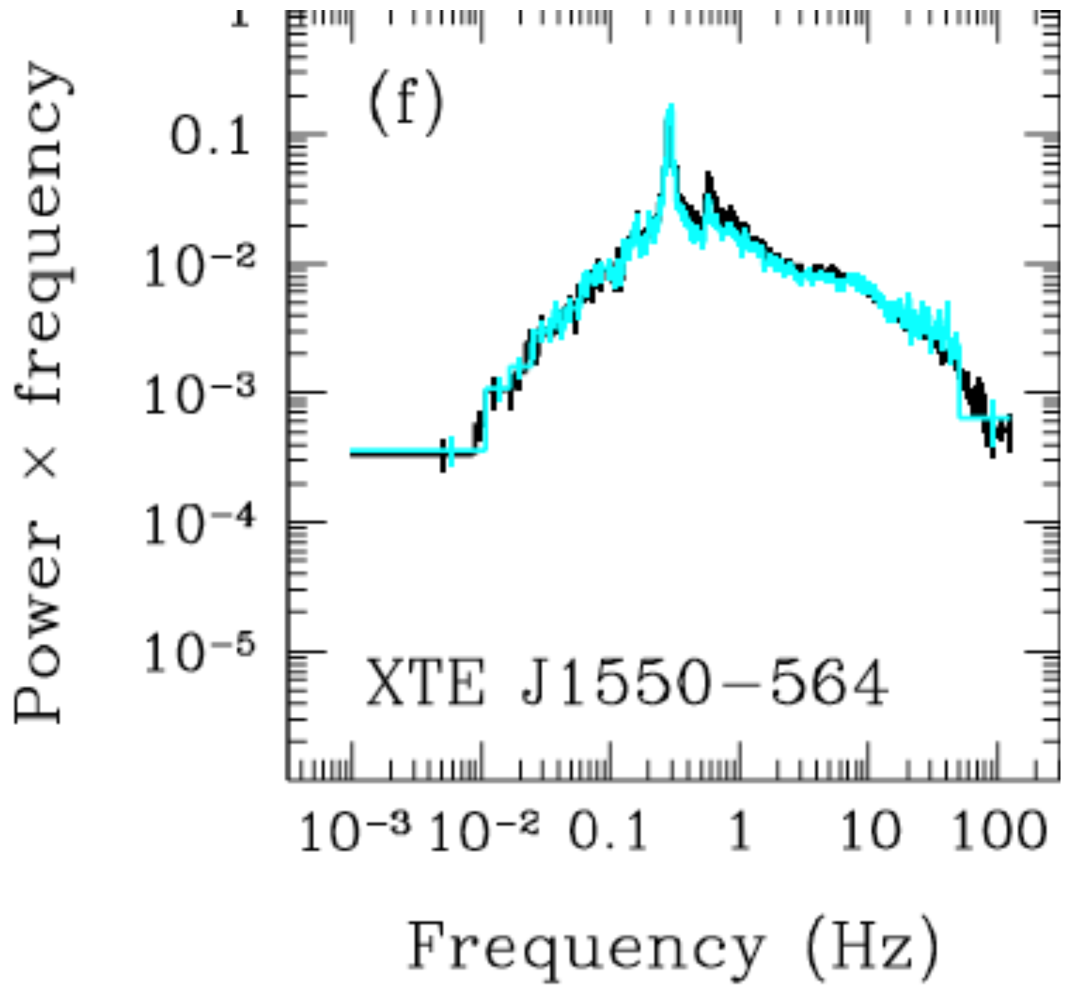



Casella et al. 2005
Motta et al. 2017

# Type-C QPOs

Gierlinski & Zdziarski 2005

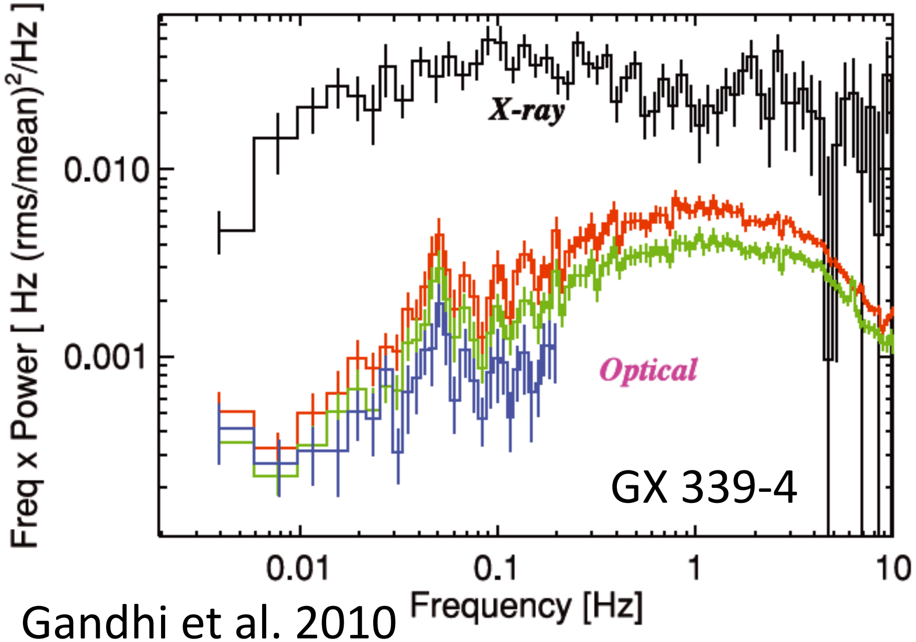



Low-frequency QPO with the second harmonic

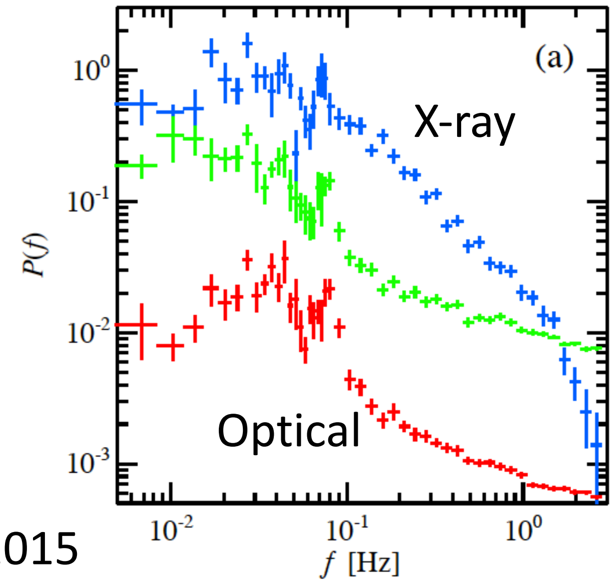
Appear at 0.05-10 Hz

Moving in frequency

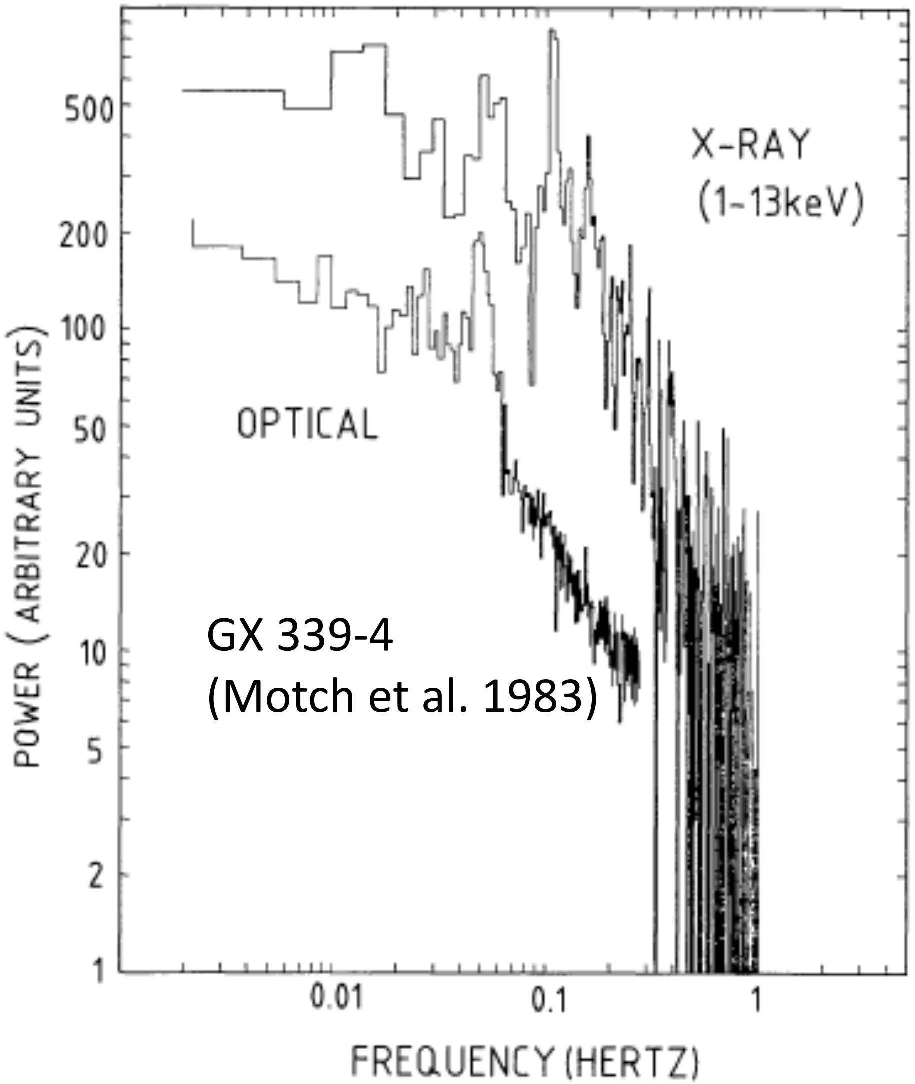
# LFQPO in optical and X-rays



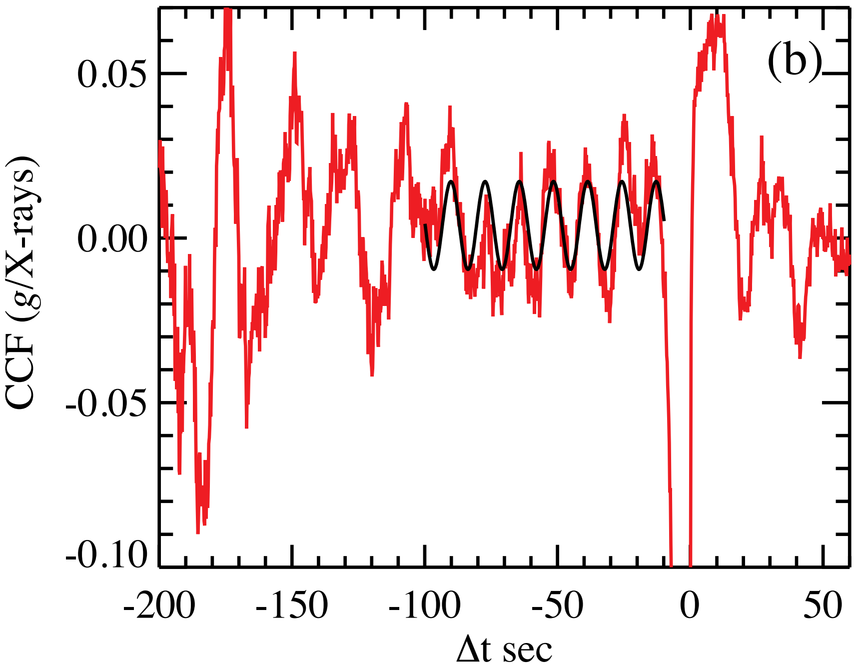

Gandhi et al. 2010

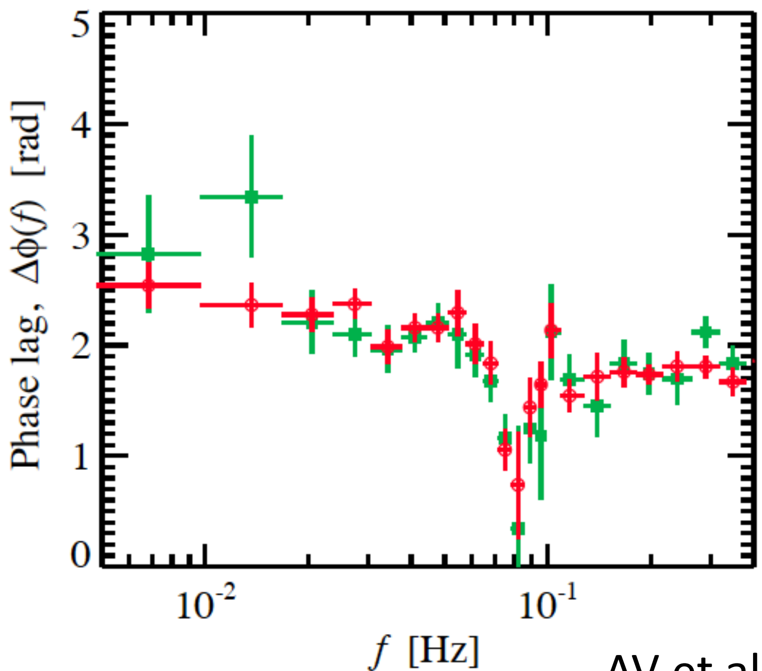



AV et al. 2015



# QPO in CCF and phase-lags




AV et al. 2015

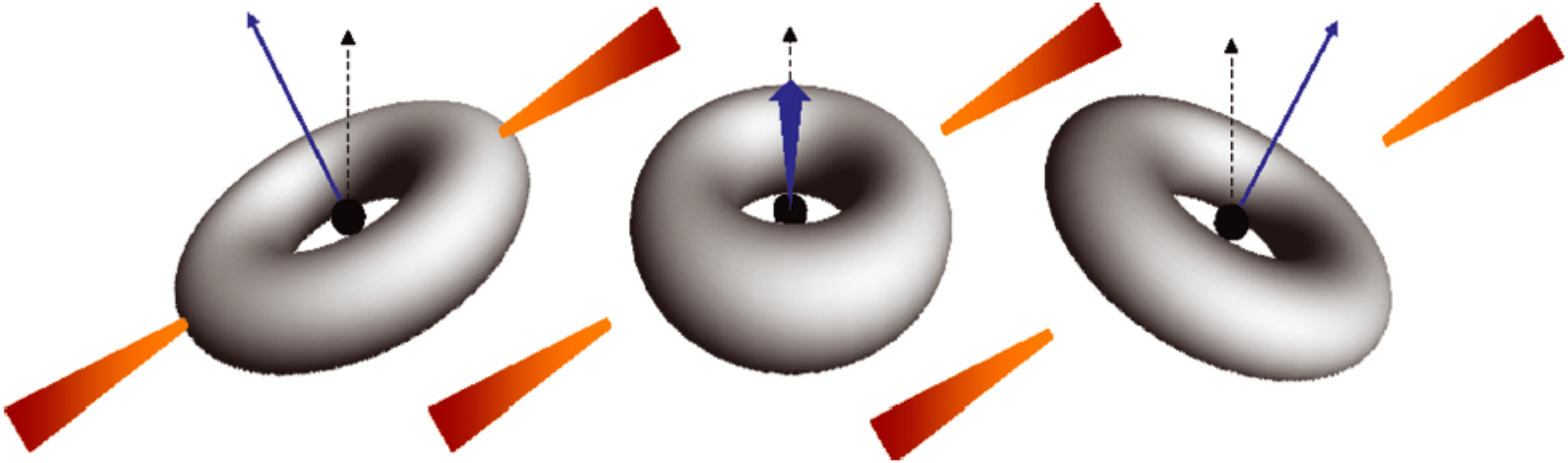
Oscillations at f=0.078 Hz

Phase lag spectrum shows sudden drop at the QPO frequency

# Quasi-periodic oscillations

- A number of kinematic models were proposed, but most of them have difficulties to predict a rather limited frequency range of oscillations
- Some people believe in the model of Fragile et al. 2007, based on the Lense-Thirring precession of the entire hot flow around the black hole spin (I am one of them!)

# Precessing hot flow



Fragile et al. 2007, Ingram et al. 2009

Lense-Thirring precession of the hot flow as a solid body, $H/R > \alpha$

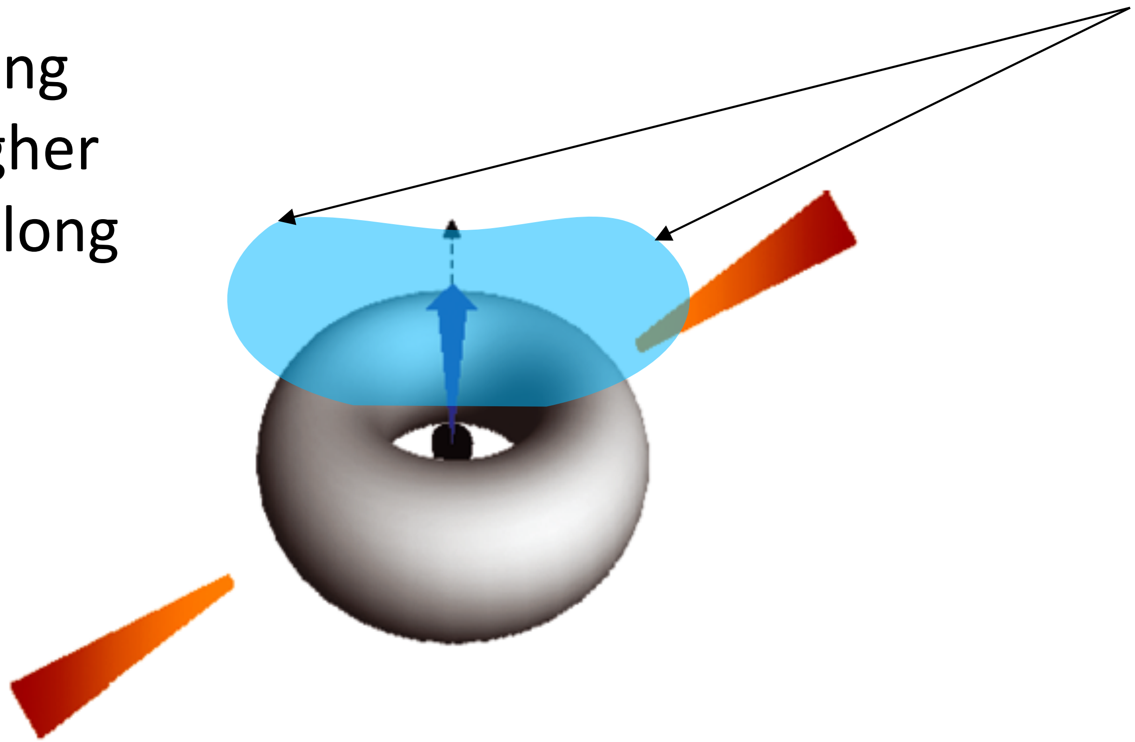
We have a kinematic model, how do we relate these oscillations with the observed flux?

# Precessing hot flow

## Emission pattern of the hot flow in X-rays

2nd harmonic because of two peaks

Photon scattering probability is higher in the direction along the hot flow



AV et al. 2013

# Precessing hot flow

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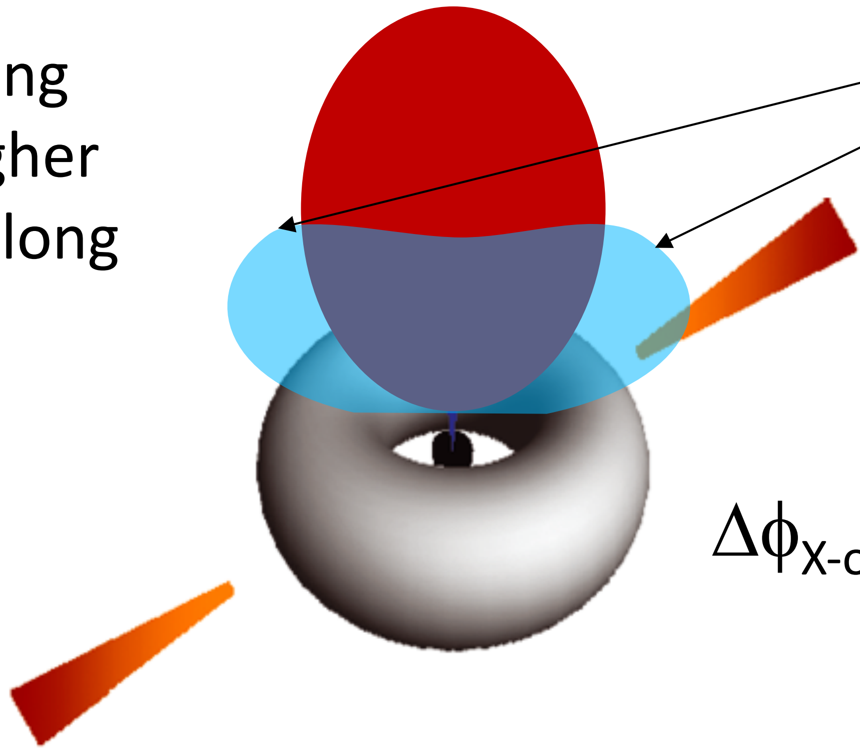


$\Delta\phi_{X\text{-}opt} = 0$ or $\pi$

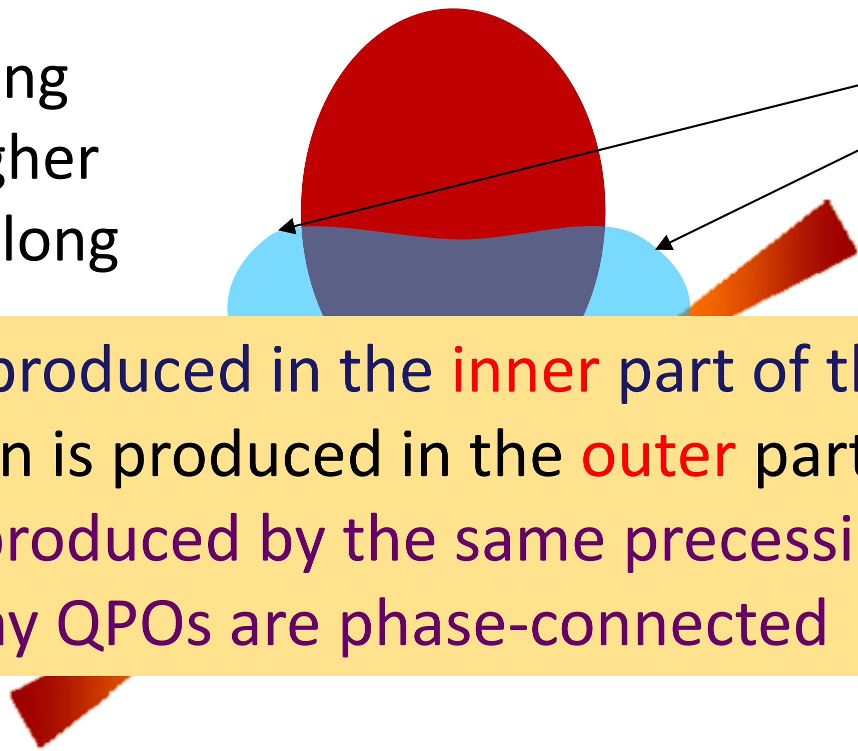
AV et al. 2013

# Precessing hot flow

## Emission pattern of the hot flow in X-rays

$2^{nd}$ harmonic because of two peaks

Photon scattering probability is higher in the direction along the hot flow



The X-rays are produced in the inner part of the flow

Optical emission is produced in the outer part of the hot flow

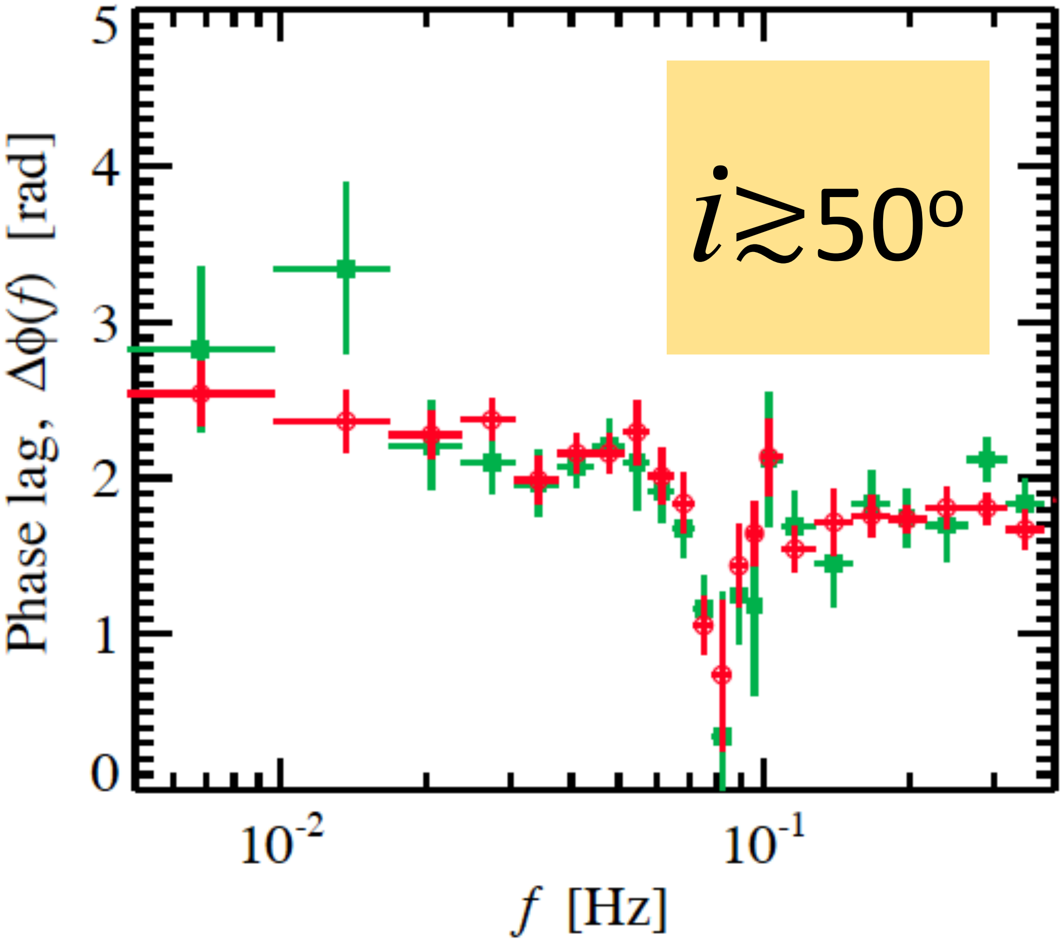
The QPOs are produced by the same precessing flow, thus the optical and X-ray QPOs are phase-connected

AV et al. 2013

# Precessing hot flow

Emission pattern of the hot flow in X-rays

Photon scatt
probability is h
in the directior
the hot flo

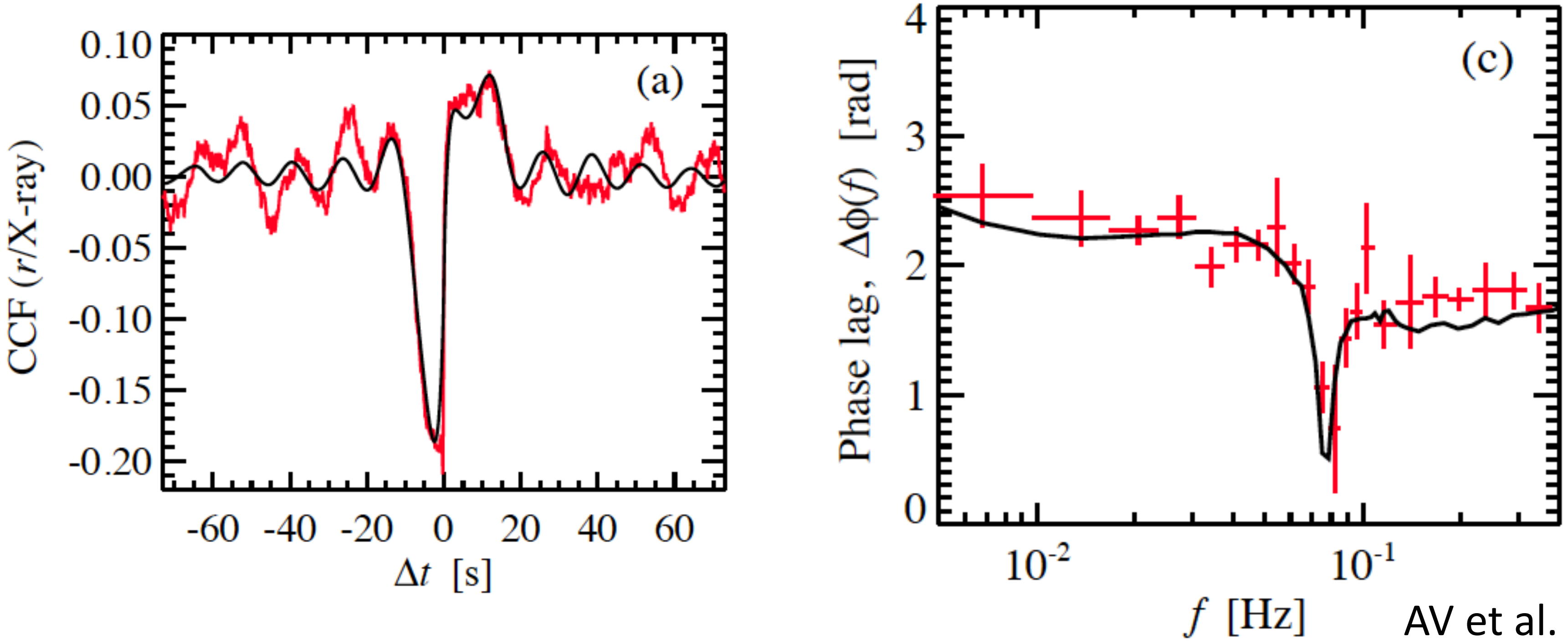



e of two peaks

r π

AV et al. 2013

# Modelling of broadband noise and QPO

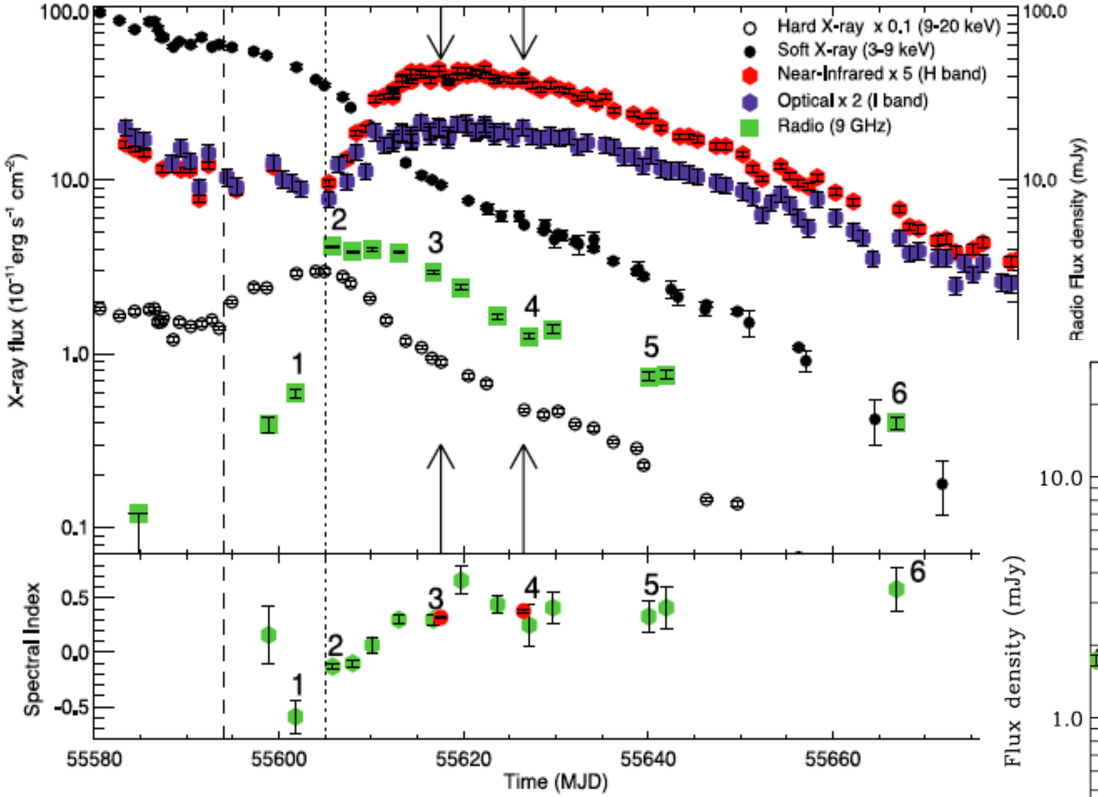


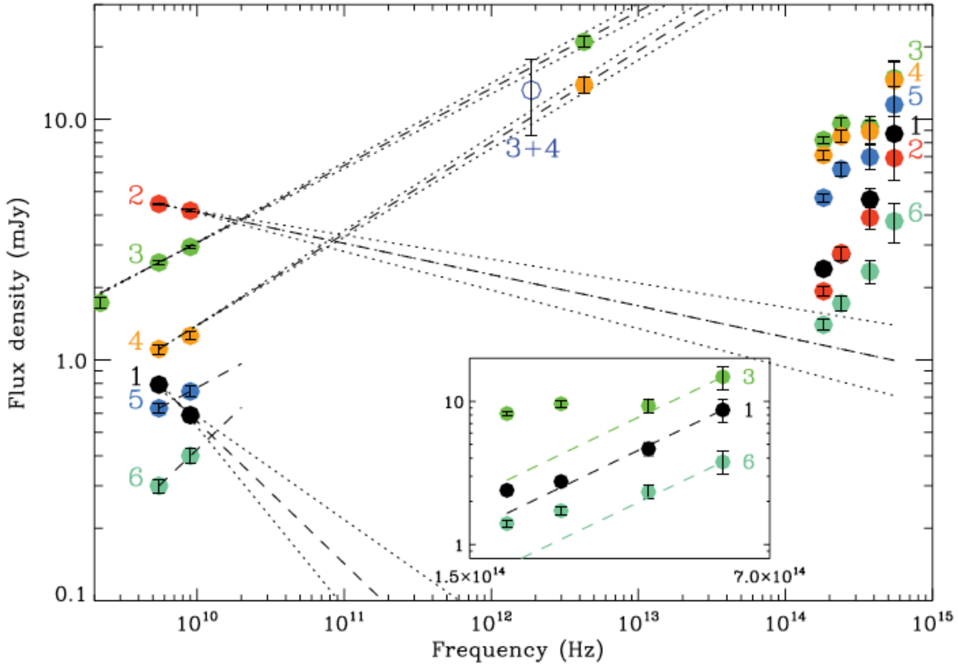

AV et al. 2015

$$x(t) \propto \big(1 + \dot{m}\,(t)\big)\big(1 + q(t)\big)$$
$$o(t) \propto \big(1 - \dot{m}\,(t)\big)\big(1 + q(t)\big) + x(t) \star r(t)$$

# IV: Long-term behaviour

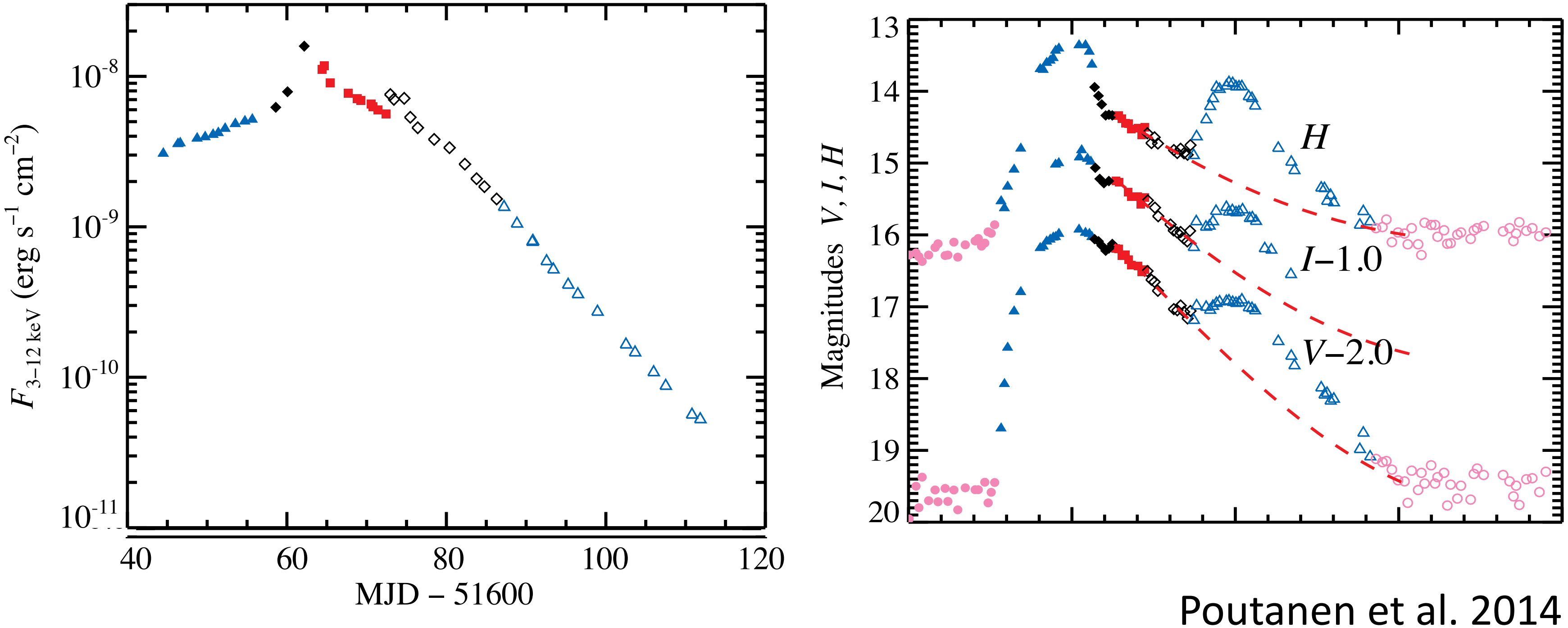
# GX 339-4 in 2010-2011




Corbel et al. 2013

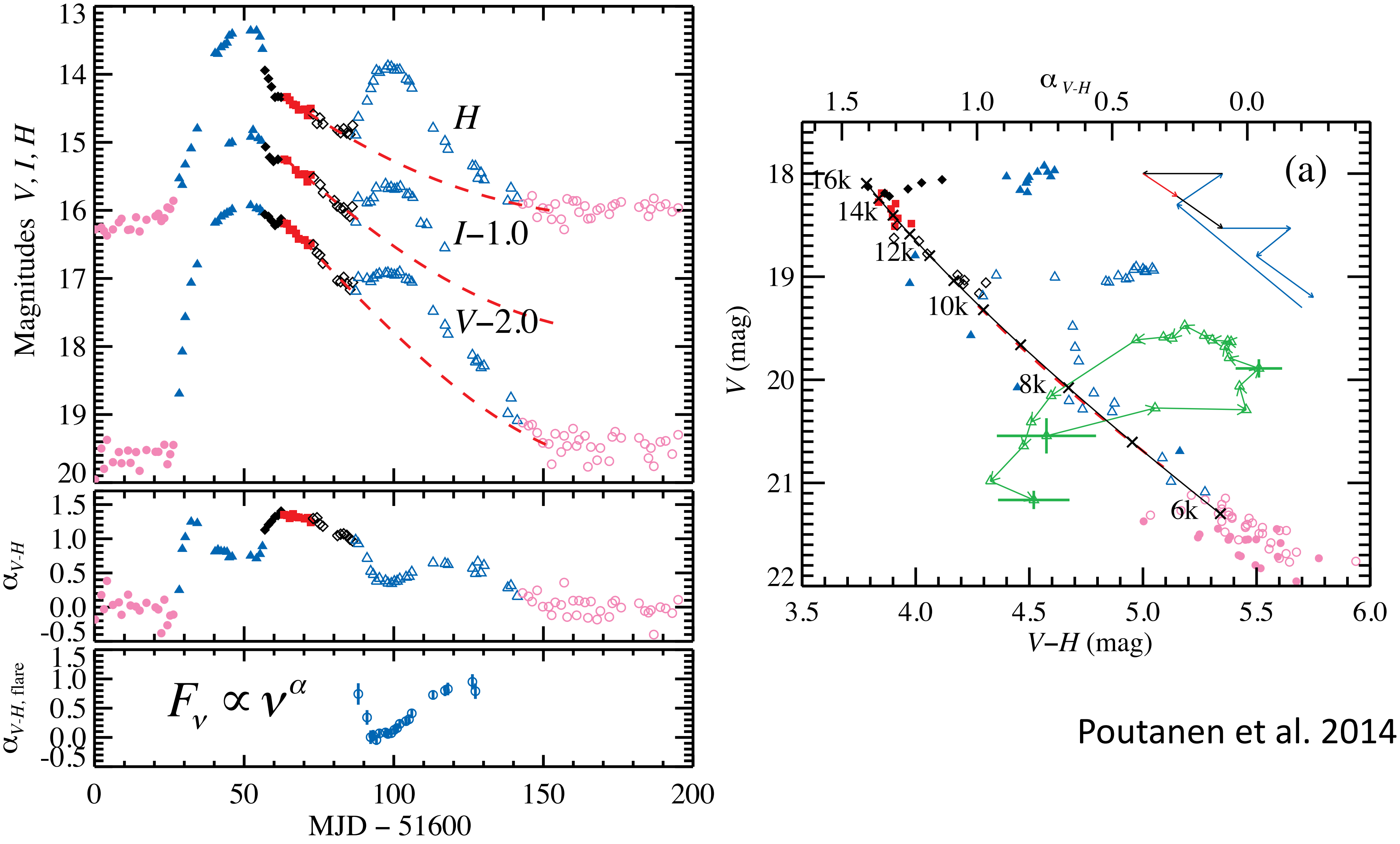
# XTE J1550-564 in 2000 in OIR




Poutanen et al. 2014

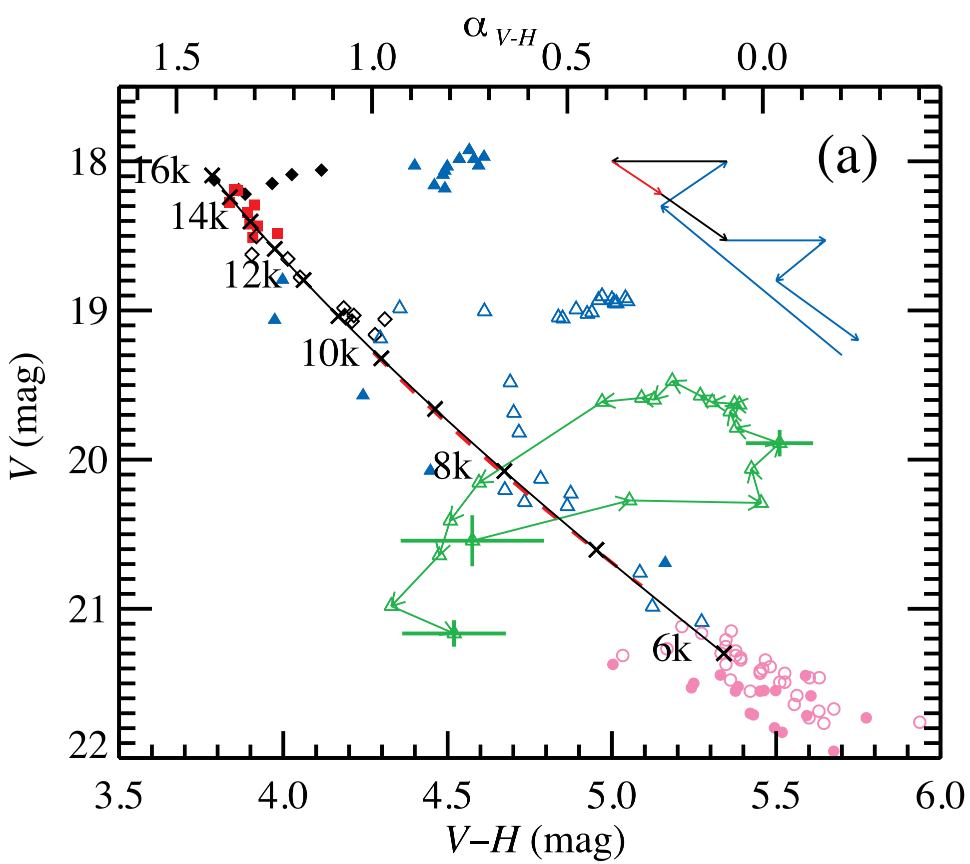
We see optical flares (blue triangles),
but no corresponding flares are observed in the X-rays

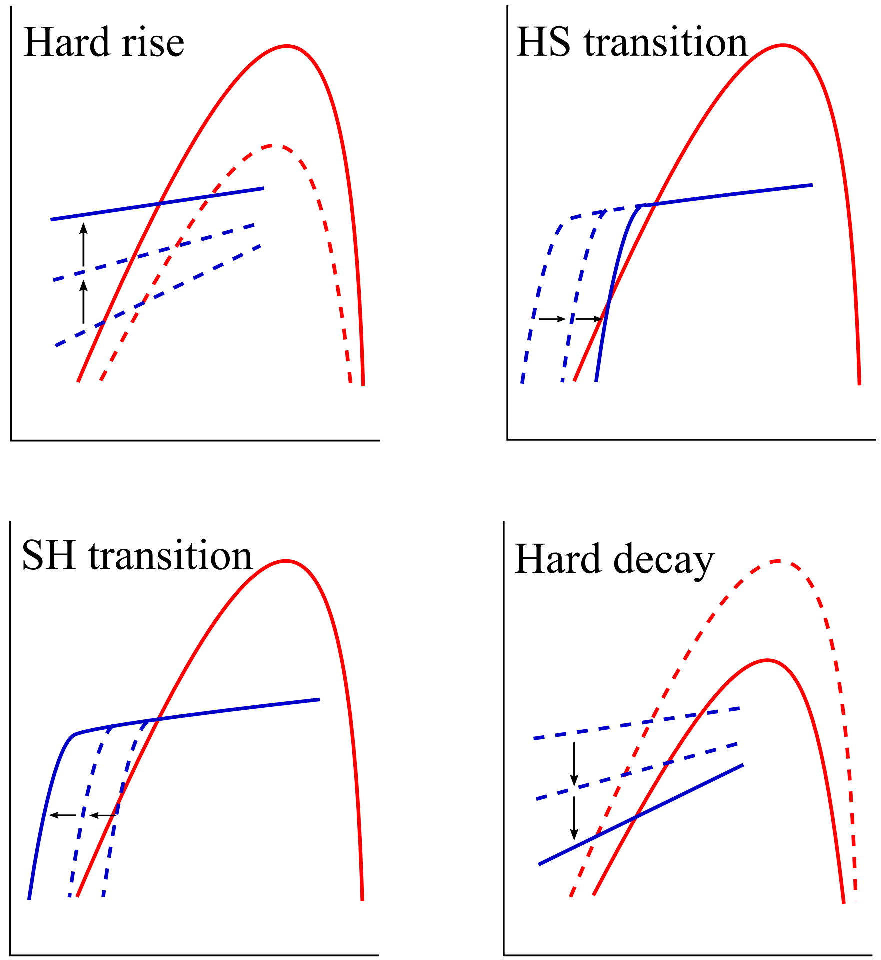
# XTE J1550-564 in 2000 in OIR

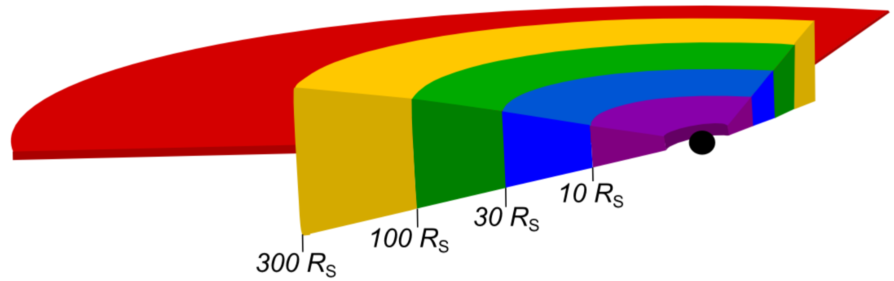



Poutanen et al. 2014

# XTE J1550-564 in 2000 in OIR



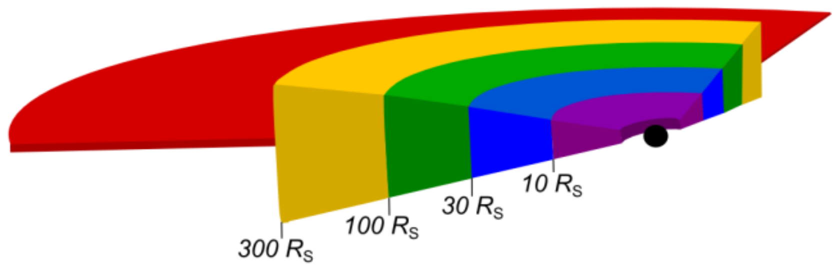




Poutanen et al. 2014

# Summary

- Hot accretion flow with non-thermal particles:
  - Naturally accounts for 100 keV temperature
  - Bright optical/infrared emission and flat spectra
  - Anti-correlation in optical/X-ray CCF
  - Phase-connected optical and X-ray QPOs → inclination
  - Consistent with model for propagating fluctuations
  - Multi-peak X-ray PSDs → $\alpha$-parameter, H/R
  - Long-term optical flares → $A_V$



# Open questions

- Spectra:
  - Radiation of simulated discs (nth radMHD)
  - Origin of non-thermal particles
  - Accretion flow-jet connection (simulations; MIR, sub-mm)
  - State transitions, hysteresis
- Variability:
  - Timescales: viscous vs. dynamical
  - Subharmonics
  - QPOs in quiescence