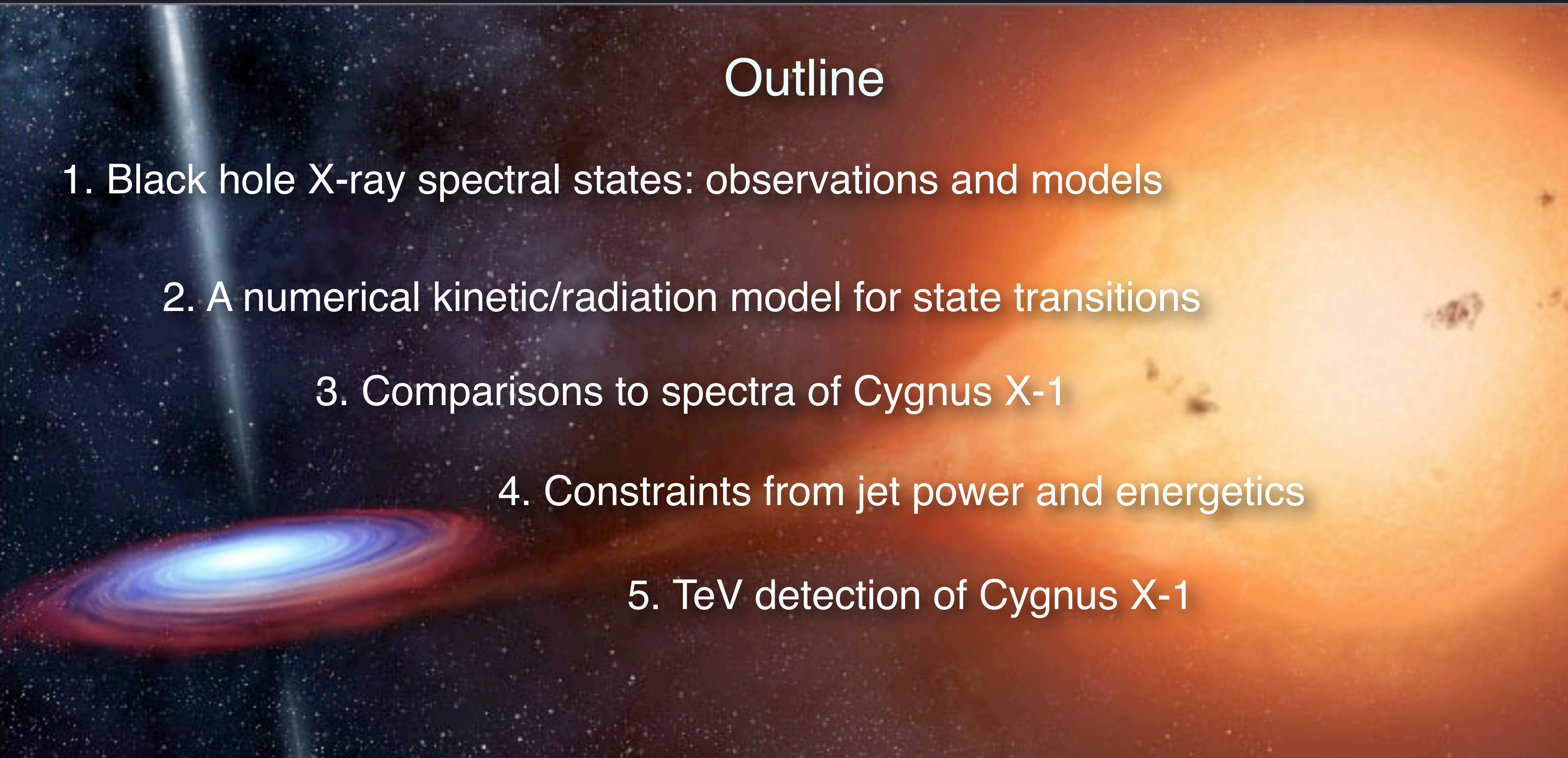
Accretion and ejection in Cygnus X-1

Julien Malzac (CESR/CNRS, Toulouse, France)



Outline

1. Black hole X-ray spectral states: observations and models

2. A numerical kinetic/radiation model for state transitions

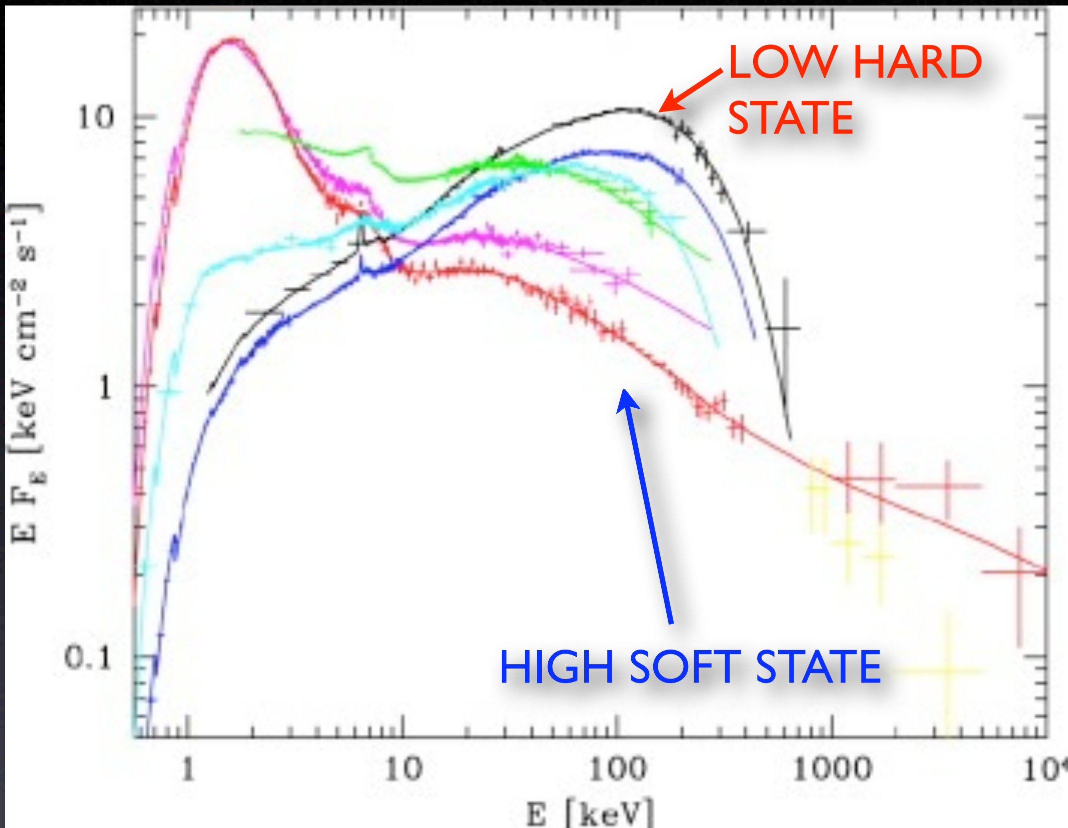
3. Comparisons to spectra of Cygnus X-1

4. Constraints from jet power and energetics

5. TeV detection of Cygnus X-1

High energy emission of accreting black holes

Cygnus X-1



Zdziarski et al 2003

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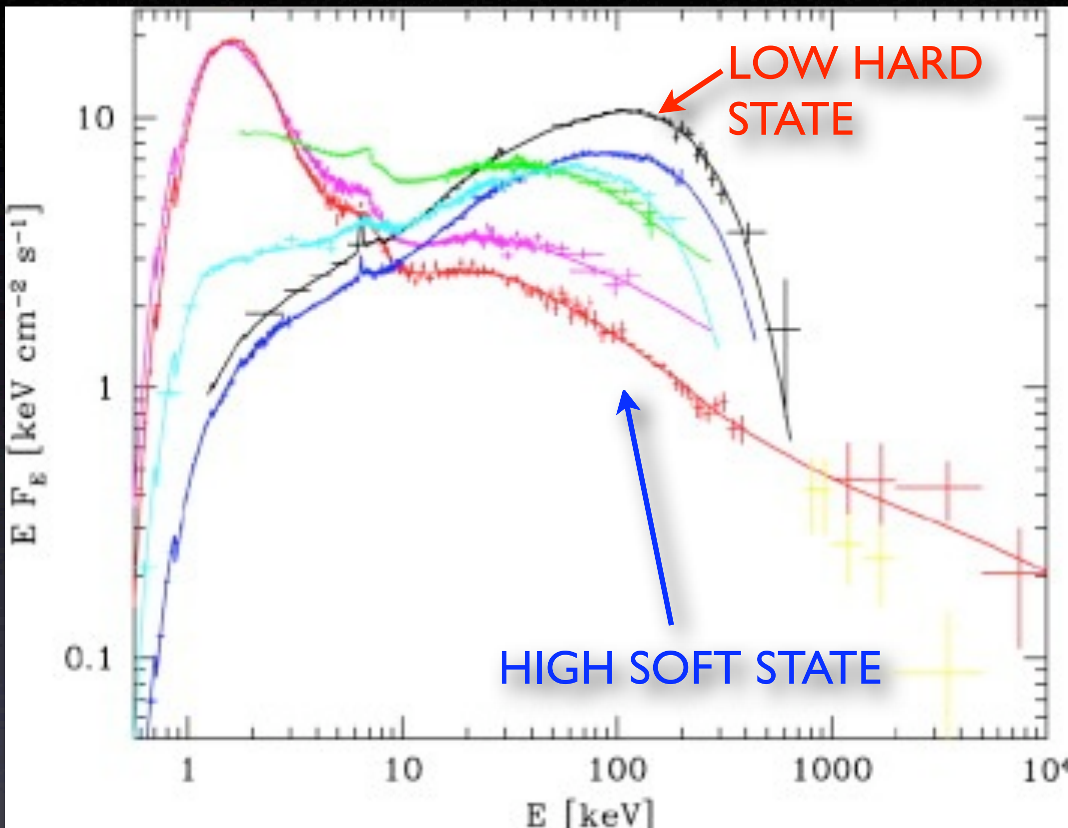

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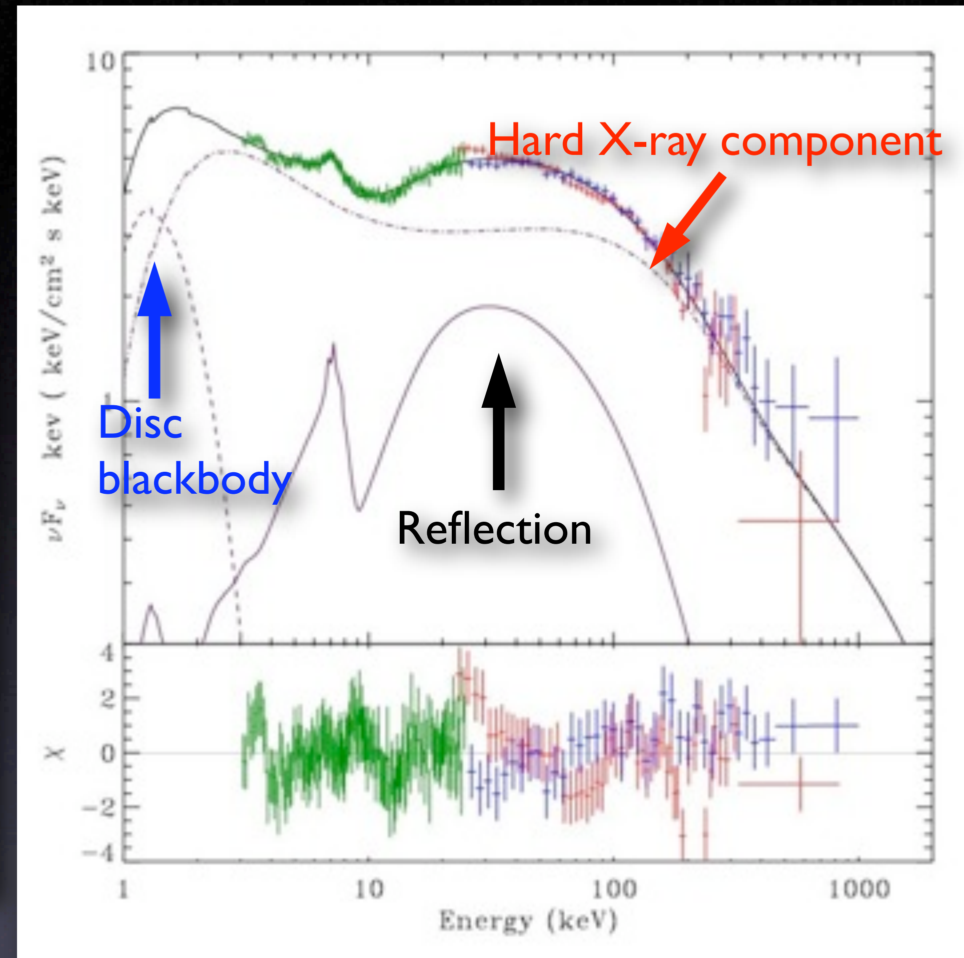
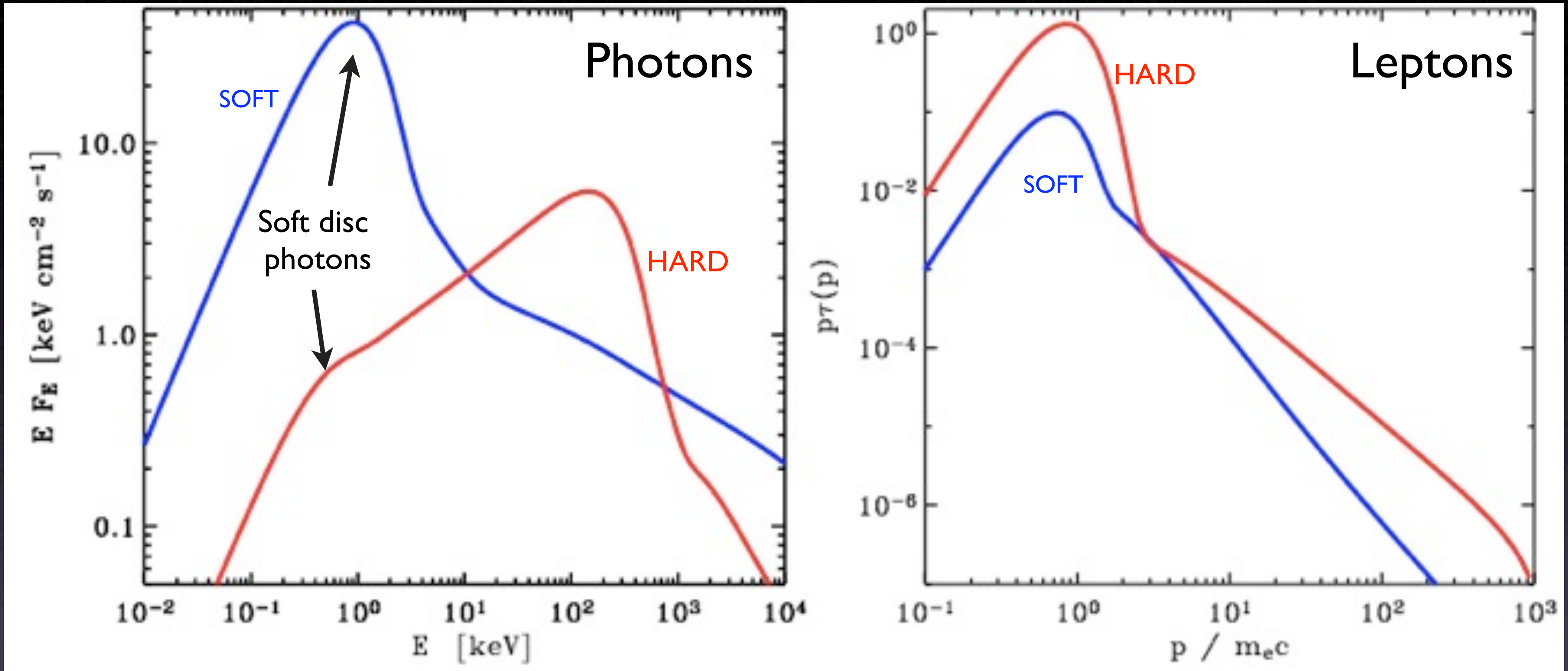


Malzac et al. 2006

LOW HARD STATE: (compact radio jet)
disc blackbody and reflection: weak / Corona: THERMAL Comptonisation

HIGH SOFT STATE:
disc blackbody and reflection: strong / Corona: NON-THERMAL Comptonisation

Hybrid thermal/non-thermal comptonisation models



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

HARD STATE: kT~50-100keV, 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 in soft state possibly due to radiative cooling by disc soft photons

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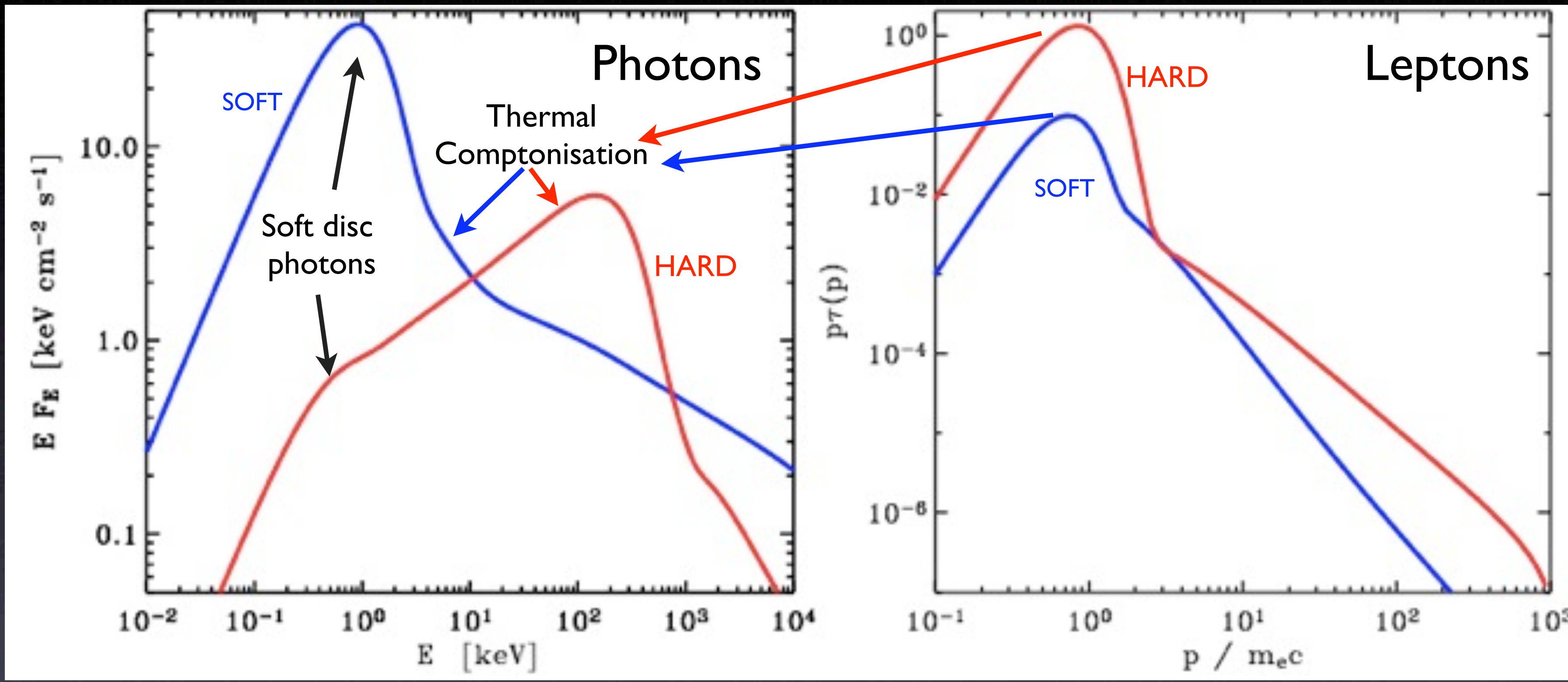

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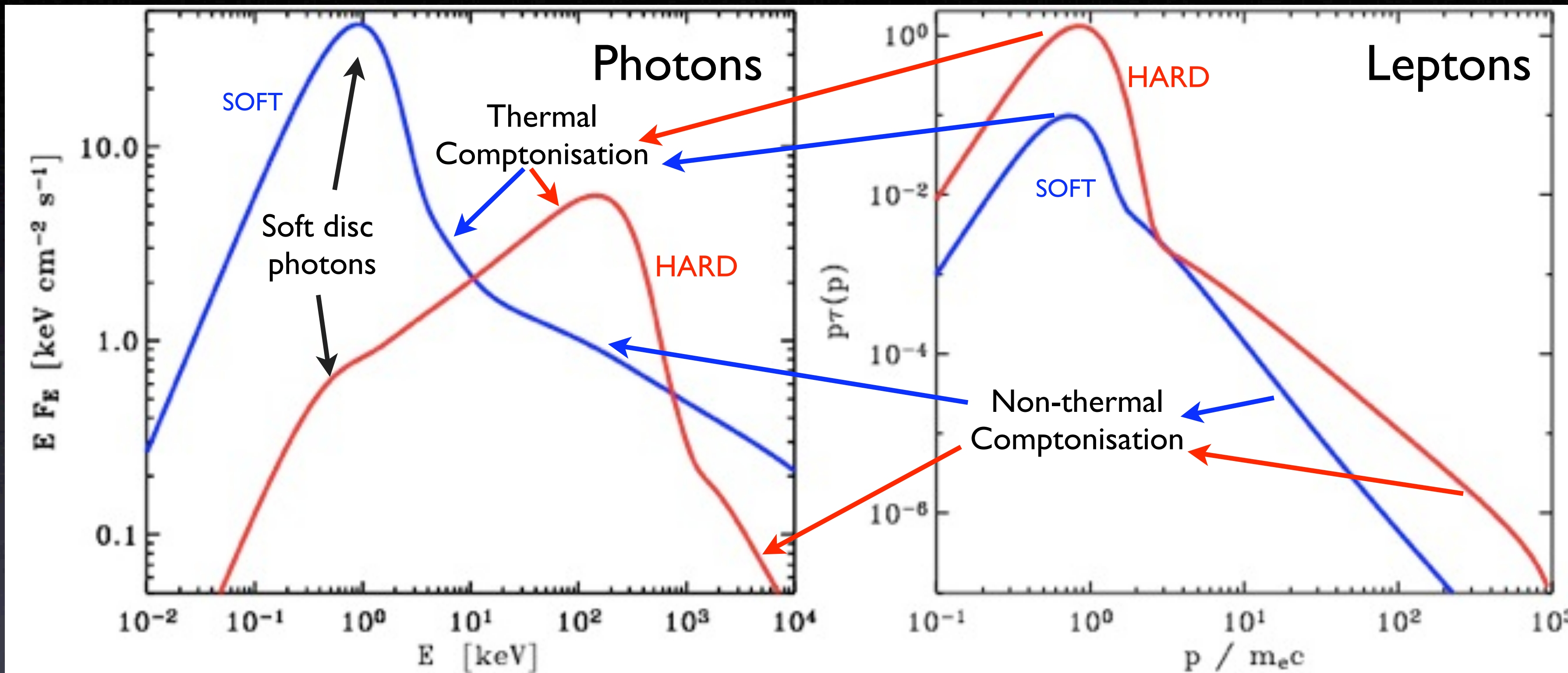

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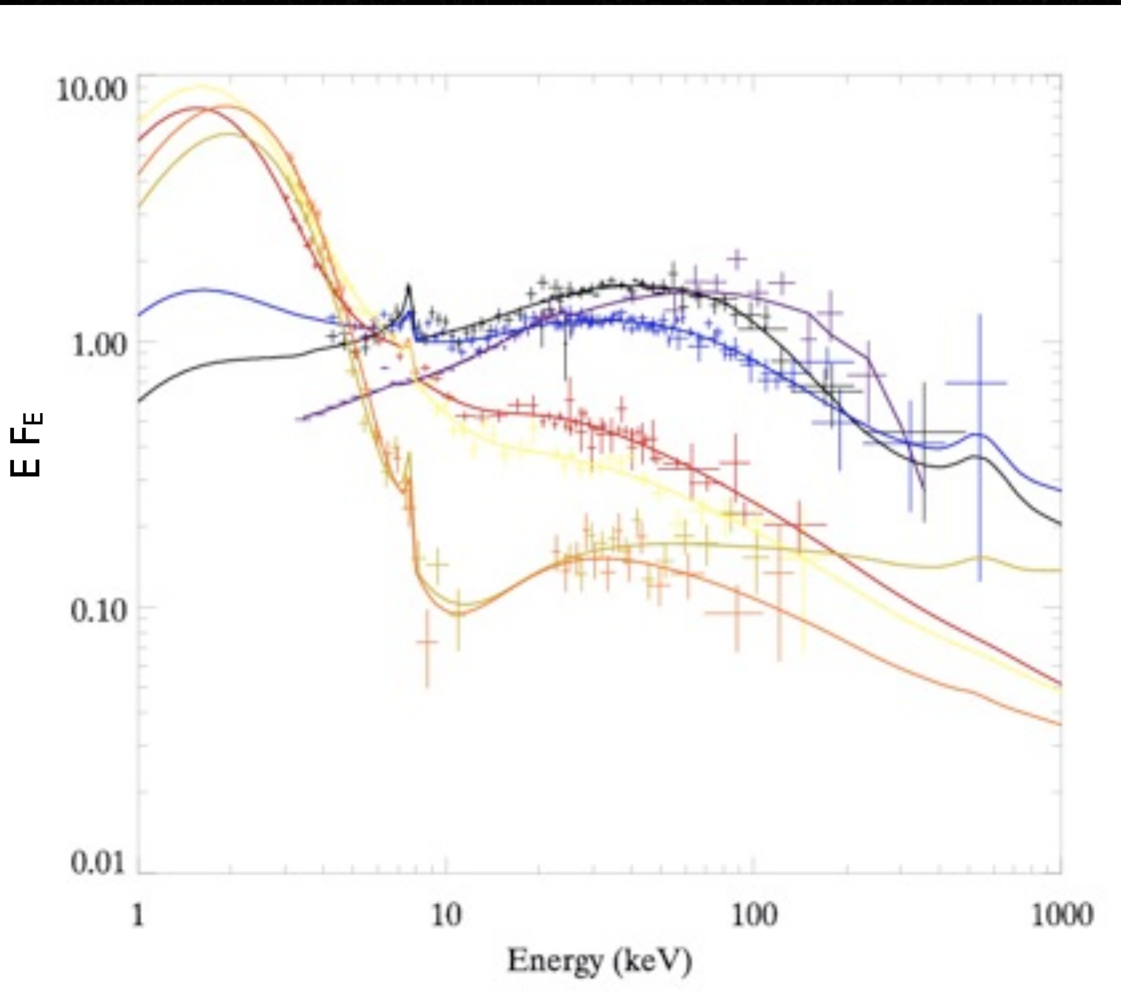
GX 339-4 during the 2004 state transition



INTEGRAL

- 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 by soft disc photons (while coronal power ~ constant)

Del Santo, Malzac, Jourdain, Belloni, Ubertini, MNRAS, 2008

see also Joinet et al. (2007), Belloni et al. (2006),

Standard picture: truncated disc model

LOW HARD STATE

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

⇒ Thermal comptonisation
in the hot (10^9 K) plasma

(Shapiro, Ligthman & Eardley 1976; Rees et al. 1982; Narayan & Yi 1994, Abramowicz et al. 1995, Esin et al. 1997, Yuan & Zdziarski 2004, Petrucci et al. 2009...)

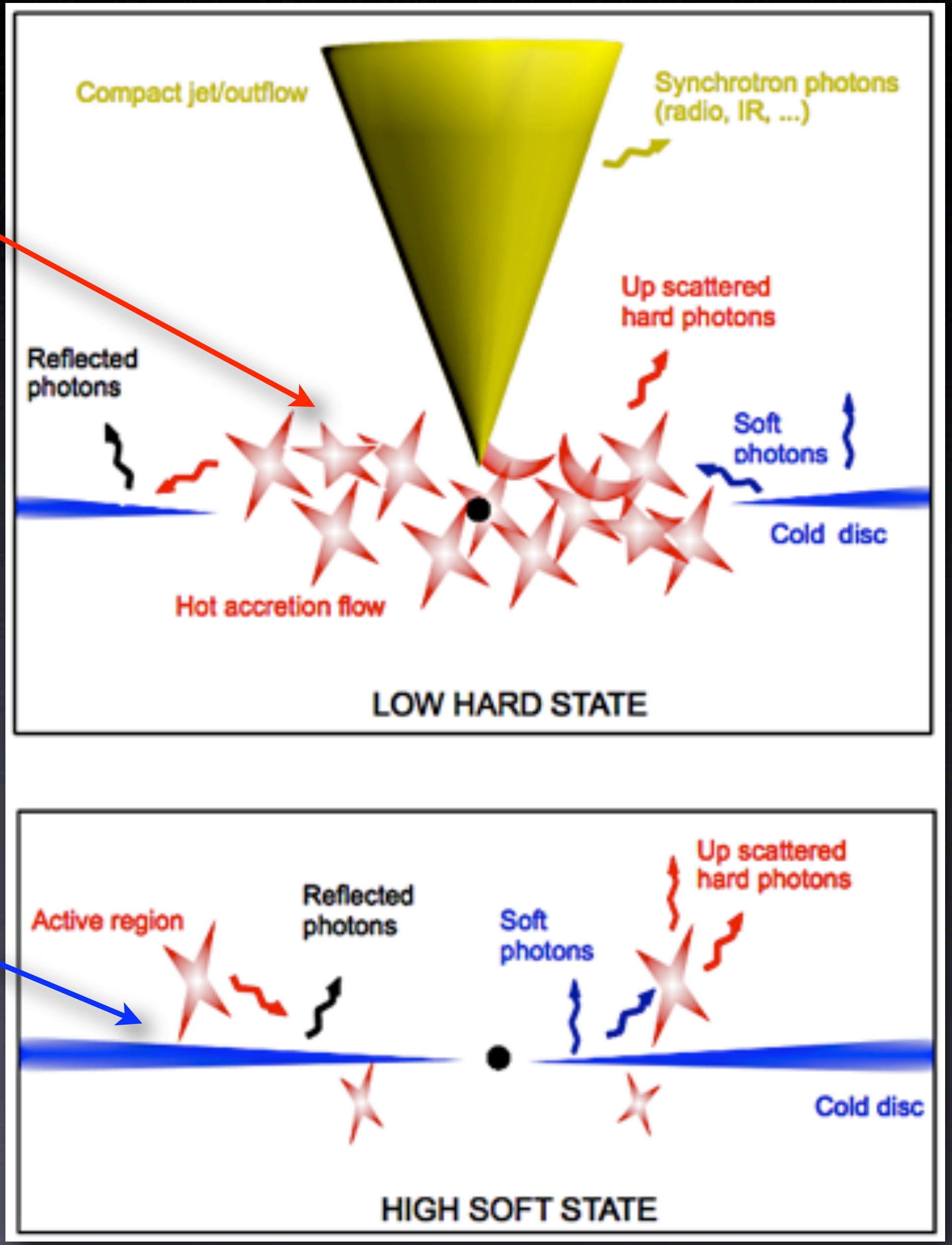
HIGH SOFT STATE

cold geometrically thin disc
down to the last stable orbit
+ weak non-thermal corona

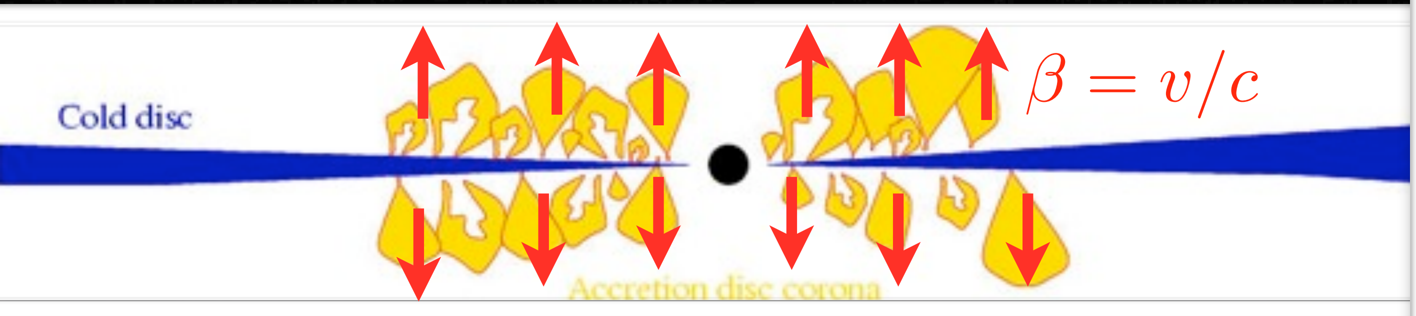
⇒ dominant thermal disc emission

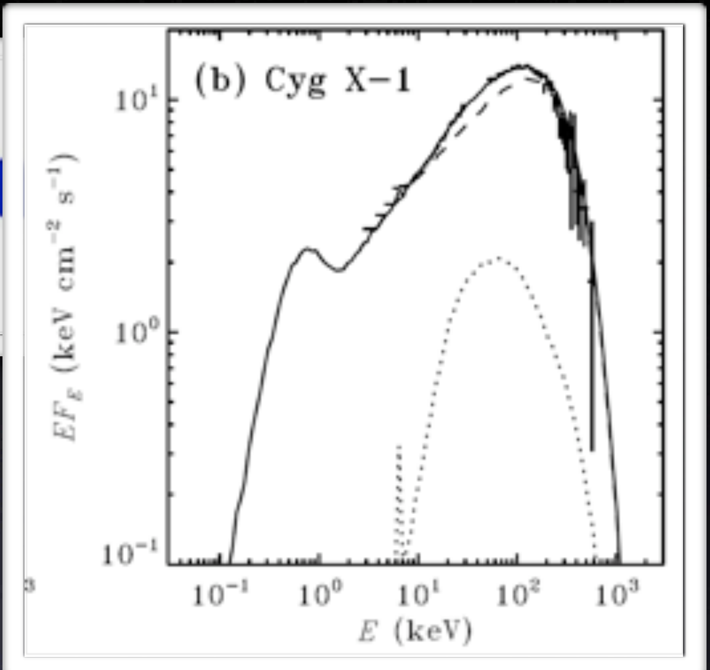
+ non-thermal comptonisation

(Shakura & Sunyaev 1973, Galeev et al. 1979, Coppi 1999)



Accretion disc corona model for the hard state





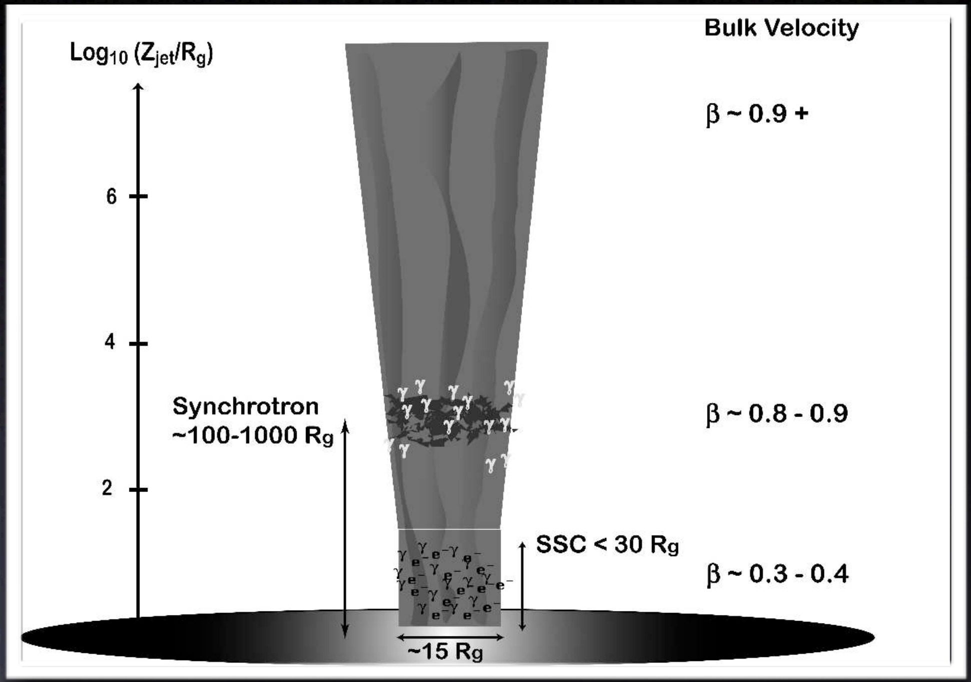
- Accretion disc corona atop a cold (i.e. non-radiating) thin disc (Bisnovatyi-Kogan & Blinikov 1976, Galeev et al 1979; Haard & Maraschi 1993)

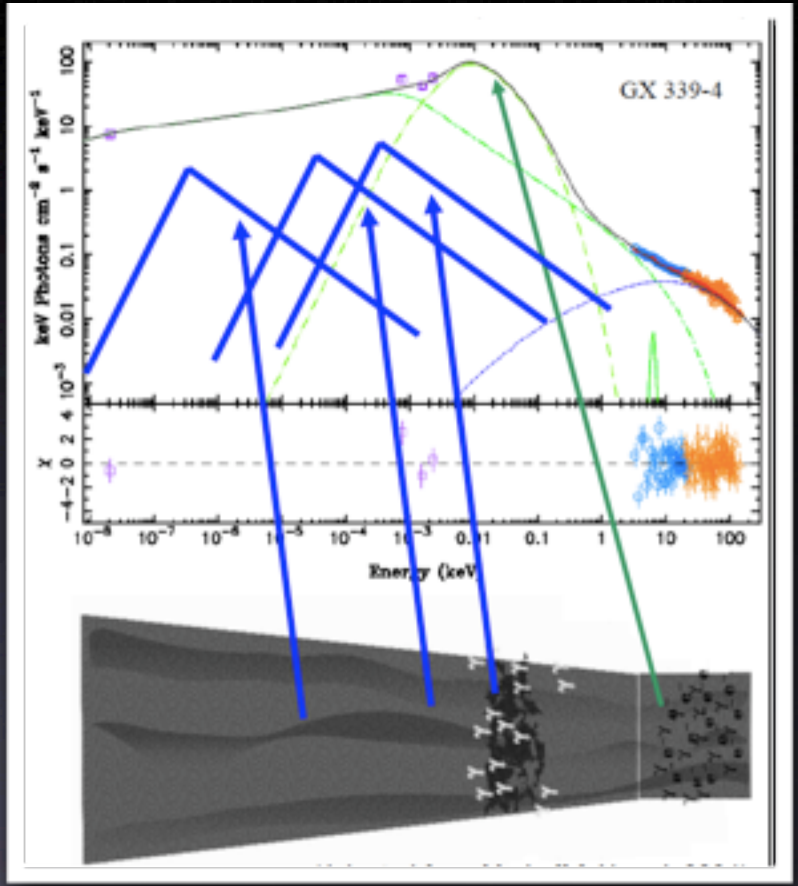
- Patchy corona outflowing with midly relativistic velocity (Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

$$\beta = 0.3$$
$$h/r = 1.25$$
$$\tau_T = 3$$

X-ray Jet models for the hard state

- Synchrotron and thermal SSC from the base of the jet
  (Markoff et al. 2001,2005)





- Bulk motion comptonisation of disc soft photons in the base of the jet (Reig et al. 2003, Giannios et al. 2004, Kylafis et al. 2008)

A new code to model radiation and kinetic processes in the corona.

➡ Evolution of electrons and photon energy distribution in a fully ionised, magnetised plasma (radiation, acceleration and Coulomb processes)

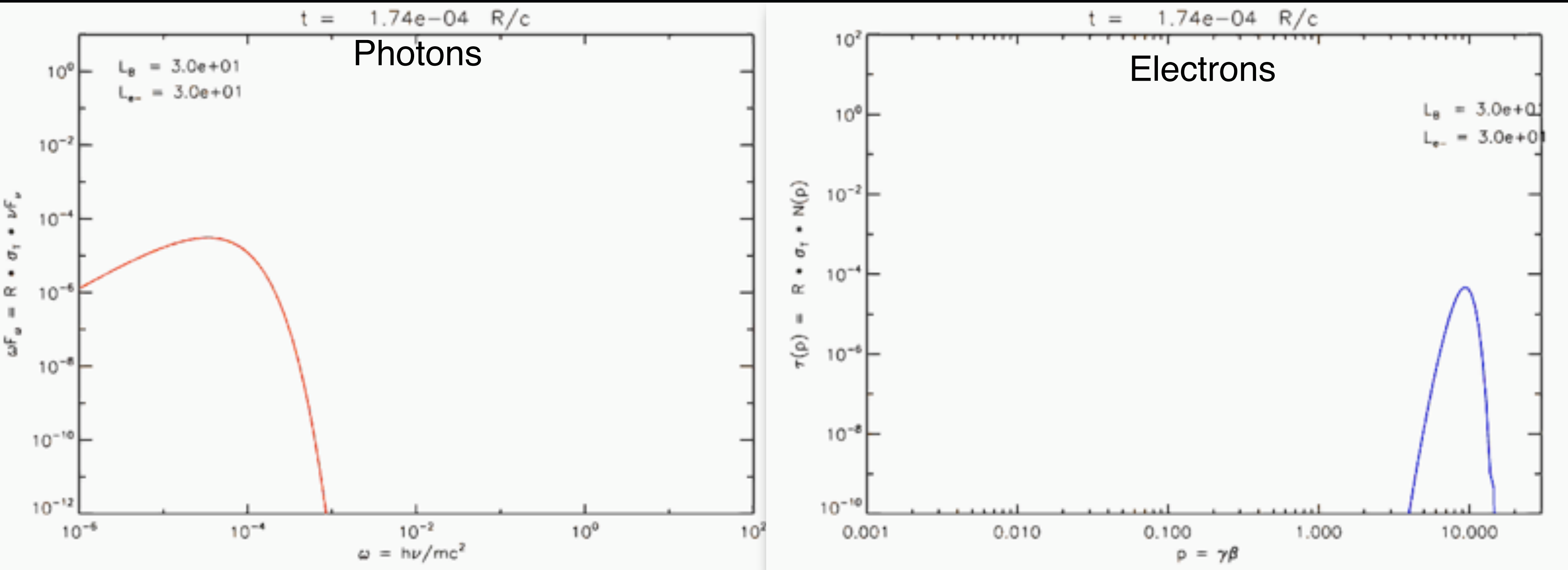
- Solve coupled time-dependent kinetic equations for leptons and photons (no assumption on the shape of the electron distributions)

- Compton, Synchrotron emission and absorption, e-e and e-p Coulomb, e+-e- pair production/annihilation, e-p bremstrahlung

(Belmont, Malzac & Marcowith, A&A 2008)

The Synchrotron boiler

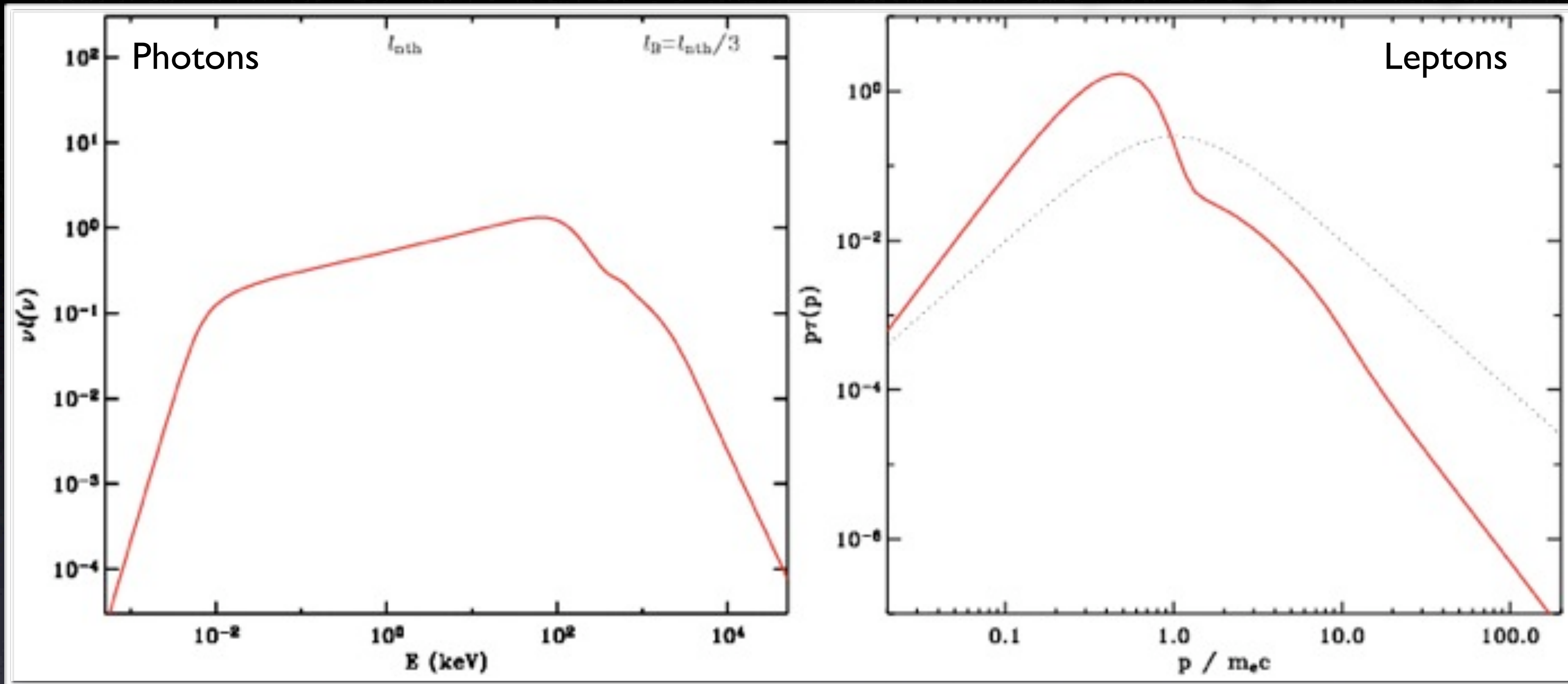
(Ghisellini, Guilbert and Svensson 1988)



- Electrons injected with γ =10 in an empty (but magnetised) region
  Synchrotron self-Compton emission
- High energy e- → synchrotron photons → 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)

Pure non-thermal SSC models (steady state)



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

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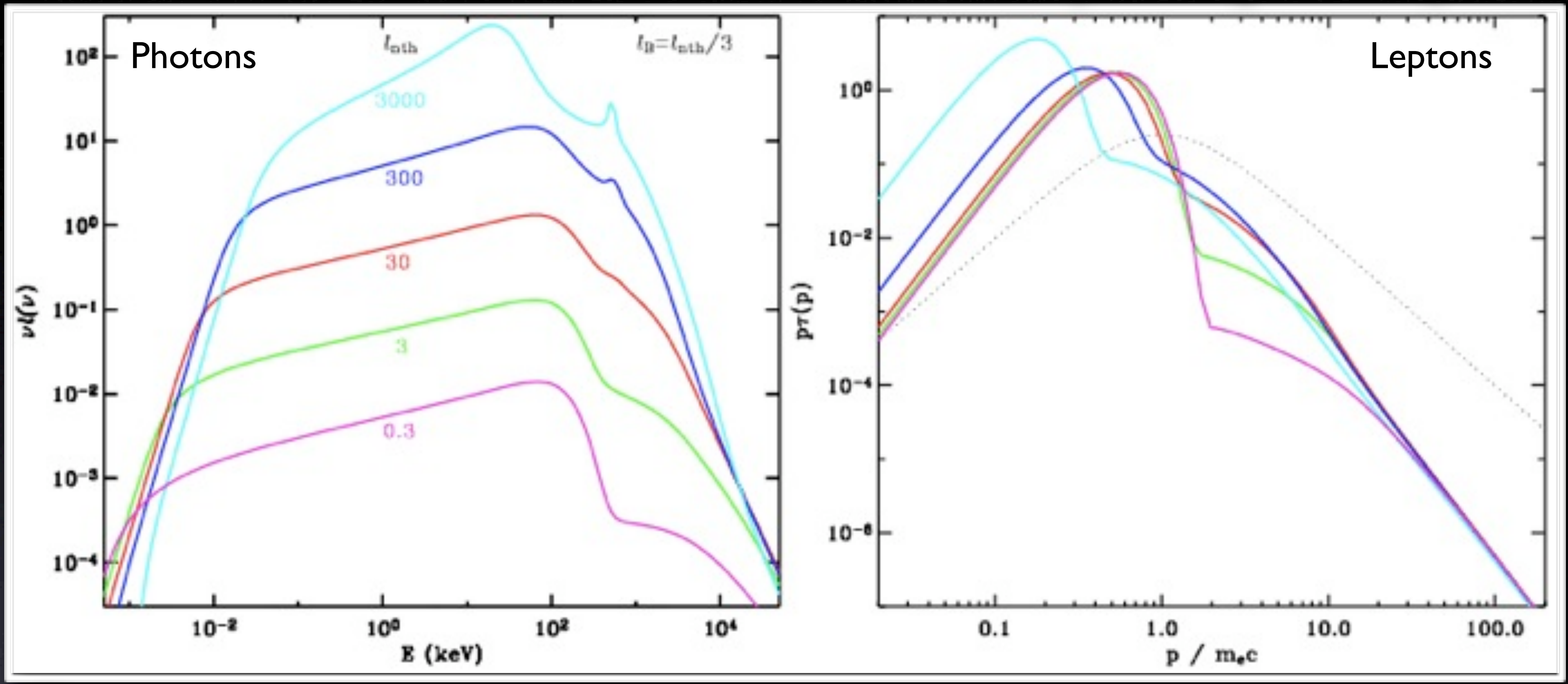

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Effect of external soft photons

- Add soft thermal photons:

➡ temperature of Maxwellian electrons decreases

➡ Compton emission increasingly dominated by non-thermal electrons

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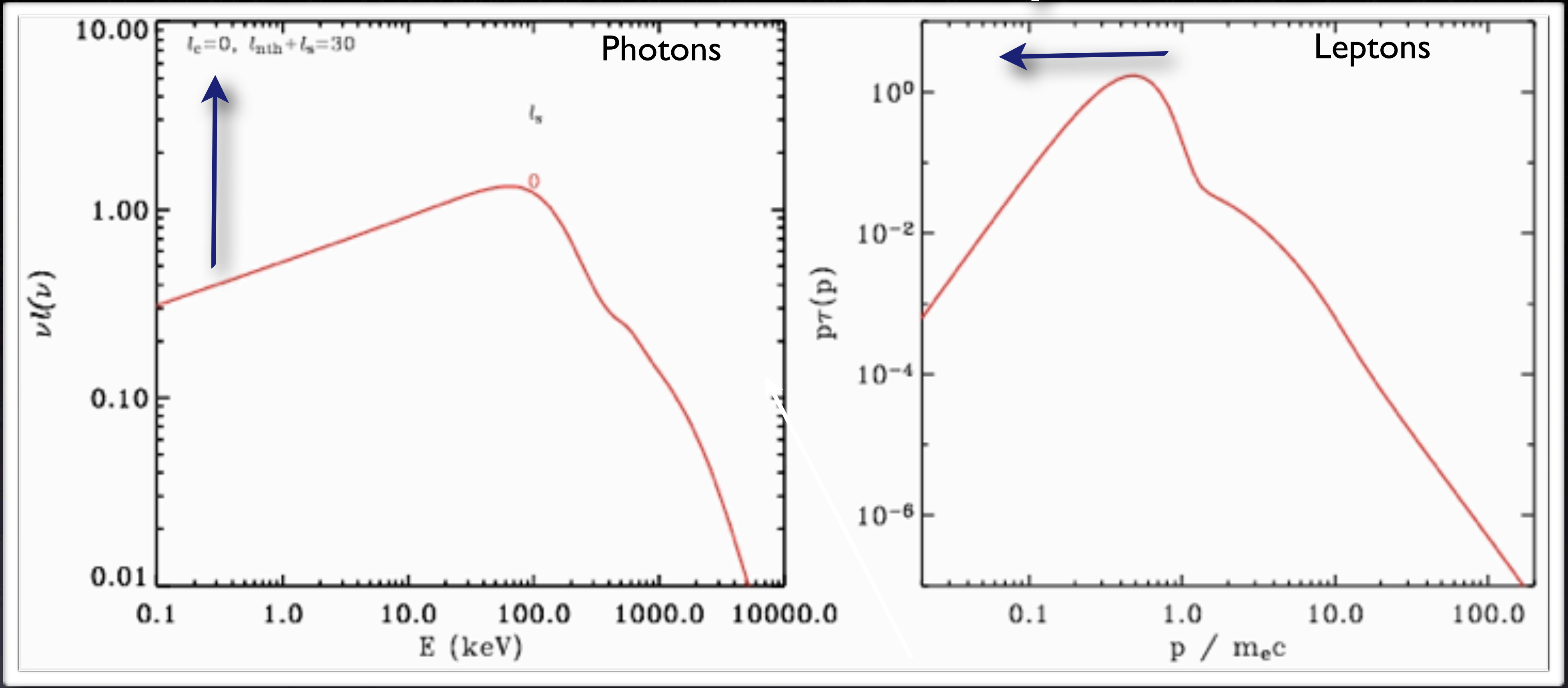

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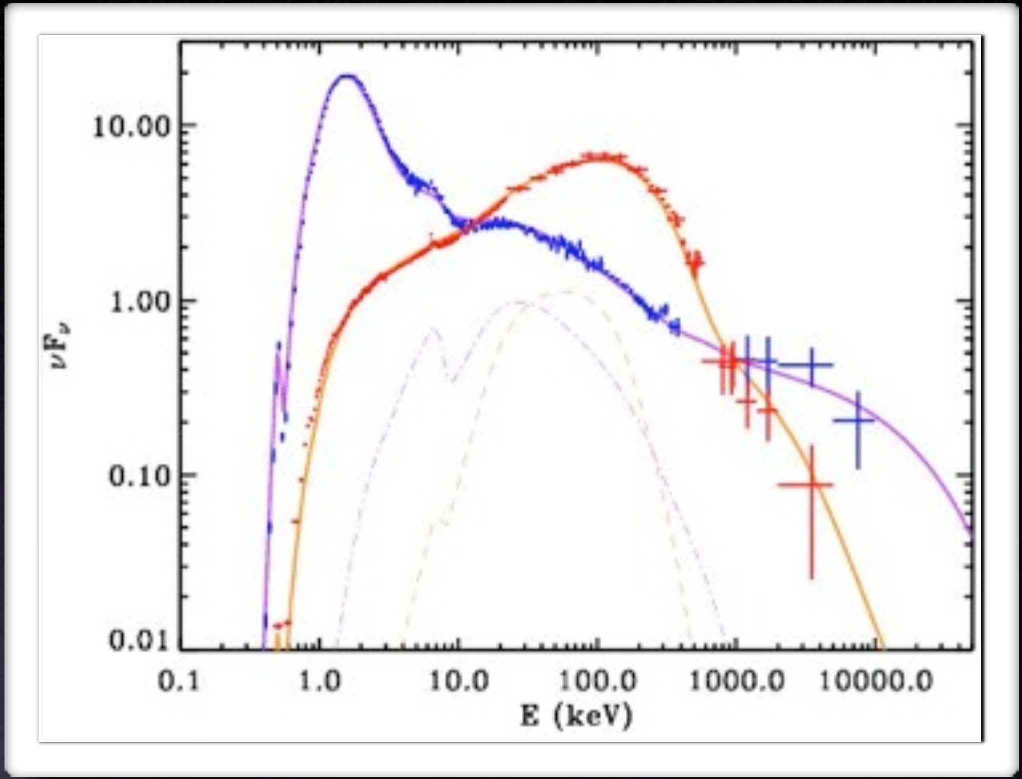
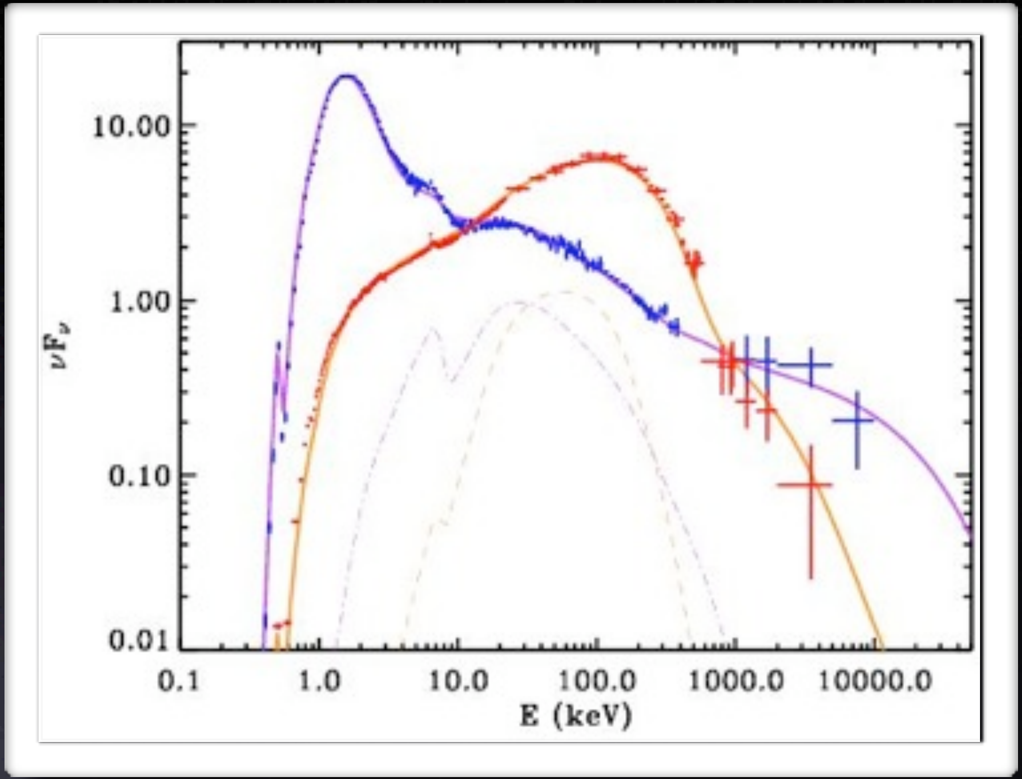
Comparisons to Cygnus X-1 spectra



(Malzac & Belmont MNRAS 2009)

Comparisons to Cygnus X-1 spectra

- Both states consistent with pure non-thermal acceleration models
- Different coronal temperatures due to more cooling by thermal disc photons in Soft state



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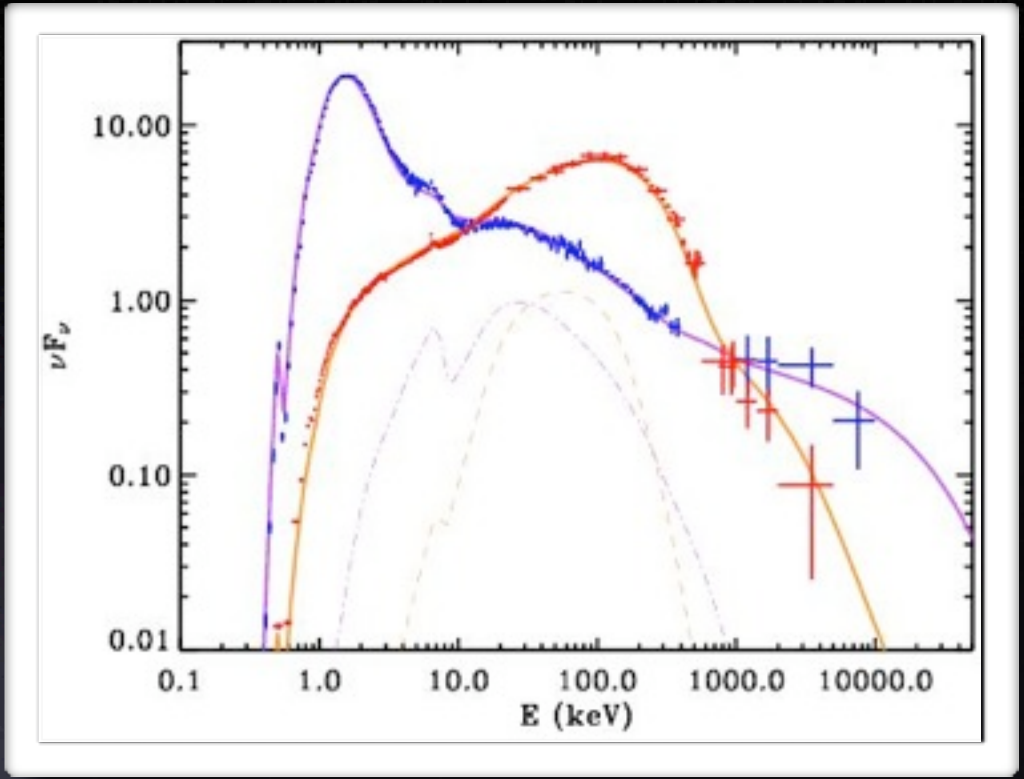


- Magnetic field in hard state: $U_B/U_R<0.3$

➡ corona unlikely to be powered by magnetic field

- Temperature of hot protons in hard state:

$$T_i < 2\ 10^{10}\ \mathrm{K} \text{ or } T_i/T_e<10$$

➡ proton temperature much lower than standard two-temperature accretion disc solutions

(Malzac & Belmont MNRAS 2009)

Jet power and velocity in Cyg X-1

- Jet powered nebula: $P_{\rm j} \simeq L_{\rm X} \simeq 2 \times 10^{37}$ erg s^{-1} (Gallo et al. 2005, Russell et al. 2007)

➡ Terminal jet velocity: $v_\infty > 0.1c$

➡ most likely $0.3c \lesssim v_\infty \lesssim 0.8c$

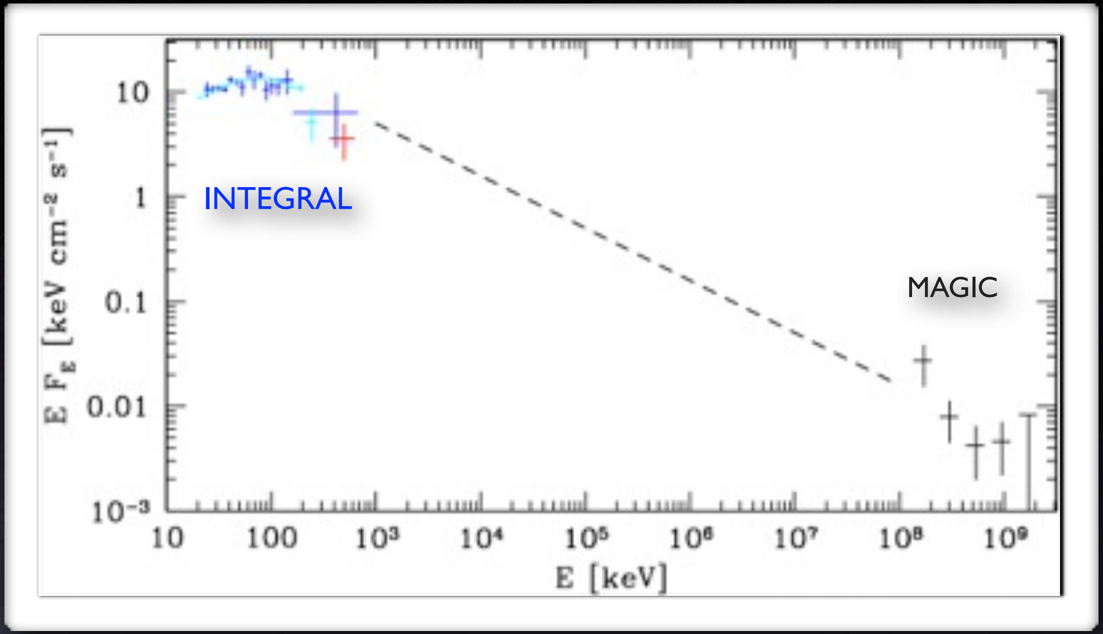
➡ accretion proceeds efficiently in the hard state

➡ cannot be strongly advection dominated

➡ X-ray emission not produced in the jet

Malzac, Belmont & Fabian, MNRAS, in press

TeV detection of Cyg X-1 by MAGIC (Albert et al., 2007)



During MAGIC detection Cyg X-1 was in a stable hard state. The brightest ever observed. Otherwise nothing unusual in X-ray light curves or spectra.

(Malzac et al. A&A 2008)

Origin of TeV emission ?

➡ in the X-ray corona radiative cooling is too strong to accelerate particles up to TeV energies

➡ shocks in jet, or interaction of outflow with wind of companion star

➡ relatively close to the black hole

➡ pair absorption does not prevent the gamma-rays from escaping
(Zdziarski, Malzac, Bednarek 2009)

Conclusions: possible models for Cyg X-1 in the hard state

- X-ray Jet models: appear to be ruled out

  (although jet may contribute to gamma-ray emission)
- Outflowing accretion disc corona:
  - corona not powered through magnetic dissipation
- Hot accretion flows models:
  - appear quite efficient
  - temperature of electrons and protons are comparable