Radiation processes and models

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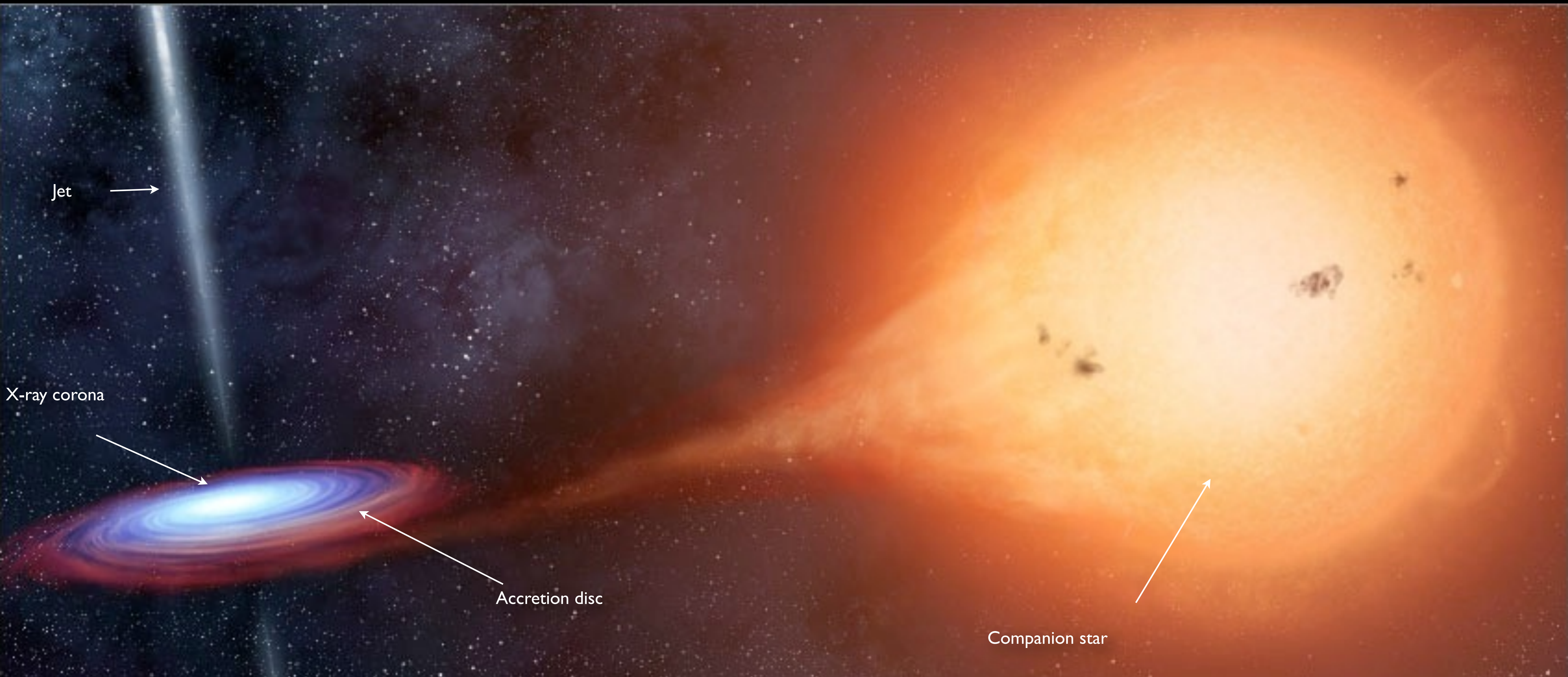
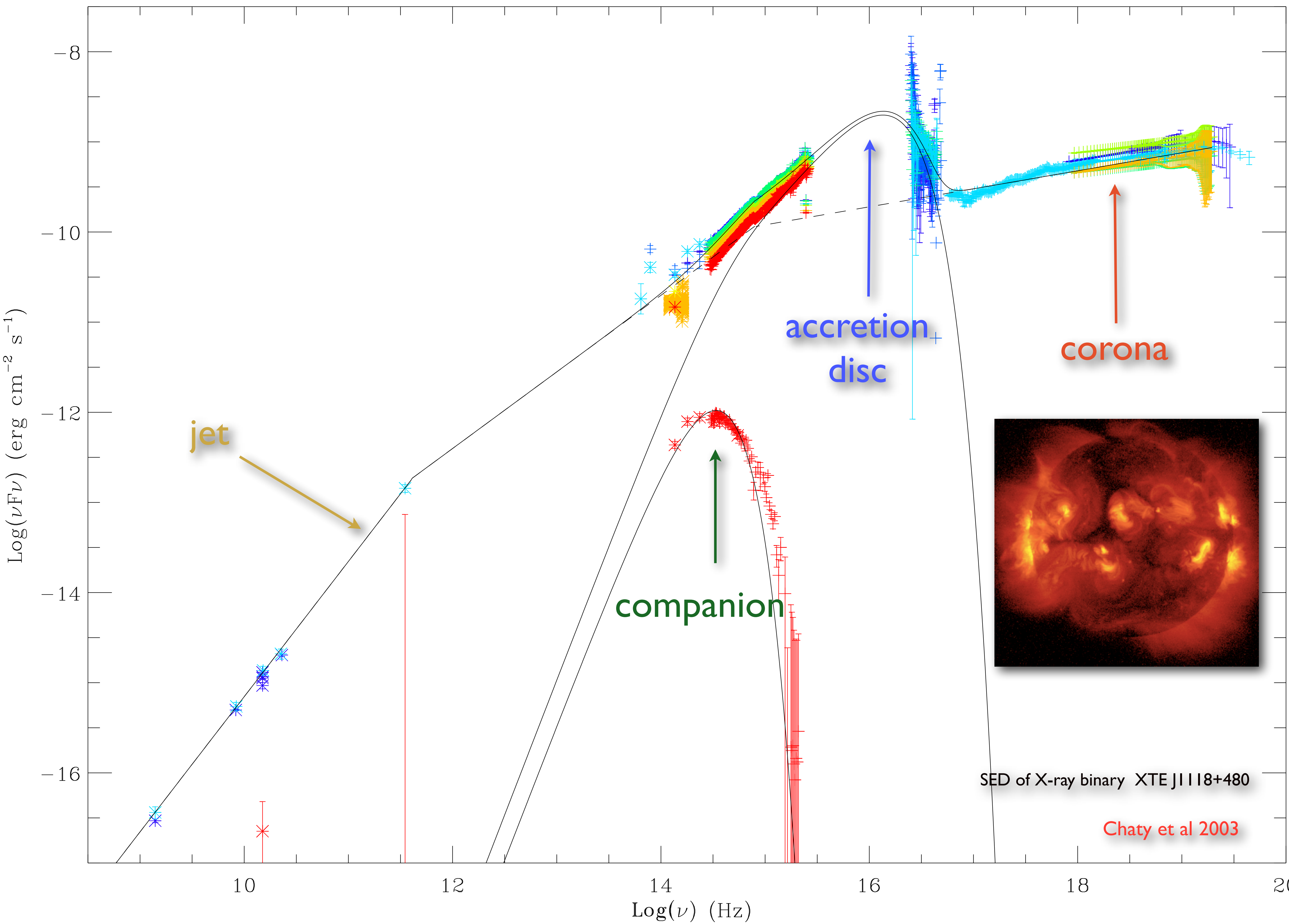
- **Lesson 1: Introduction to compact object physics**
- **Lesson 2: Radiation processes**
- **Lesson 3: Models for accreting black hole binaries: accretion flows**
- **Lesson 4: Models for accreting black hole binaries: compact jets**

CHAOS

Models for the multi wavelength emission of black hole binaries: Accretion flows

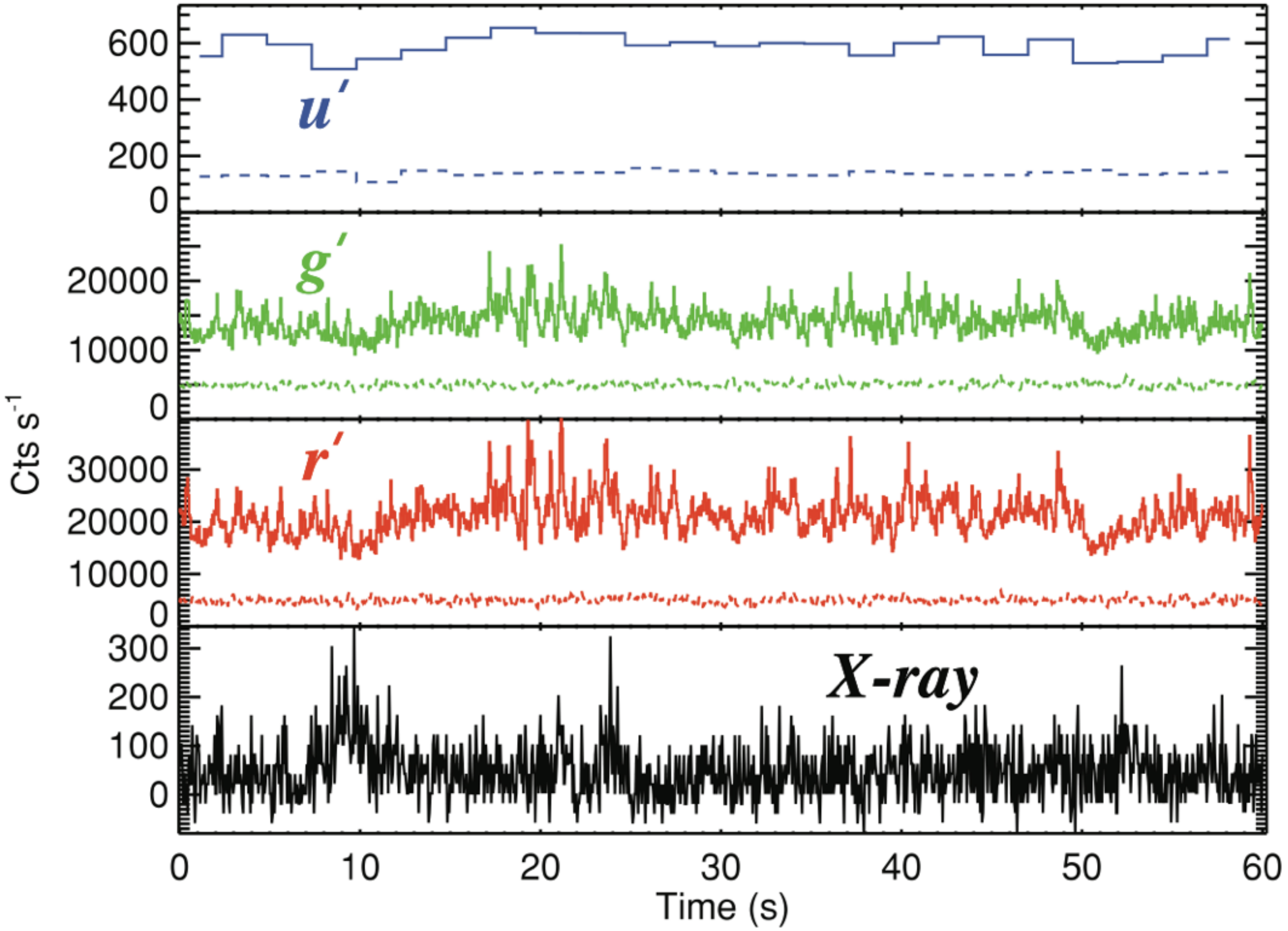




Log(νFν) (erg cm^{-2} s^{-1})
−8
−10
−12
−14
−16
10
12
14
16
18
20
Log(ν) (Hz)
jet
companion
accretion disc
corona
SED of X-ray binary XTE J1118+480
Chaty et al 2003

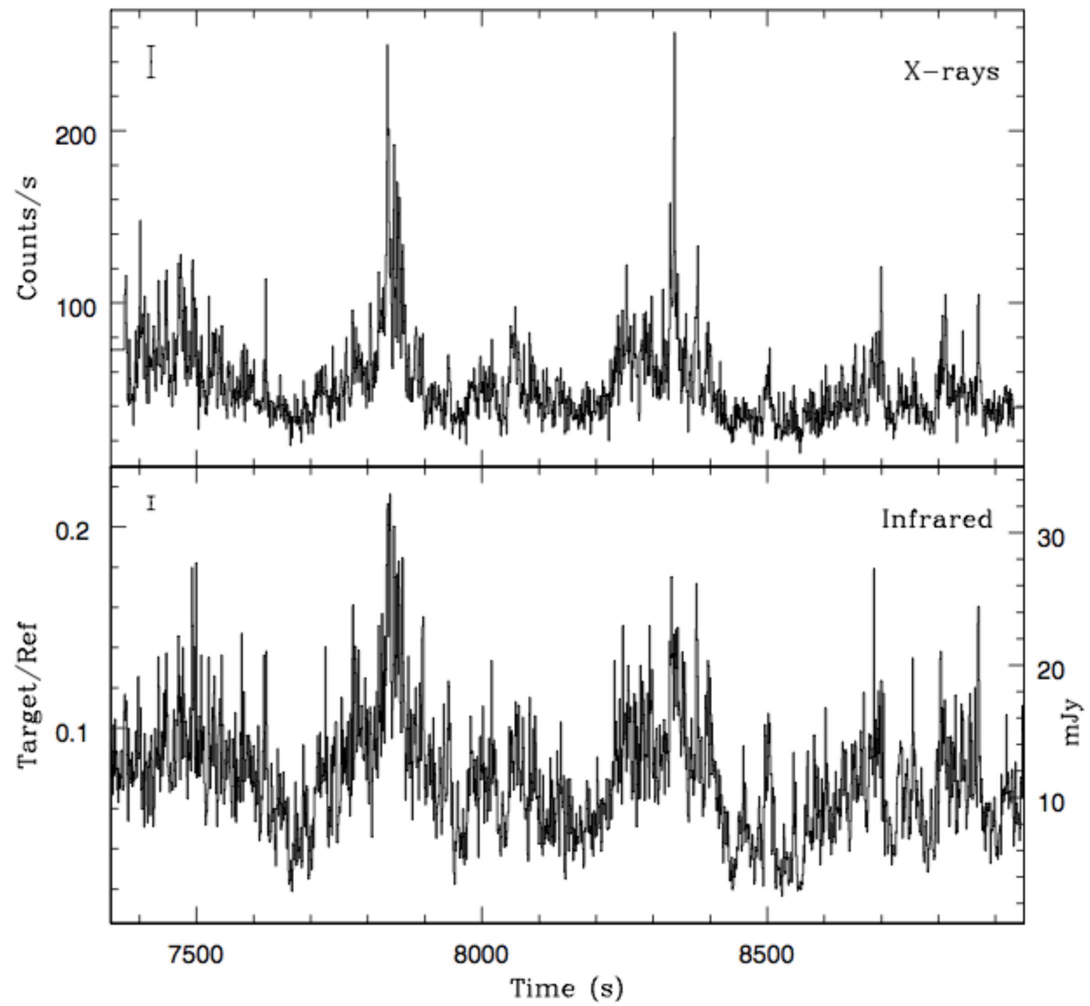
Fast IR/optical and X-ray flickering

Optical



Gandhi et al. 2010

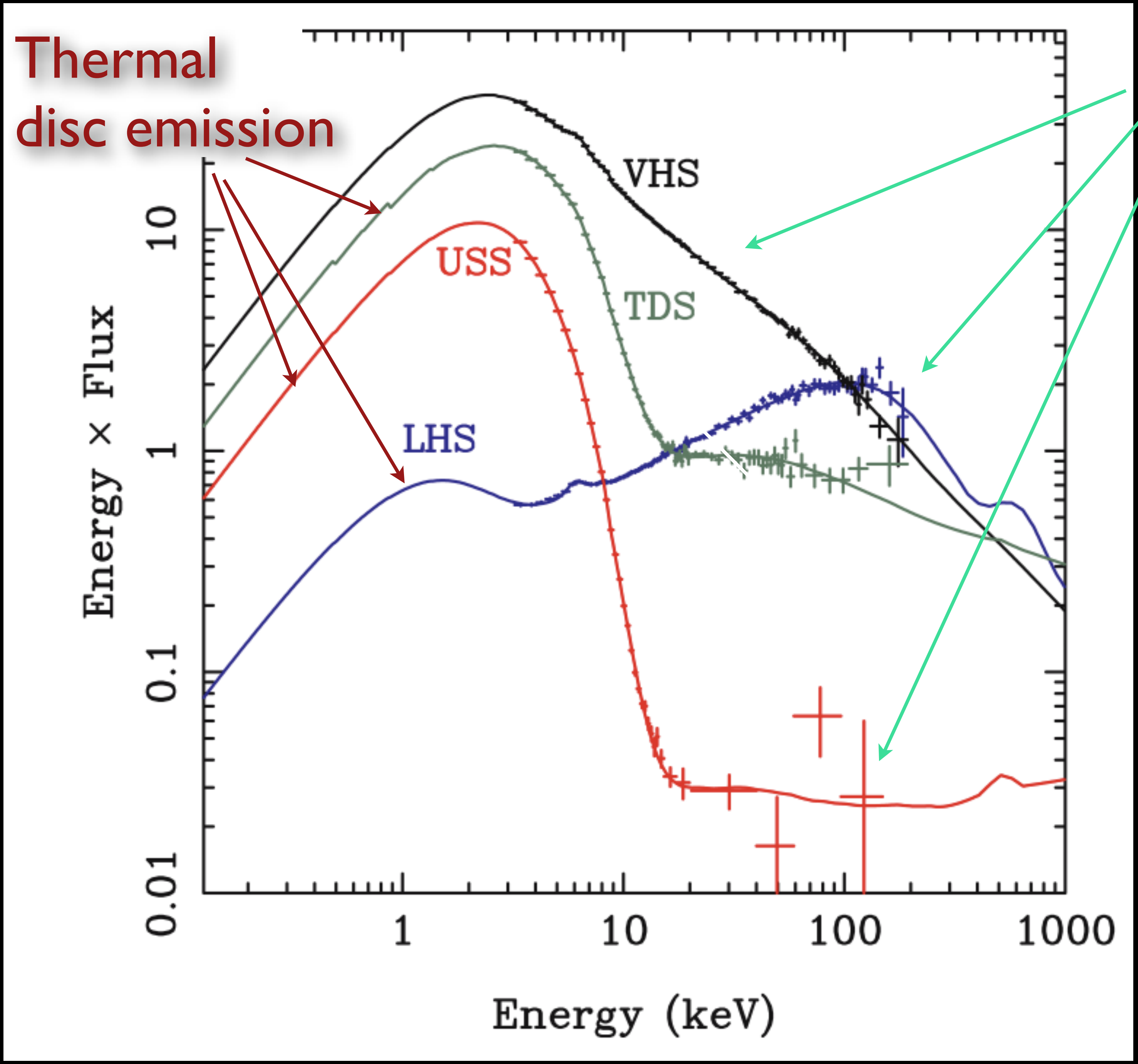
Infrared



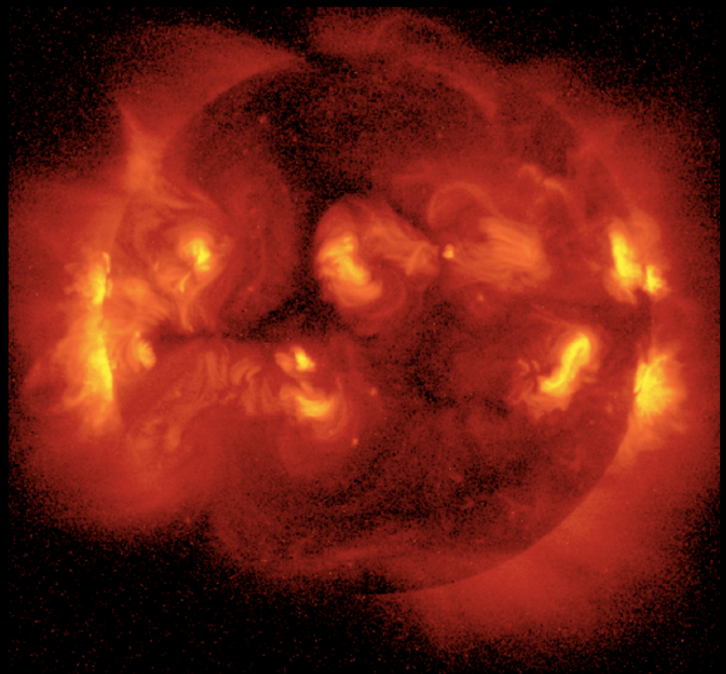
Casella et al. 2010

Observations of GX 339-4

X-ray spectra of BH binaries

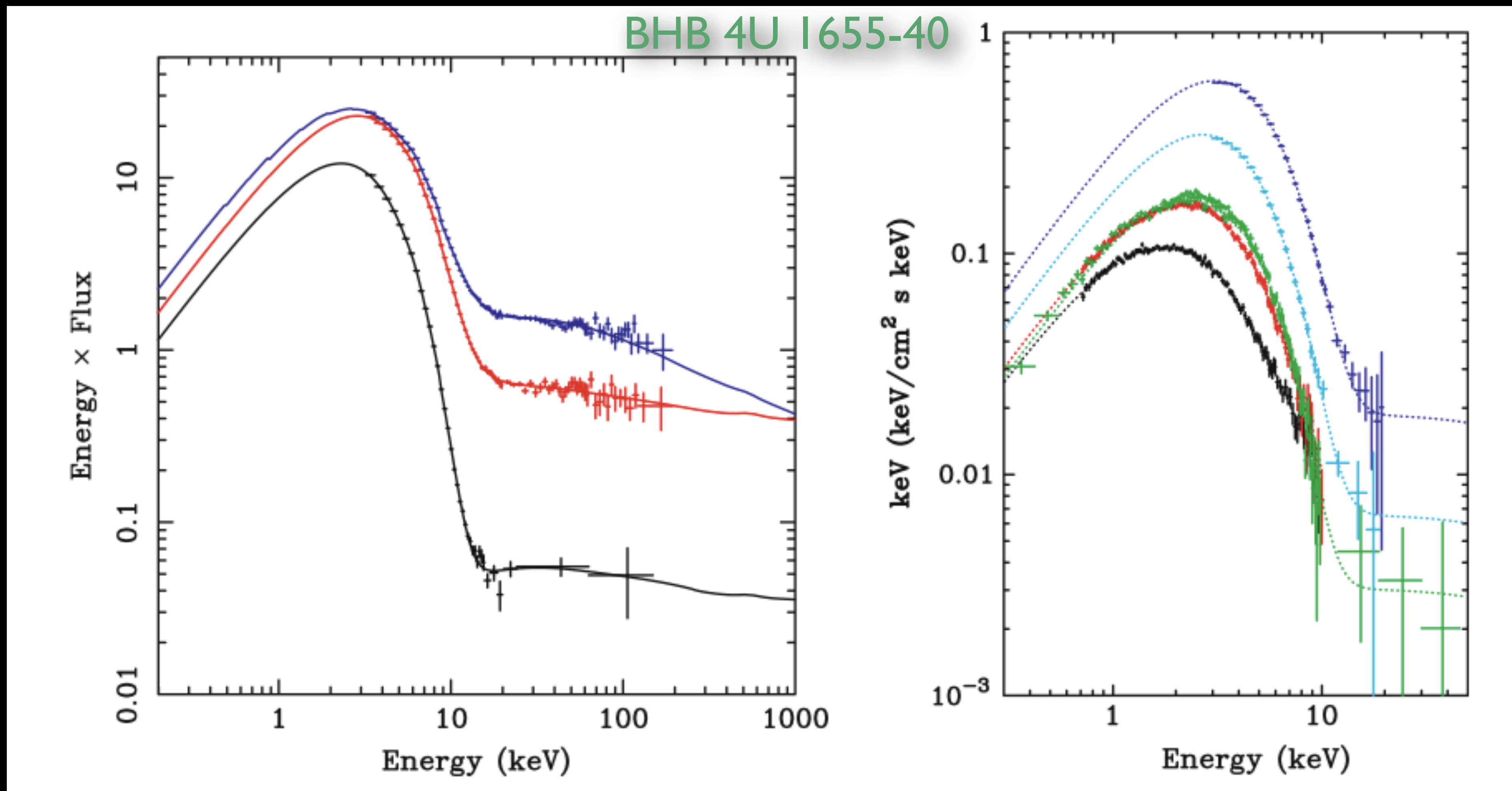


Non-thermal
emission:
'the corona'



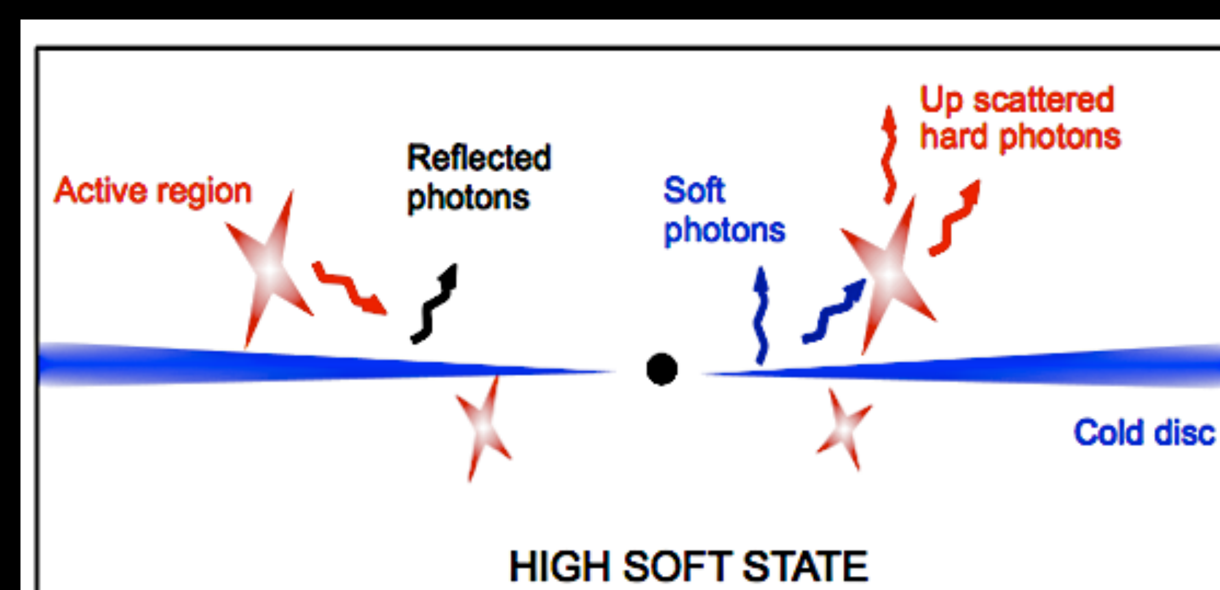
from Done et al. 2007

Soft state of Black Hole binaries



Observed in a narrow range of luminosities (~0.01 -0.1 L_{Edd})

X-ray spectrum dominated by soft thermal emission: perfect for tests of accretion disc models and measurements of parameter of the inner accretion disc

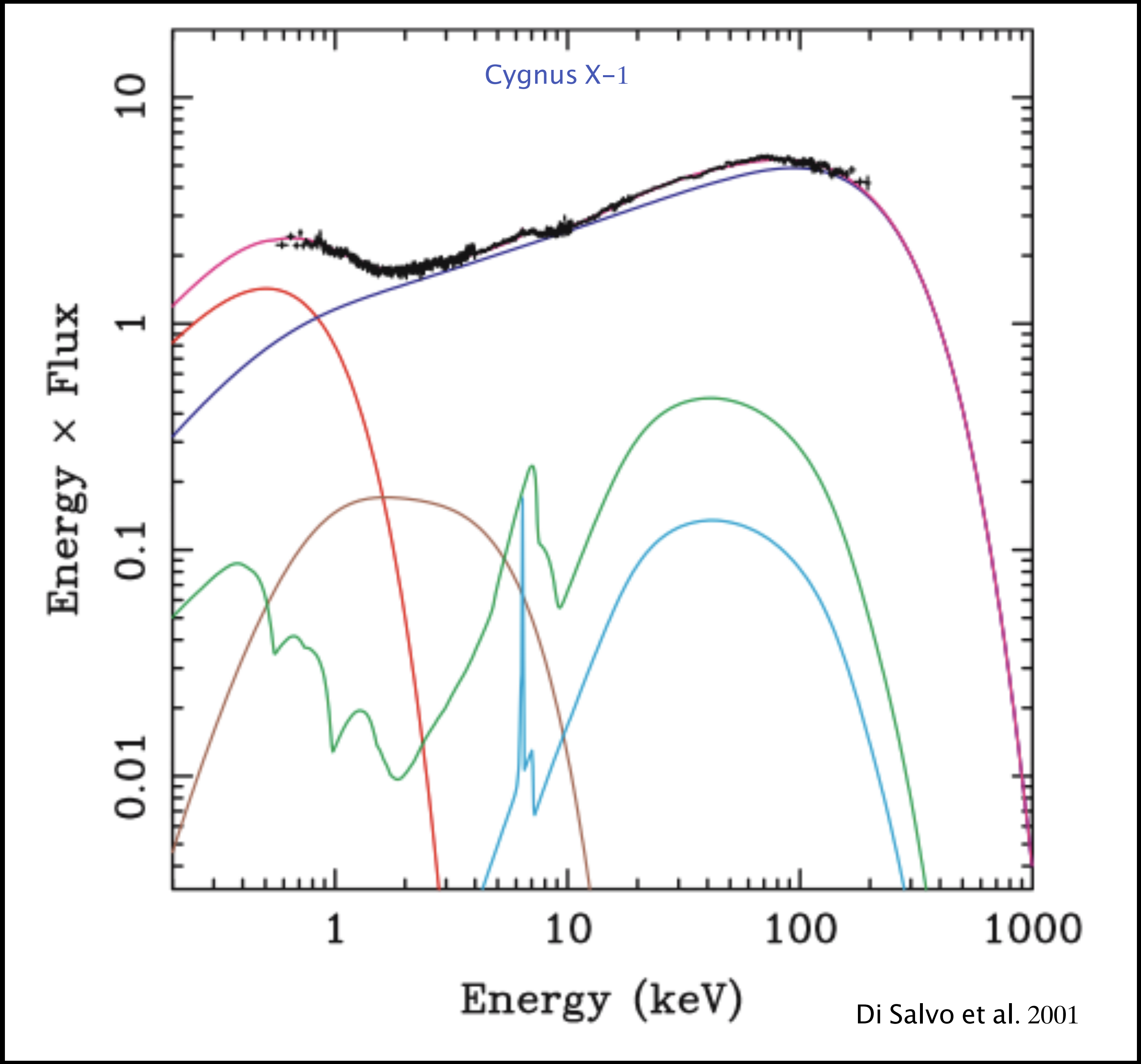


Hard state

- Observed only at $L<0.1\ L_{Edd}$
- Thermal emission from accretion disc barely detected (T_{in}~0.1 KeV)
- X-ray emission dominated by power-law Γ = 1.4 – 1.9
- High energy cut-off at ~100 keV
- Fits with Thermal comptonisation models:

$$\tau = 0.5 - 3.5,\ kT_e = 30 - 200\,\mathrm{keV}$$

- Reflection amplitude is small R~0.3
- Associated with the presence of a compact radio jet



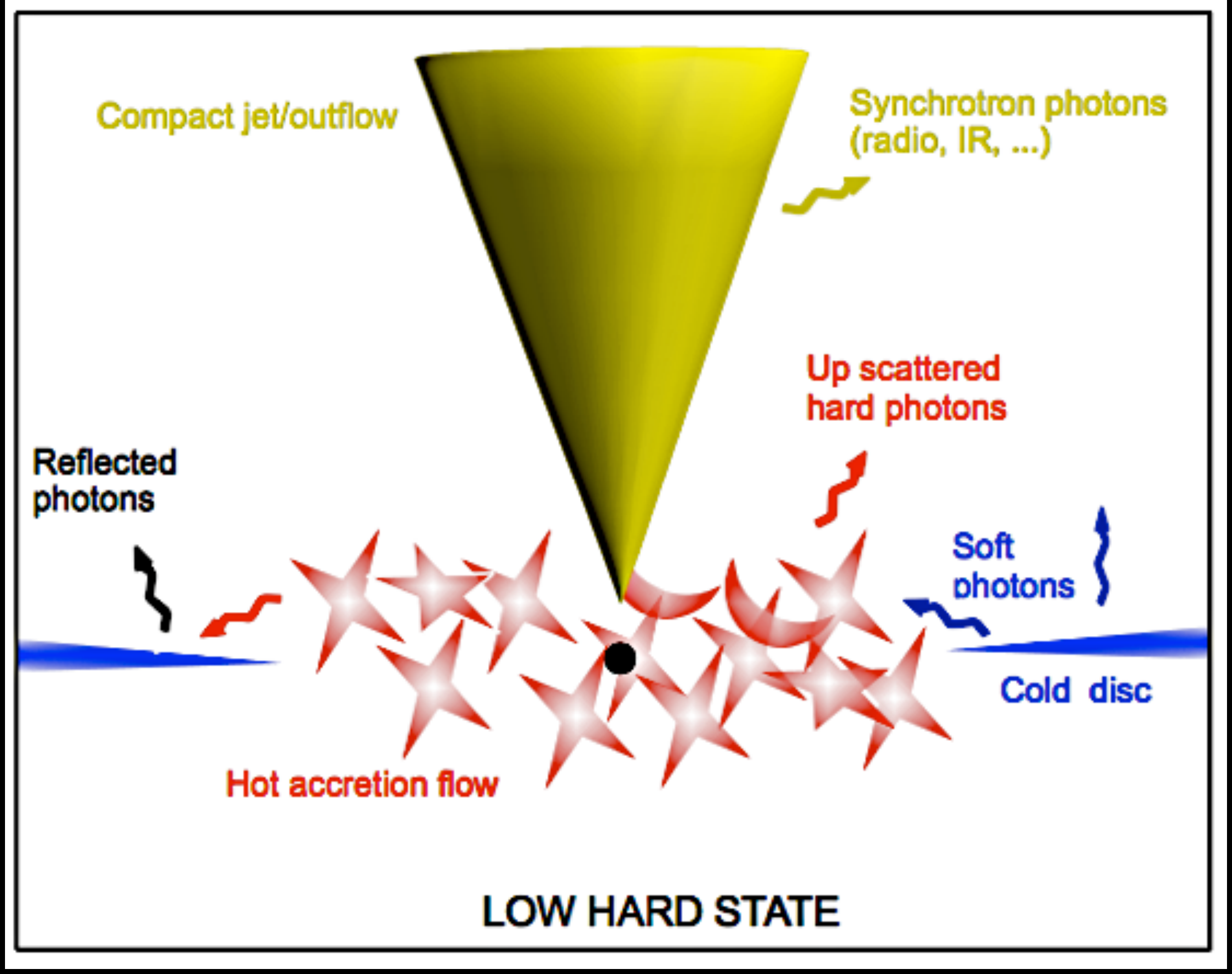
High electron temperatures in the corona + weak reflection suggest that the corona and the disc see each other with a small solid angle.

Truncated disc model

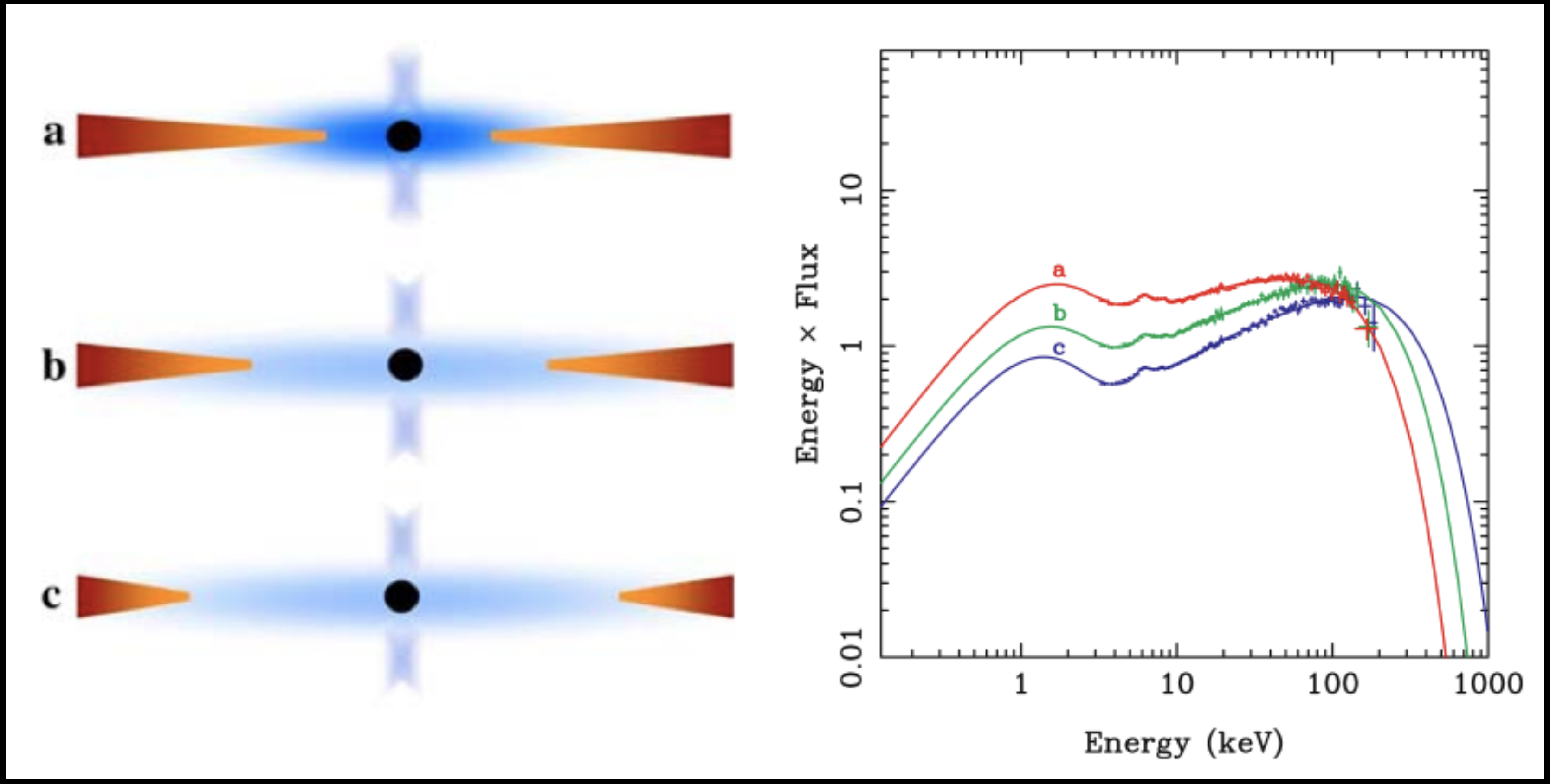
HARD STATE

- Cold disc truncated at ~ 100-1000 Rg
  + hot inner accretion flow

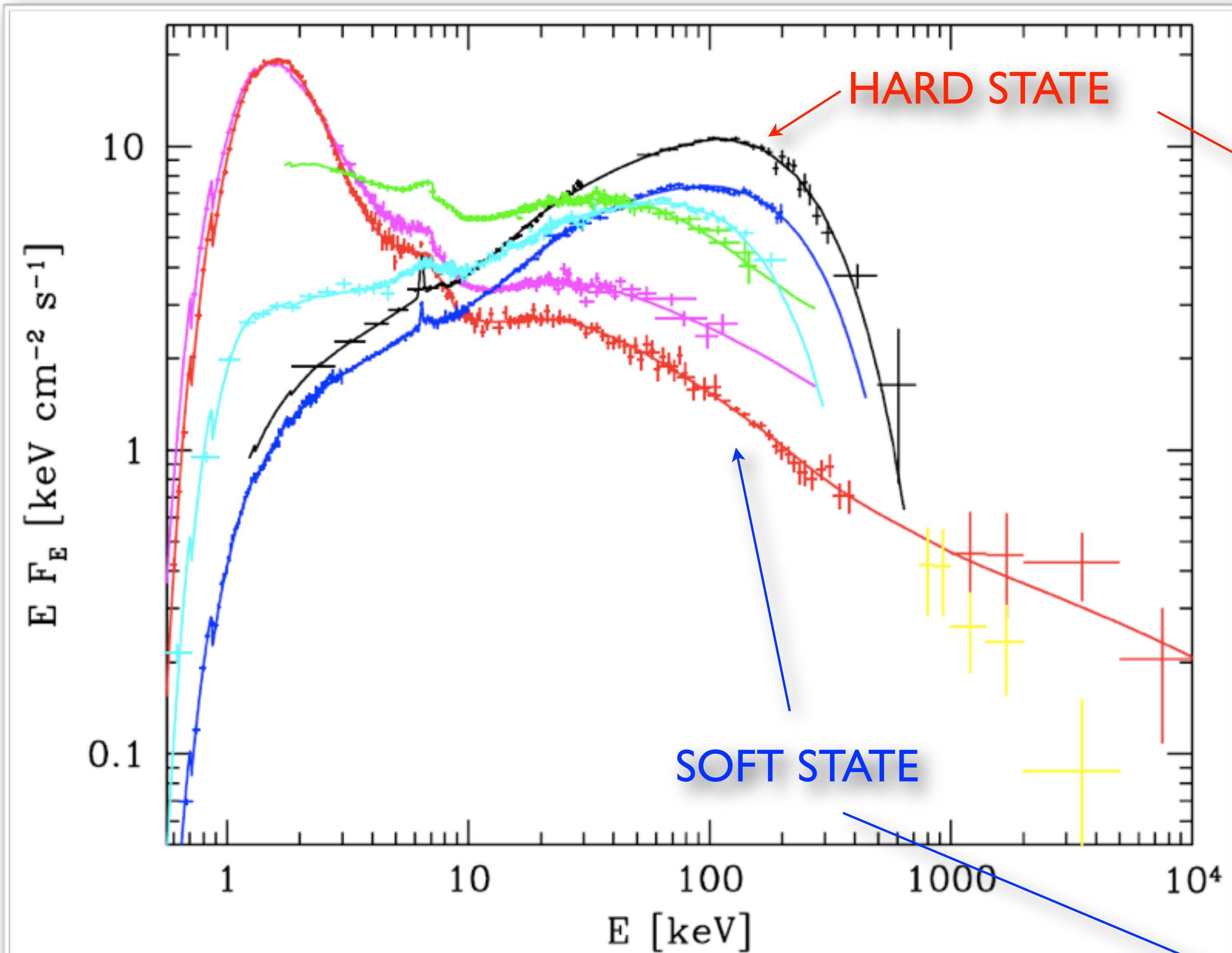
- Corona=hot accretion flow
  (ADAF, CDAF, RIAF….)



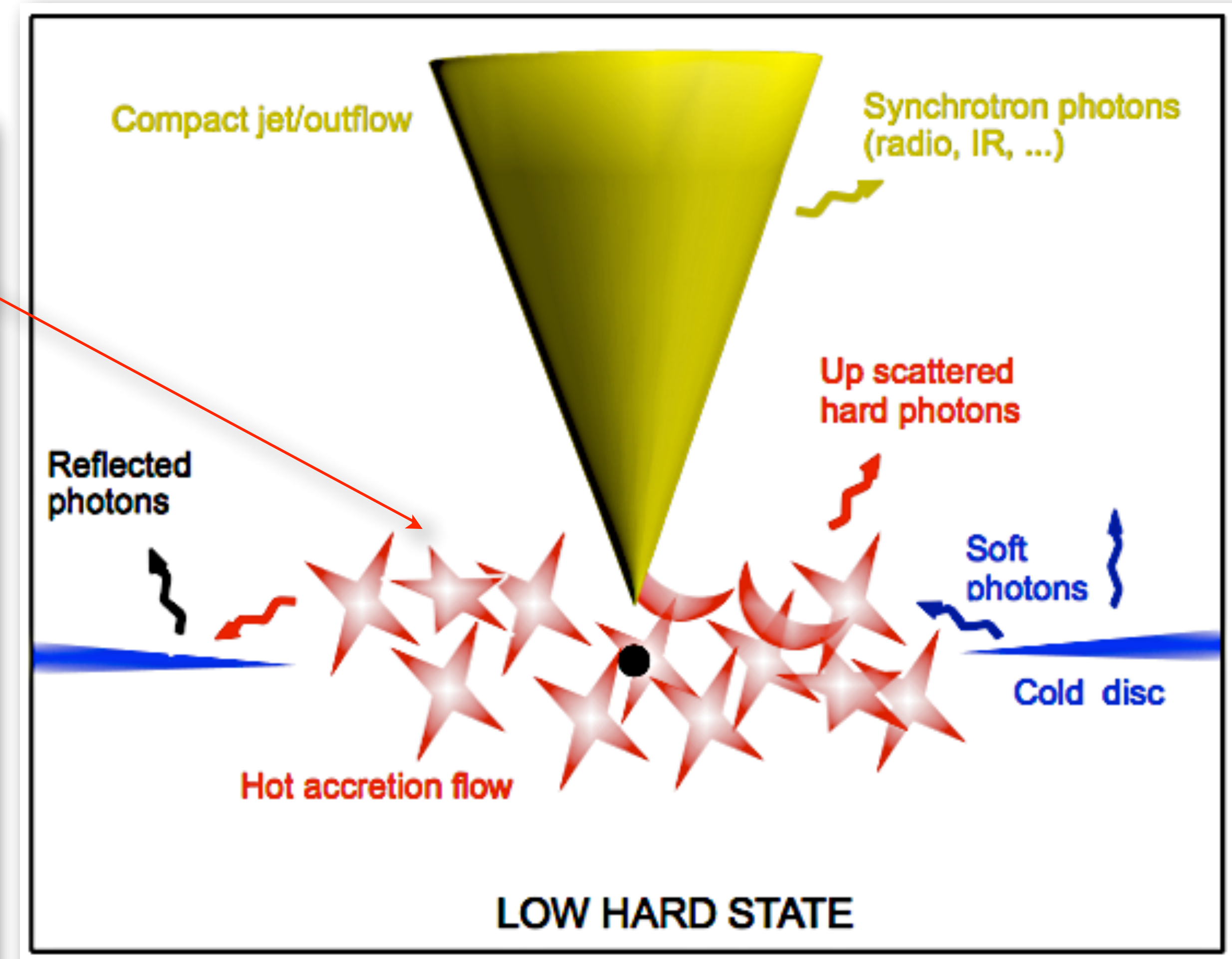
see Done et al. 2007 and references therein

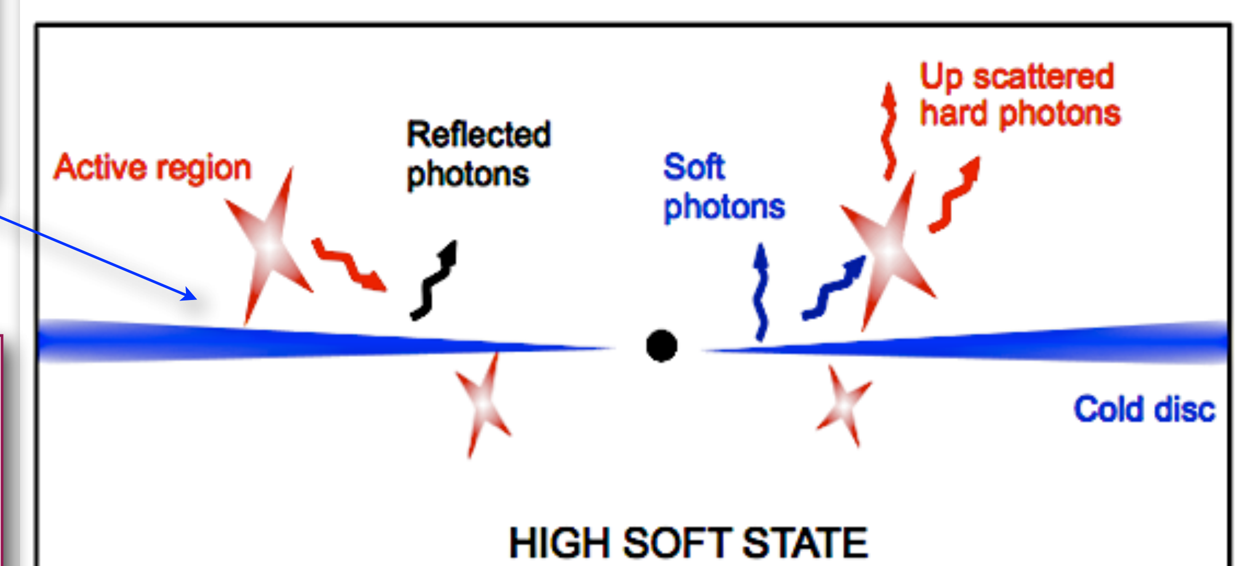


Non-thermal particles in the corona



Zdziarski et al 2003

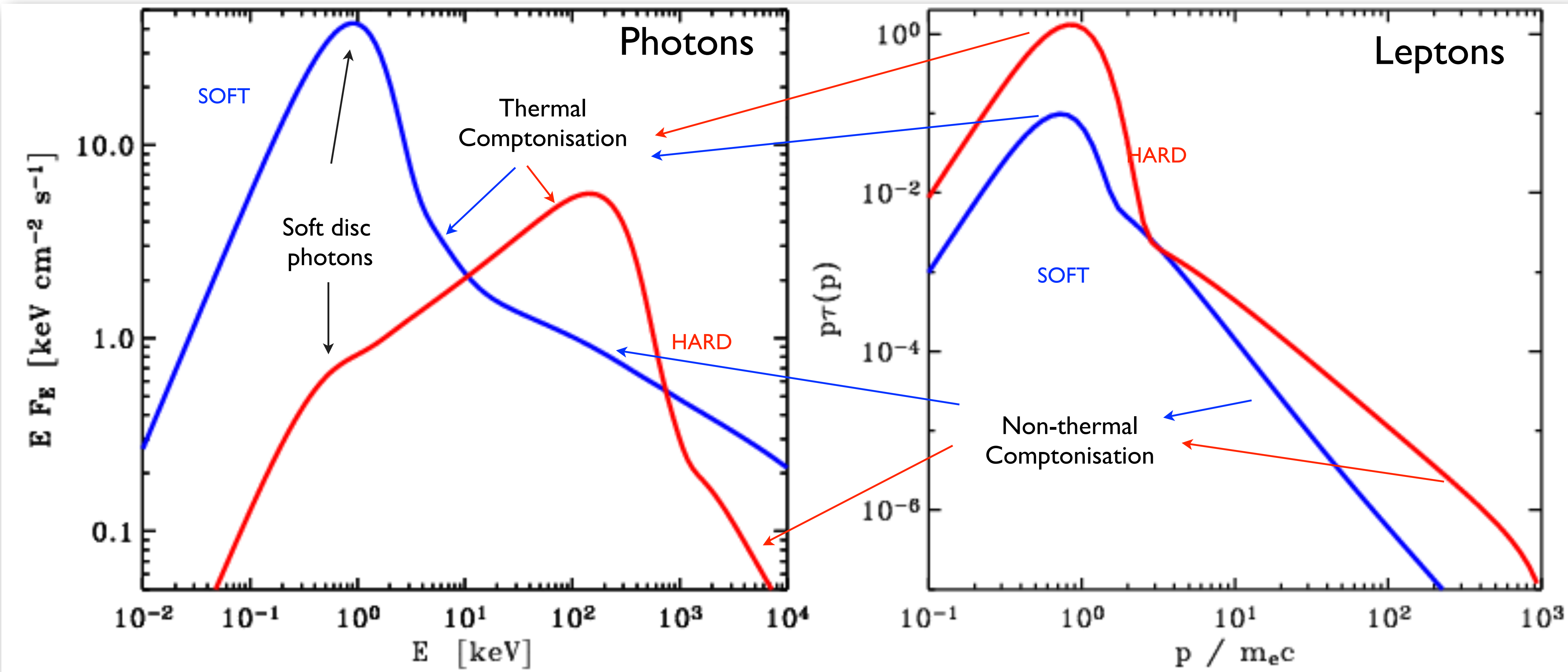




HARD STATE: (compact radio jet)
disc blackbody: weak / Corona: mostly THERMAL electrons

SOFT STATE:
disc blackbody: strong / Corona: mostly NON-THERMAL electrons

Hybrid thermal/non-thermal comptonization models



- Comptonising electrons have similar energy distribution in both states: Maxwellian+ non-thermal tail

HARD STATE: kT~50-100 keV, τ_T~1-3: Thermal comptonisation dominates

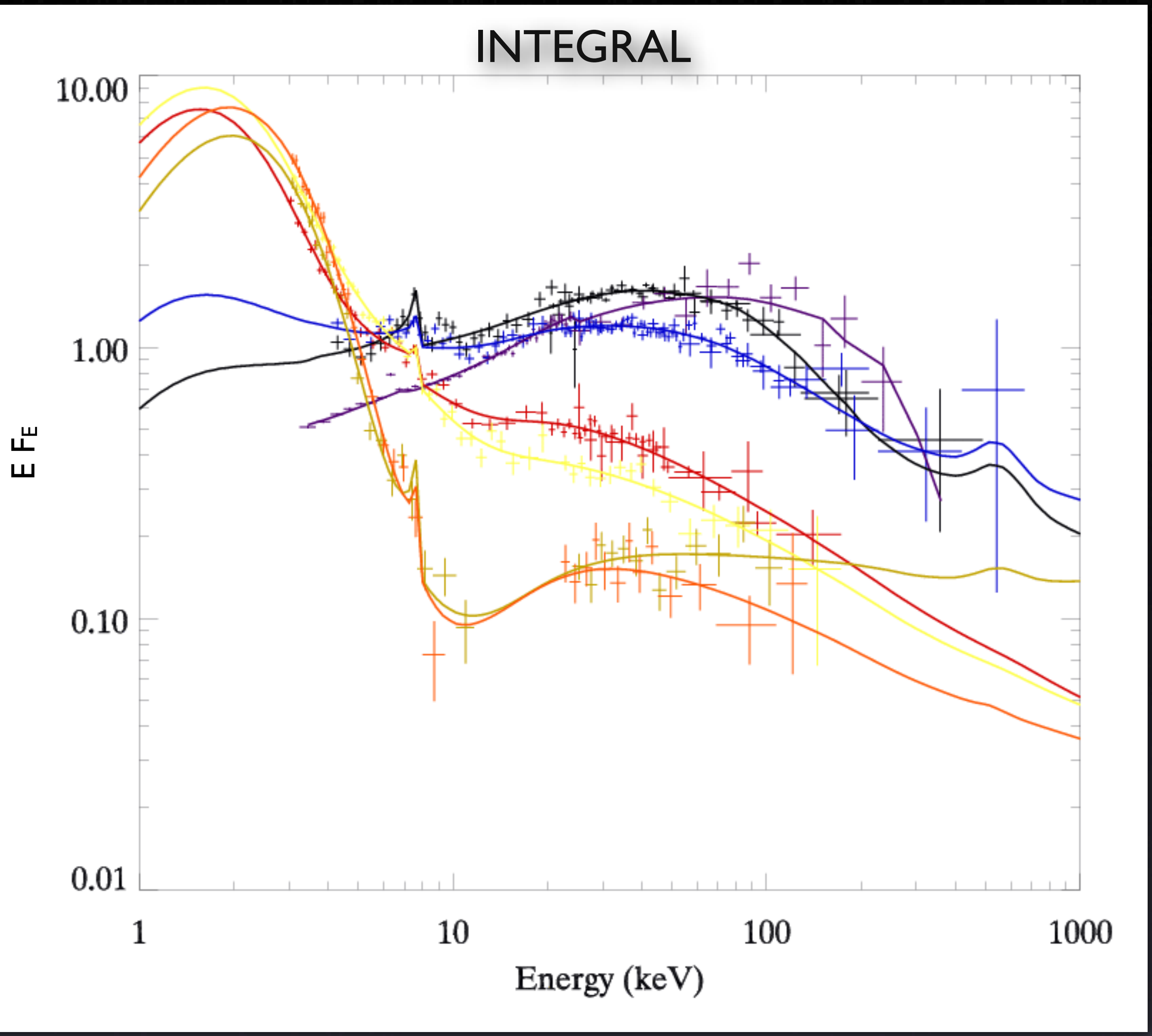
SOFT STATE: kT~10-50 keV, τ_T~0.1-0.3: Inverse Compton by non-thermal electrons dominates

- Lower temperature of corona in soft state possibly due to radiative cooling by soft disc photons

- EQPAIR

(Poutanen & Coppi 1998; Coppi 1999; Gierlinski et al. 1999, Zdziarski ..., Done ...)

GX 339-4 during the 2004 state transition



Del Santo, et al., MNRAS, 2008

- Smooth transition from thermal to non-thermal Comptonisation
- Fits with hybrid thermal/non-thermal models (EQPAIR) during the Hard to Soft transition:

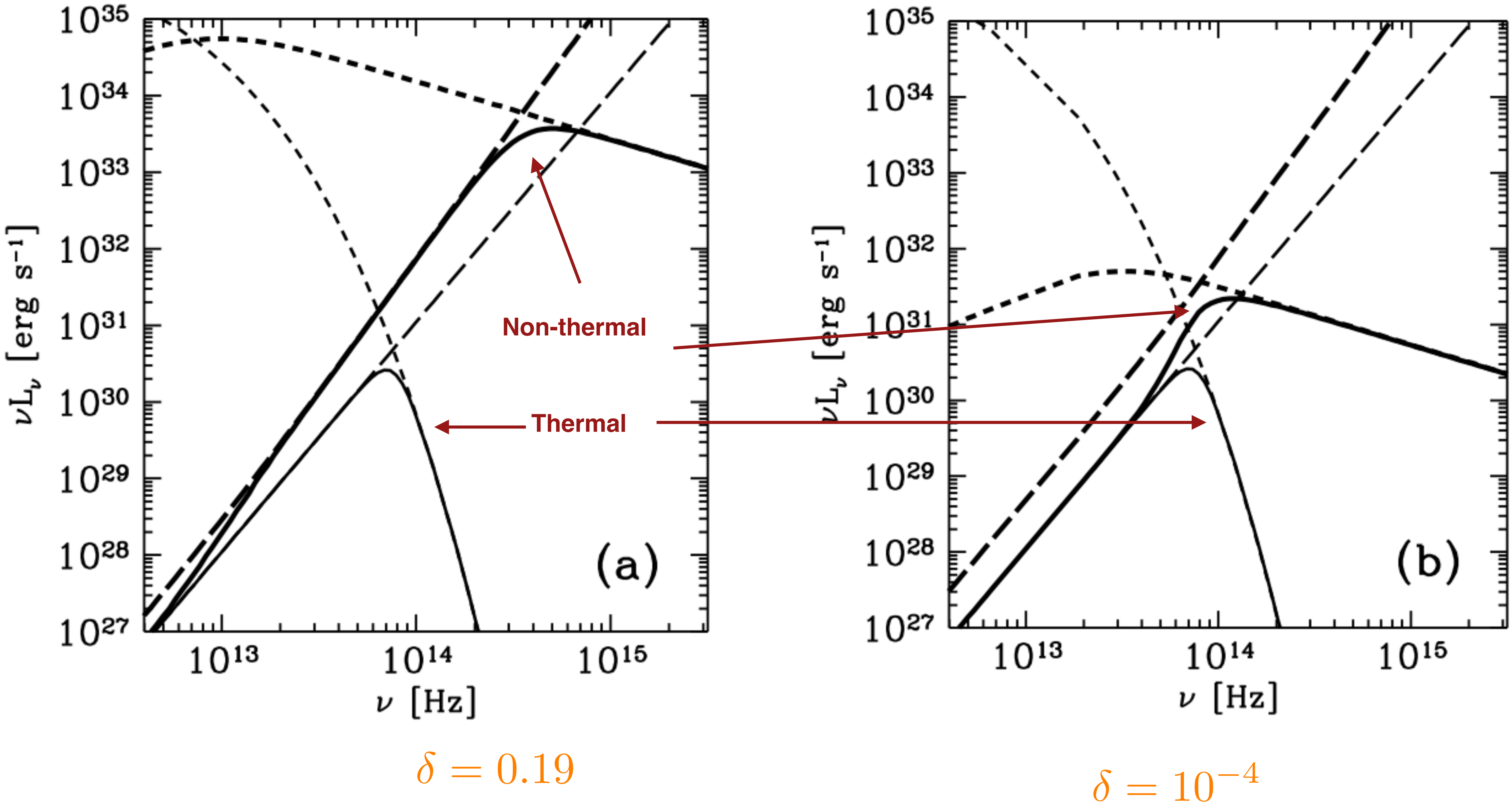
➡ softening driven by dramatic cooling of the coronal electrons by soft disc photons

Effects of magnetic field in hot flow/corona

- Cyclo-synchrotron radiation= seed photons for comptonization, enhanced cooling of the Maxwellian electrons
- Cyclo-synchrotron self-absorption= fast electron thermalisation

(Belmont, Malzac & Marcowith, A&A 2008; Vurm & Poutanen 2009)

Hybrid model: synchrotron emission in optical

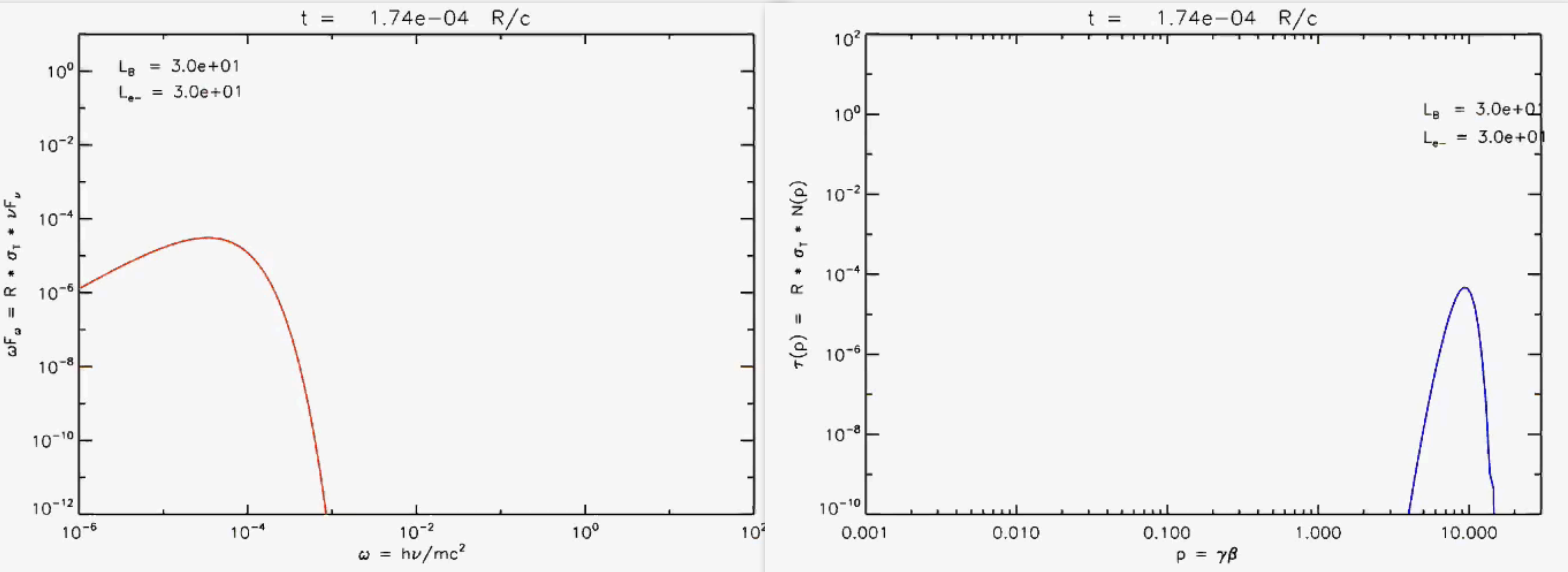


- Optical synchrotron flux considerably increased by non-thermal particles

Wardzinski & Zdziarski 2002

Effects of magnetic field: the Synchrotron boiler

(Ghisellini, Guilbert and Svensson 1988)

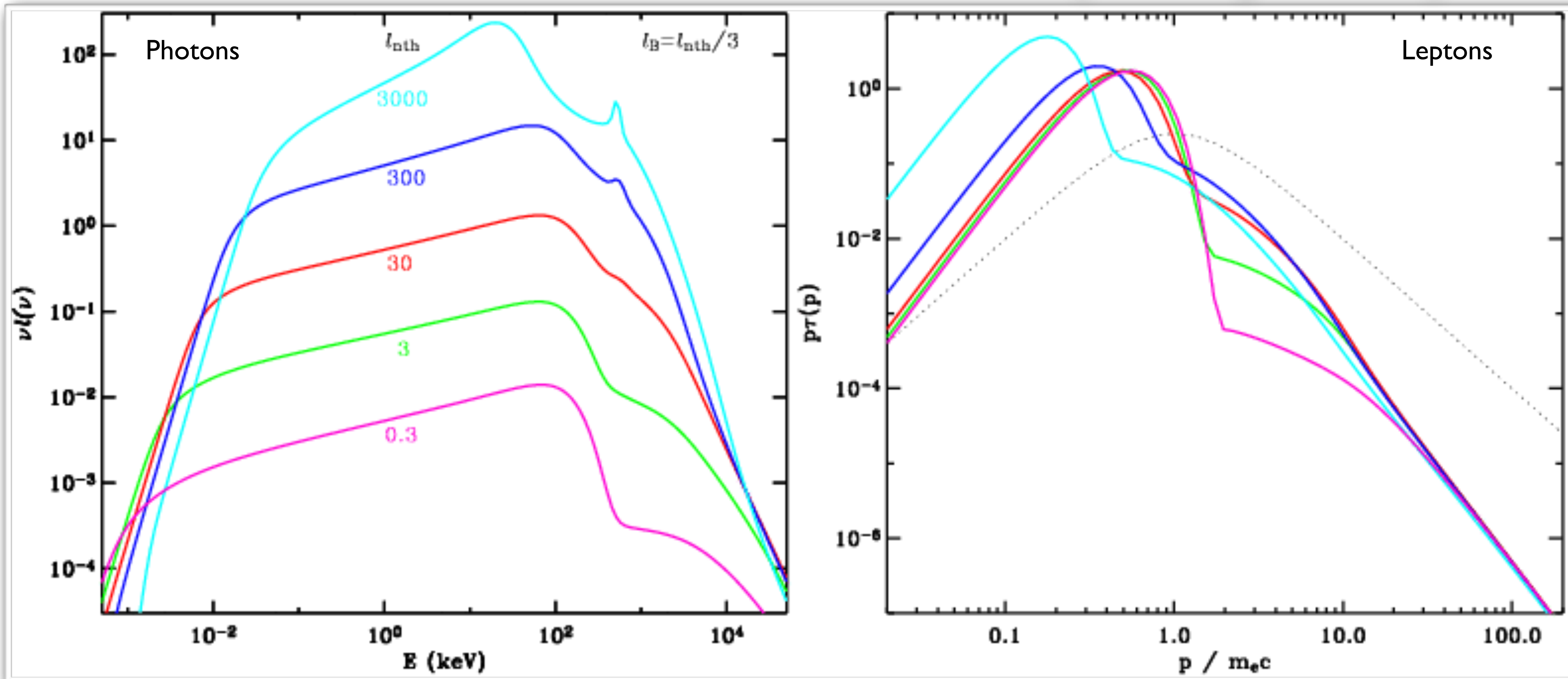


- Electrons injected with γ =10 in an empty (but magnetised) region
  Synchrotron self-Compton emission

- High energy e- → synchrotron photons → self-absorbed by lower energy e-
  - ➡ transfer of energy between particles
  - ➡ 'thermalizing' effect on the electron distribution
  - ➡ At steady state: hybrid thermal/non thermal lepton distribution

(Belmont, Malzac & Marcowith, A&A, 2008; Vurm & Poutanen 2009)

Pure non-thermal SSC models (steady state)



- Magnetic field B at ~equipartition with radiation , $l_B=(\sigma_T/m_e c^2)\ R\ B^2/(8\pi)$
- Continuous POWER-LAW electron injection $\Gamma_{inj=3}$, $l_{nth}= (\sigma_T/m_e c^3)\ L/R$

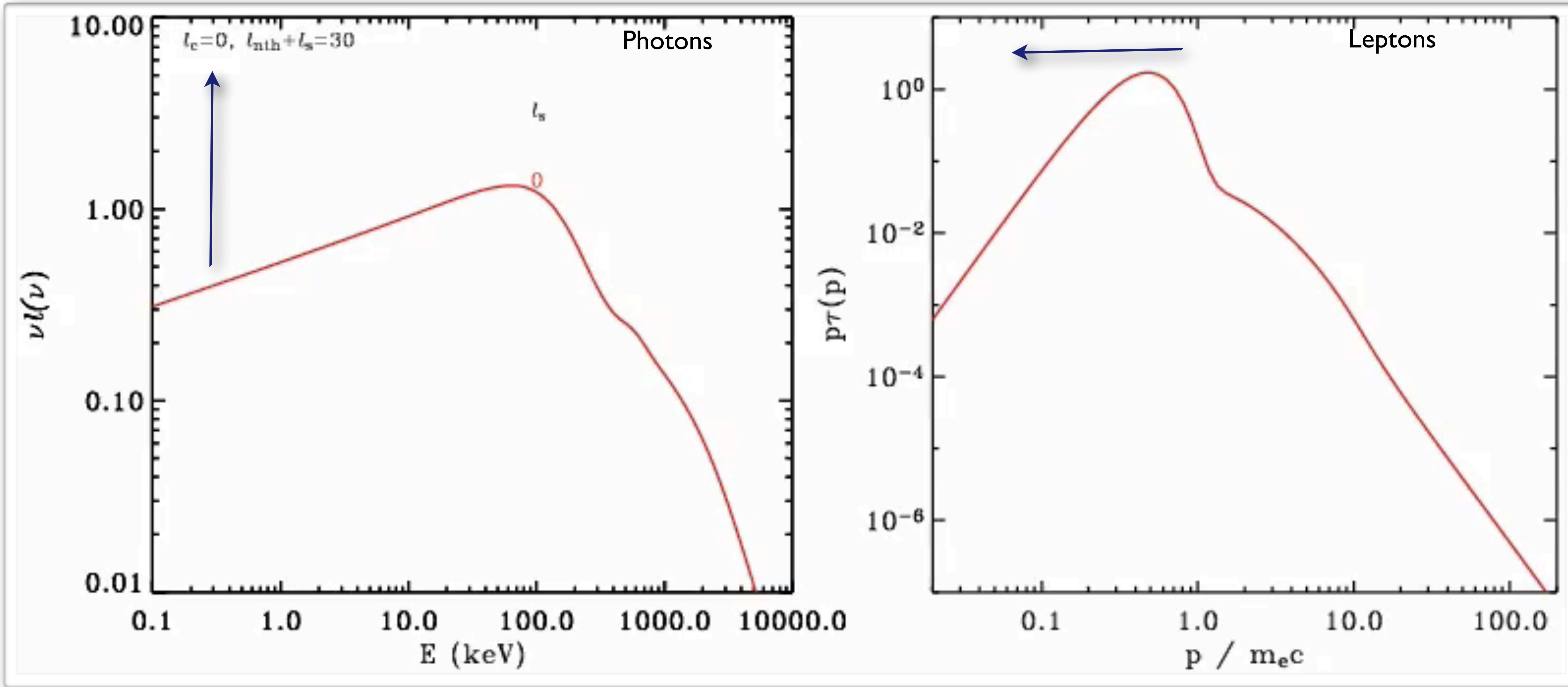
➡ Cooling and thermalisation through synchrotron self-Compton + e-e Coulomb

➡ Equilibrium distribution: Maxwellian+ non-thermal tail

➡ spectra look like hard state !

(Malzac & Belmont MNRAS 2009)

Effect of external soft photons



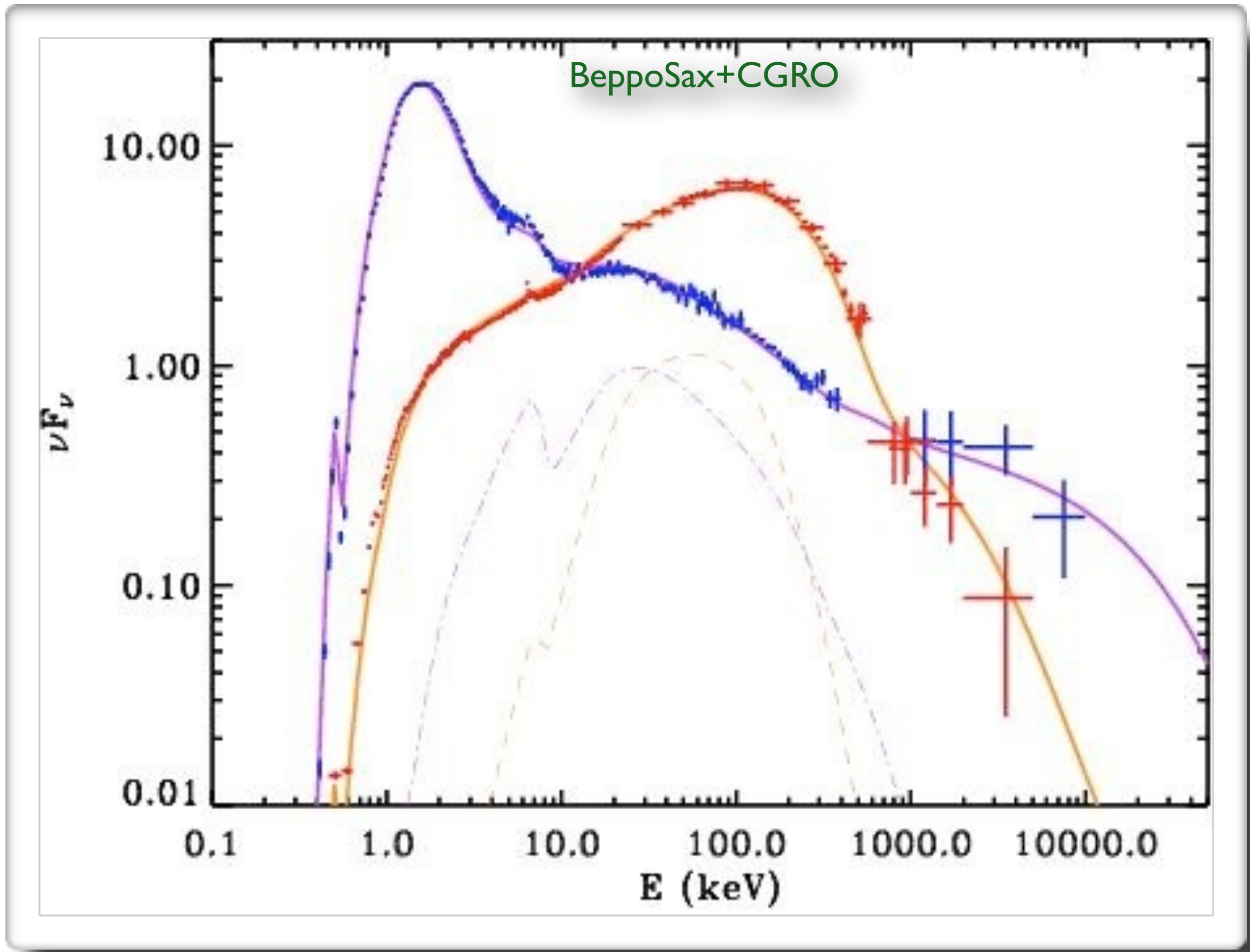
- Add soft thermal photons:

➡ temperature of Maxwellian electrons decreases

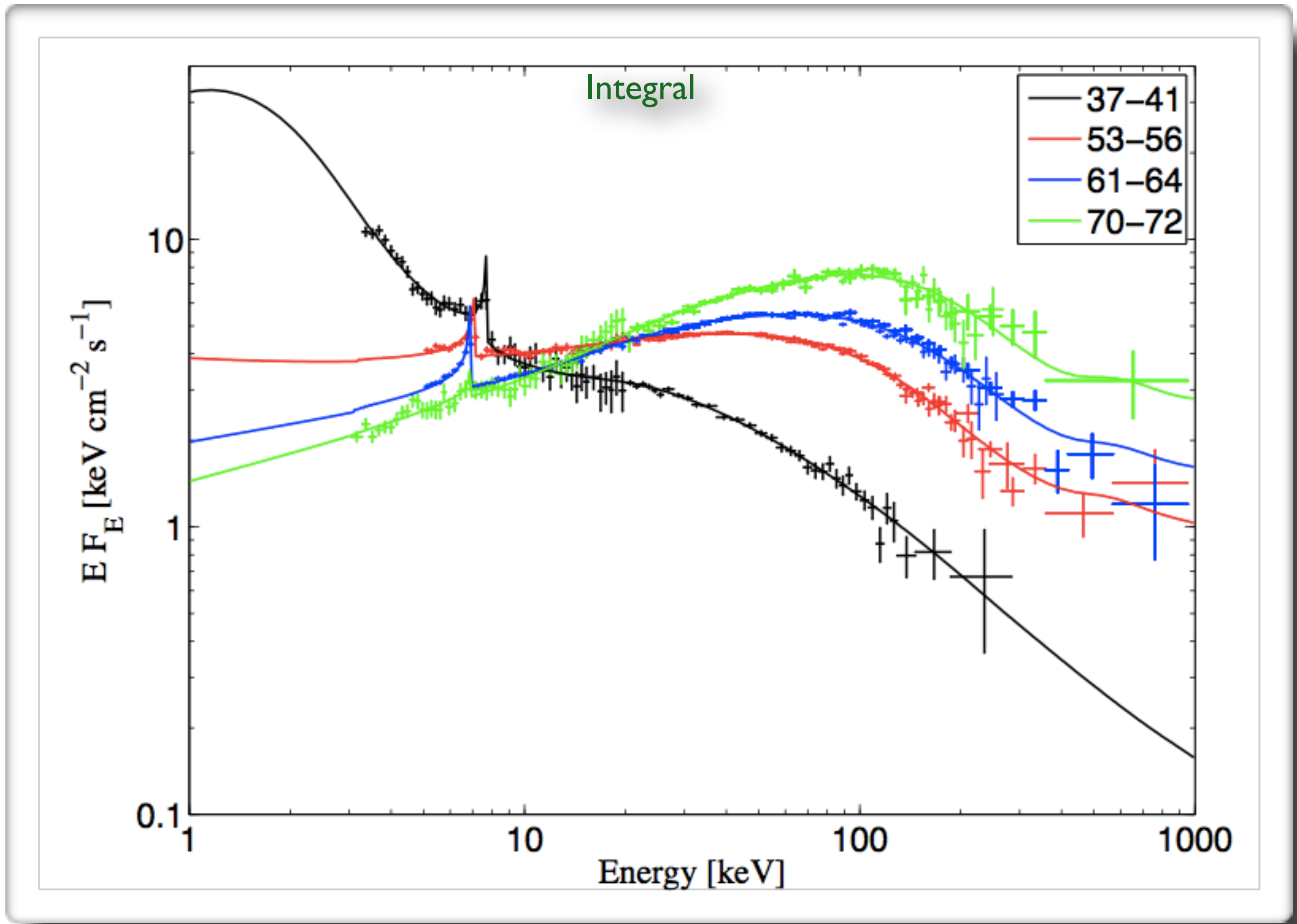
➡ Compton emission increasingly dominated by non-thermal electrons

➡ looks like a state transition!

Comparison to data (one-zone model)



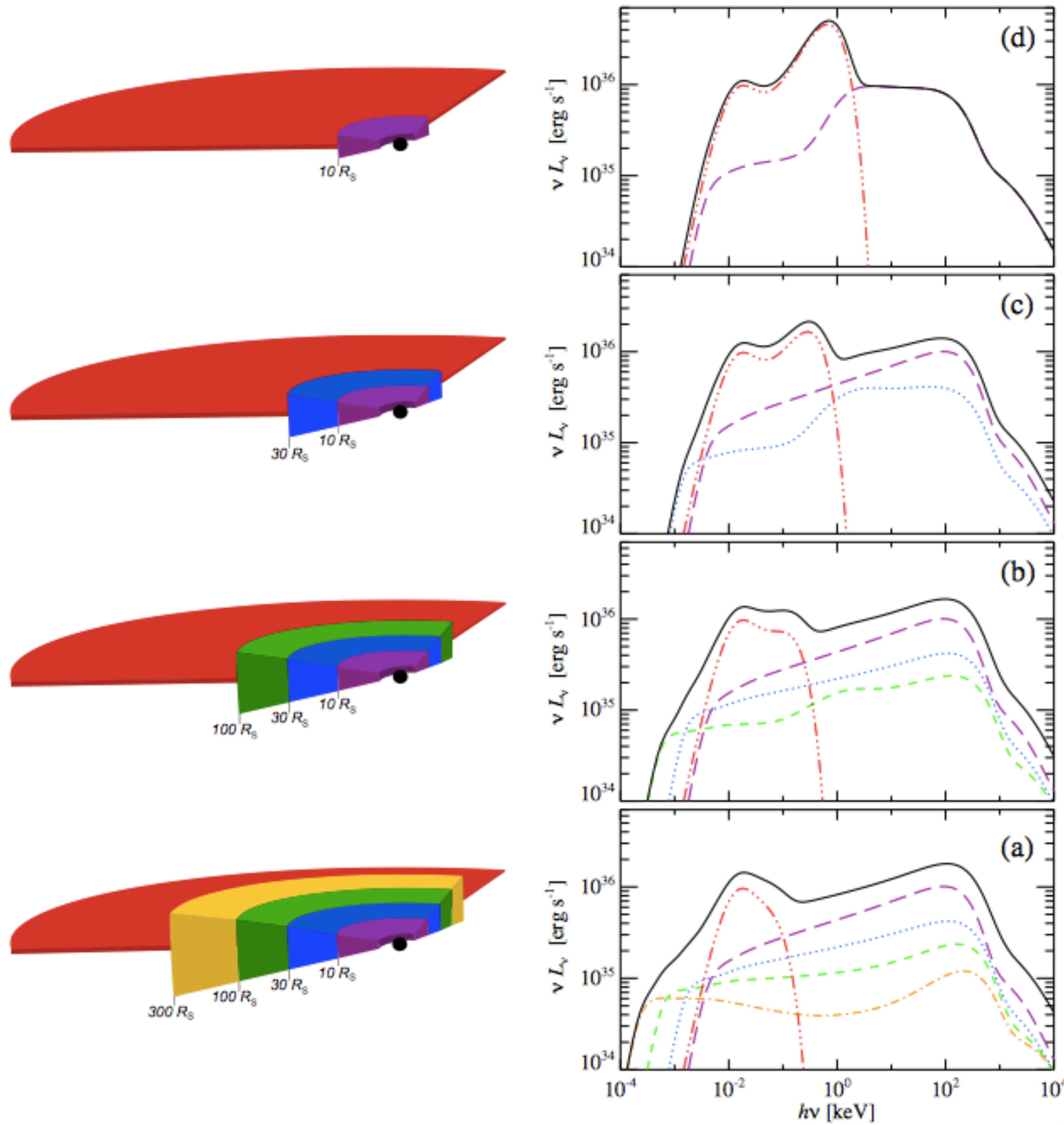
Malzac & Belmont 2009; Poutanen & Vurm 2009



Droulans et al. 2010; Del Santo et al. 2013

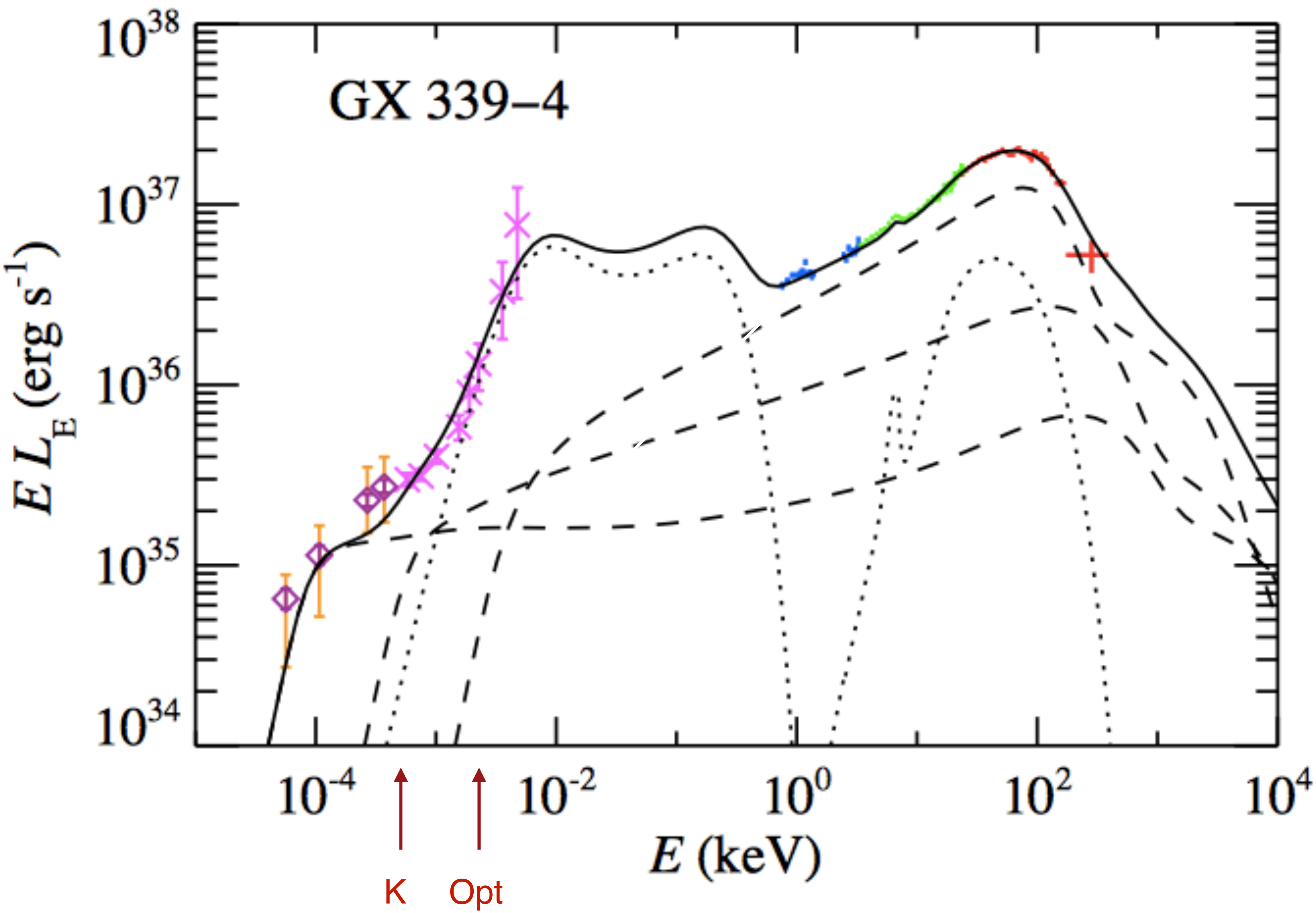
- All spectral states consistent with pure non-thermal acceleration models,
- Hard state compatible with pure synchrotron Comptonization
- Spectral transitions: thermal disc photons cool down the corona in softer states
- Spectral fits with BELM: first constraints (upper limits) on coronal magnetic field B and ions temperature T_{ions} in all spectral states

multi zone-model: Hybrid hot accretion flows



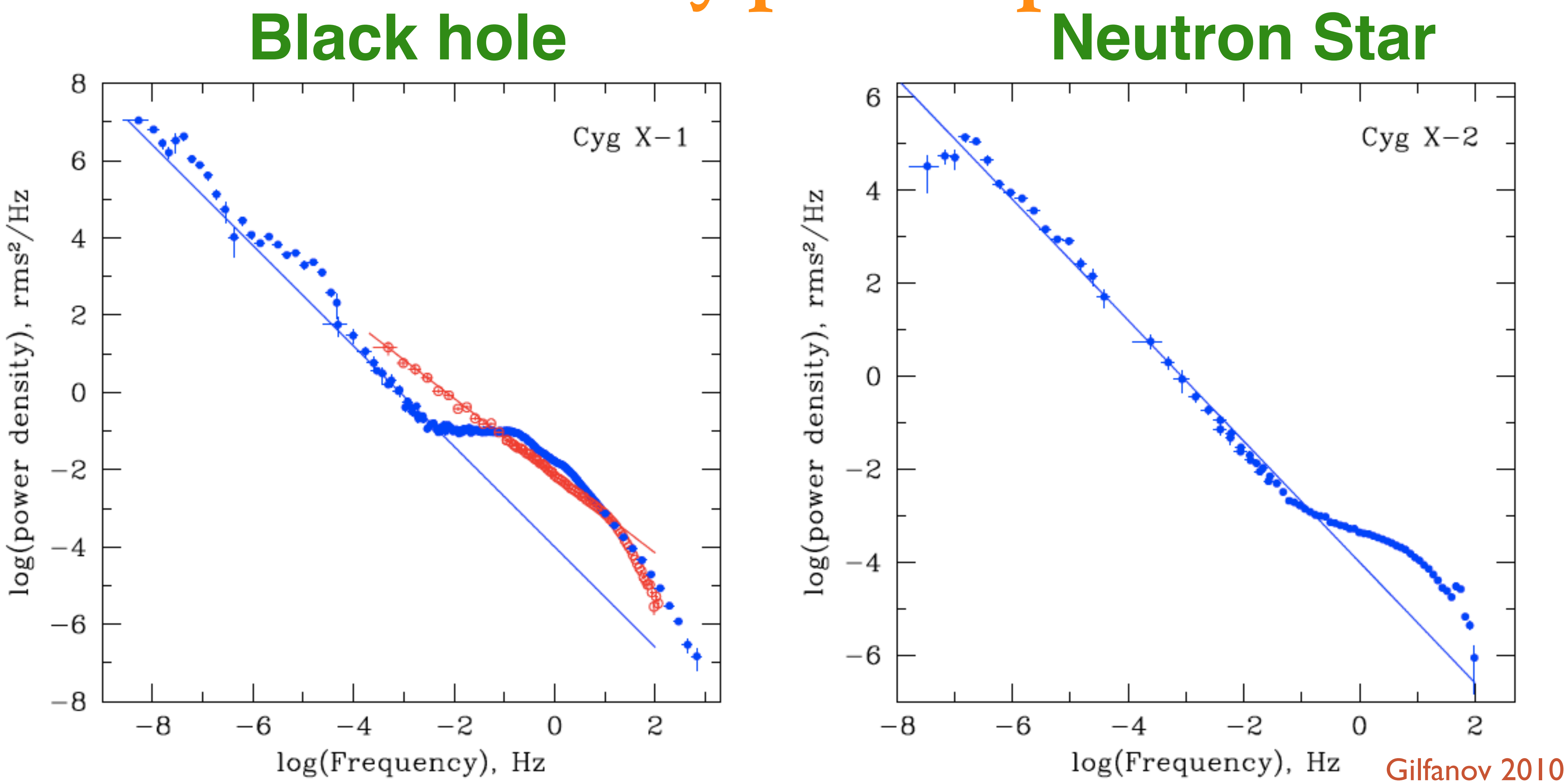
Poutanen & Veledina 2014

Hybrid hot accretion flows



Poutanen & Veledina 2014

Multi-scale variability in persistent sources
X-ray power spectra



- Strong variability from ms to several years times scales !
- 1/f noise at low frequencies + band limited noise at high fourier frequencies

Time scales

- X-ray emitting region is small $R < 100 R_G \simeq 1500 \left(\frac{M}{10 M_\odot} \right) \quad \text{km}$

- Time scales in X-ray emitting region:

Orbital time-scale: $$t_K = 0.3 \left(\frac{M}{10 M_\odot} \right) \left(\frac{R}{50 R_g} \right)^{-3/2} \quad s$$

Vicous time-scale: $$t_{vis} = (H/R)^{-2} \frac{t_K}{2\pi\alpha}$$

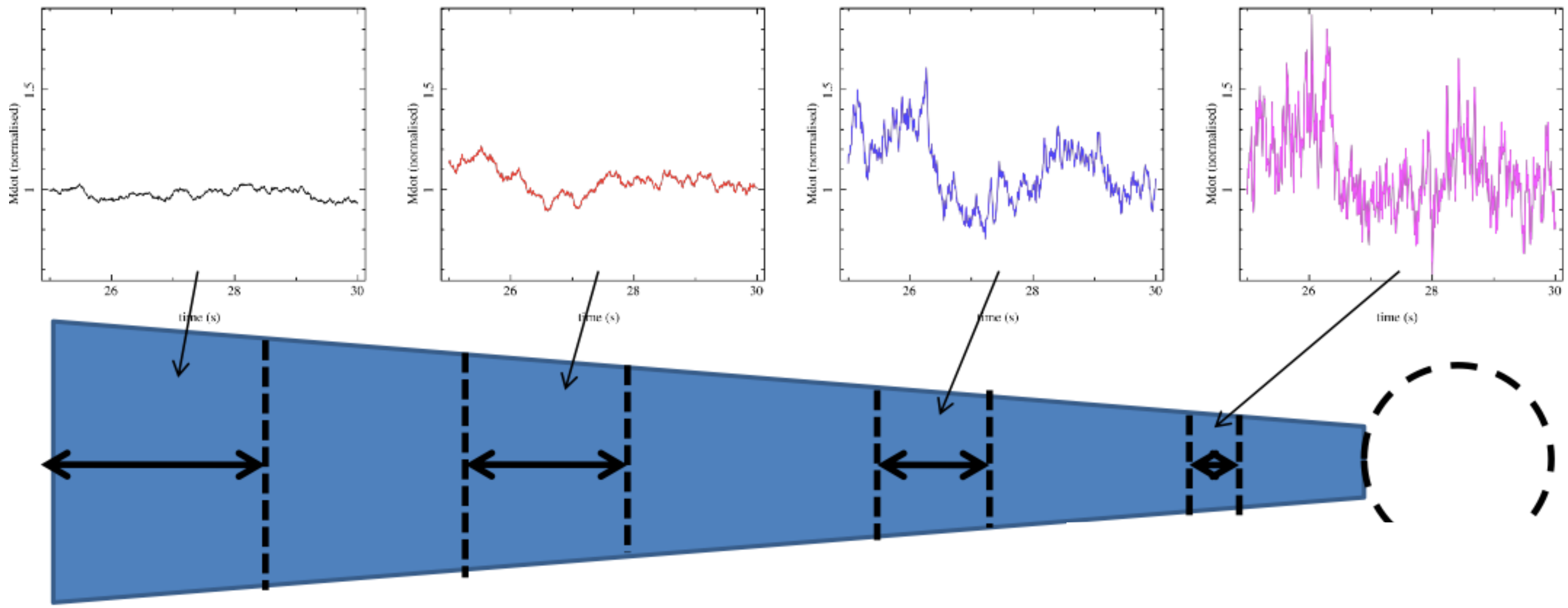
- Thin disc, gas pressure dominated: $H/R \sim 10^{-2} \quad t_{vis} \simeq 10^4 t_K \sim 10^3 \mathrm{s}$

- Hot flow: $H/R \sim 0.3 \quad t_{vis} \simeq 10\, t_K \sim 1 - 10\, \mathrm{s}$

- High Fourier frequencies can be produced in this region

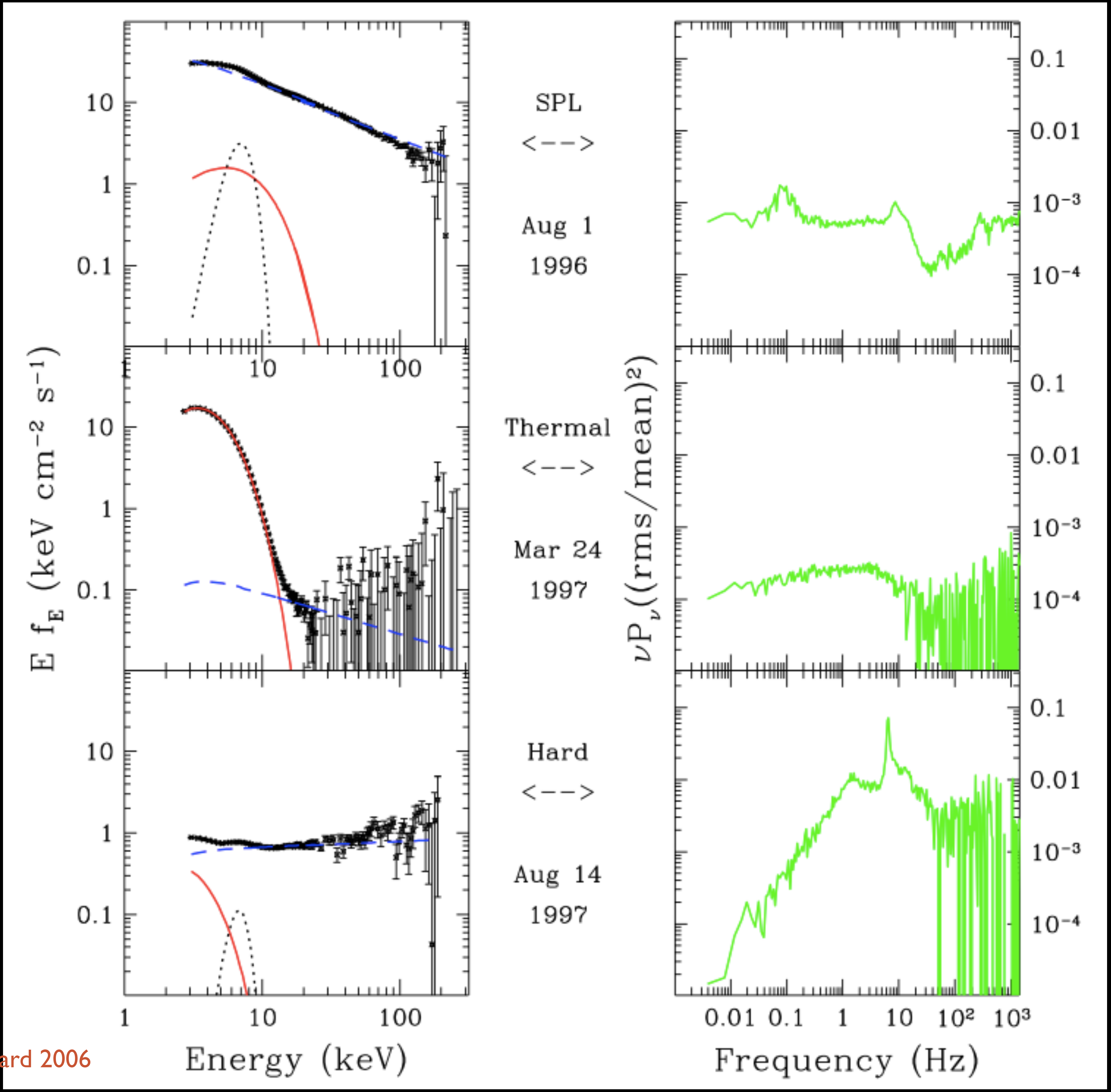
- But the longest observed times scales are too long to be produced in the region of main energy release. Must be generated in the outer parts of the accretion flow

Propagating mass accretion rate fluctuations



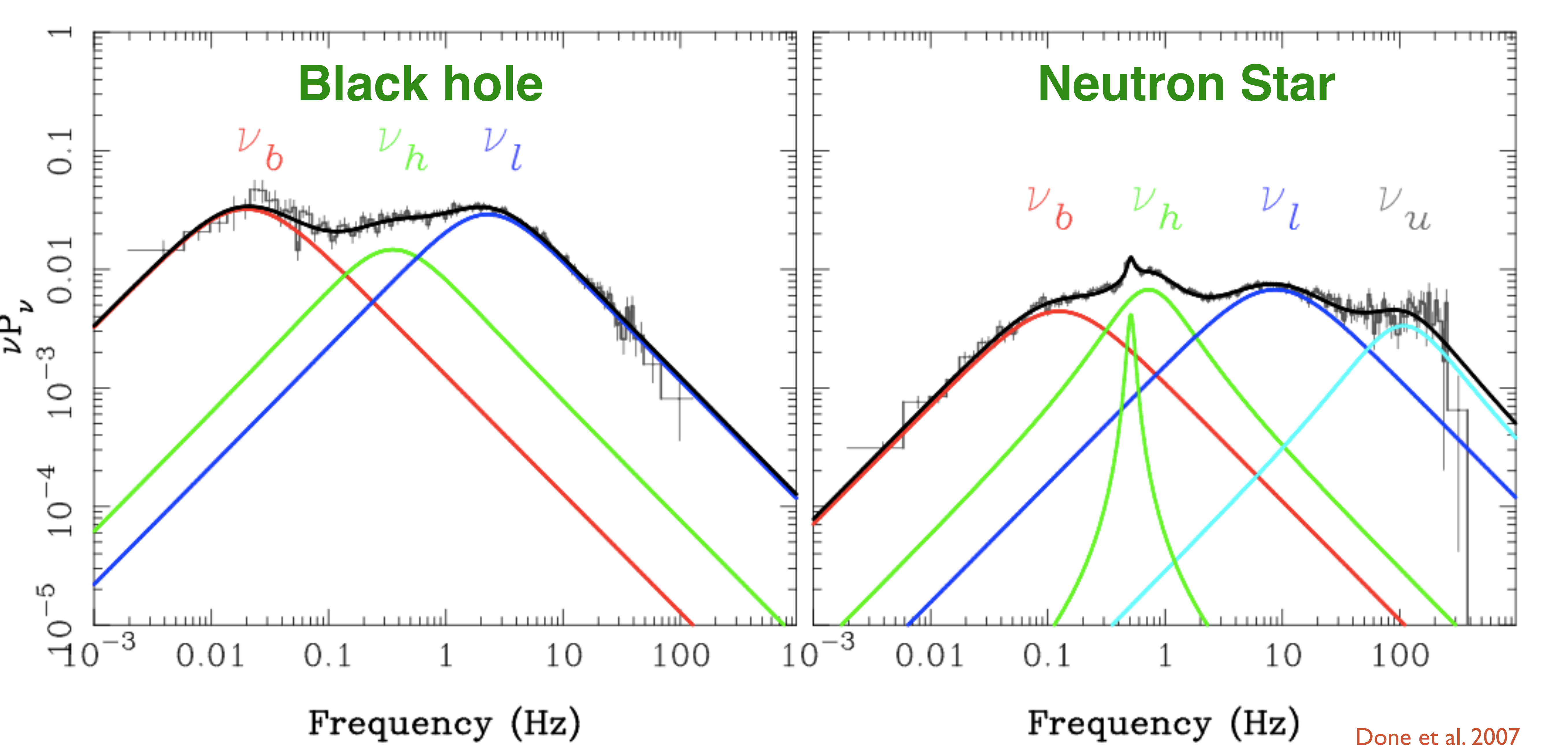
- Long times scales produced at large distances (turbulent fluctuations of mass accretion rate ?) and propagate inward on viscous time scale until they reach X-ray emitting region (within 100 R)
- Accretion disks model may produce 1/f noise (Lyubarskii 1997; King et al. 2004; Arevalo & Uttley 2006, Mayer & Pringle 2006, …)
- Explains observed rms-flux correlation (Uttley et al. 2005)

Rapid variability depends on spectral state



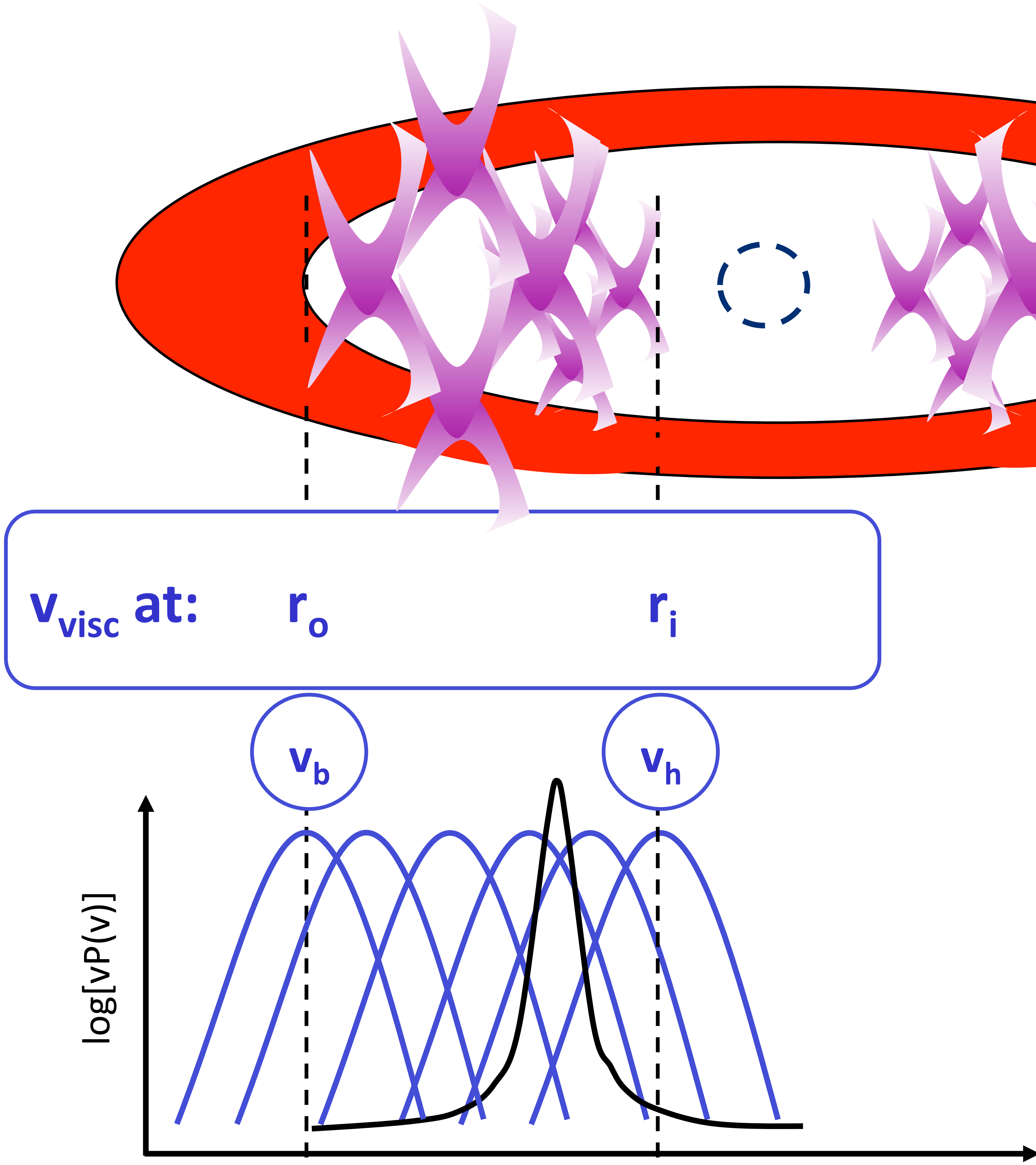
McClintock & Remillard 2006

Fast variability: X-ray power spectra in hard state



- Band limited noise (Broad Lorentzians) + often Low frequency QPO
- NS present high frequency component absent in BHs. Variability from NS surface ?

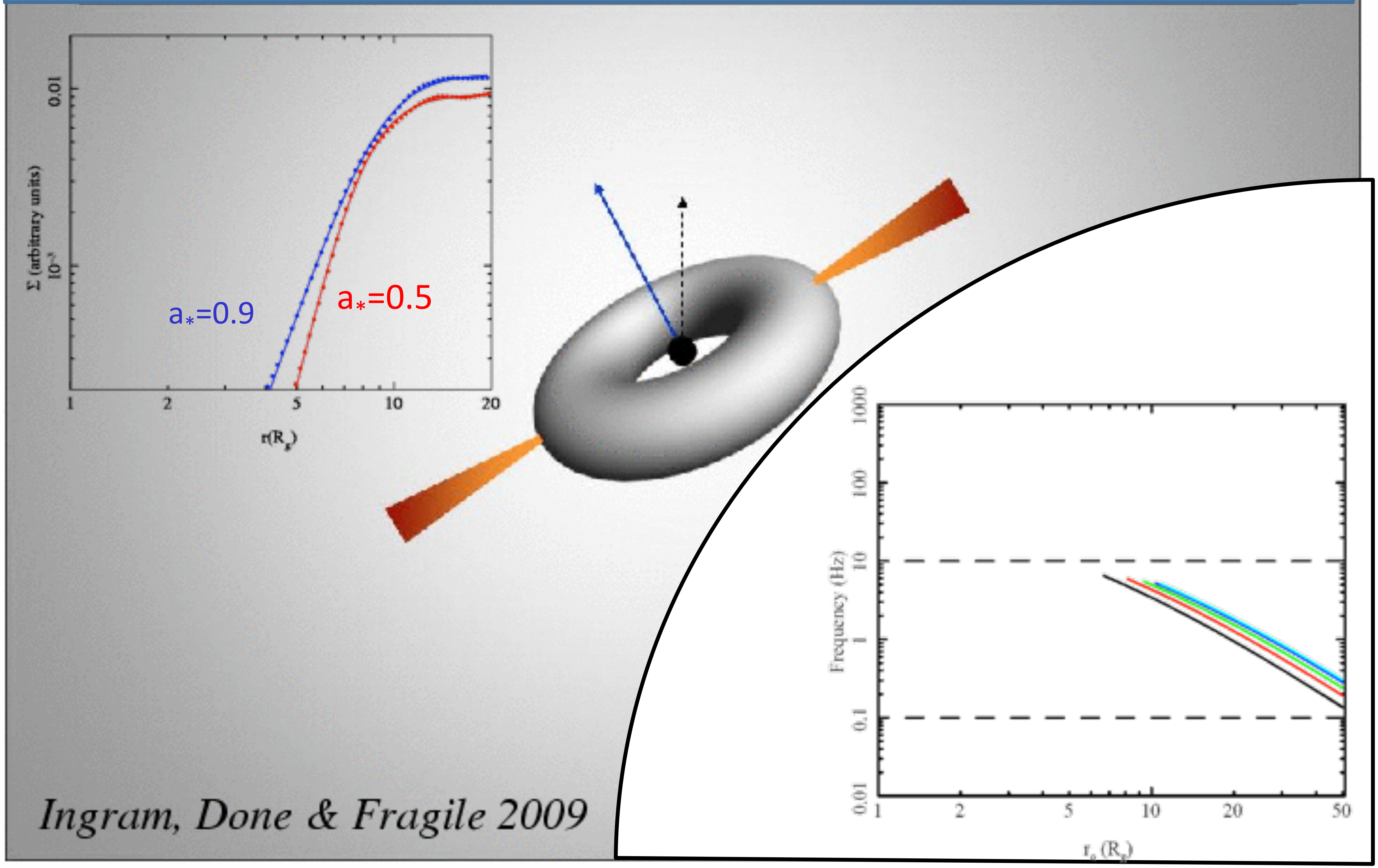
Possible interpretation of band limited noise: propagation of fluctuations in hot flow



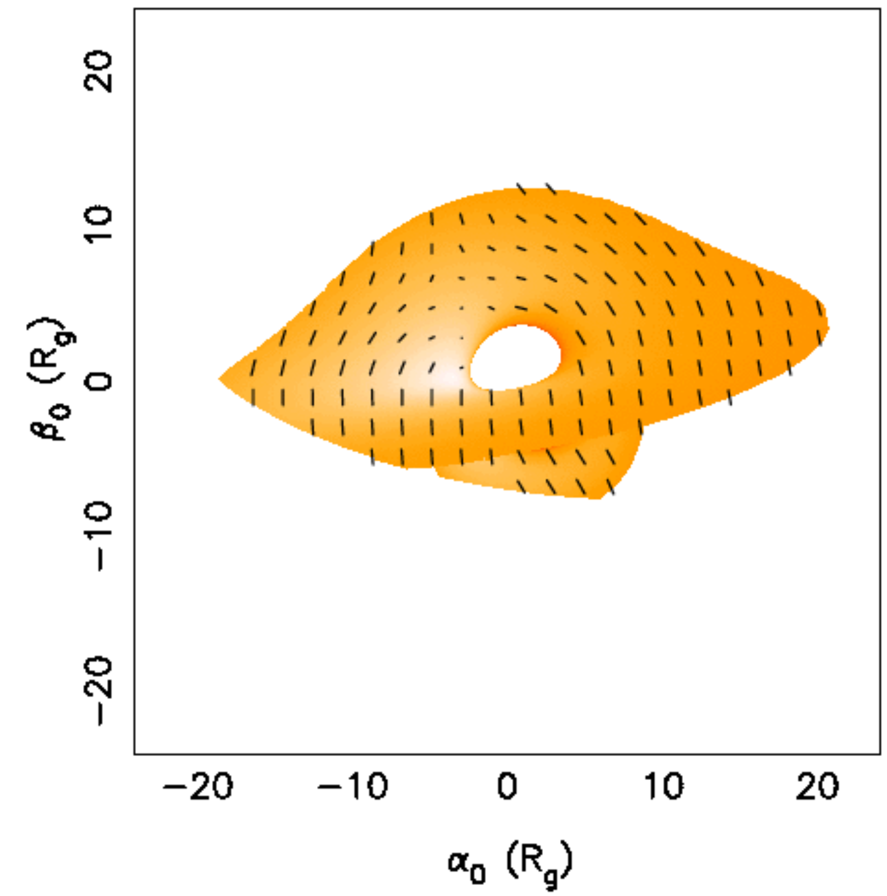
Lense-Thirring QPO (Ingram, Done & Fragile 2009 – IDF09)

Ingram & Done 2011

QPO Model: Lense-Thirring precession of the flow

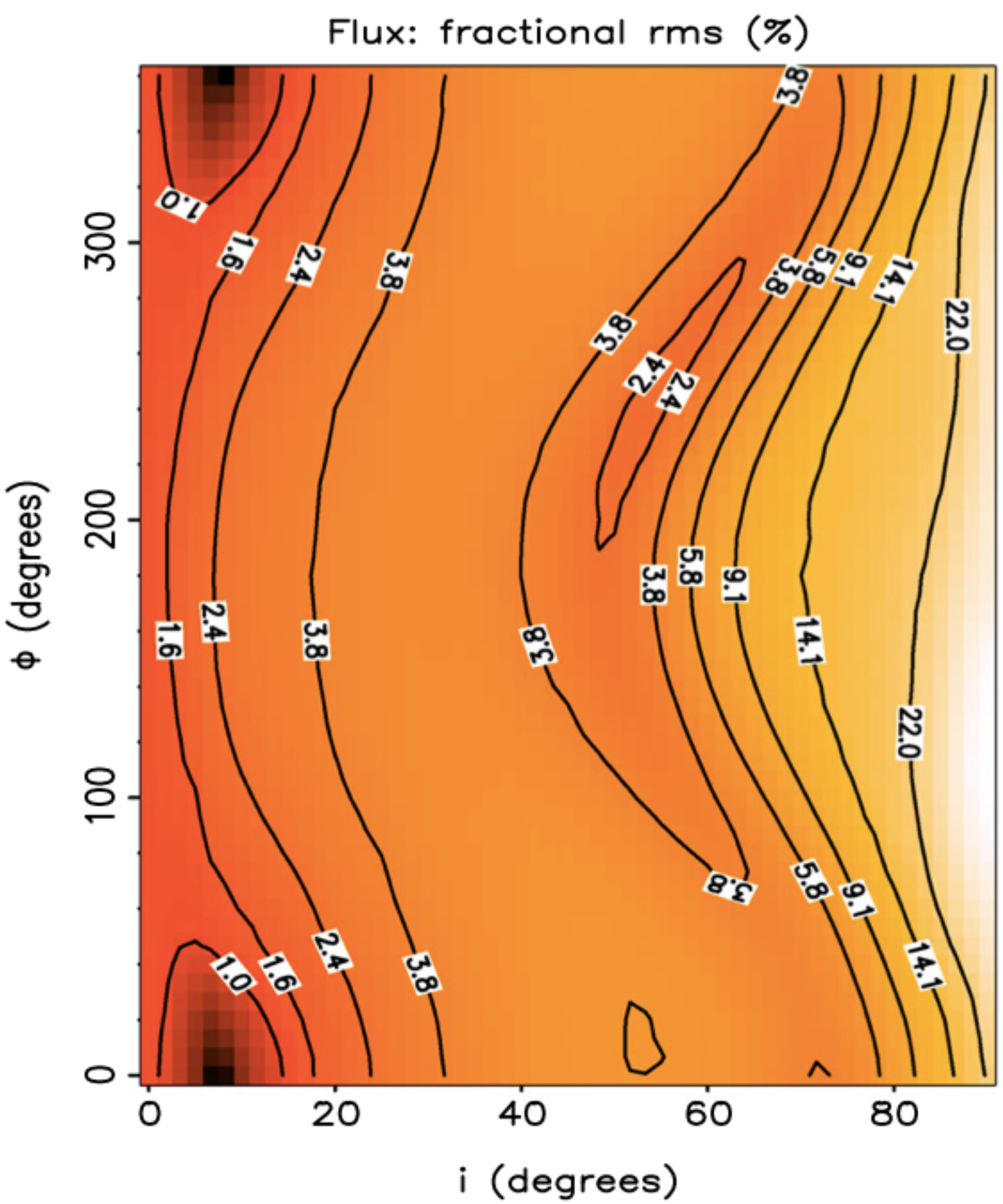


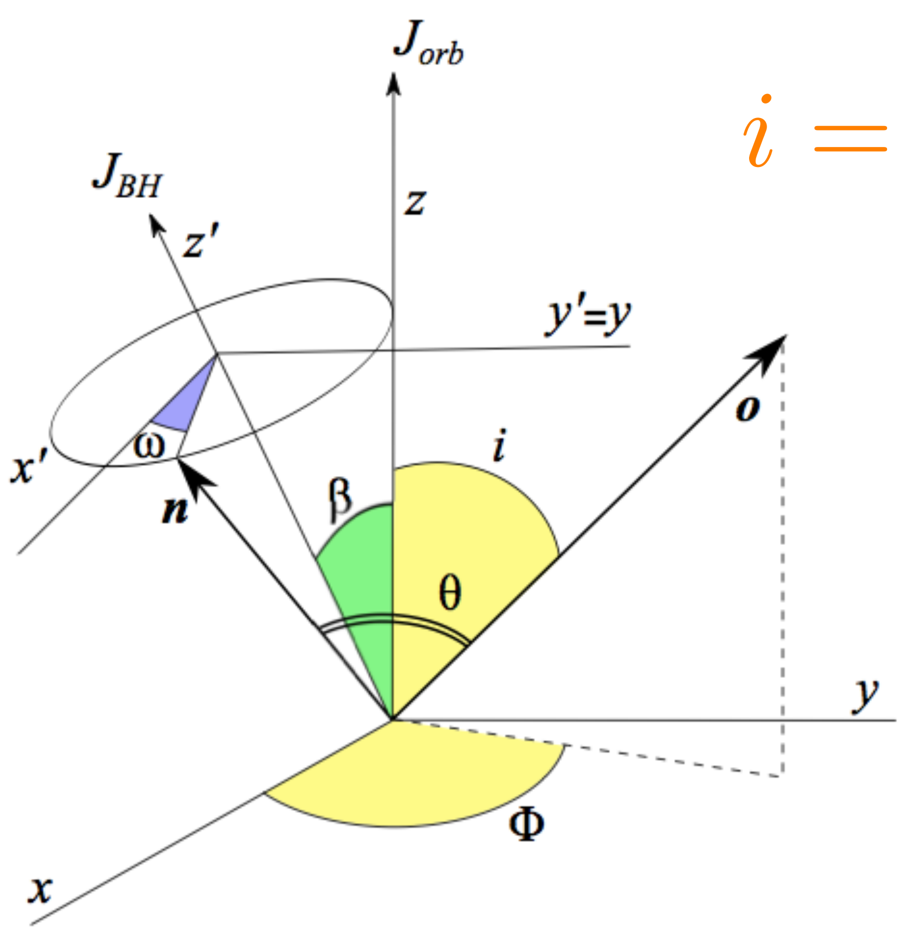
- Modulation due to relativistic light bending and Compton anisotropy
- QPO rms amplitude up to ~10 %
- Modulation of polarisation angle and amplitude predicted



$i = 70^o \quad \Phi = 180^o$

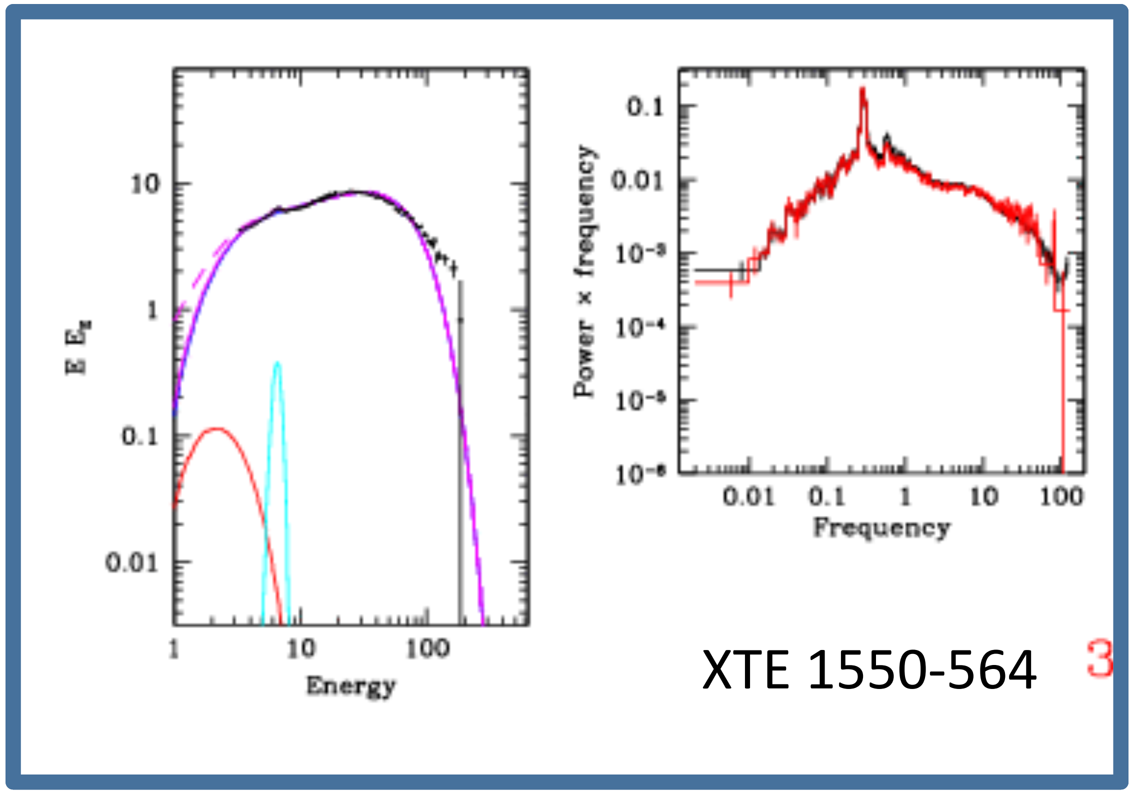
$\beta = 10^o$





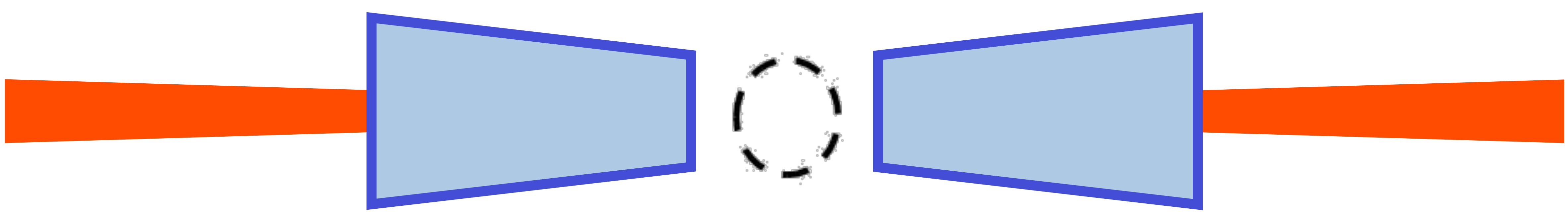
Ingram et al. 2015

The truncated disc model



Cool, optically thick disc thermalises to emit a multi coloured black body spectrum

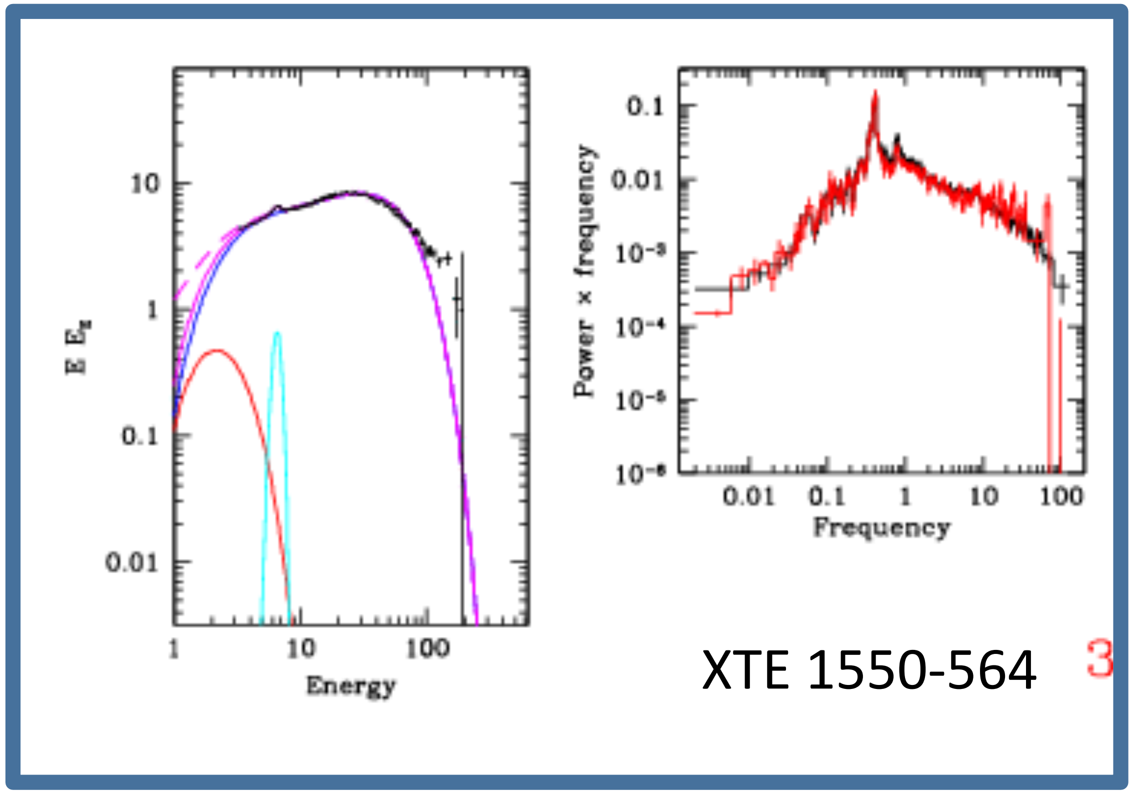
Hot electrons in high scale height, optically thin flow Compton upscatter disc seed photons to give power law emmission

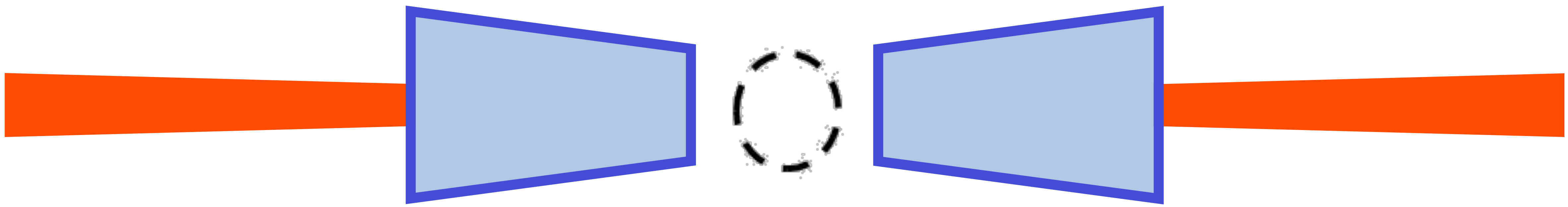


Moving truncation radius varies the number of seed photons seen by the flow

(A. Ingram)

The truncated disc model





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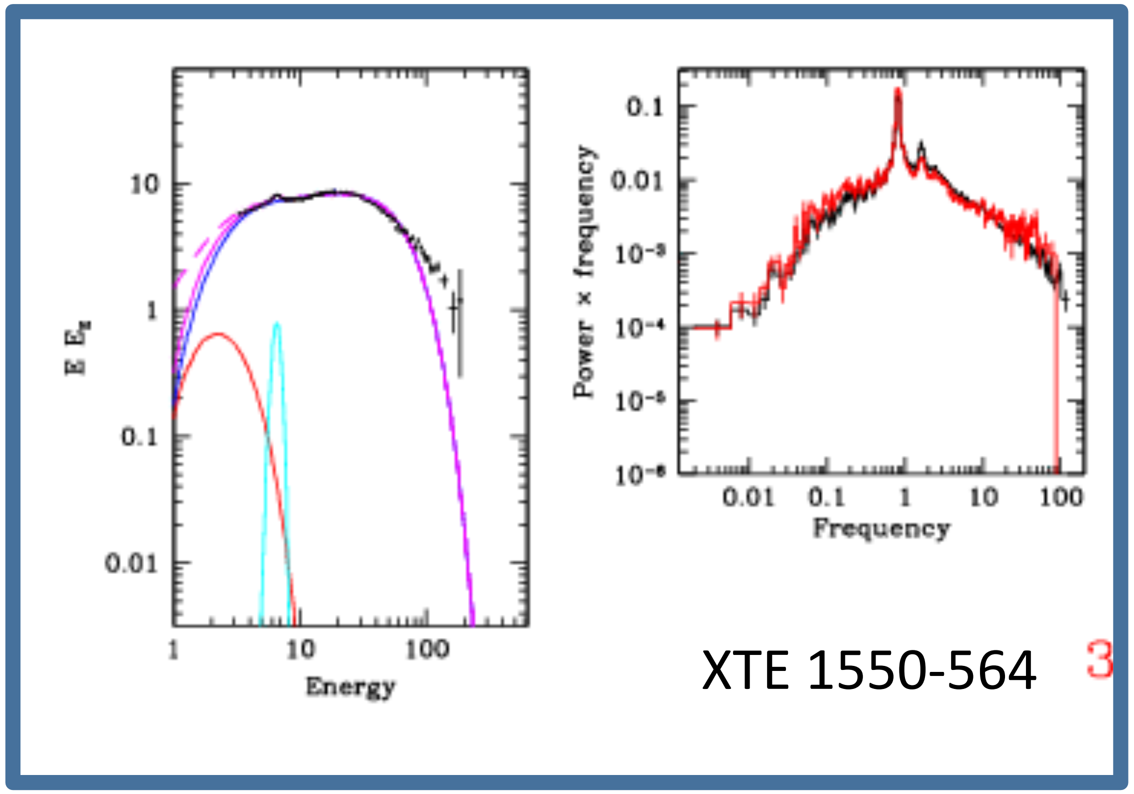

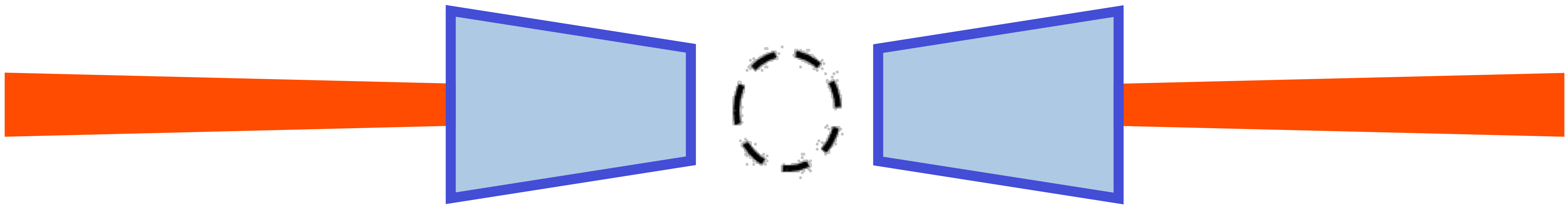

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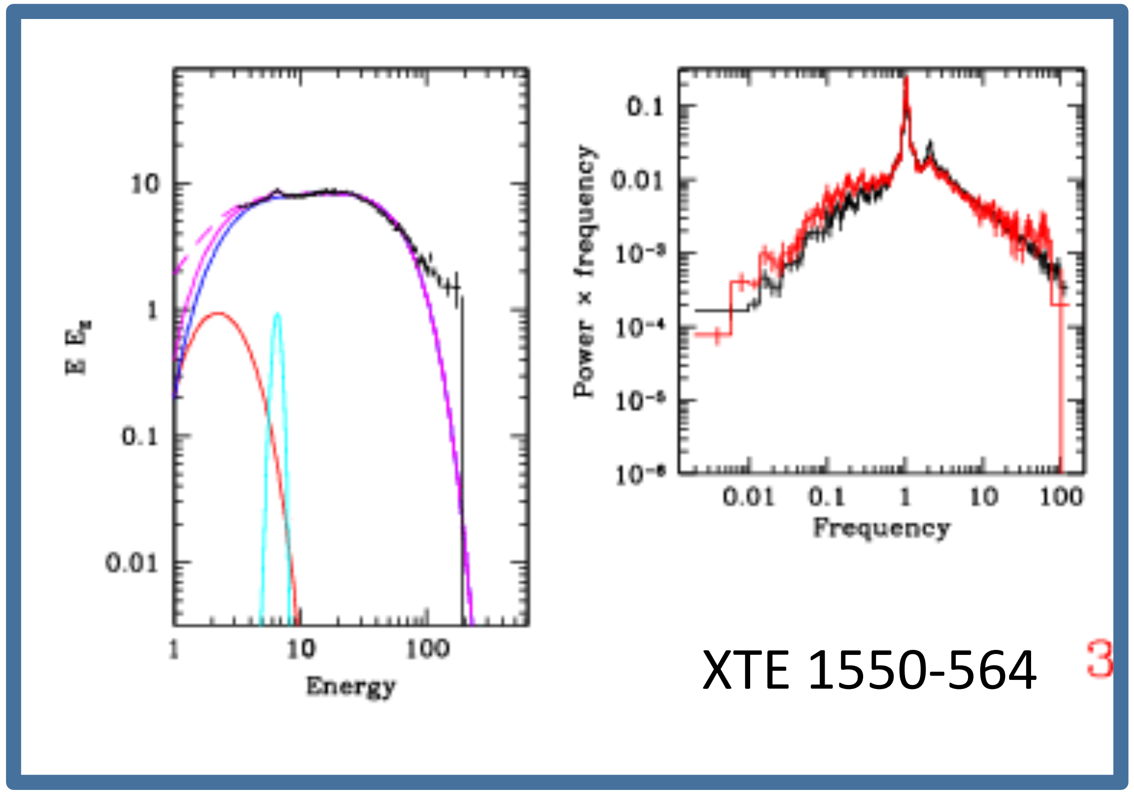

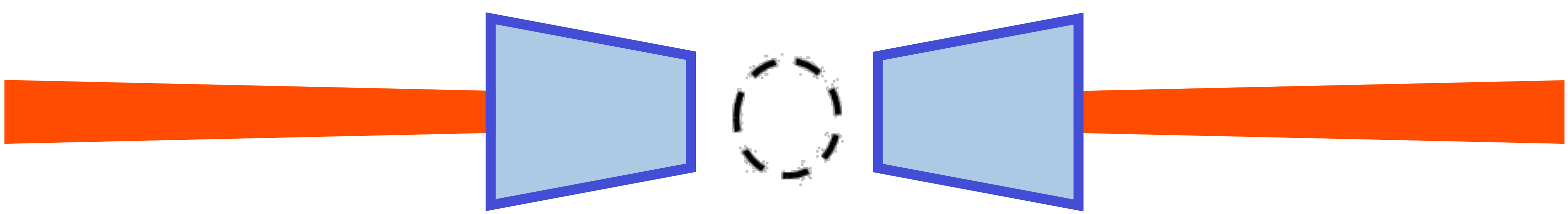

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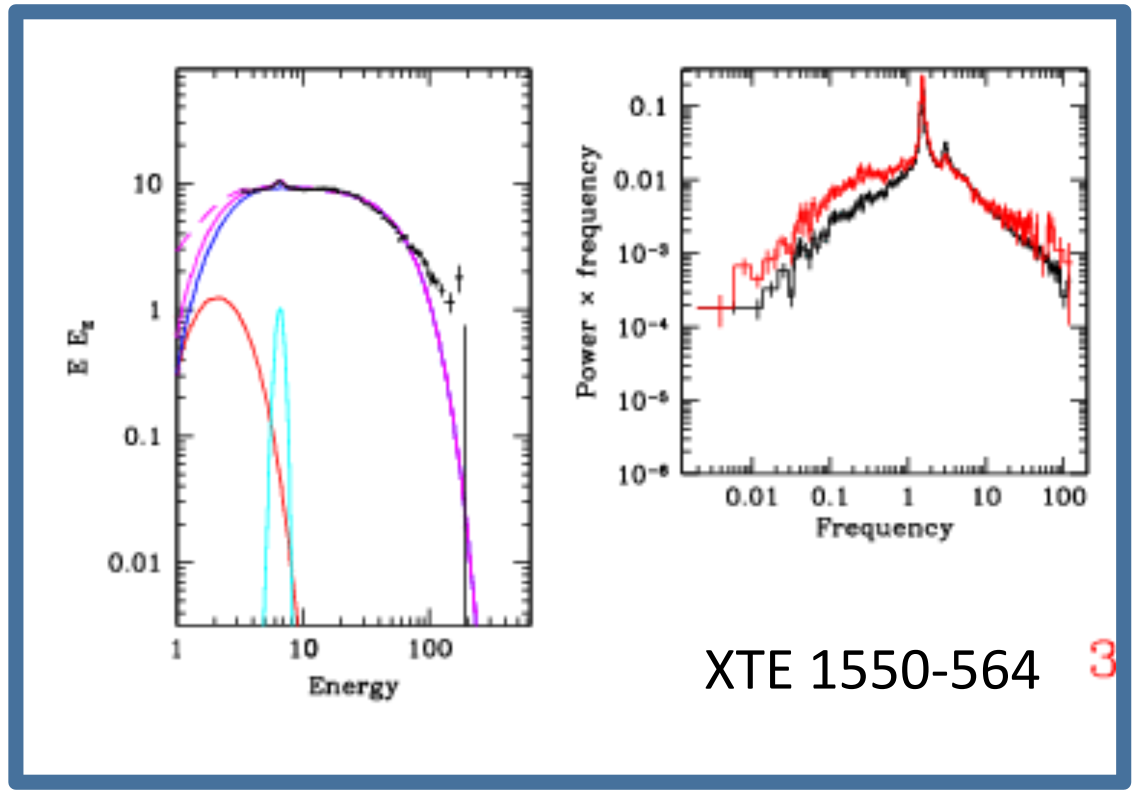

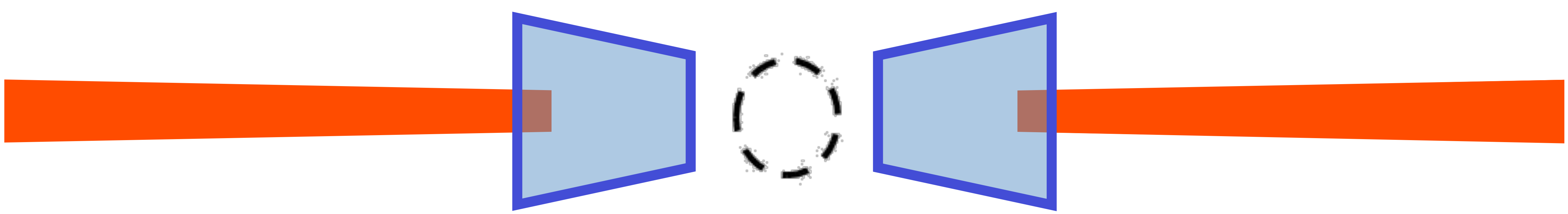

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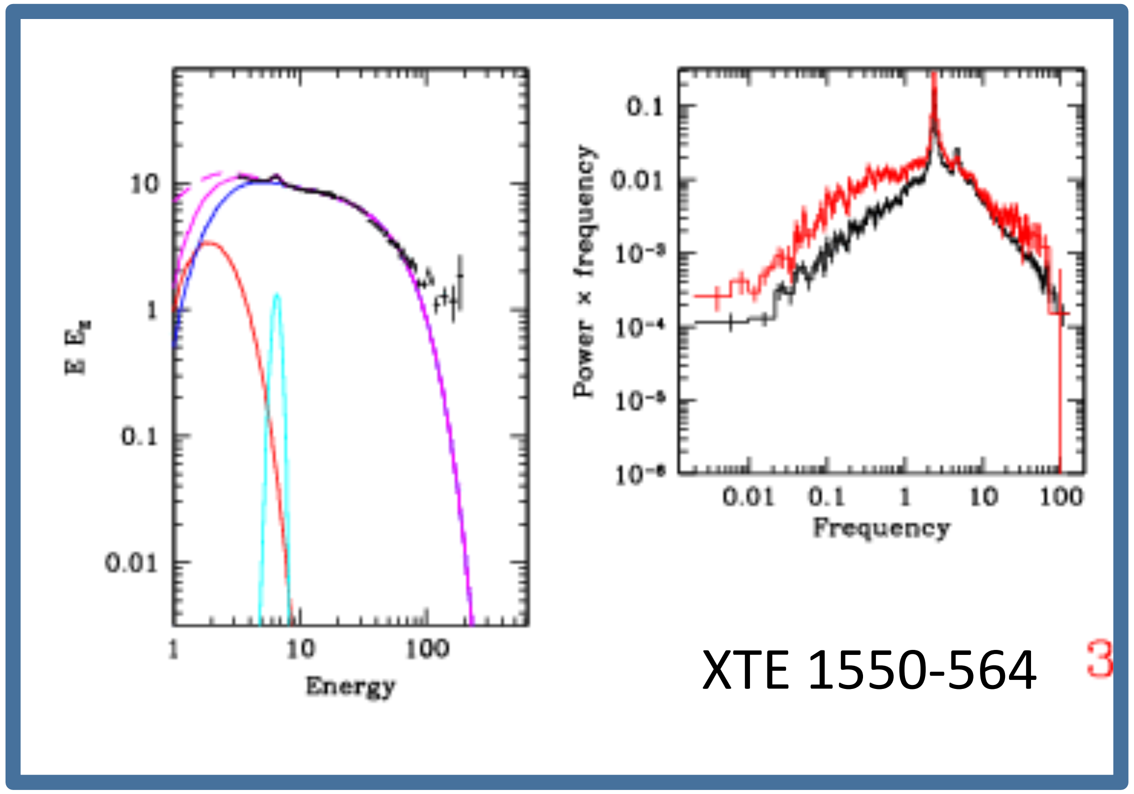

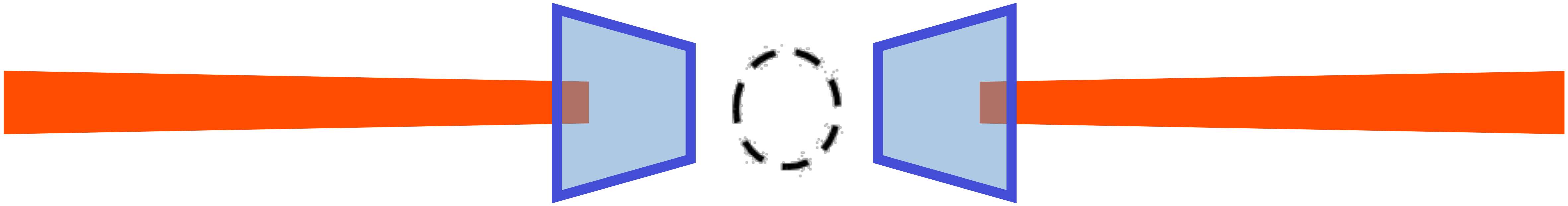

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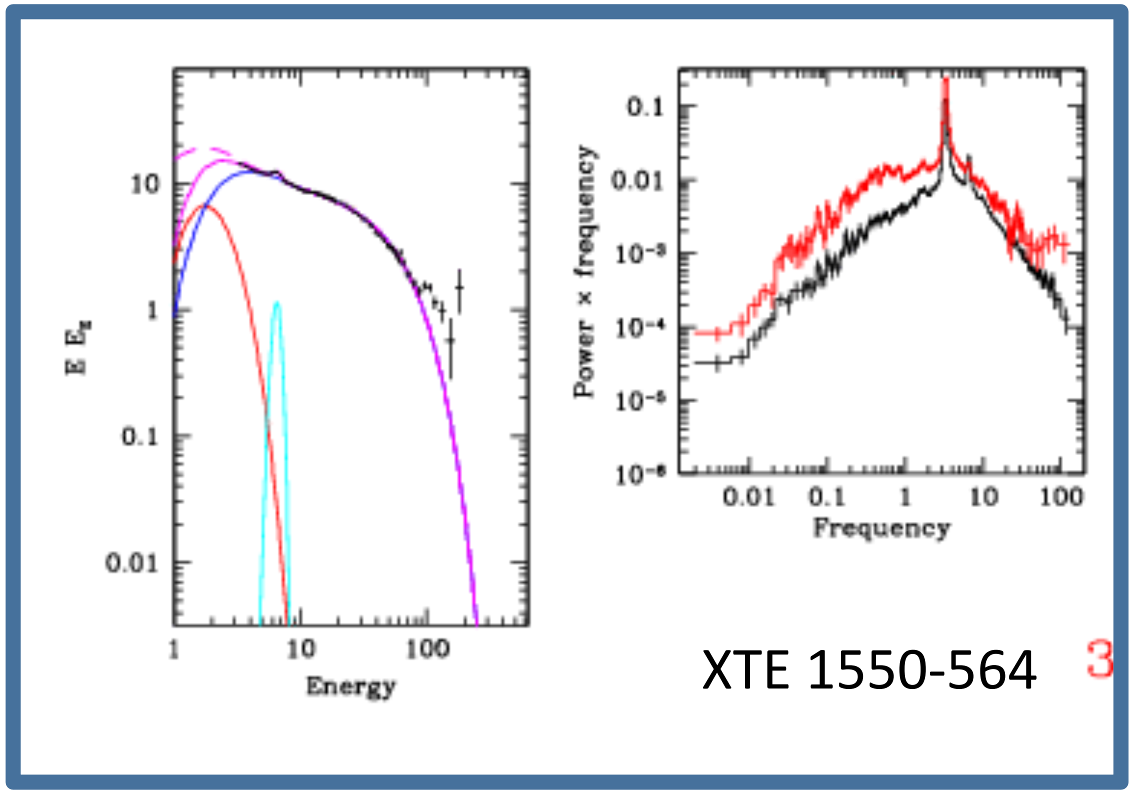

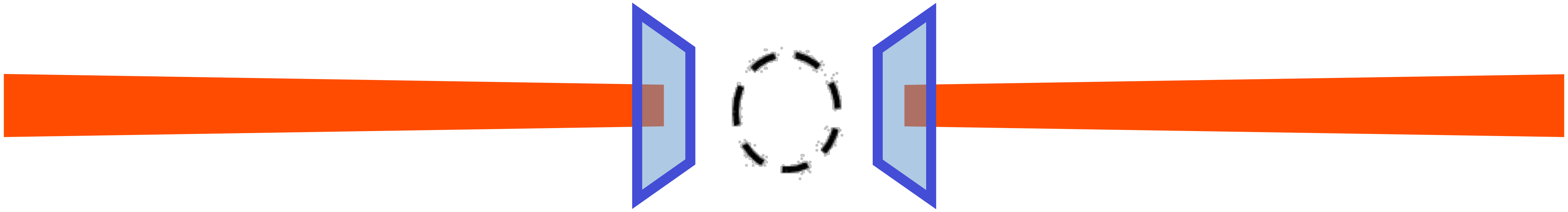

Moving truncation radius varies the number of seed photons seen by the flow

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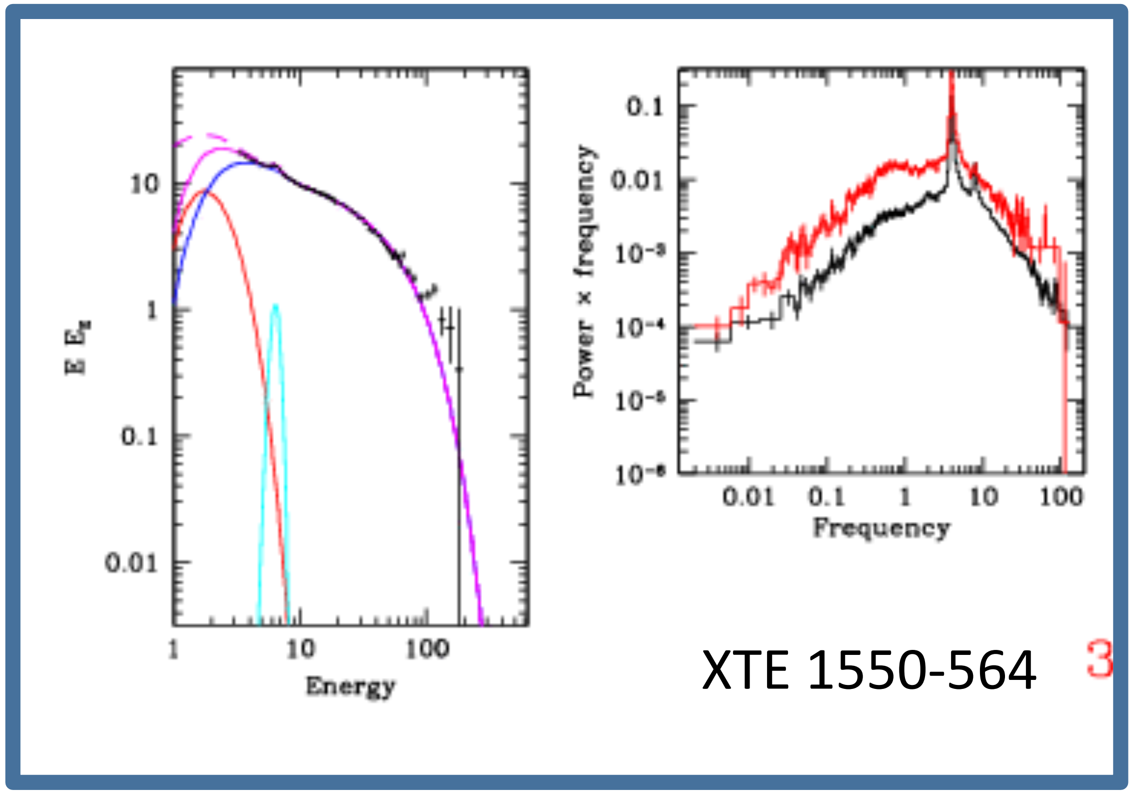
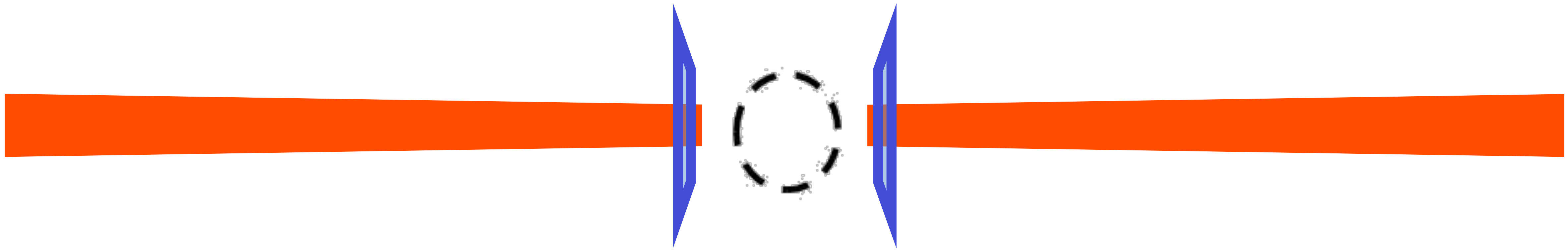
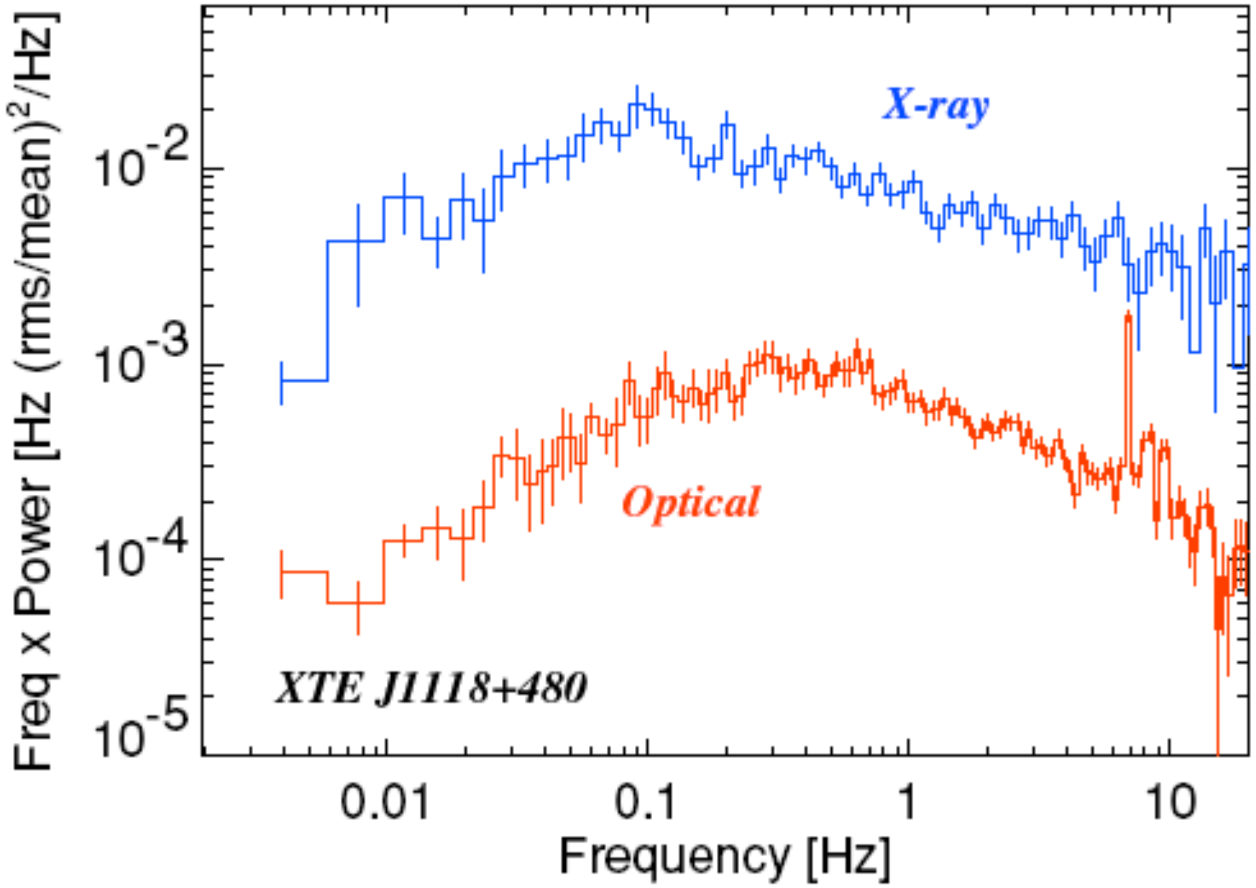


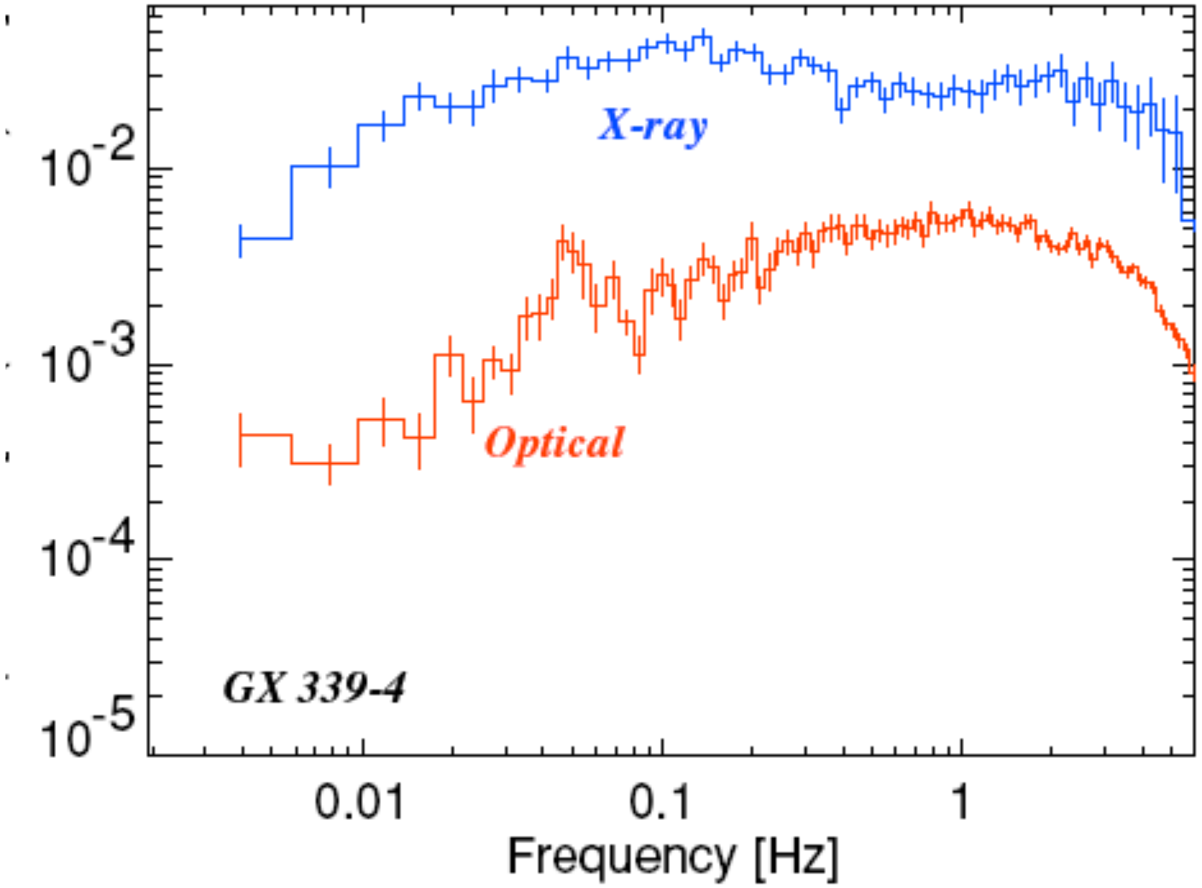


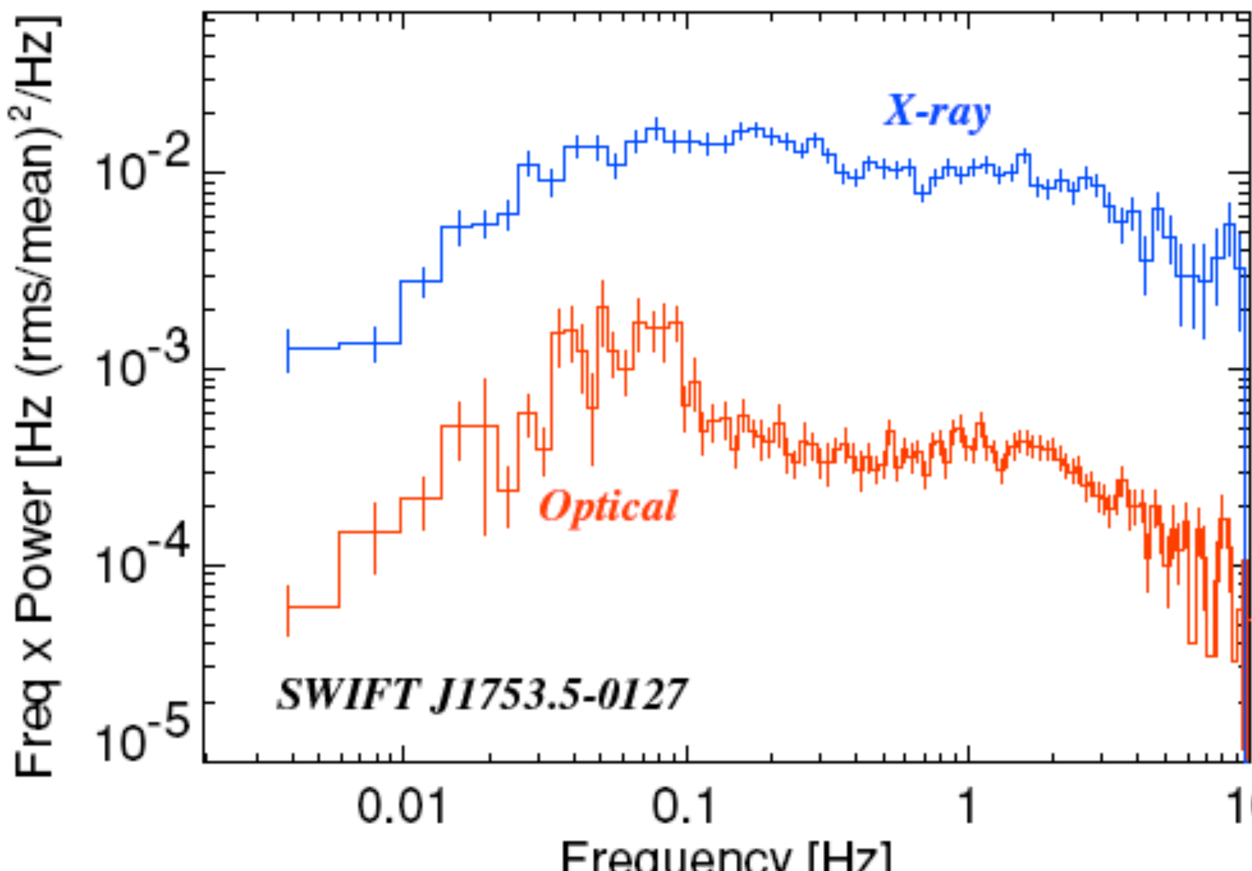
Moving truncation radius varies the number of seed photons seen by the flow

Rapid Optical variability in several XRBs



r.m.s^2 normalized
(e.g. Belloni+90)





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

(Gandhi 2009)

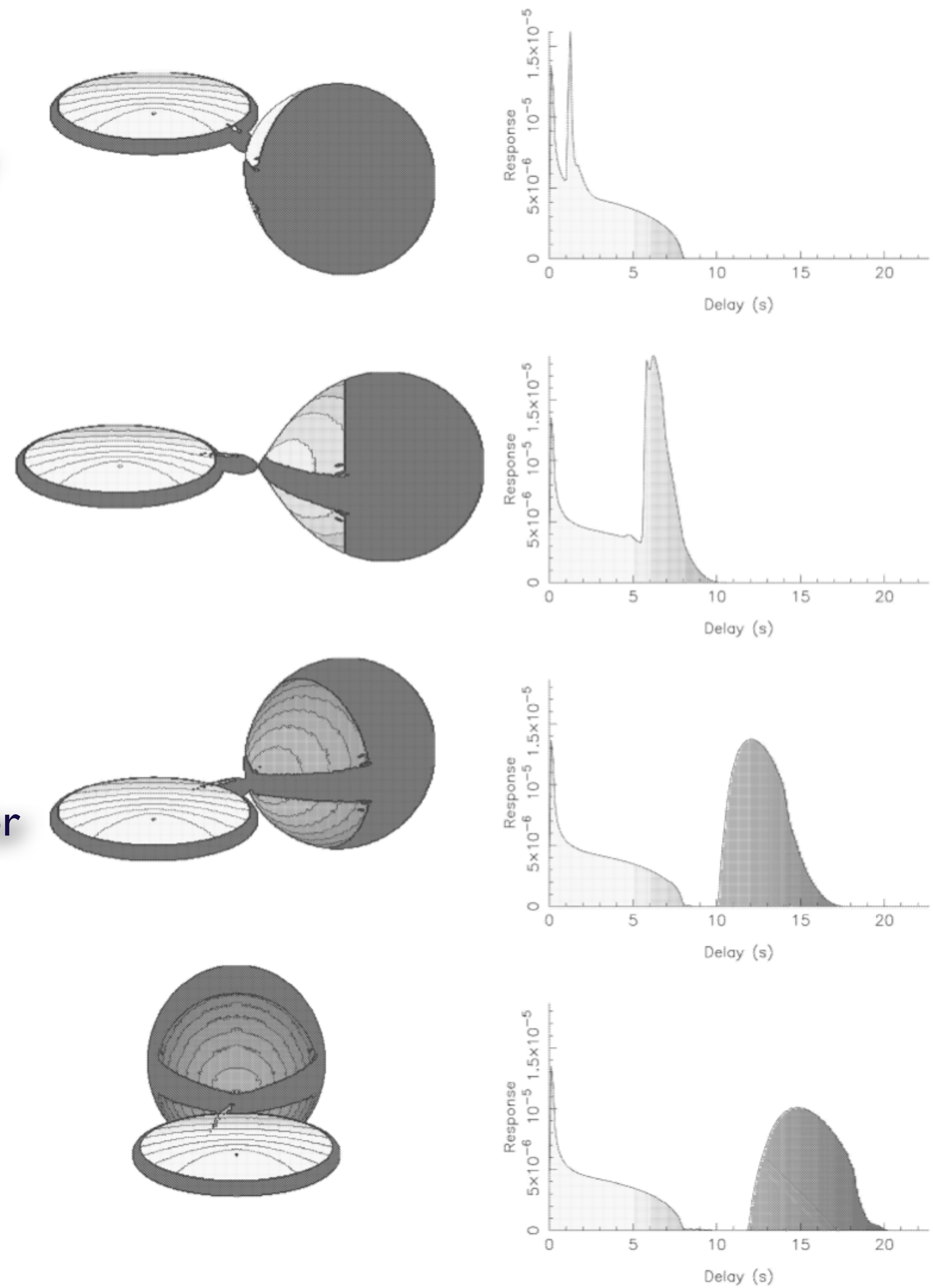
Origin of fast optical variability: echoes of X-ray variability ?

- Reprocessing of X-ray illumination in outer accretion disc and conpanion
- Optical band responds linearly to X-ray fluctuations:

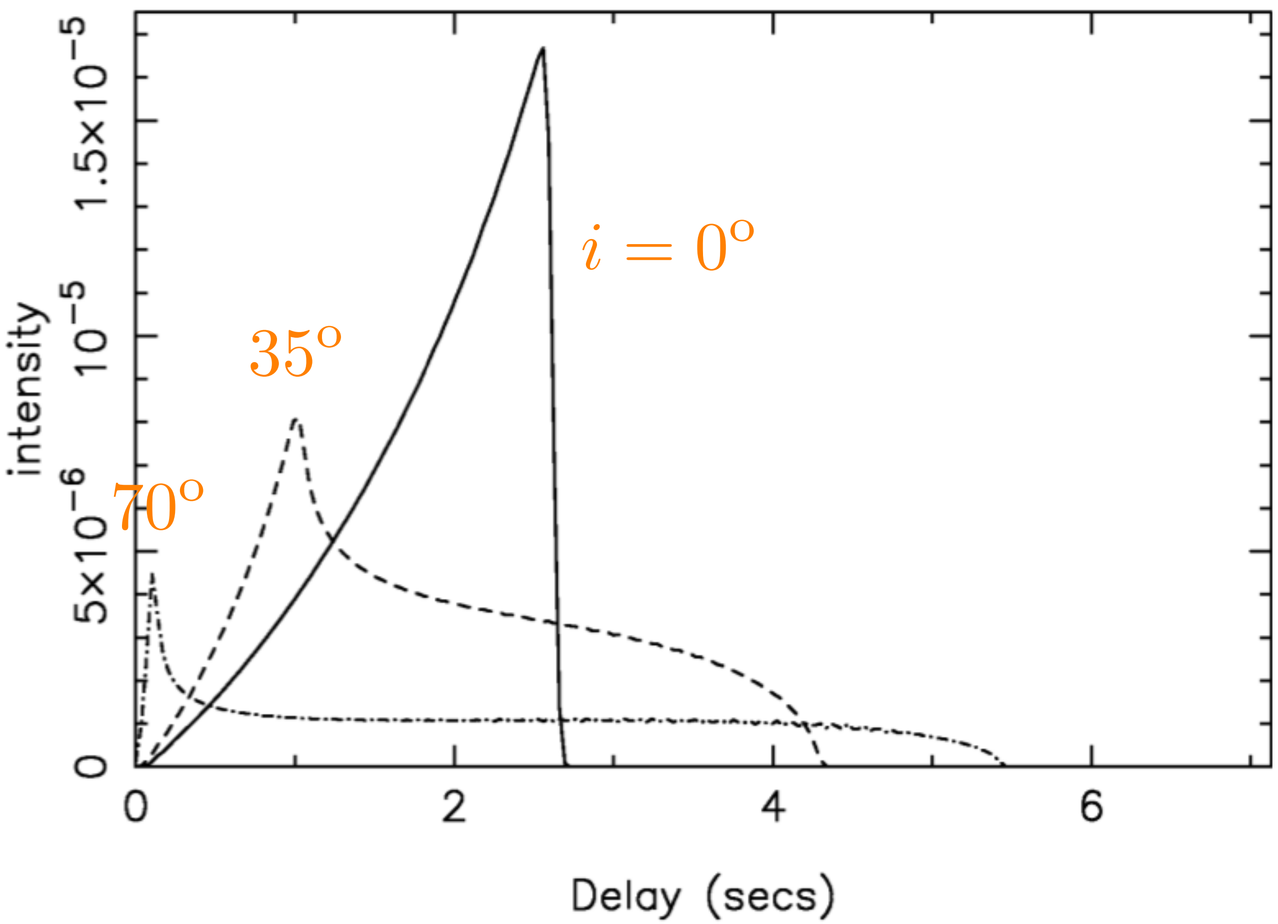
$$\delta o(t) = \int_{-\infty}^{t} \delta x(t')r(t-t')dt'$$

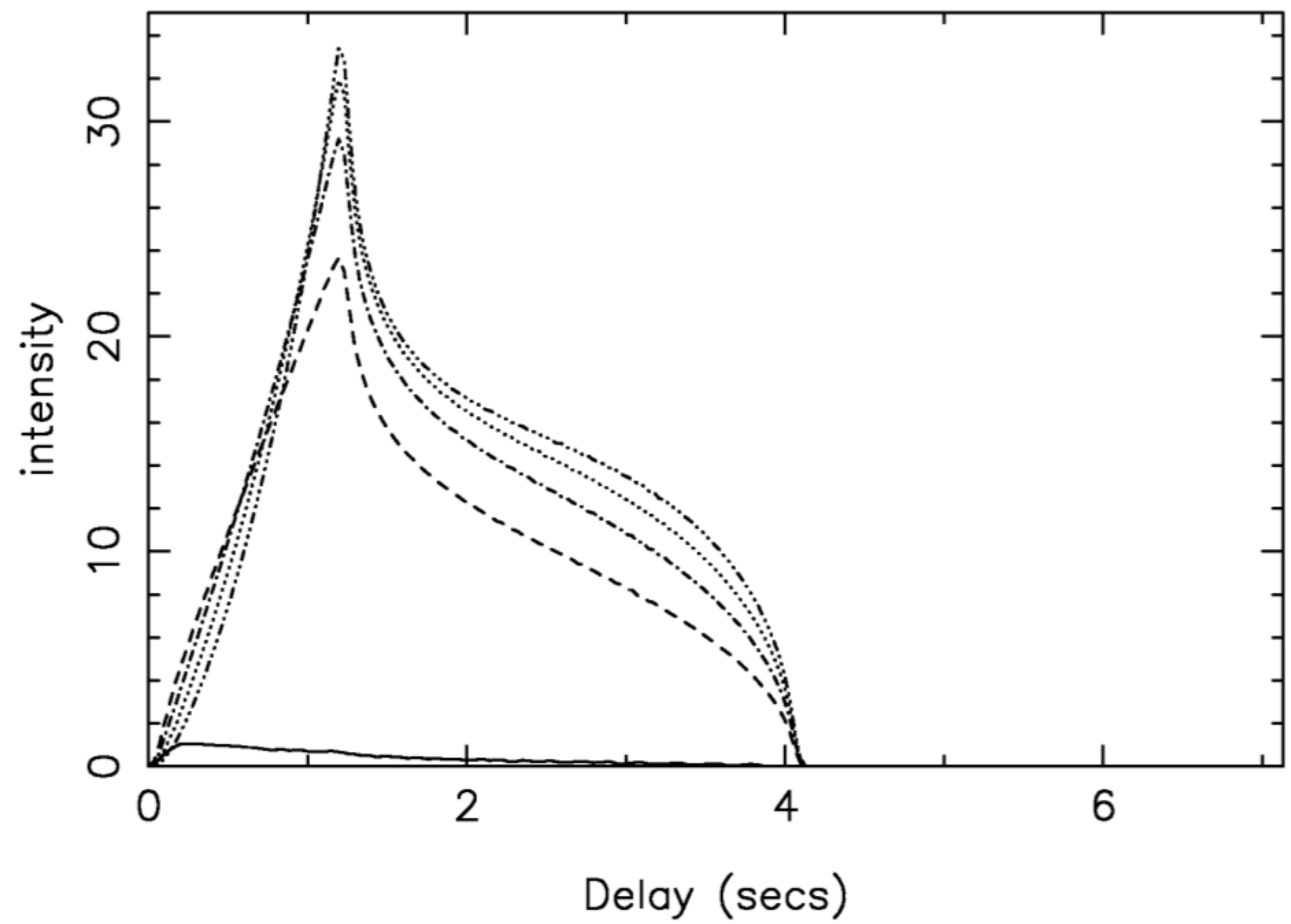
- Response function r can be calculated for a given geometry

O'Brien et al. 2002



Origin of fast optical variability: echoes of X-ray variability ?





- Predictions of reprocessing model:

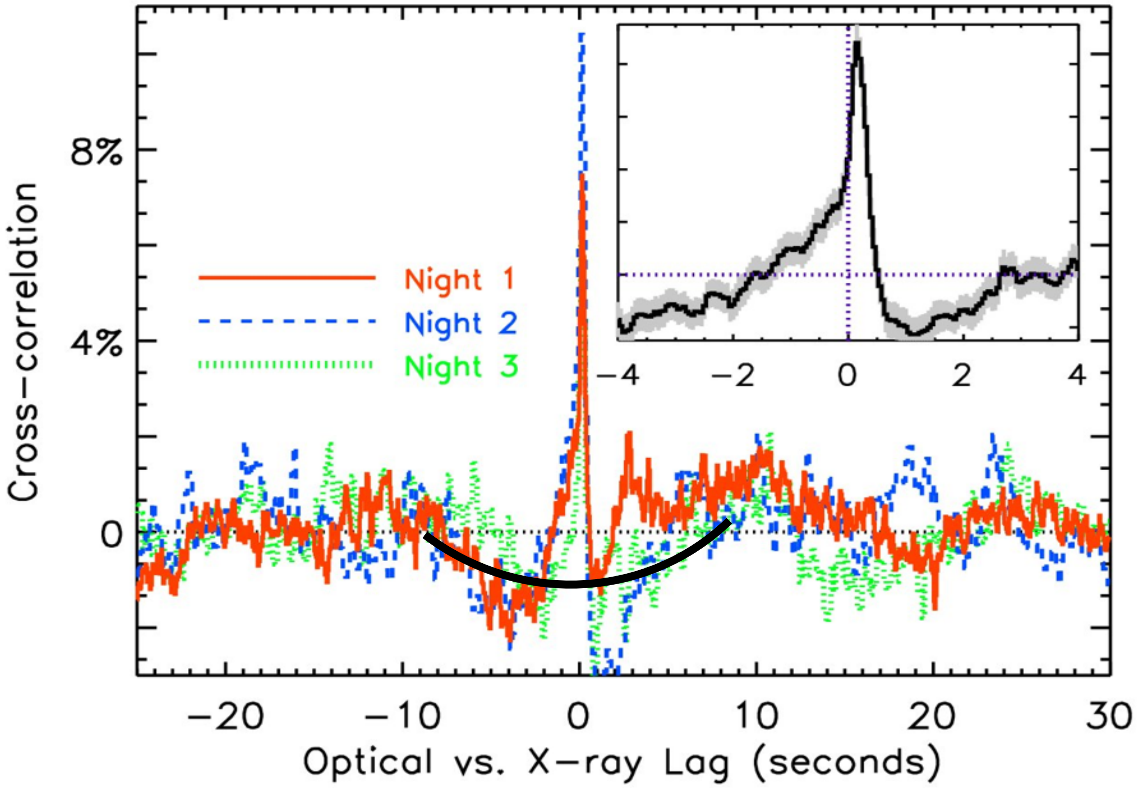
  - Optical correlated with the X-ray flux
  - Optical lags by ~ 1 s
  - Optical varies on longer times scales than X-ray variability: sub-second time scale variability is strongly damped.

- Reprocessing is difficult to avoid, and yet these predictions are not always verified

O'Brien et al 2002

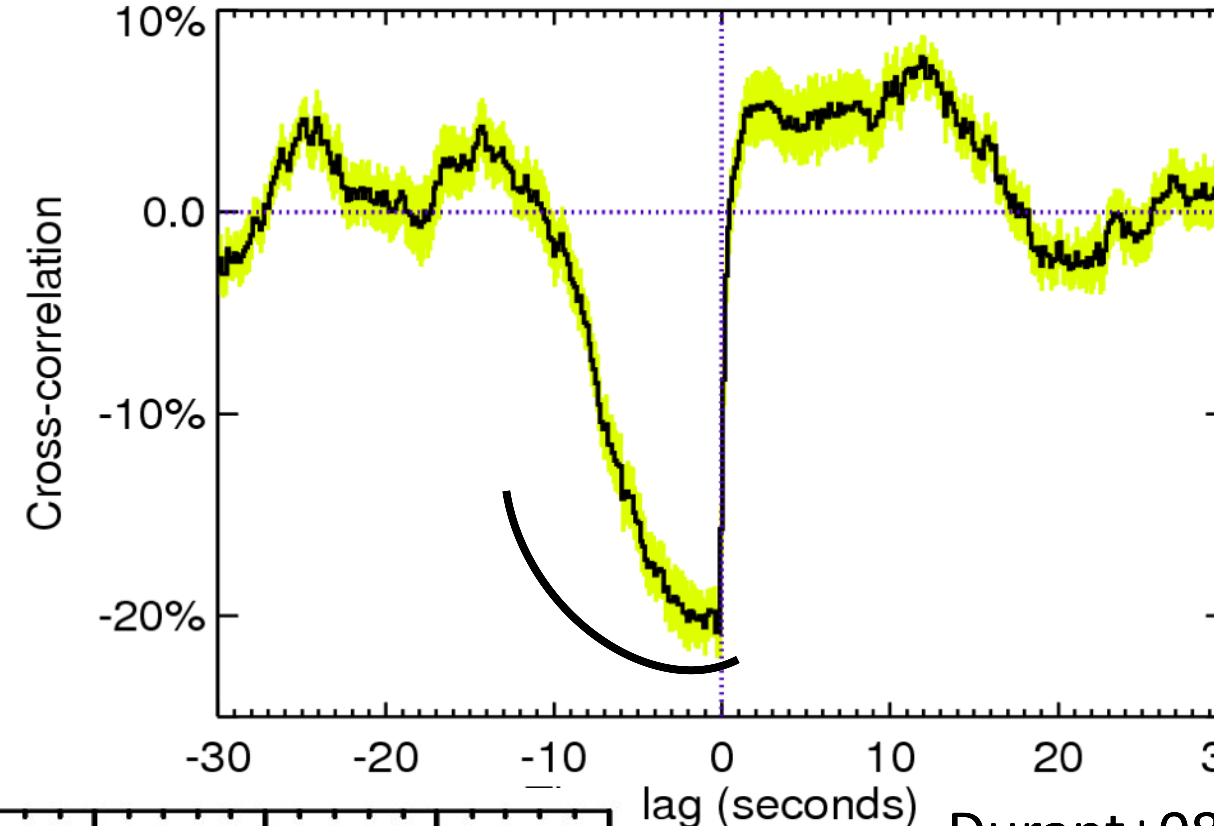
Observed Opt/X-ray cross correlation functions

GX 339-4

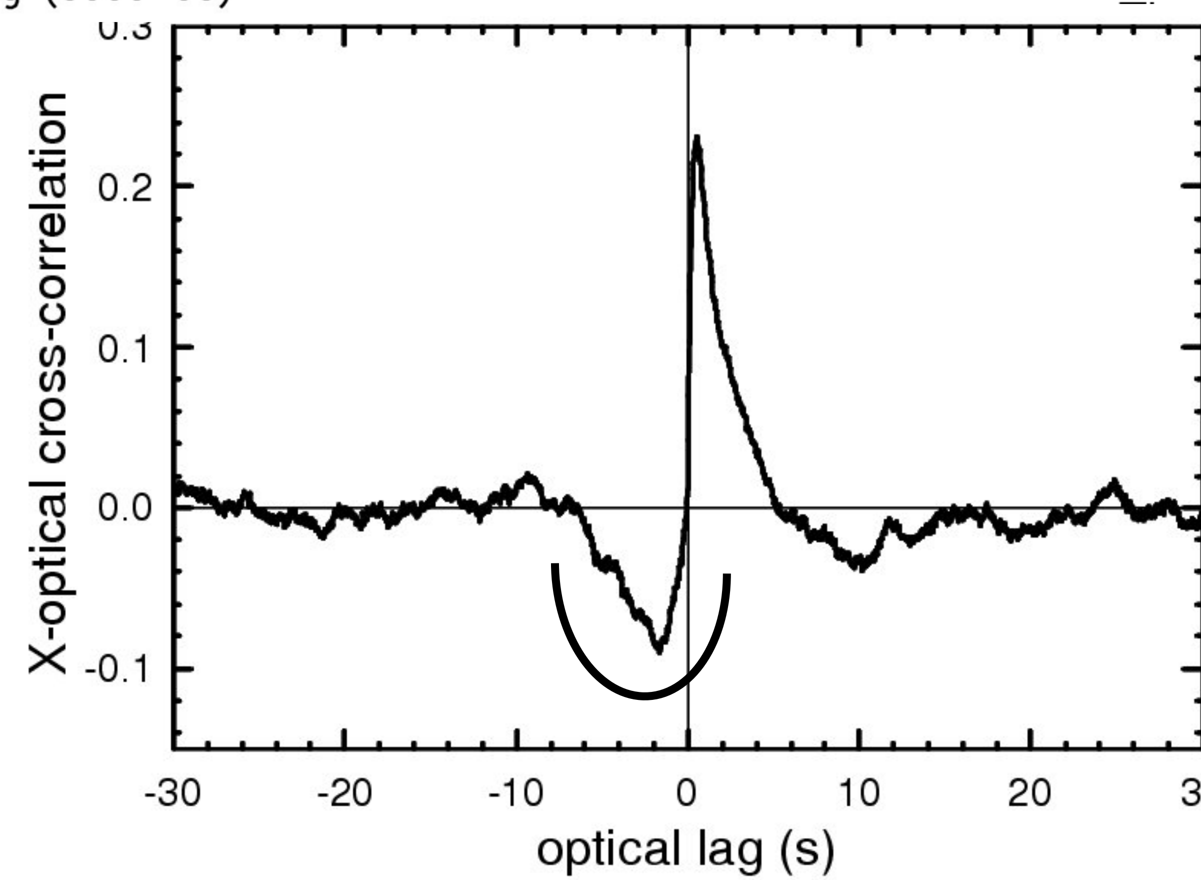


Gandhi+08, 10

Swift J1753.5-0127



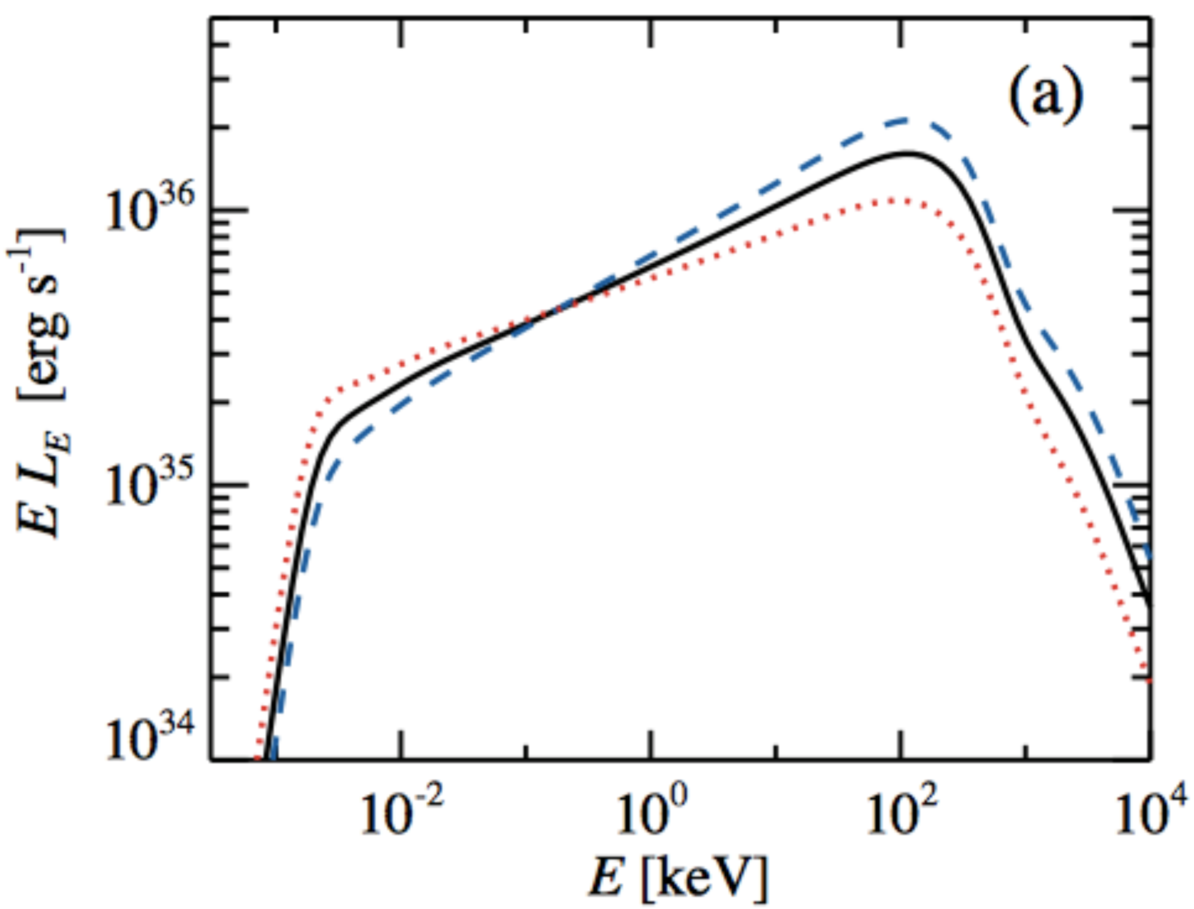
Durant+08, 09
Hynes+09

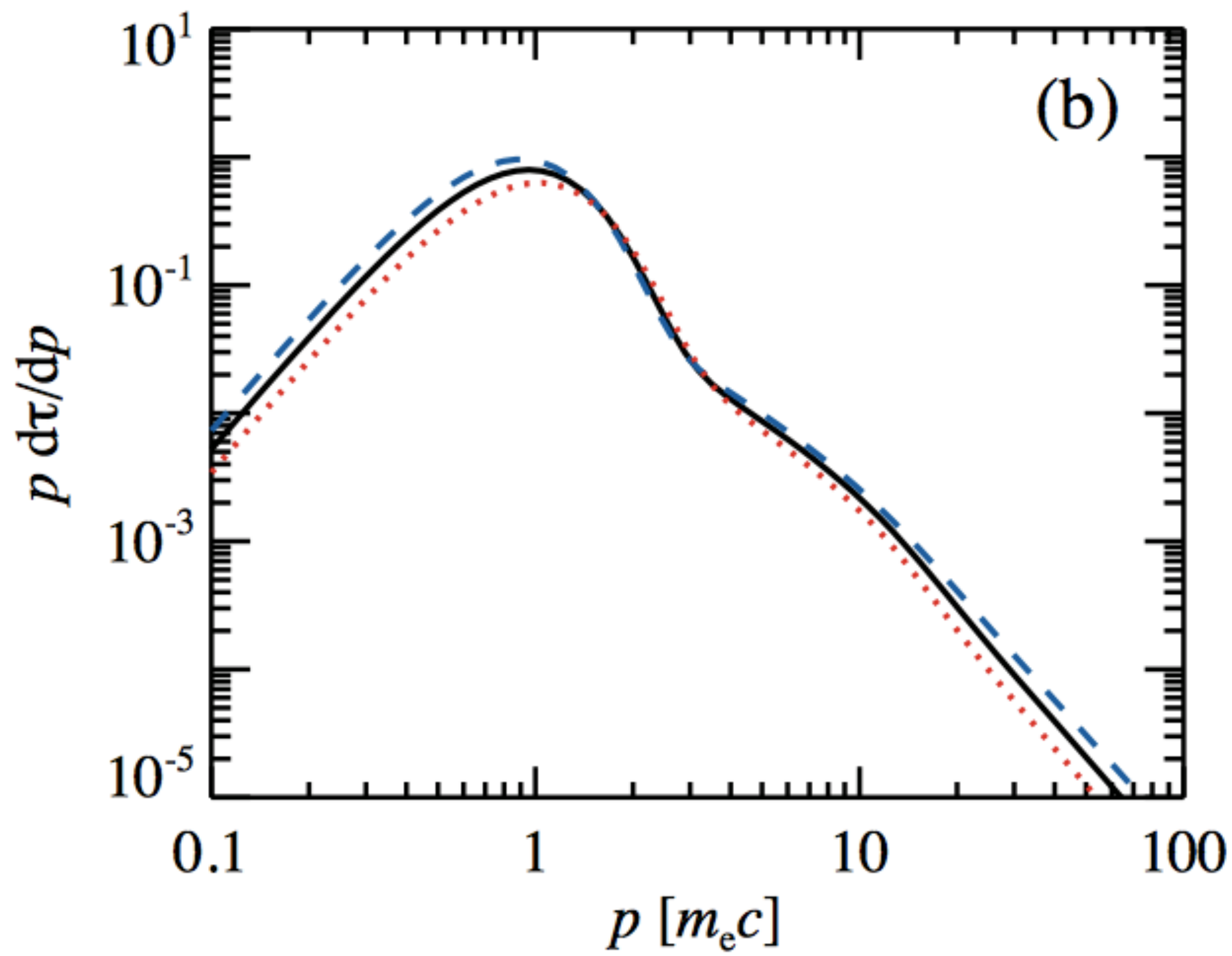


XTE J1118+480:
Kanbach+01,
Hynes+03

P. Gandhi

Fast optical variability from hot accretion accretion flow

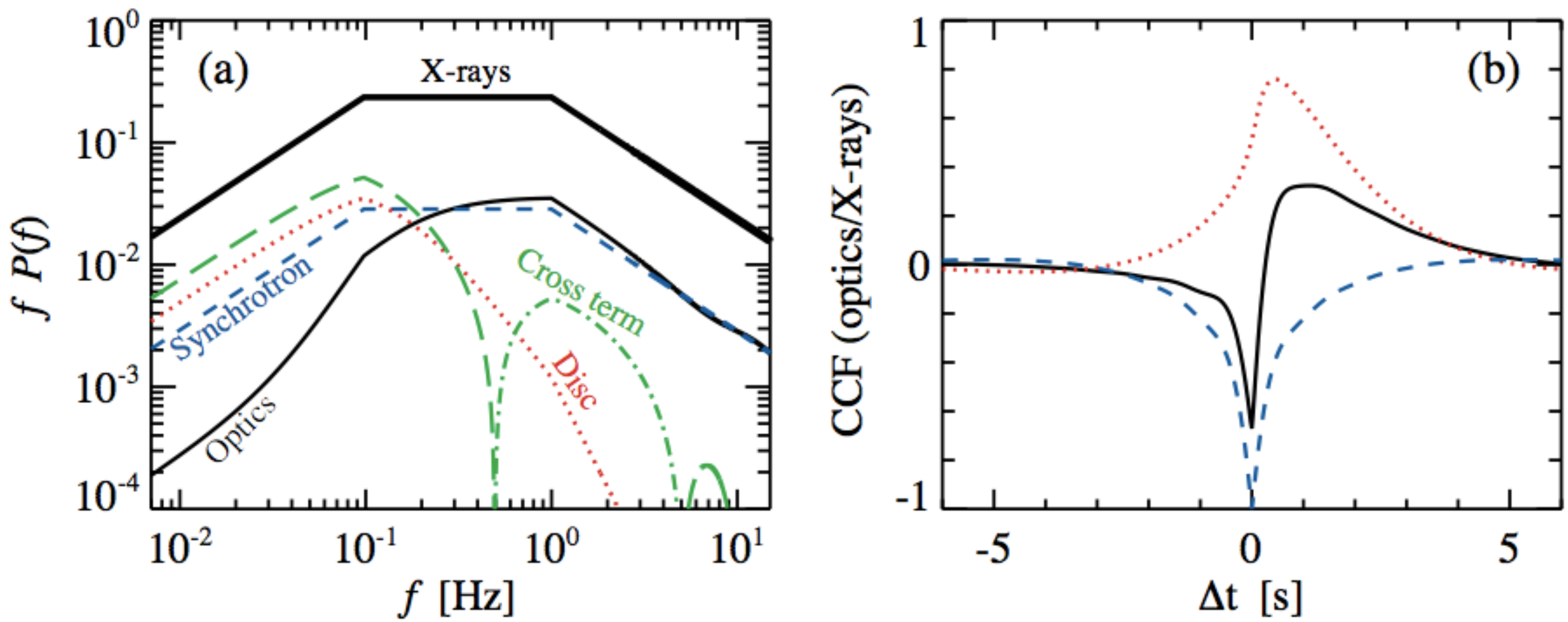




- Hybrid hot flow model: $L \propto \dot{m}$ $\tau \propto \dot{m}$
- Assuming
- Moderate fluctuations of $\dot{m}$ leads to ANTI-corellation between X-rays and optical

Poutanen & Veledina 2014

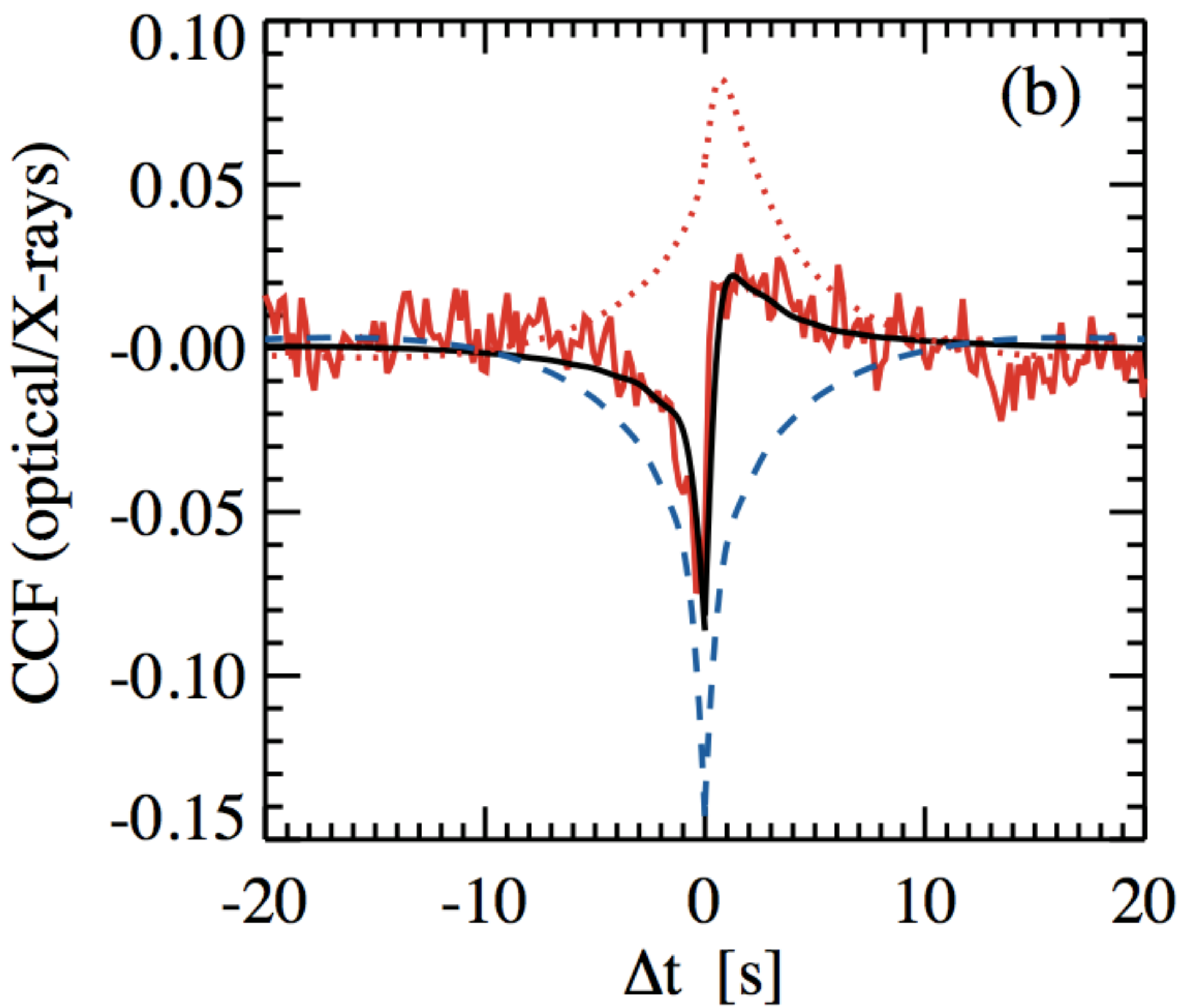
Model combining disc reprocessing and synchrotron radiation



- Fourrier transform of optical lc: $$O(f) = S(f) + D(f) \propto X(f)\left[-1 + r_{\rm ds} R(f)\right]$$
- Optical power spectrum: $$P_{\rm O}(f) \propto P_{\rm X}(f)\left\{1 + r_{\rm ds}^2 \left|R(f)\right|^2 - 2 r_{\rm ds} {\rm Re}\left[R(f)\right]\right\}$$

Poutanen & Veledina 2014

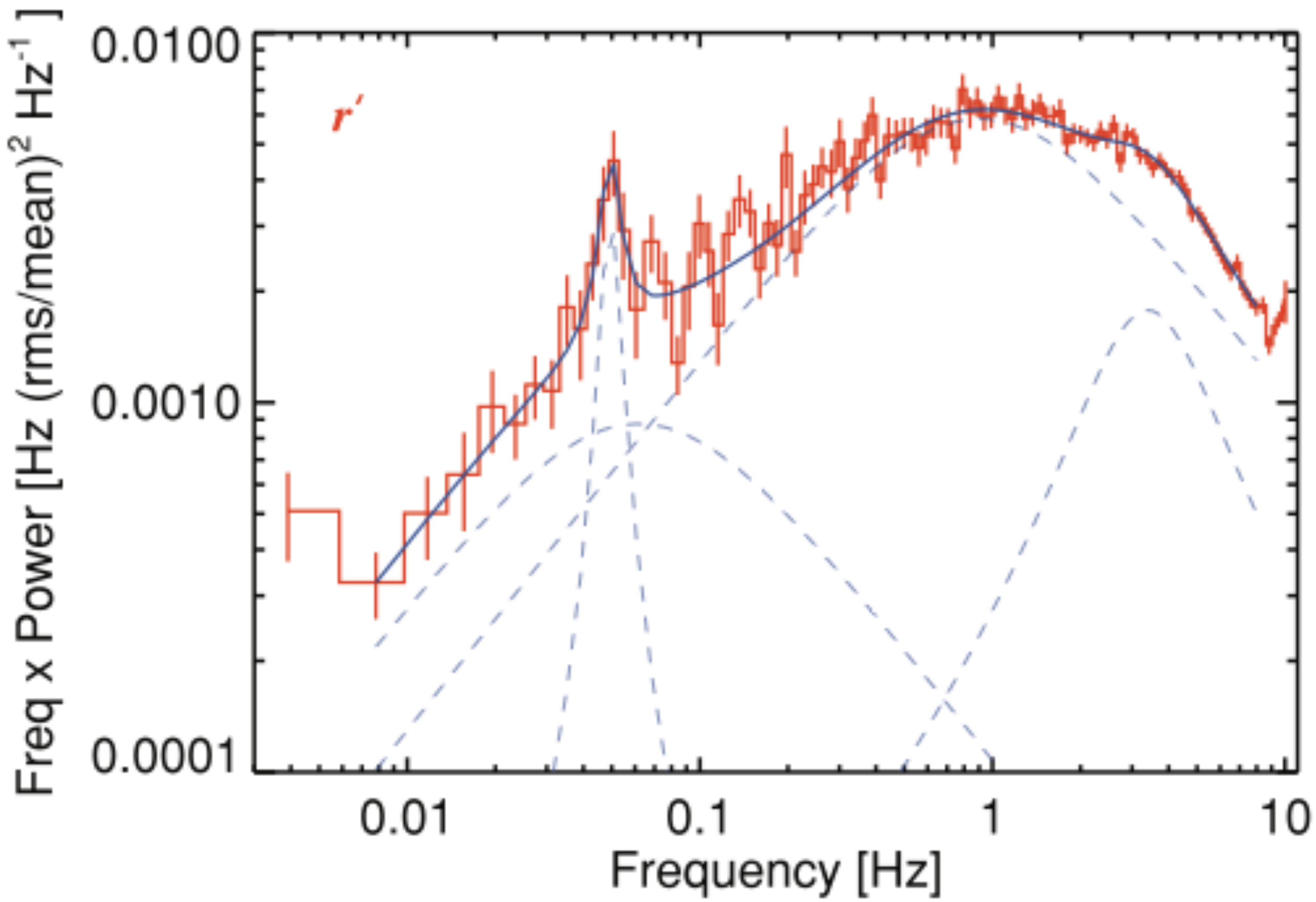
Model combining disc reprocessing and synchrotron radiation



Swift J1753.5−0127 in 2008

Poutanen & Veledina 2014

Optical QPOs

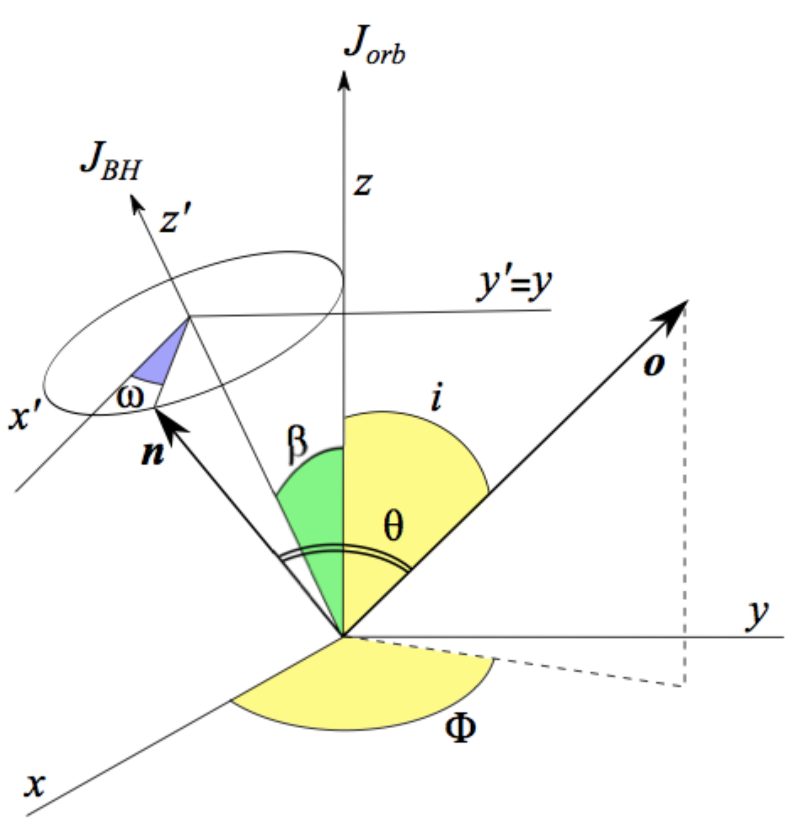


Gandhi et al. 2010

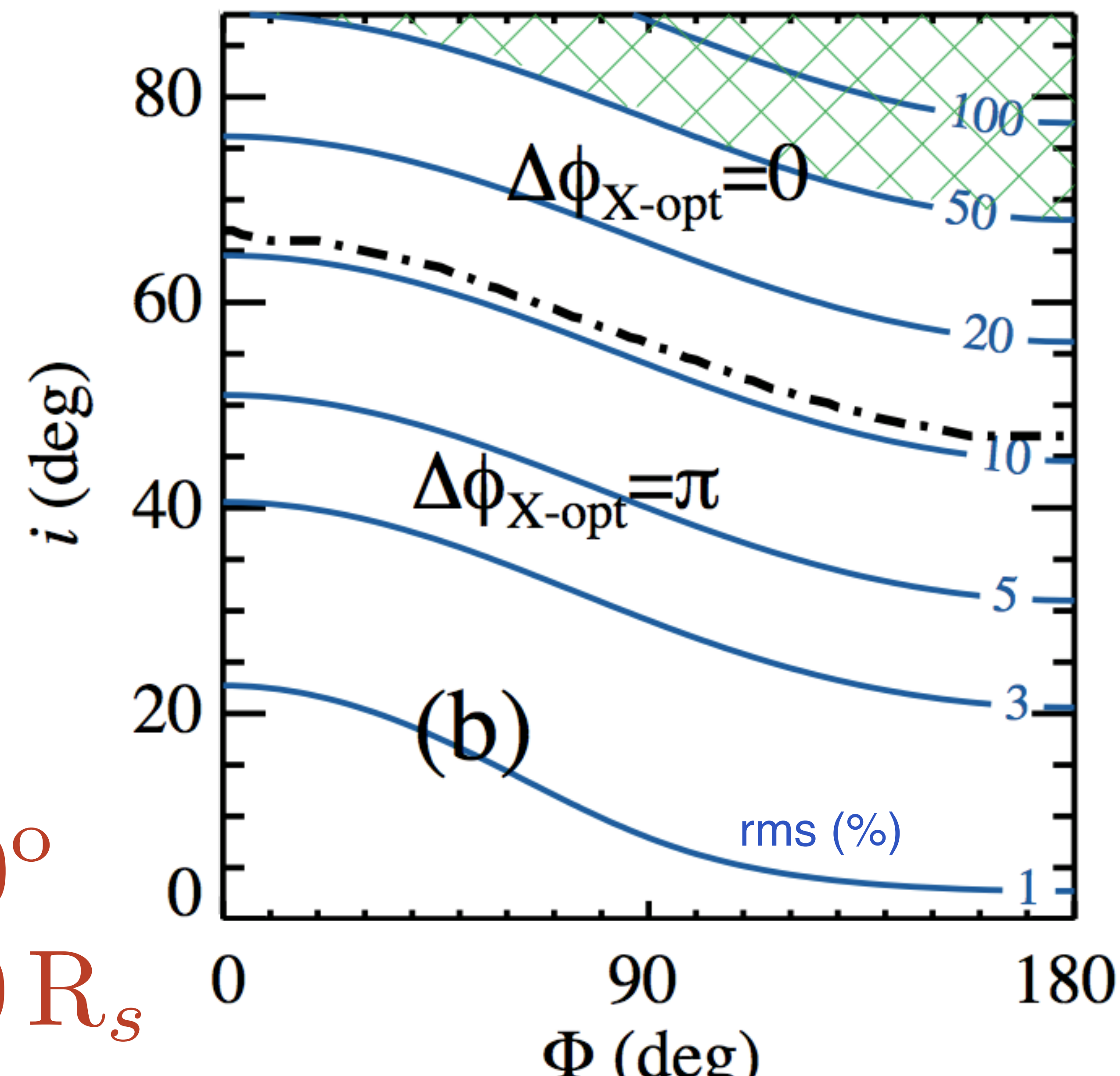
- Optical LF QPOs detected in several hard state sources with RMS~ 3-10 %
- Sometimes associated to X-ray QPO (but not always)

Optical QPOs from LT precession

- Dominant contribution to synchrotron flux comes from partially self absorbed synchrotron.
- Effective synchrotron self-absorption optical depth depends on viewing angle. Specific synchrotron intensity is modulated: $I_s \propto 1 - \exp\left[-\tau / \cos\theta(t)\right]$

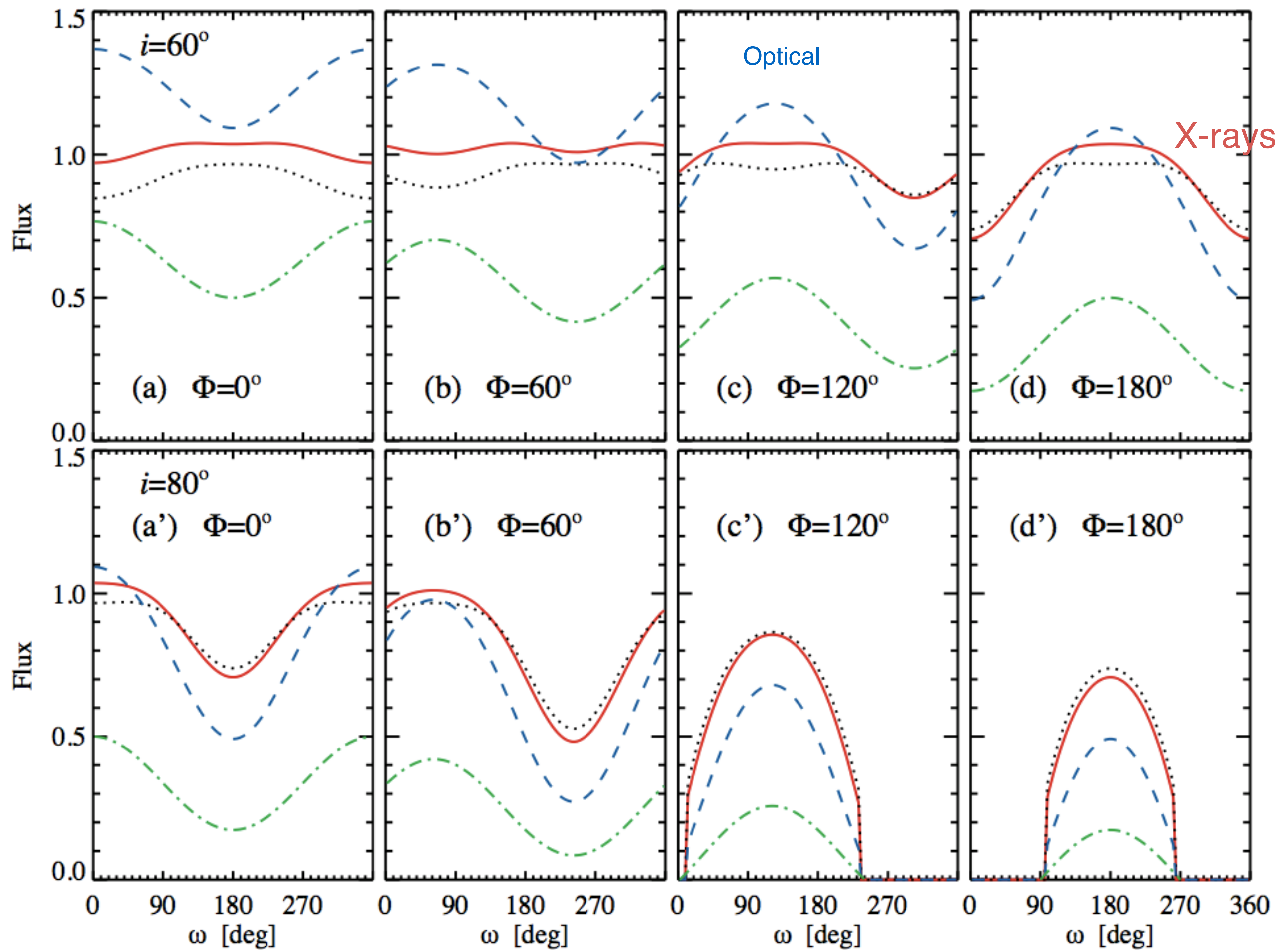


$\beta = 10^{\circ}$
$R = 30\,\mathrm{R}_s$



Veledina et al. 2014

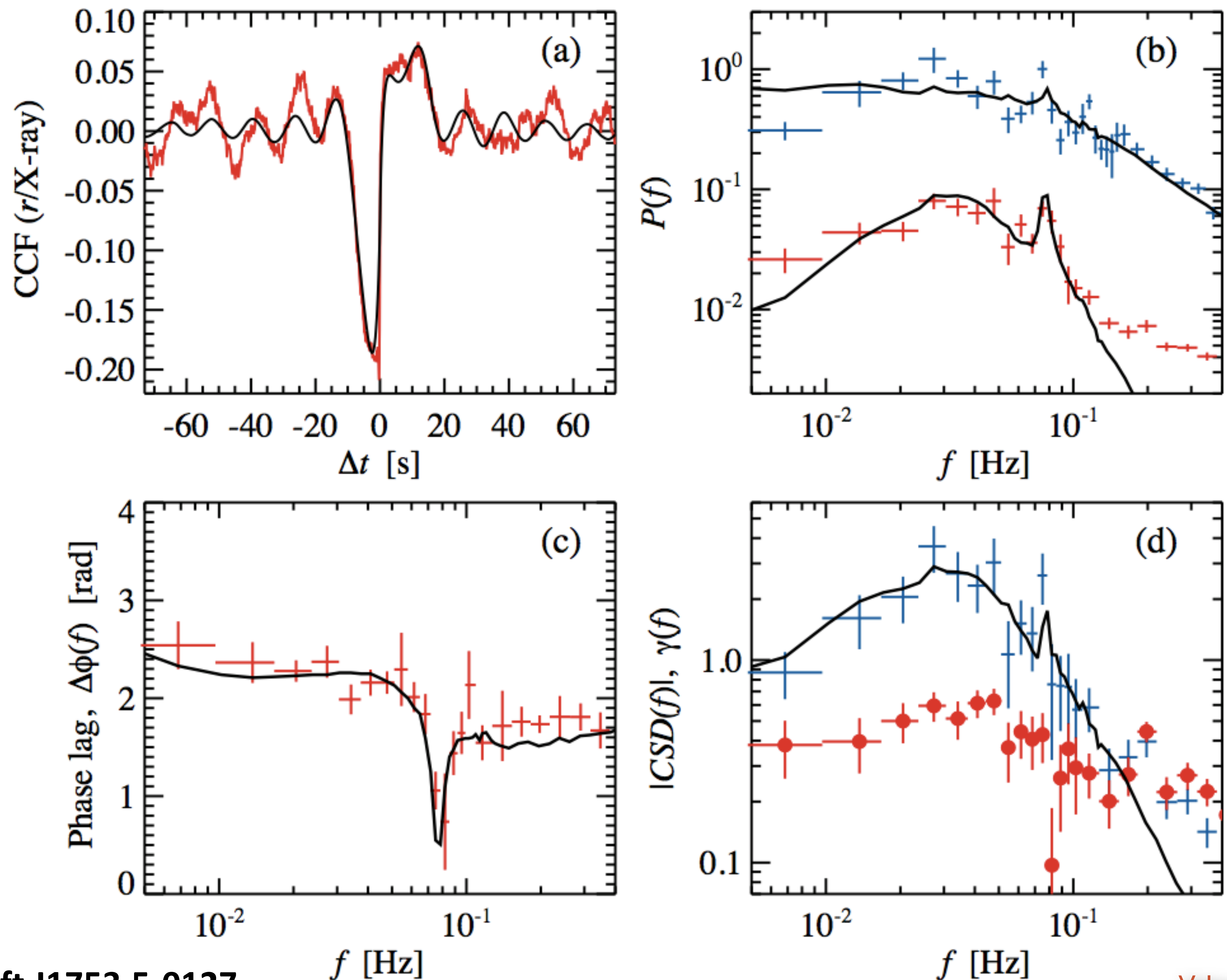
Optical QPOs from LT precession



Simple prescription for angular dependence of hot flow Comptonized radiations allows one to estimate phase lag between X-ray and optical QPO:

Veledina et al. 2014

QPO and broadband noise model correlated variability



Swift J1753.5-0127

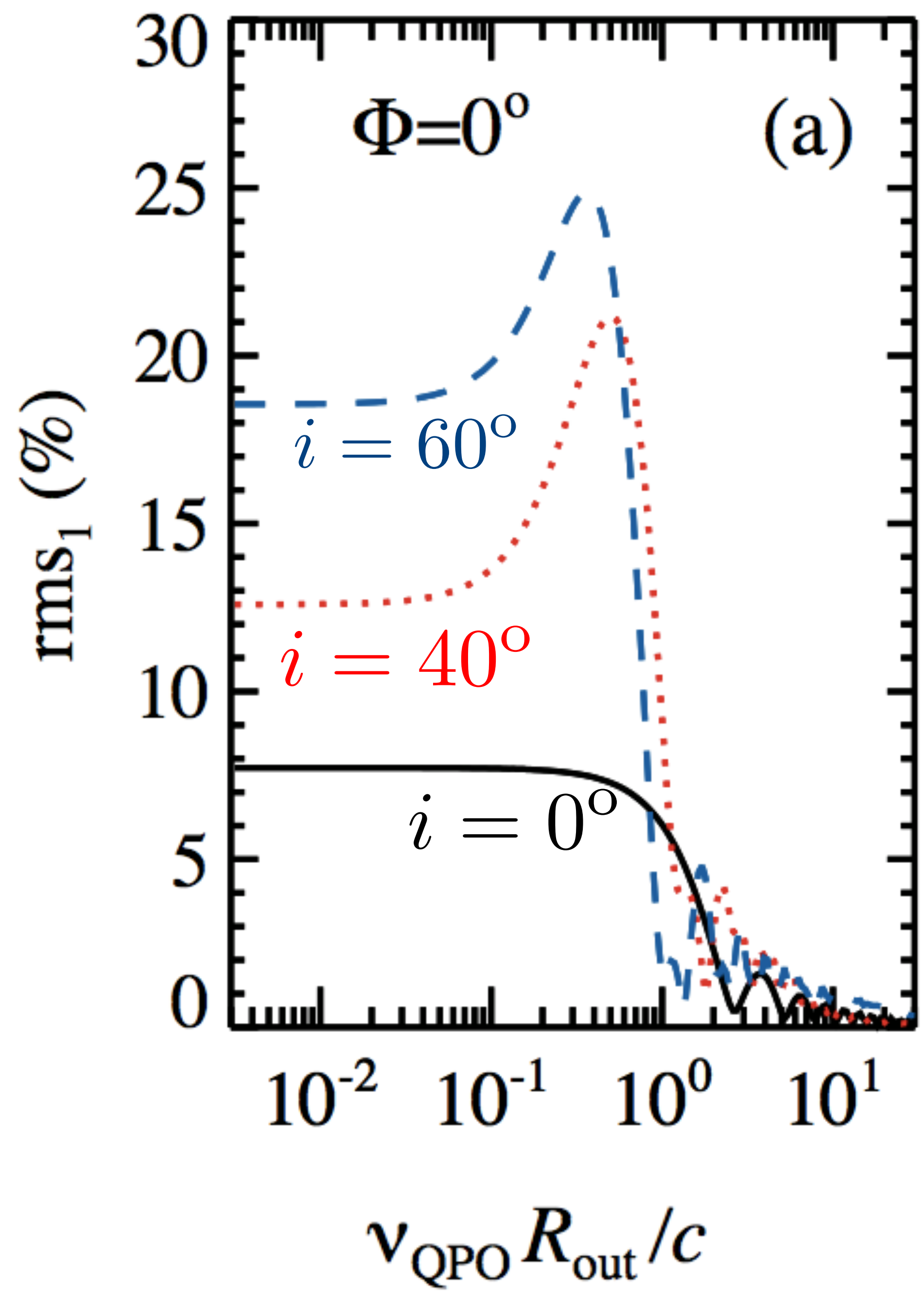
Veledina et al. 2015

Optical QPOs from disc reprocessing

- Varying disc illumination of outer accretion disc due to LT precession of the hot flow also leads to modulation of reprocessed radiation

- QPO only if precession period longer than light crossing time of disc:

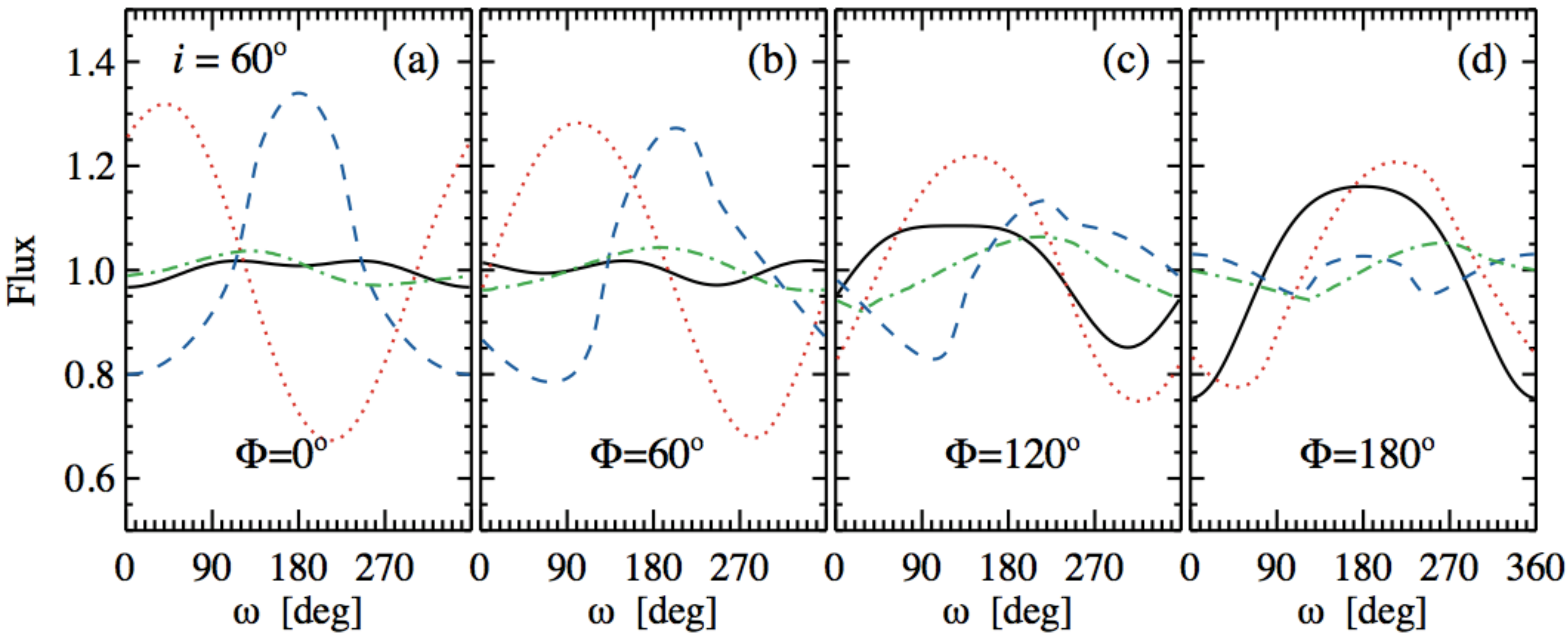
$$\nu_{\mathrm{QPOmax}} \simeq \frac{c}{R_{disc}} \simeq \frac{2}{3}\left(\frac{P_{\mathrm{orb}}}{1\,\mathrm{hr}}\right)^{-2/3}\left(\frac{M}{10\,M_{\odot}}\right)^{-1/3} \quad \mathrm{Hz}$$



Veledina & Poutanen 2014

Optical QPOs from reprocessing

- Optical QPO wave form (and X-ray/opt phase lag) depends on QPO frequency



Veledina & Poutanen 2014

Conclusions

- Model ingredients:
  - Truncated disc
  - Hot flow with non-thermal electrons
  - Propagation of fluctuations
  - LT precession of hot flow
- Produces:
  - Observed evolution of SED and X-ray PDS in hard state (change in R
  - Observed optical variability and Opt/X-ray correlations