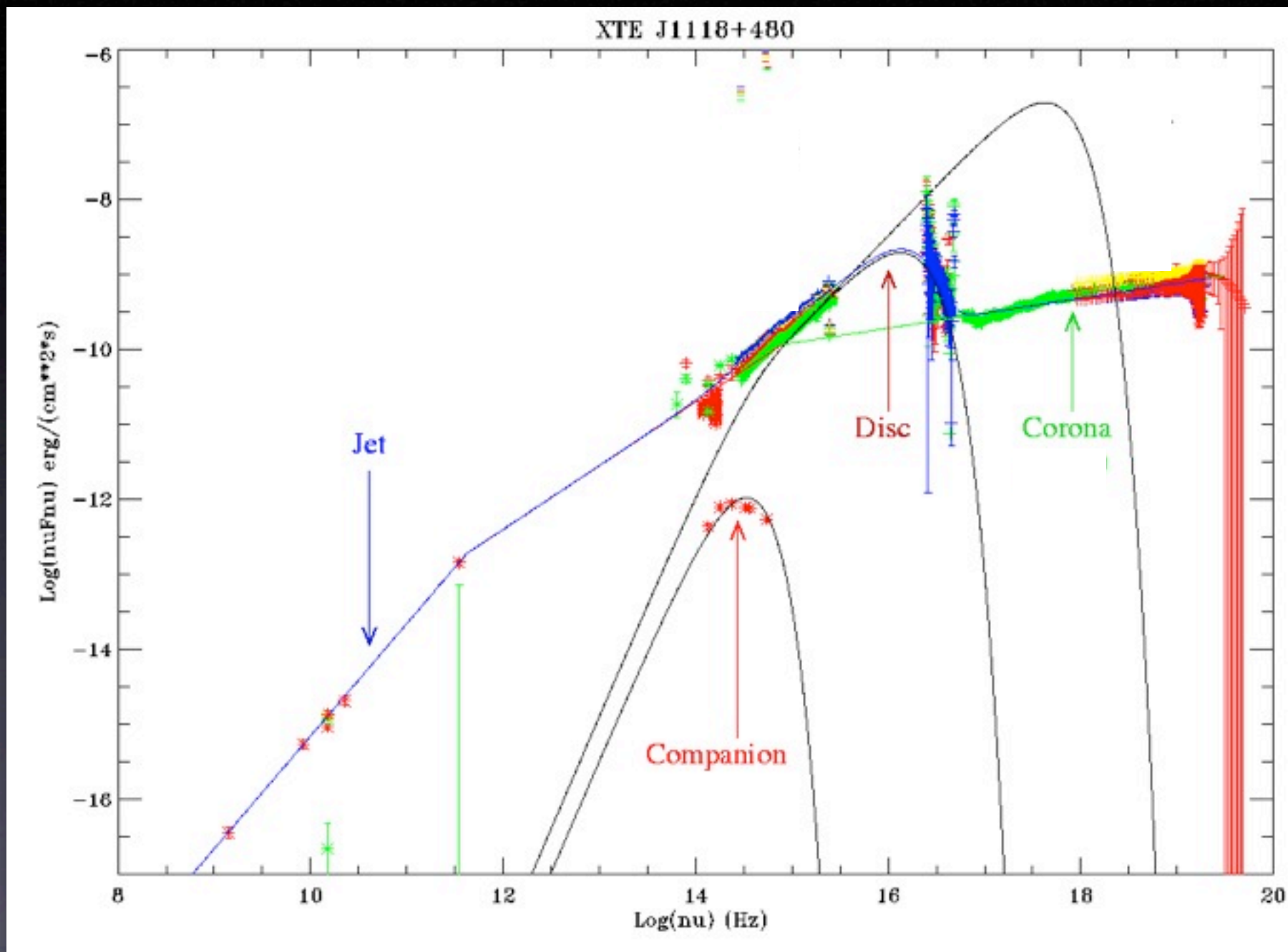

Accretion flow models from wide band X-ray spectroscopy

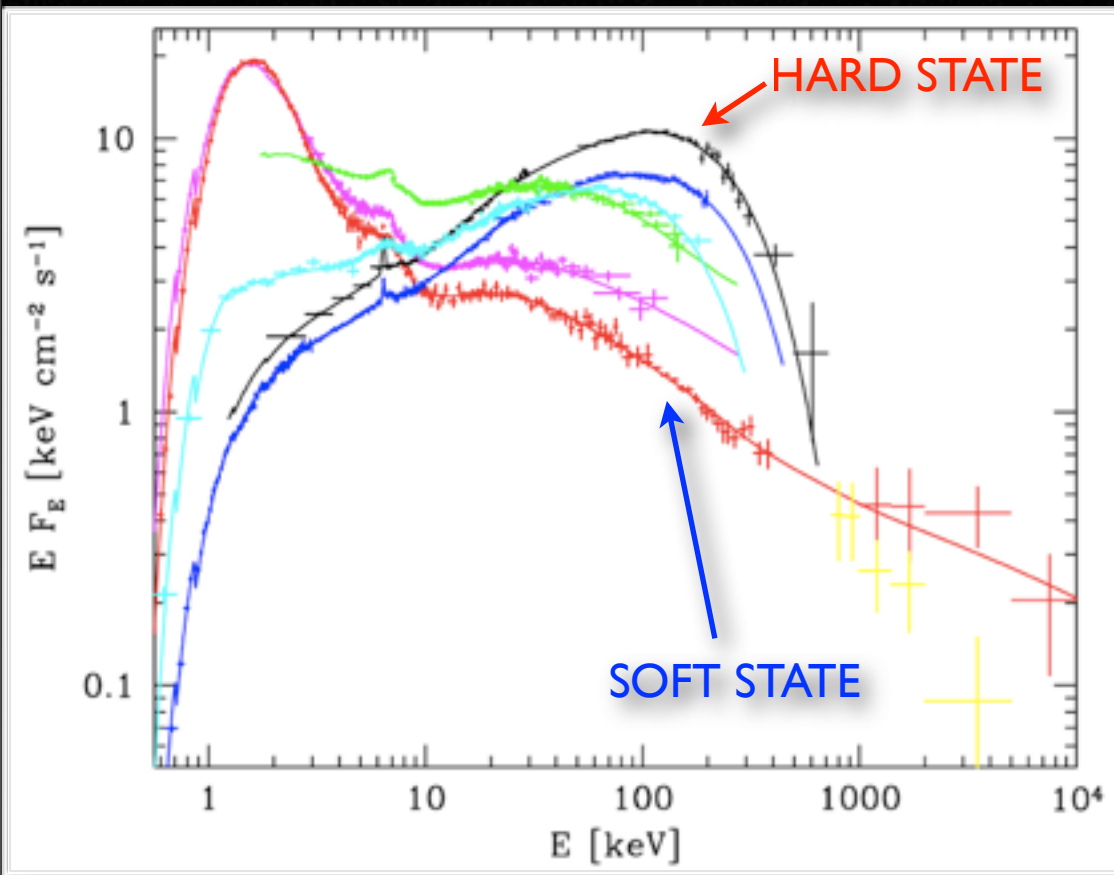
- Phenomenological approach
- Limited to black hole X-ray binaries
- Only luminous sources ($L > 0.01 L_{\text{Edd}}$)

Julien Malzac (IRAP, CNRS, Toulouse, France)

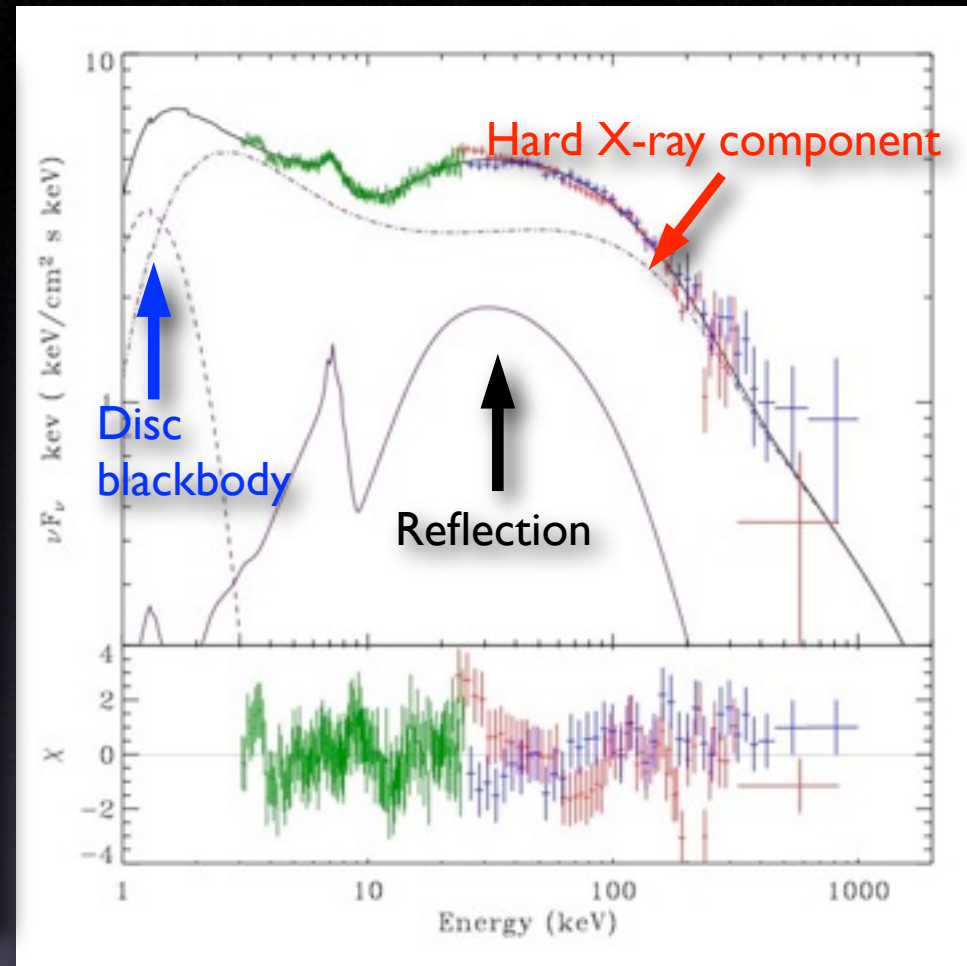


Chaty et al., MNRAS, 2003

Broad band X-ray spectra



Zdziarski et al 2003



Malzac et al. 2006

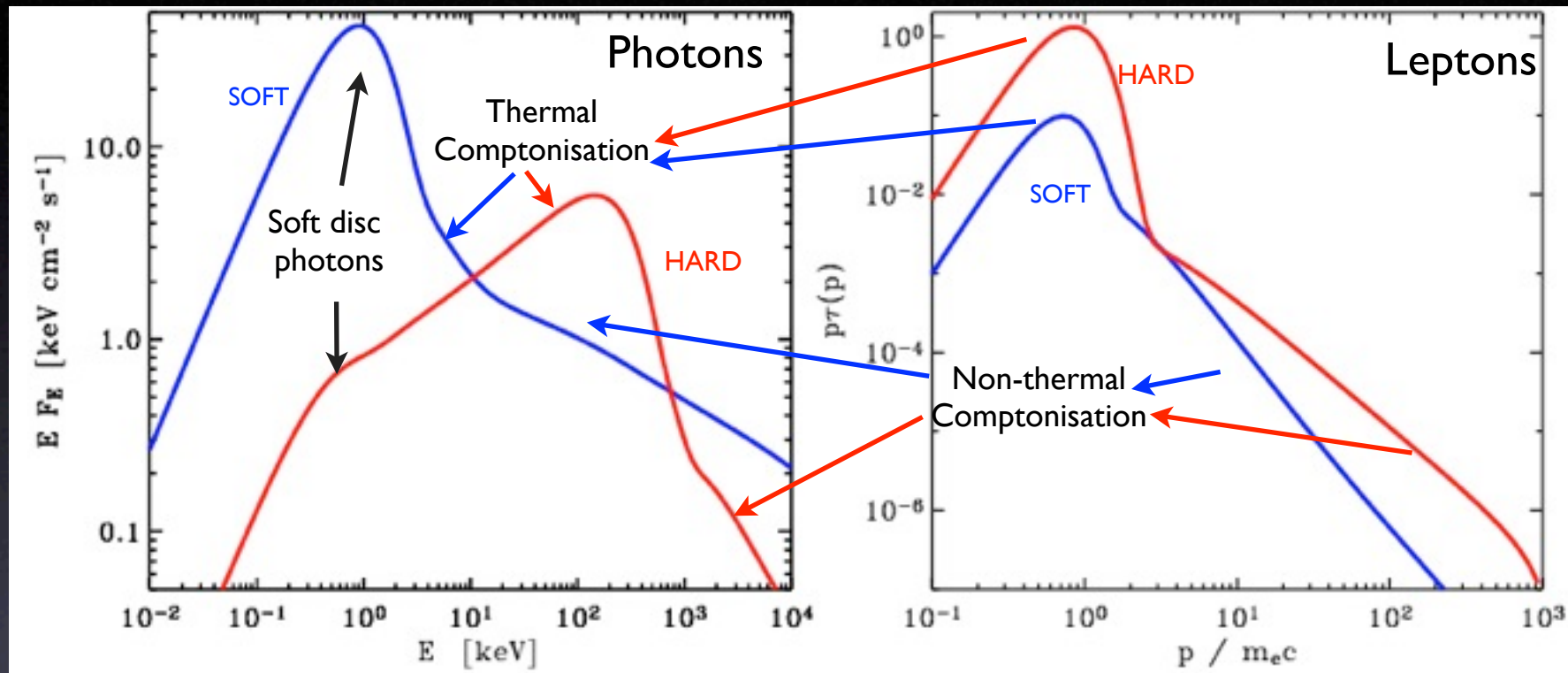
LOW HARD STATE: (compact radio jet)

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

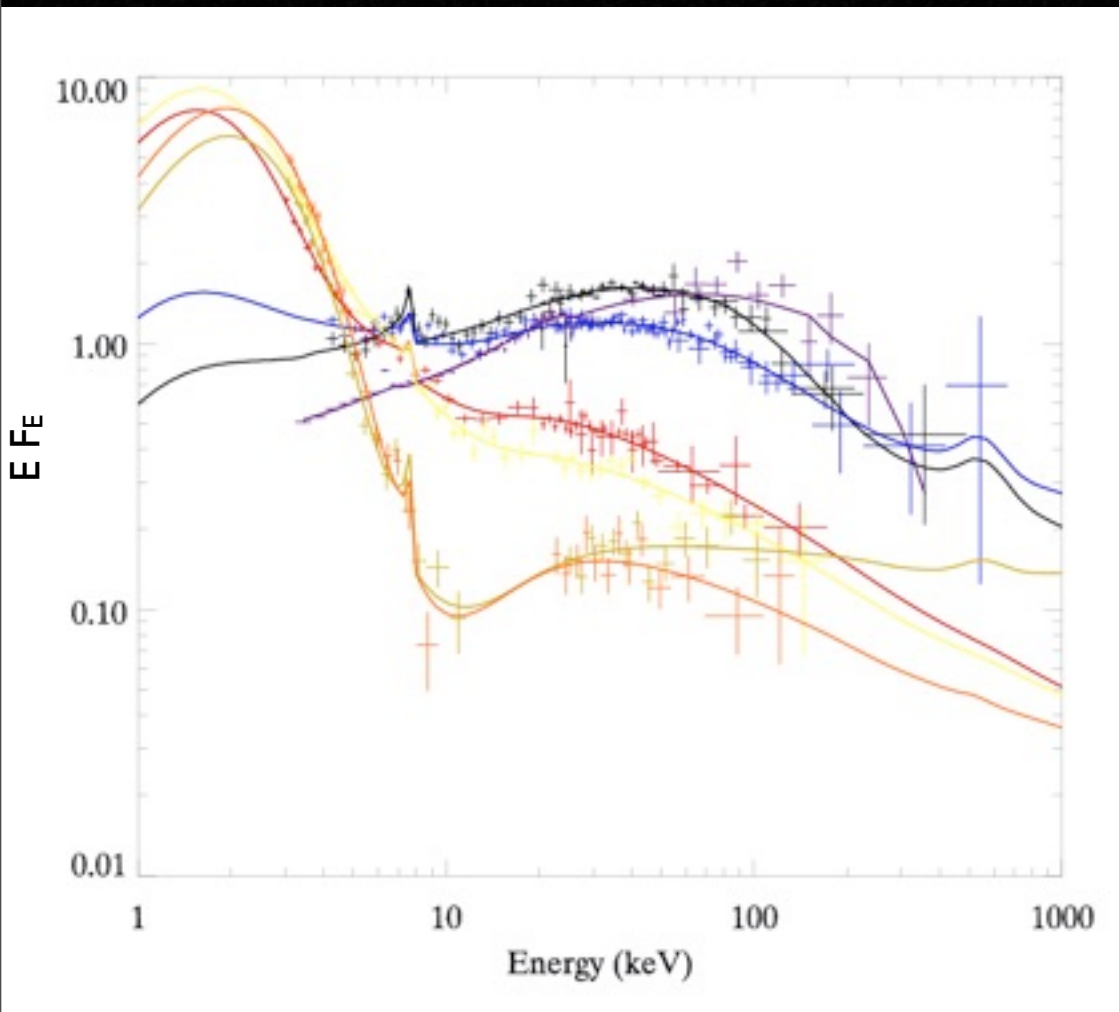
HARD STATE: $kT \sim 50-100 \text{ keV}$, $\tau_T \sim 1-3$: Thermal comptonisation dominates

SOFT STATE: $kT \sim 10-50 \text{ keV}$, $\tau_T \sim 0.1-0.3$: Inverse Compton by non-thermal electrons dominates

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

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

GX 339-4 during the 2004 state transition

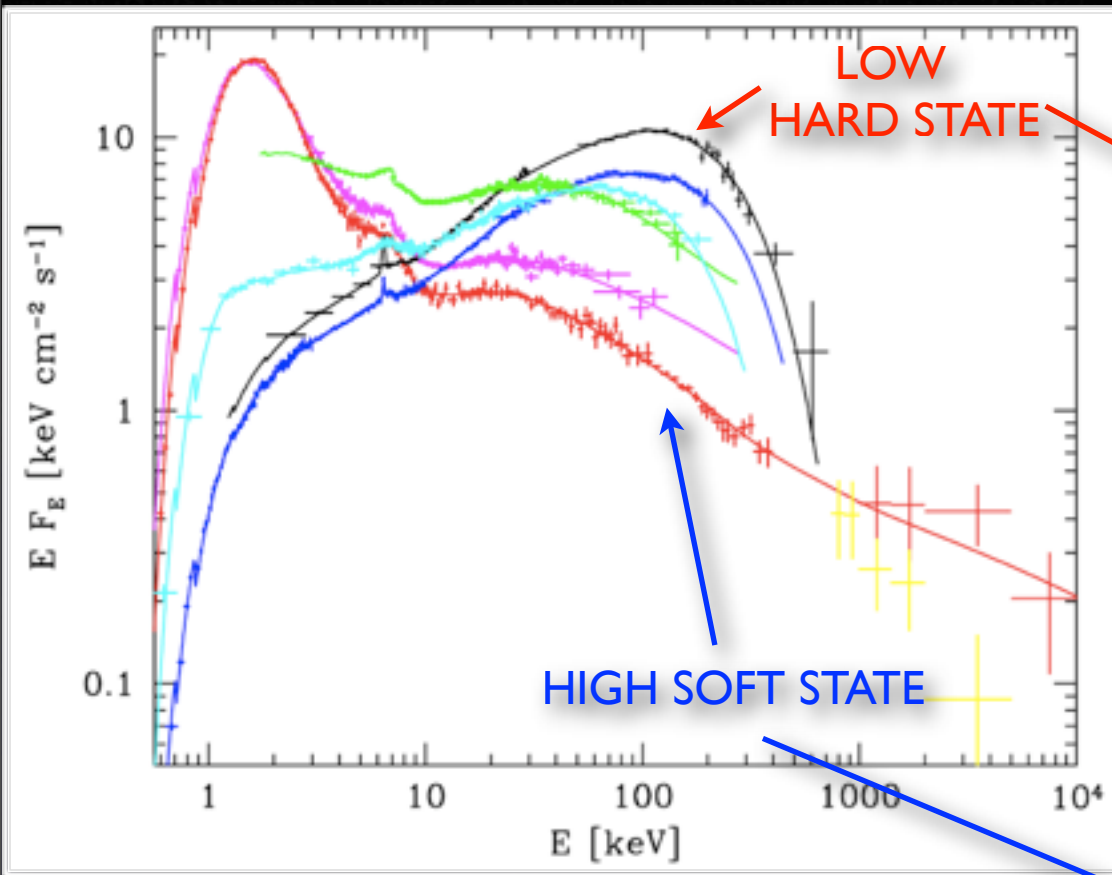


INTEGRAL

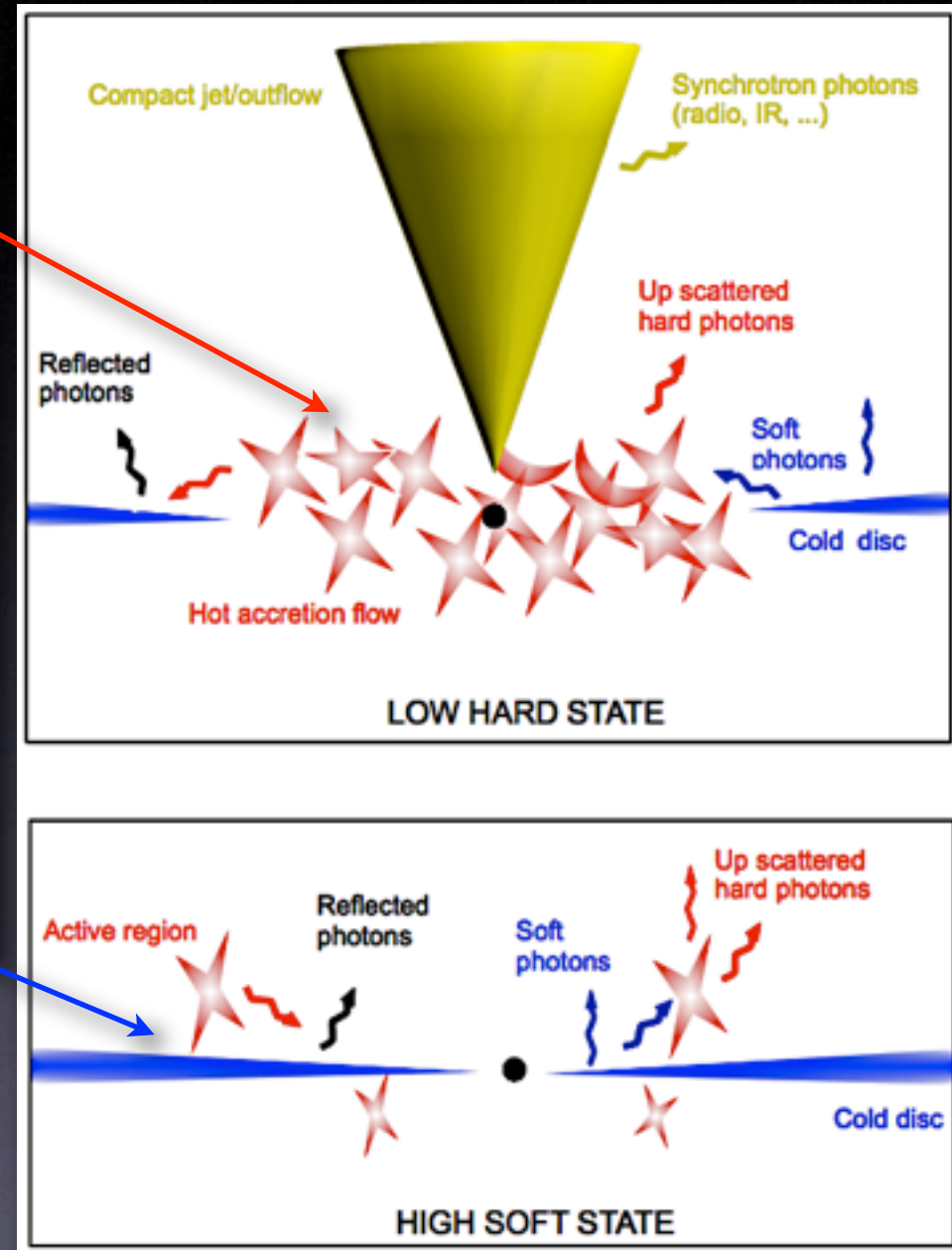
Del Santo, et al., MNRAS, 2008

- 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

Standard picture: truncated disc model



Zdziarski et al 2003



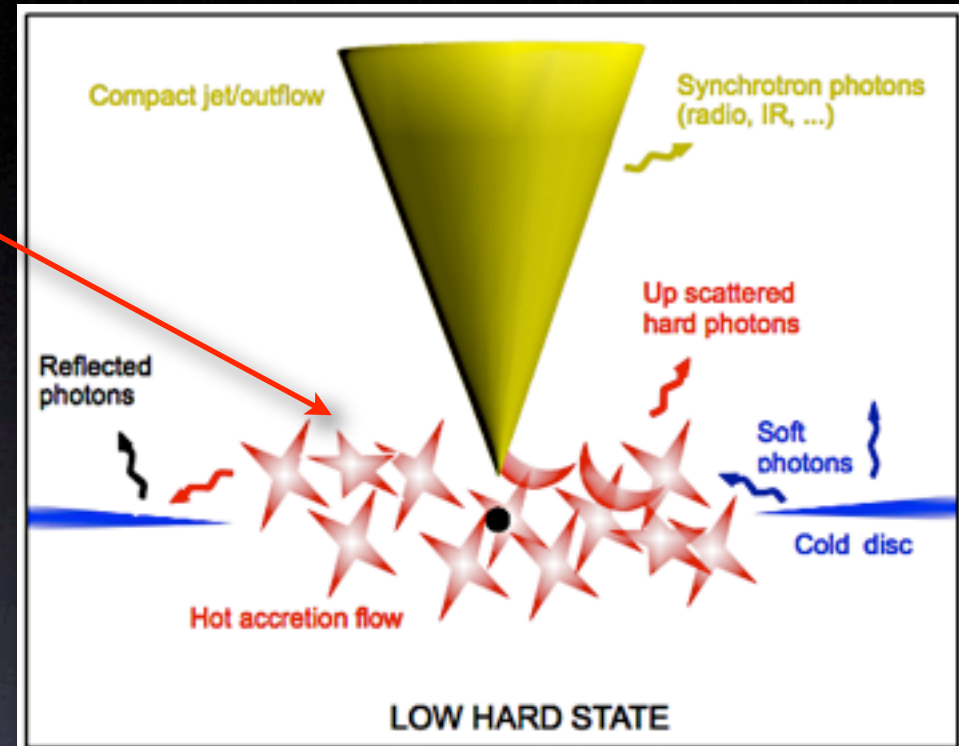
Standard picture: truncated disc model

LOW HARD STATE

cold disc truncated at $\sim 100-1000 R_g$
+ hot inner accretion flow

\Rightarrow Thermal Comptonisation
in the hot (10^9 K) plasma

(Shapiro, Lighman & Eardley 1976; Rees et al. 1982;
Narayan & Yi 1994, Abramowicz et al. 1995, Esin et al.
1997, Yuan & Zdziarski 2004, Petrucci et al. 2010...)



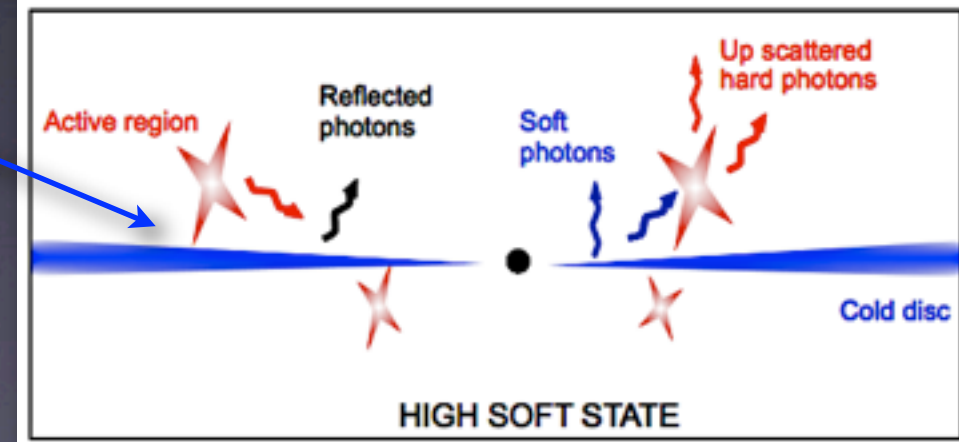
HIGH SOFT STATE

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

\Rightarrow dominant thermal disc emission

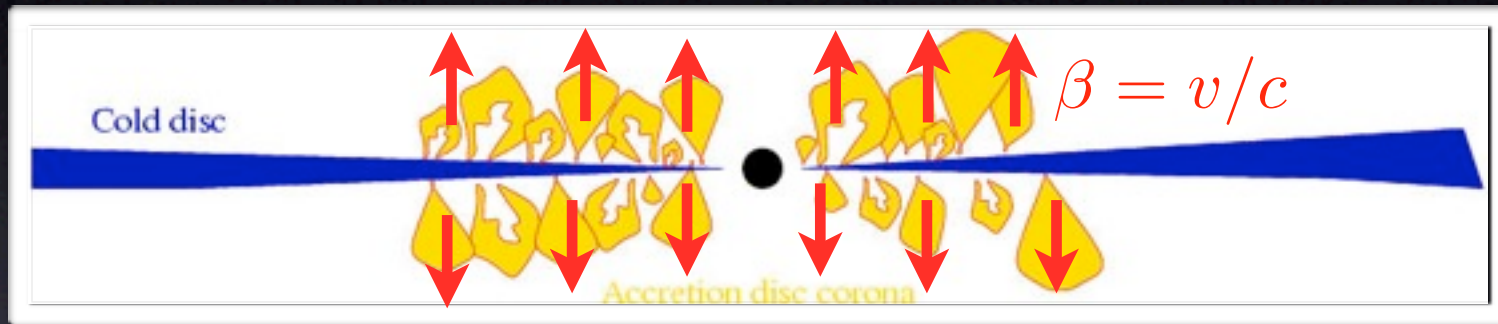
+ non-thermal Comptonisation

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



Alternative models for the hard state

- Accretion disc corona outflowing with mildly relativistic velocity above a cold (i.e. non-radiating) thin disc



(Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

- X-ray Jet Models

(Markoff et al. 2001,2005; Reig et al. 2003; Giannios et al. 2004; Kylafis et al. 2008)

Global energy budget in Cyg X-1

● Jet powered nebula: $P_j \simeq L_X \simeq 2 \times 10^{37} \text{ erg s}^{-1}$ (Gallo et al. 2005, Russell et al. 2007)



Global energy budget in Cyg X-1

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Global energy budget in Cyg X-1

● Jet powered nebula: $P_j \simeq L_X \simeq 2 \times 10^{37} \text{ erg s}^{-1}$ (Gallo et al. 2005, Russell et al. 2007)

➔ accretion proceeds efficiently in the hard state

➔ cannot be strongly advection dominated

➔ not enough power to eject corona with $\tau_T > 1$
to infinity with relativistic speed

➔ X-ray corona \neq Jet

BELM: a code to model radiation and kinetic processes in the corona

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

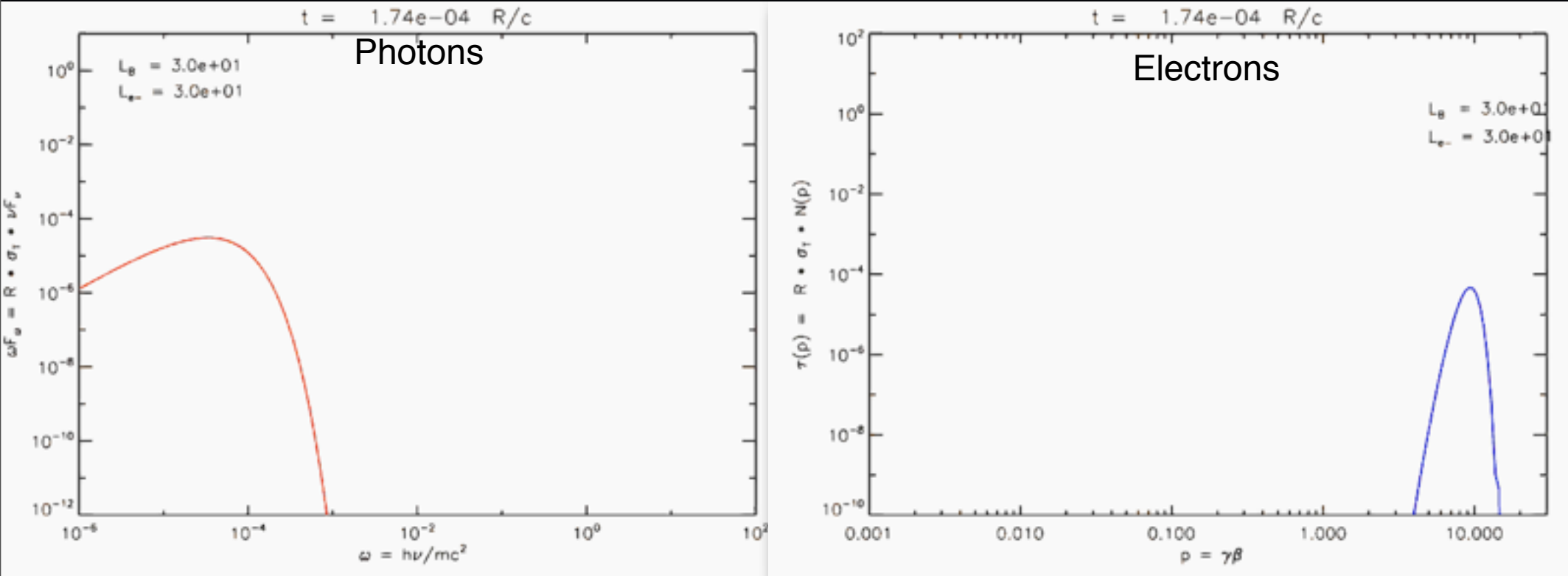
● Solve coupled time-dependent kinetic equations (one zone) for leptons and photons (no assumption on the shape of the electron distributions)

● Compton, Synchrotron emission and absorption, e-e and e-p Coulomb, e^+e^- pair production/annihilation, e-p bremsstrahlung

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

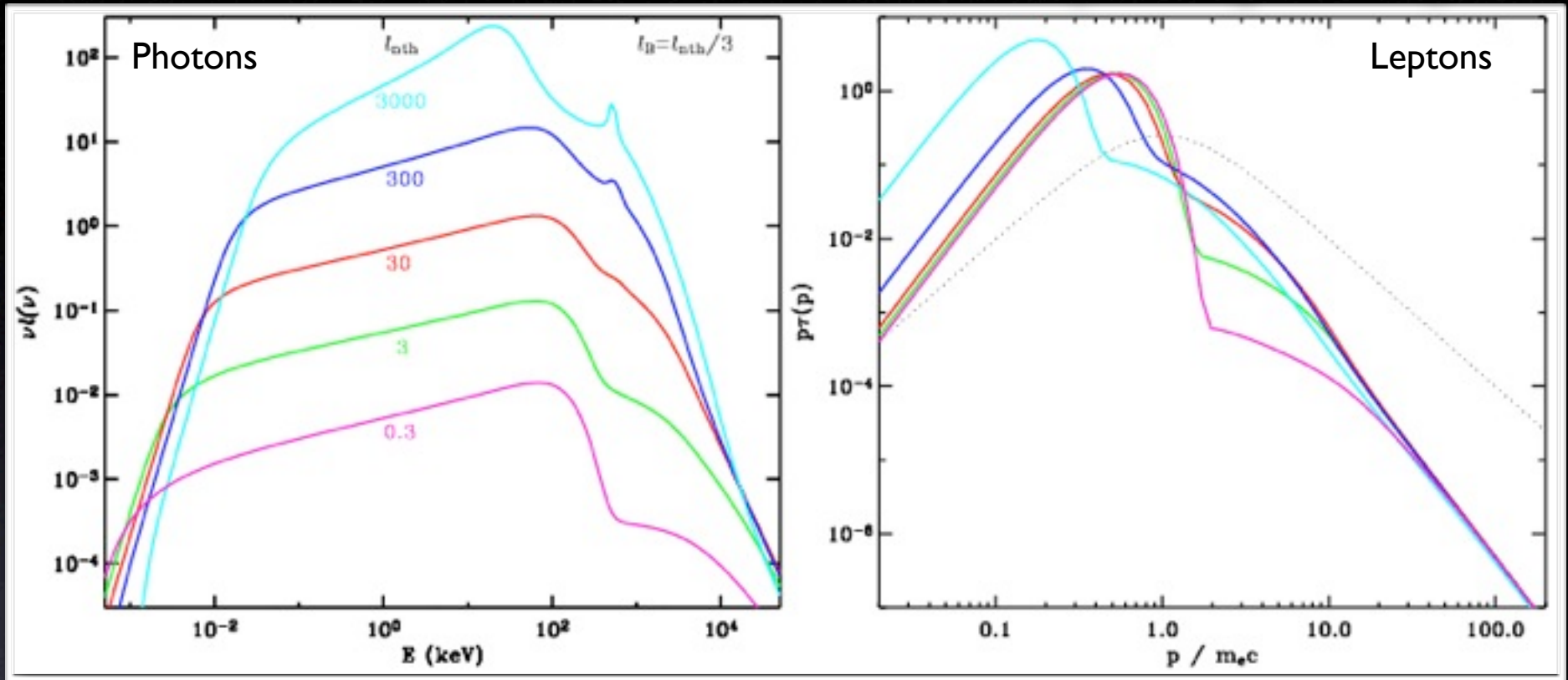
The Synchrotron boiler

(Ghisellini, Guilbert and Svensson 1988)



- Electrons injected with $\gamma = 10$ in an empty (but magnetised) region
Synchrotron self-Compton emission
- High energy $e^- \rightarrow$ synchrotron photons \rightarrow self-absorbed by lower energy e^-
 \rightarrow transfer of energy between particles
 - \rightarrow 'thermalizing' effect on the electron distribution
 - \rightarrow At steady state: hybrid thermal/non thermal lepton distribution

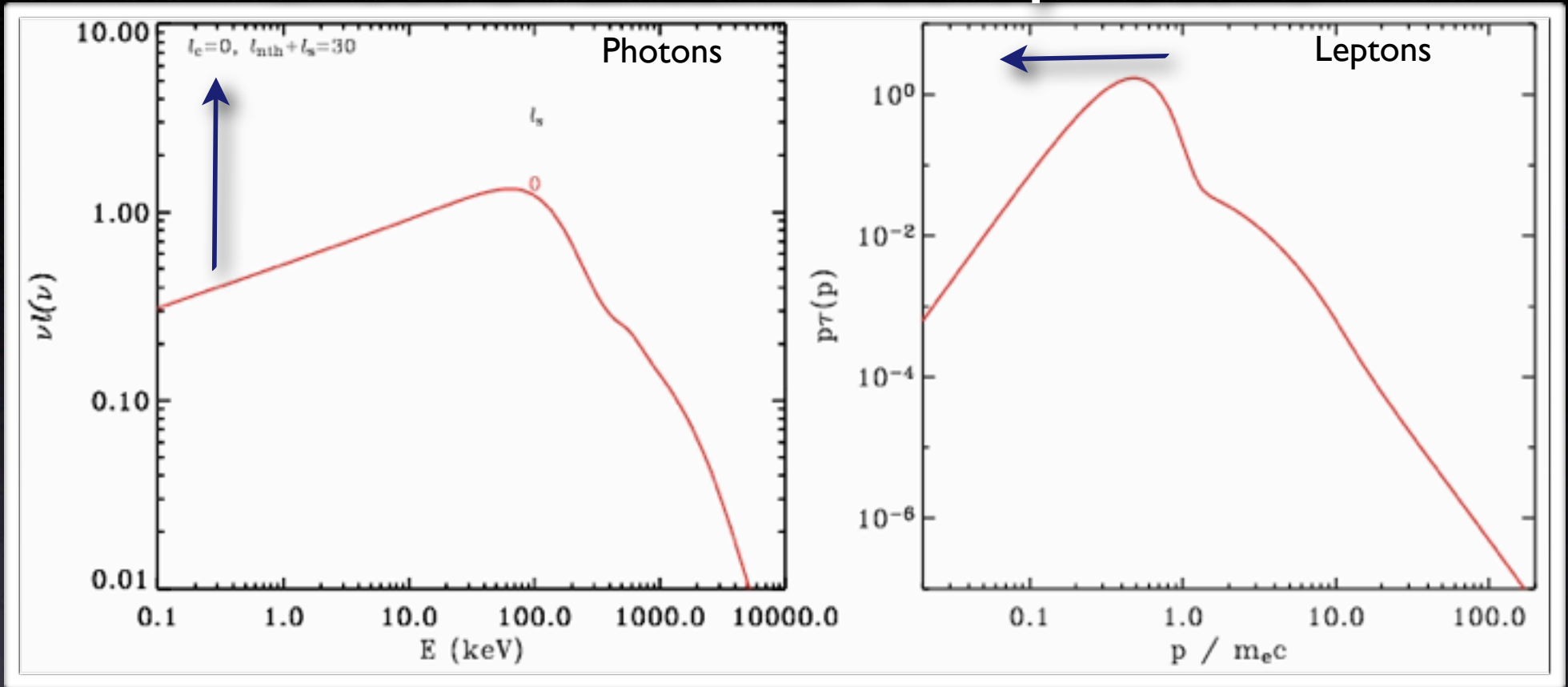
Pure non-thermal SSC models (steady state)



- Magnetic field B at \sim 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

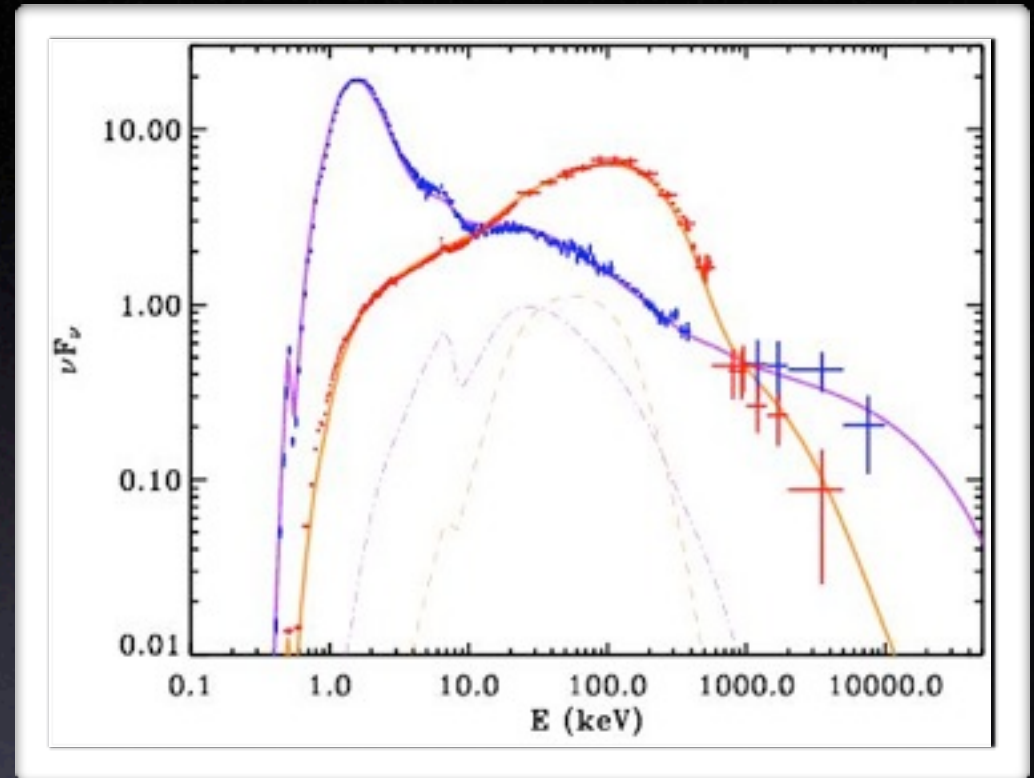


- Add soft thermal photons:
 - ➔ temperature of Maxwellian electrons decreases
 - ➔ Compton emission increasingly dominated by non-thermal electrons
 - ➔ looks like a state transition!

(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



If B is large in hard state:

➔ non-thermal electrons generate too much synchrotron

➔ Maxwellian electrons are too cold

➔ **weak (i.e. strongly sub-equipartition) magnetic field**

➔ **corona unlikely to be powered by magnetic field**

(Malzac & Belmont 2009 ; Poutanen & Vurm 2009)

Model with hot protons

In addition to non-thermal acceleration we now assume that electrons are heated through Coulomb interactions with a population of hot thermal protons (two-temperature plasma):

- Good agreement with data
but non-thermal electron injection is required in both Low Hard and High Soft states
- Temperature of hot protons in hard state:
 $T_i < 2 \cdot 10^{10} \text{ K}$ or $T_i/T_e < 10$
➔ proton temperature much lower than standard two-temperature accretion disc solutions
- Similar constraints on B and T_i obtained for GX339-4 in a bright hard state (Droulans et al. 2010)

Can hot accretion flows explain the bright hard state sources?

● In the context of alpha discs, (i.e. $Q_{\text{vis}} = -\alpha P_{\text{gas}} R \frac{d\Omega}{dr}$),

there is no hot flow solutions with $\tau_{\text{T}} \geq 1$: cooling is too strong.

➔ standard hot flow solutions cannot be applied

● A possible fix:

1) Assume $P_{\text{mag}} \geq P_{\text{gas}}$

2) Modified viscosity law: $Q_{\text{vis}} = -\alpha(P_{\text{gas}} + P_{\text{mag}})R \frac{d\Omega}{dr}$

➔ solutions with $\tau_{\text{T}} \geq 1$ $T_{\text{i}}/T_{\text{e}} \sim 2 - 10$ $P_{\text{mag}}/P_{\text{gas}} \sim 2$

(e.g. Oda et al 2010, Bu et al 2009, Fragile & Meier 2009)

- Hot accretion flow solutions
- Accretion disk coronae → strong magnetic field
- MHD jet models

but...

- Non-thermal high energy excess → weak magnetic field

If B is large:

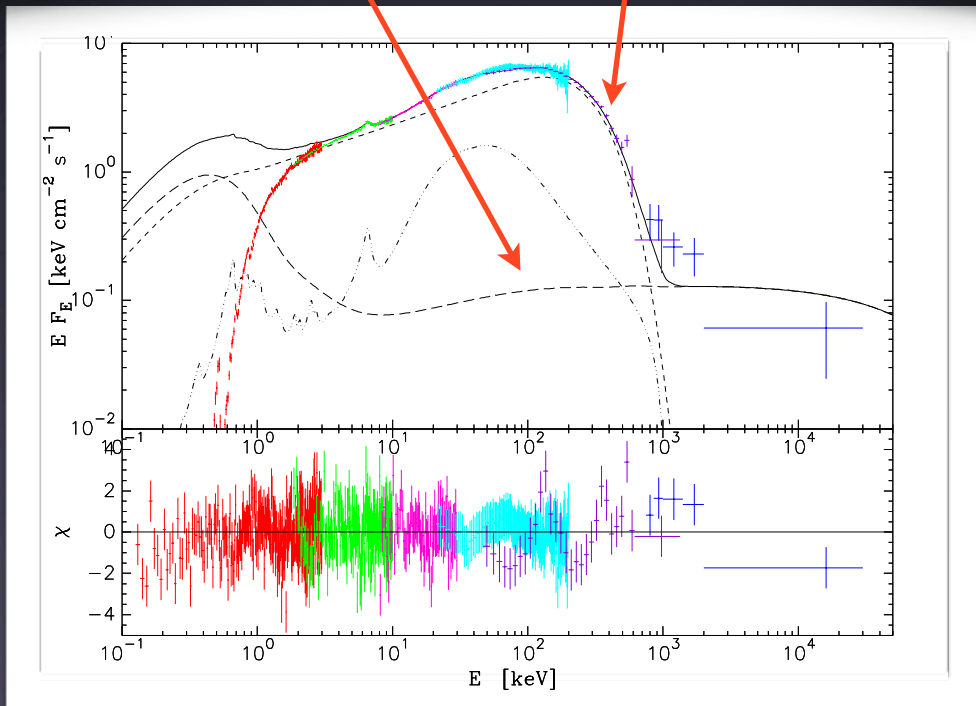
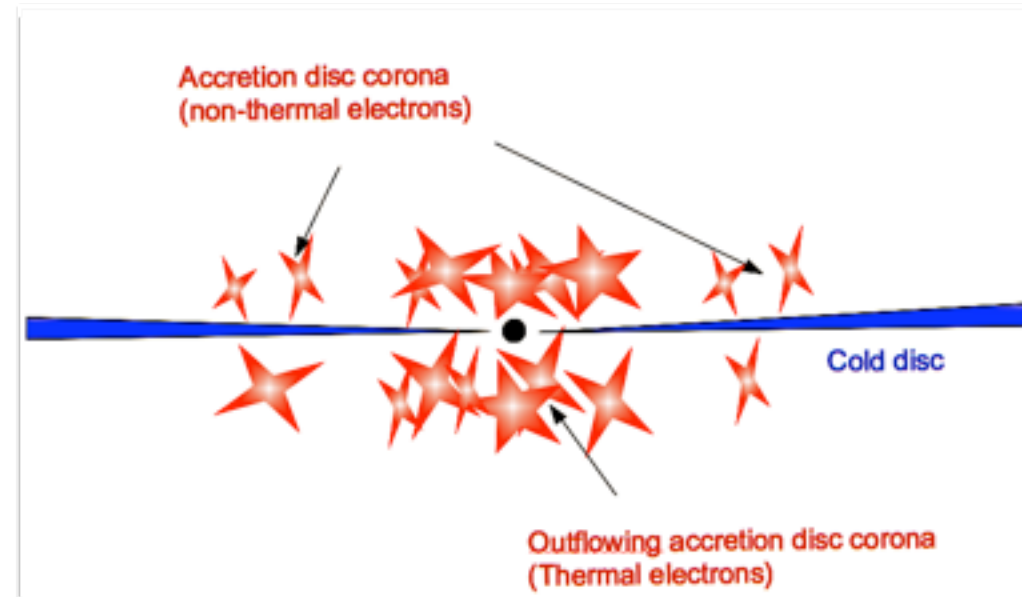
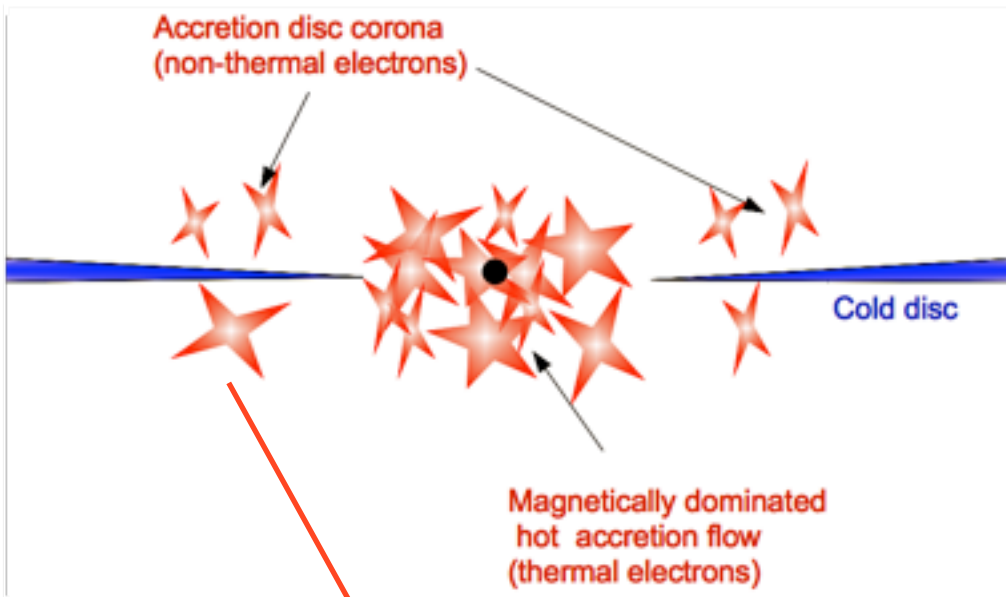
- non-thermal electrons generate too much synchrotron
- Maxwellian electrons are too cold

????

Constraint of low B removed if thermal and non-thermal
Comptonisation produced in different locations

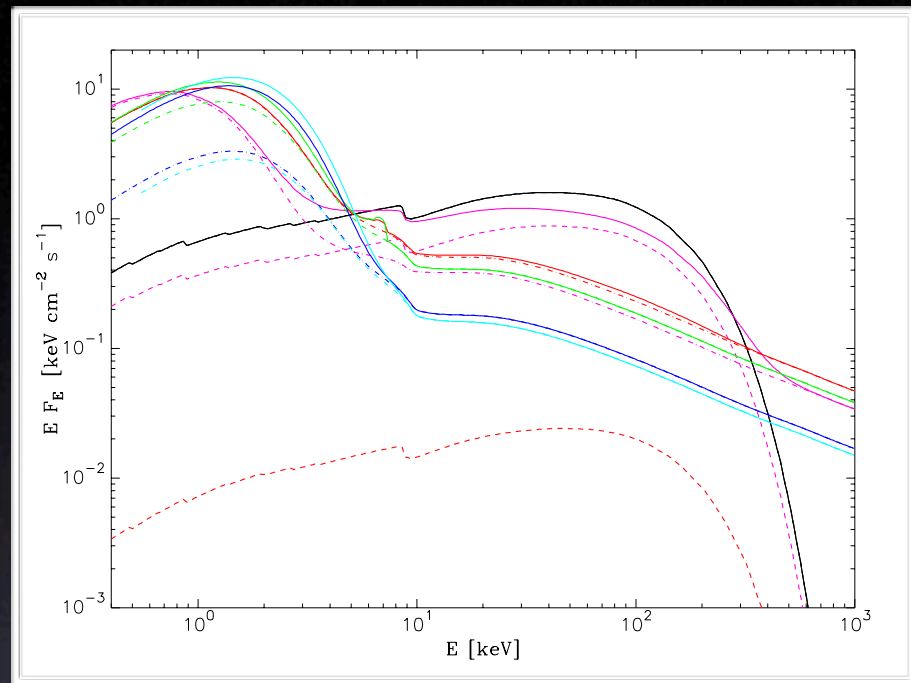
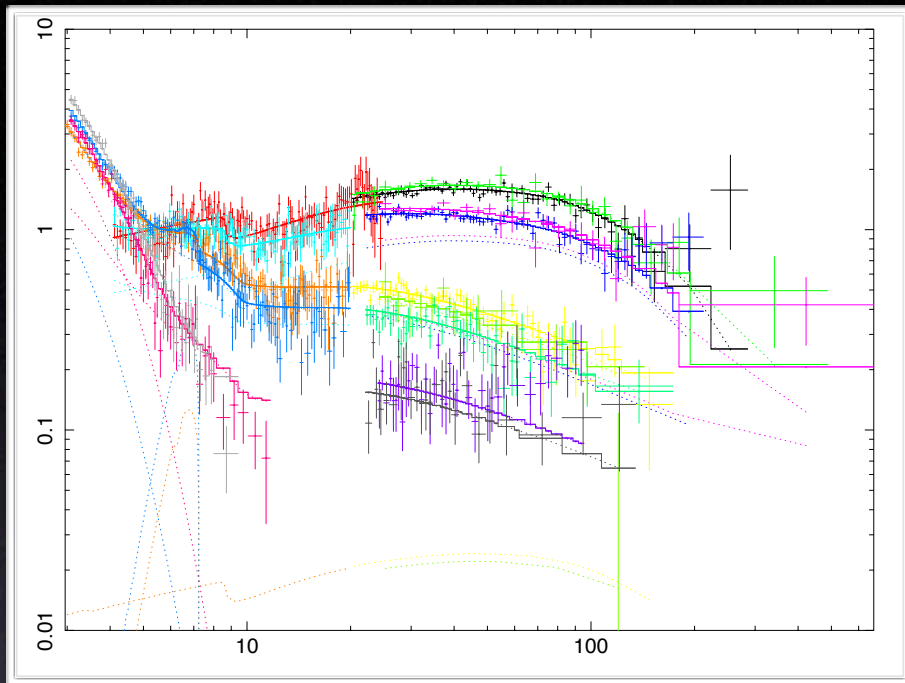
→ multi-zone corona ?

A two-component model for the LHS



- Thermal comptonisation component dominates hard X-ray emission
- Non-thermal component reproduces soft X-ray excess and MeV emission

Spectral state transitions revisited



● INTEGRAL data from GX339-4 during state transition consistent with a corona model with 2 zones (pure thermal and non-thermal).

● Shapes of thermal and non-thermal components are constant. Only temperature of disc blackbody and normalisations vary during transition.

Conclusions:

- In the best documented sources, none of the 'usual' accretion flow models really fits the data
- Magnetically dominated hot flow models seem promising
- Magnetic field likely to be strong, effects on
 - accretion flow dynamics
 - particle thermalisation / cooling
 - radiation
- If so the structure of the corona appears complex: multi-zone models appear required