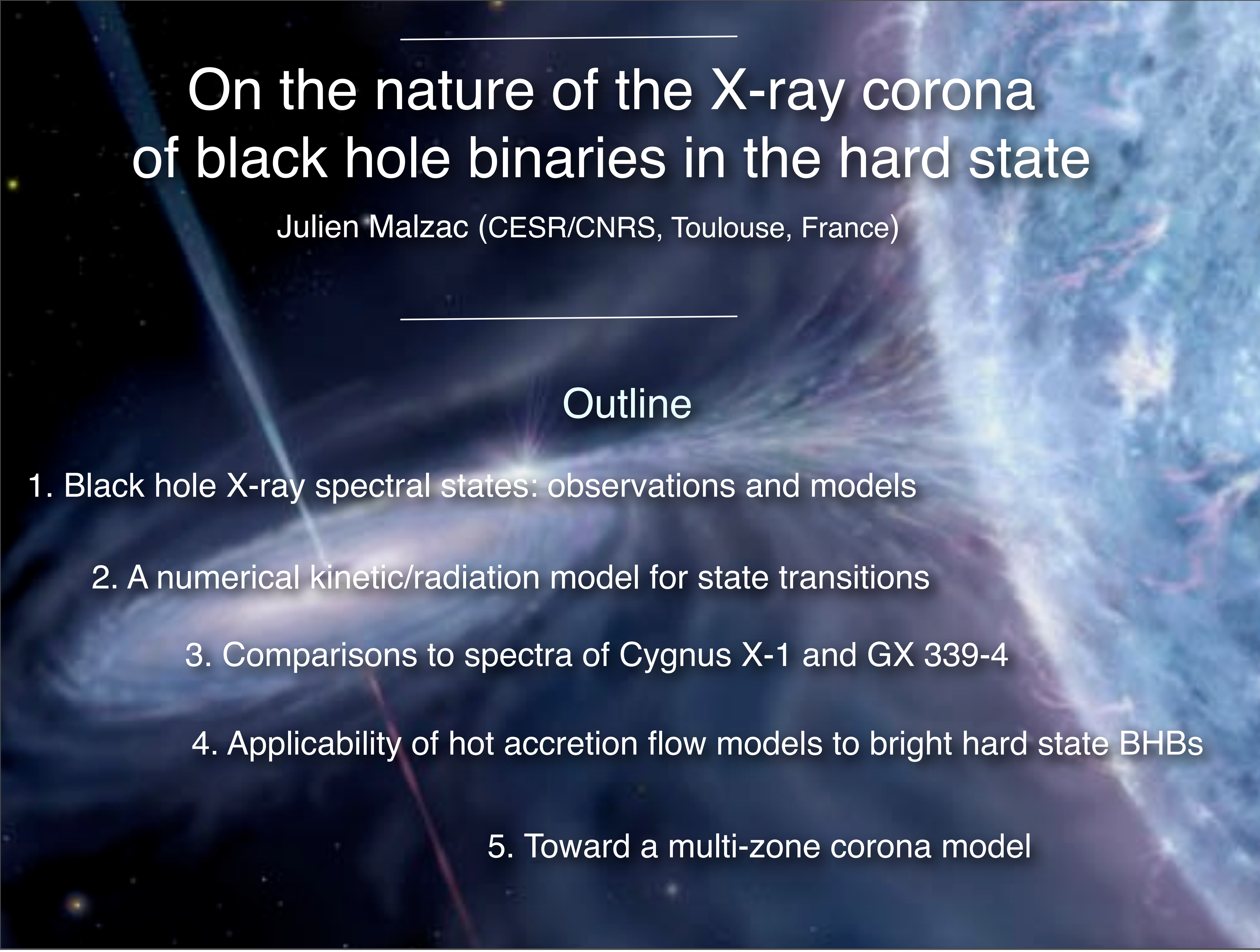


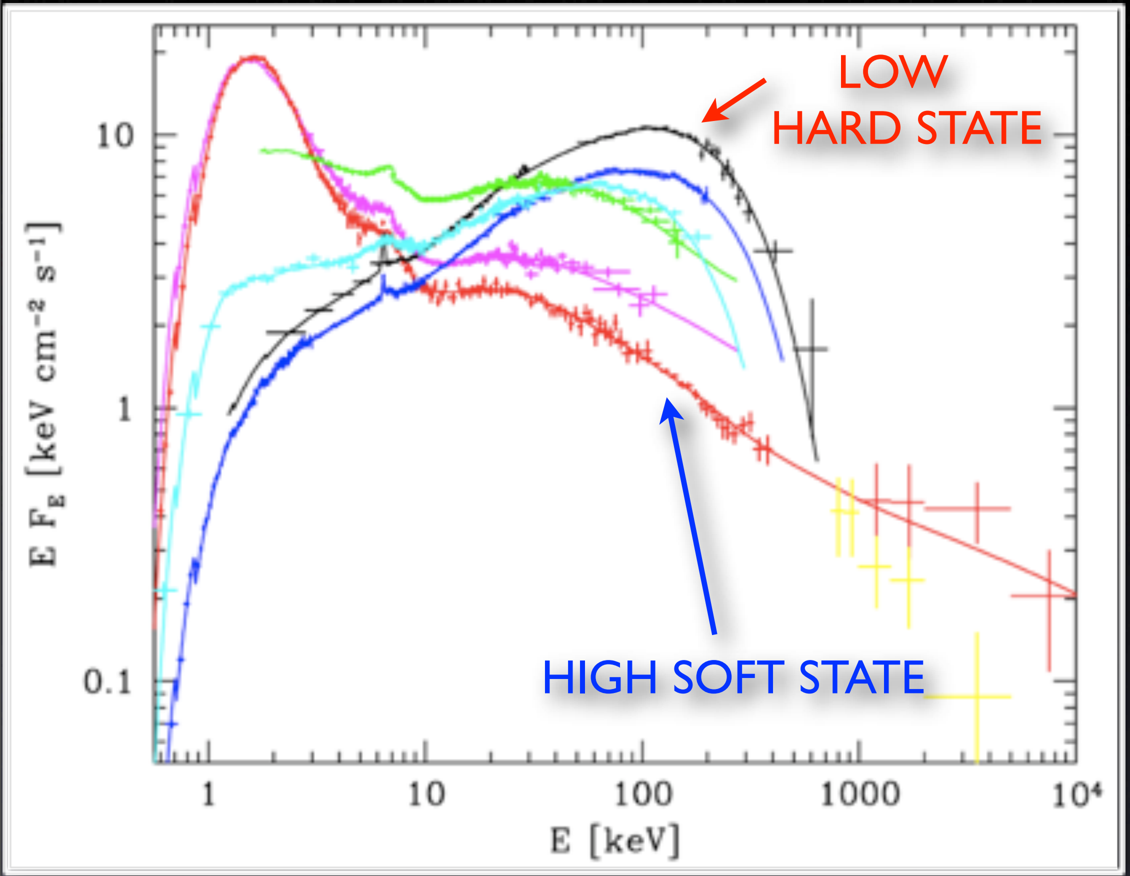
On the nature of the X-ray corona of black hole binaries in the hard state

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 and GX 339-4
4. Applicability of hot accretion flow models to bright hard state BHBs
5. Toward a multi-zone corona model

High energy emission of Cygnus X-1



Zdziarski et al 2003

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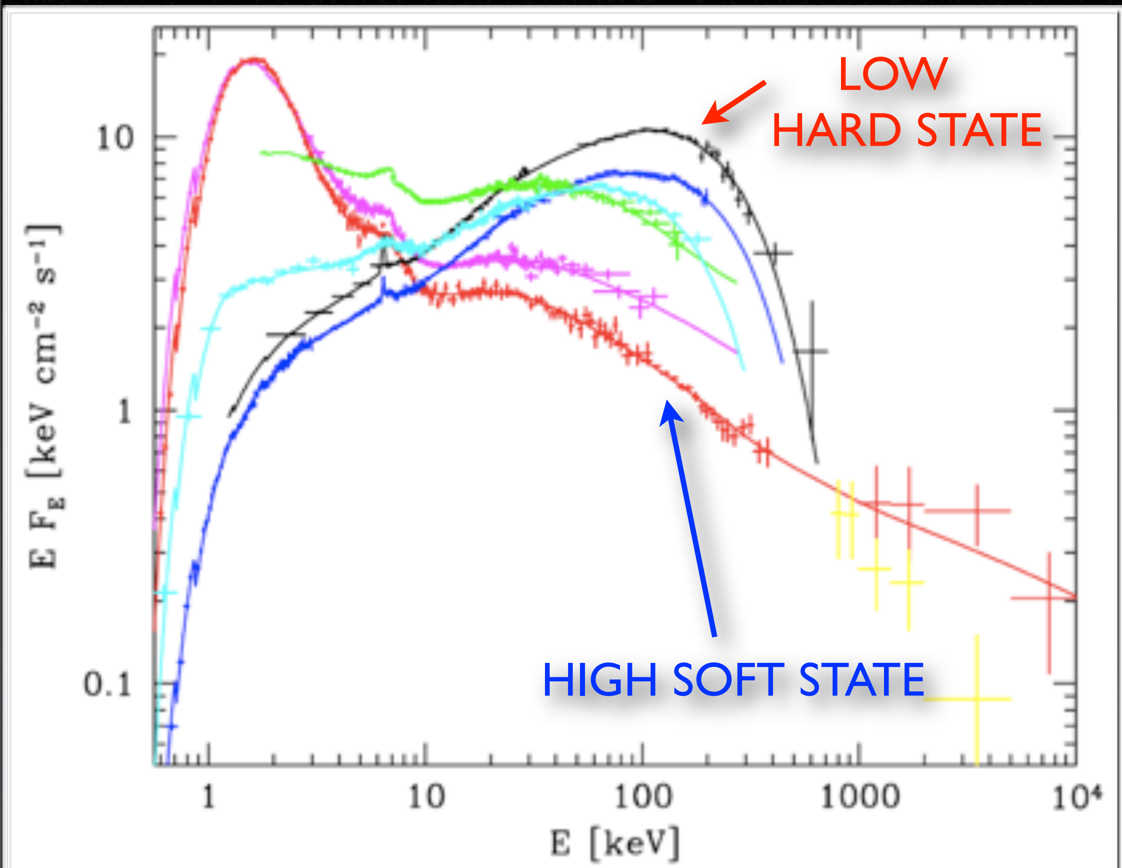

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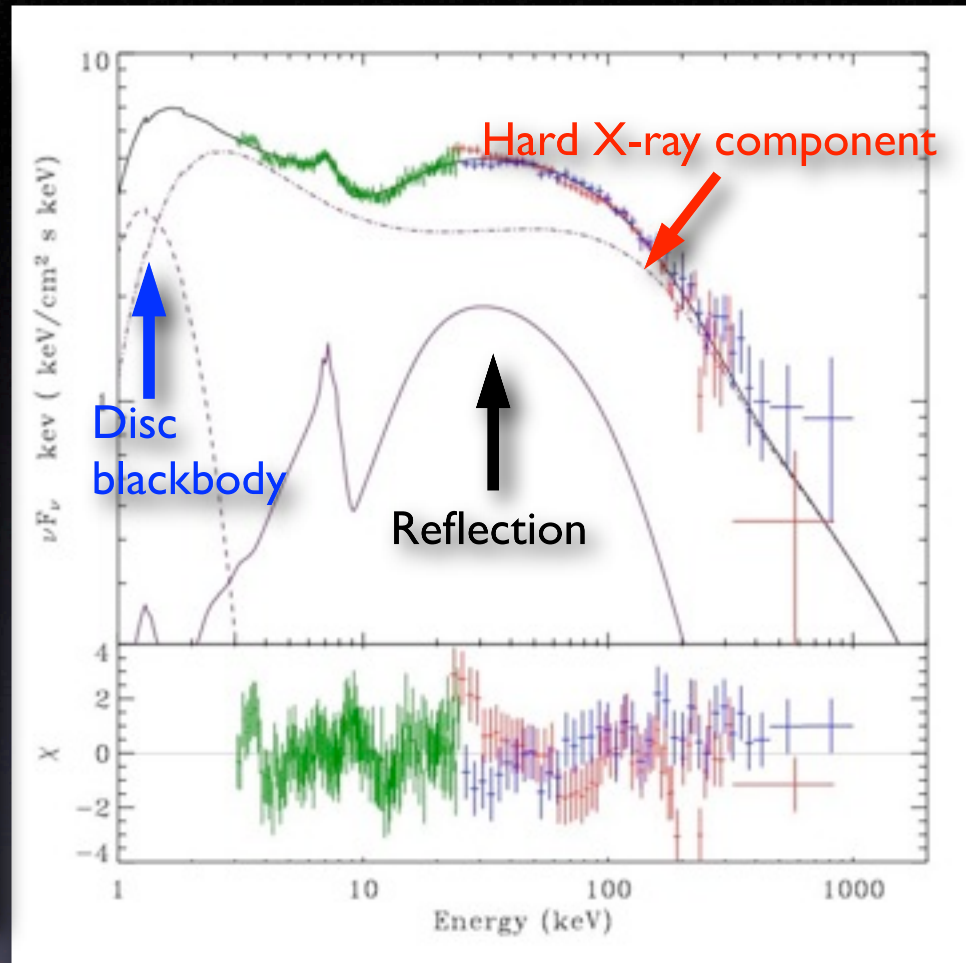


Malzac et al. 2006

LOW HARD STATE: (compact radio jet)

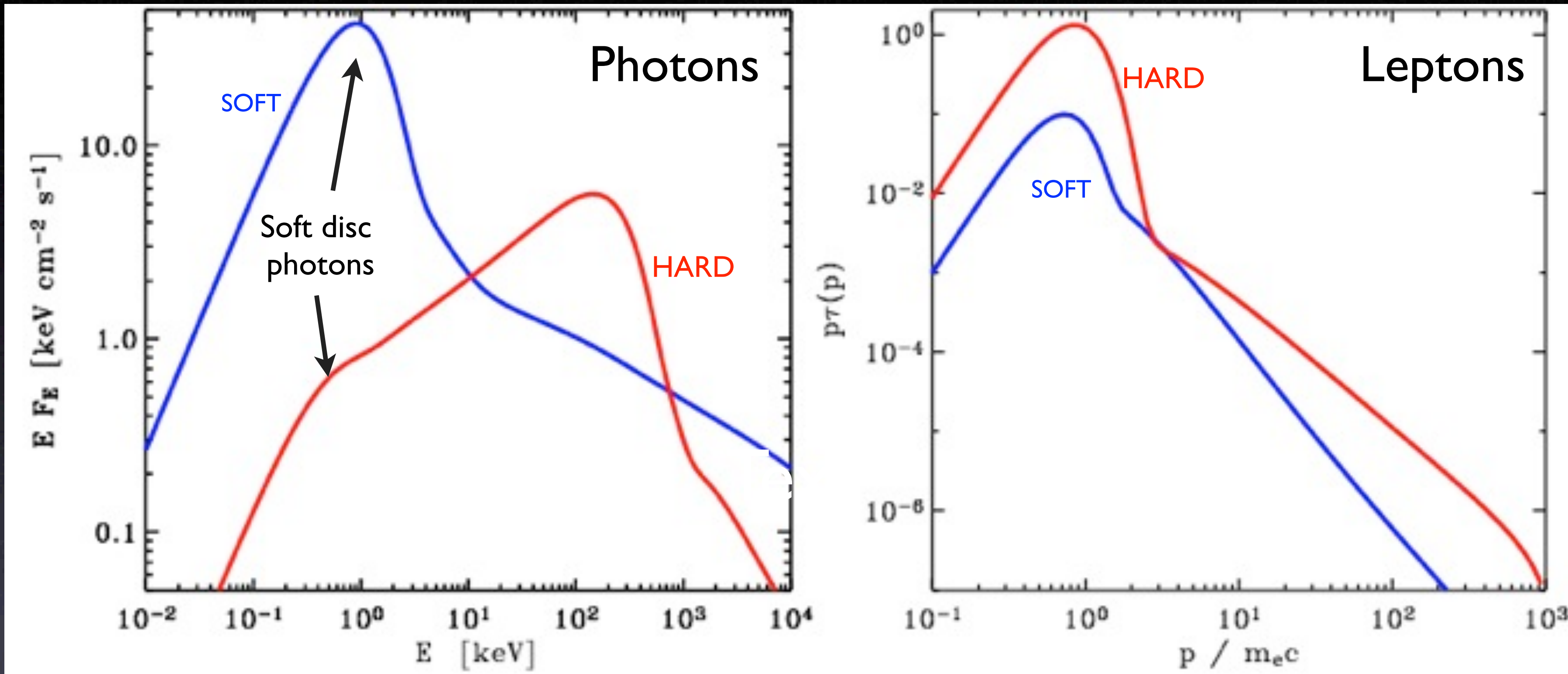
disc blackbody and reflection: weak / Corona: THERMAL Comptonisation

HIGH SOFT STATE:

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

Hybrid thermal/non-thermal comptonisation models

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



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

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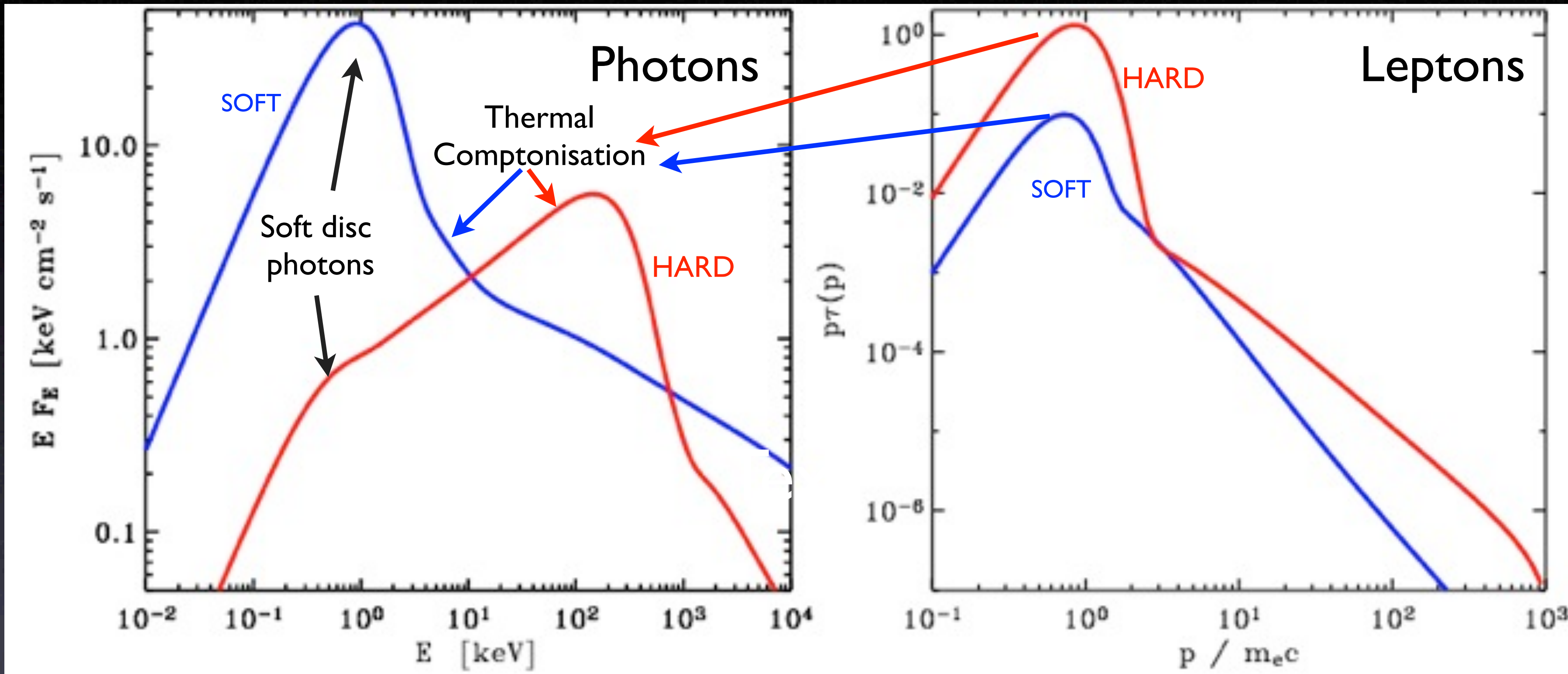

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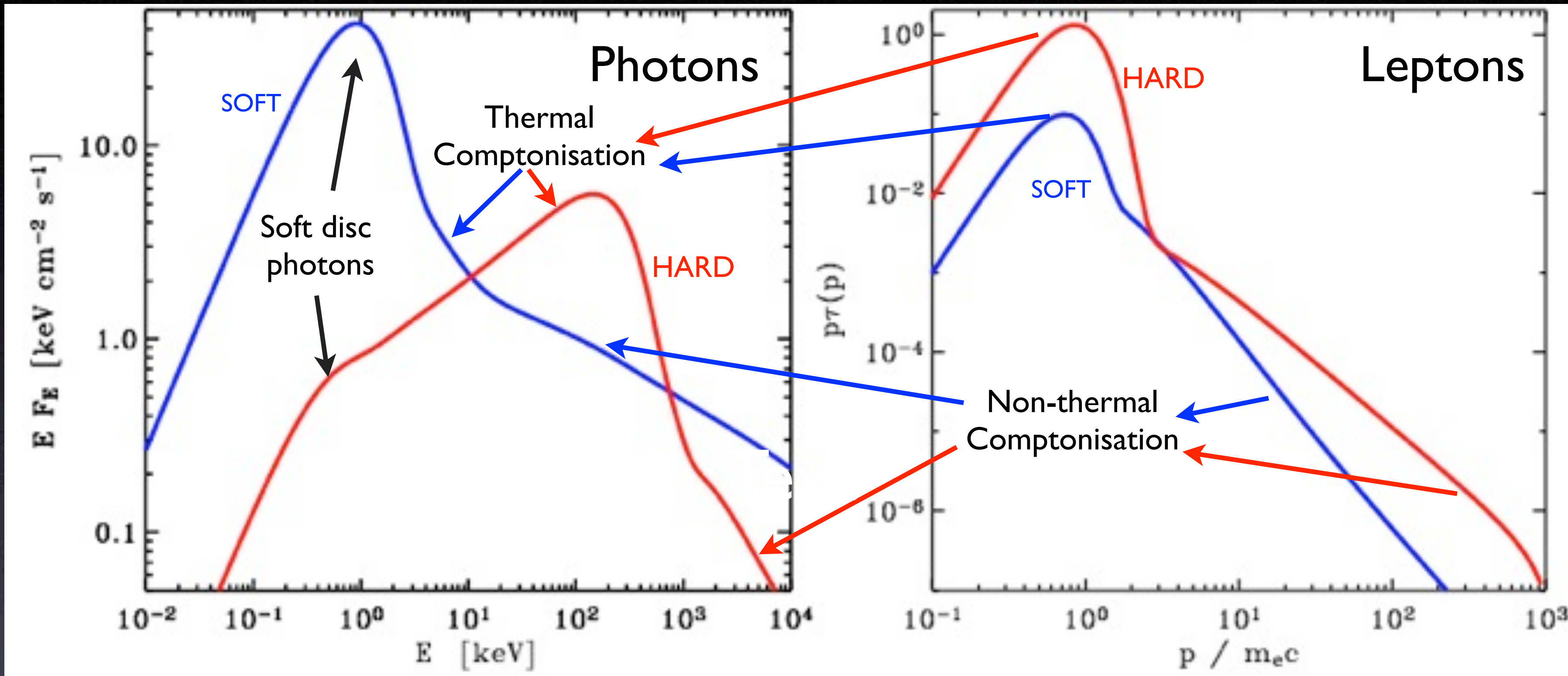

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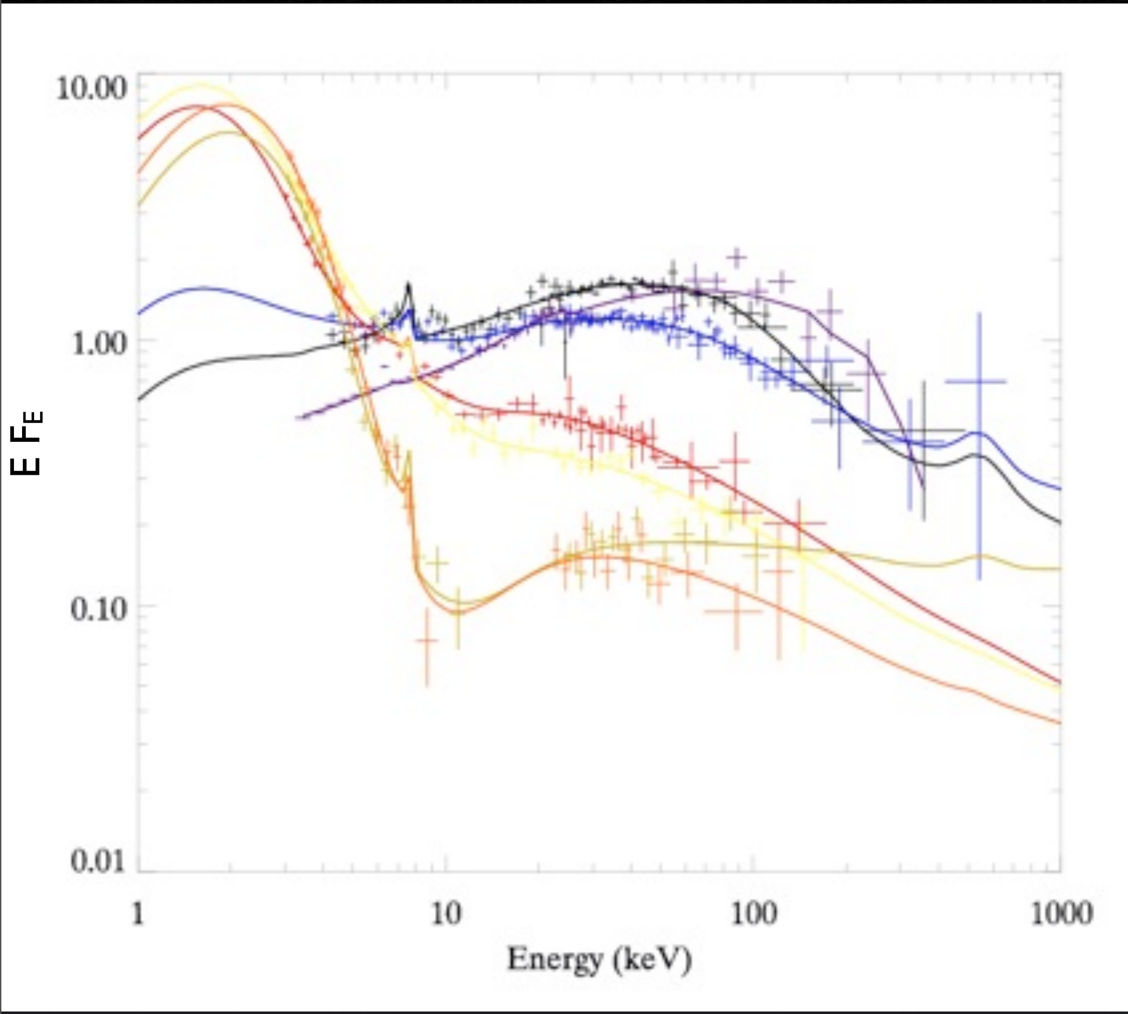
GX 339-4 during the 2004 state transition



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 of the coronal electrons by soft disc photons

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

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

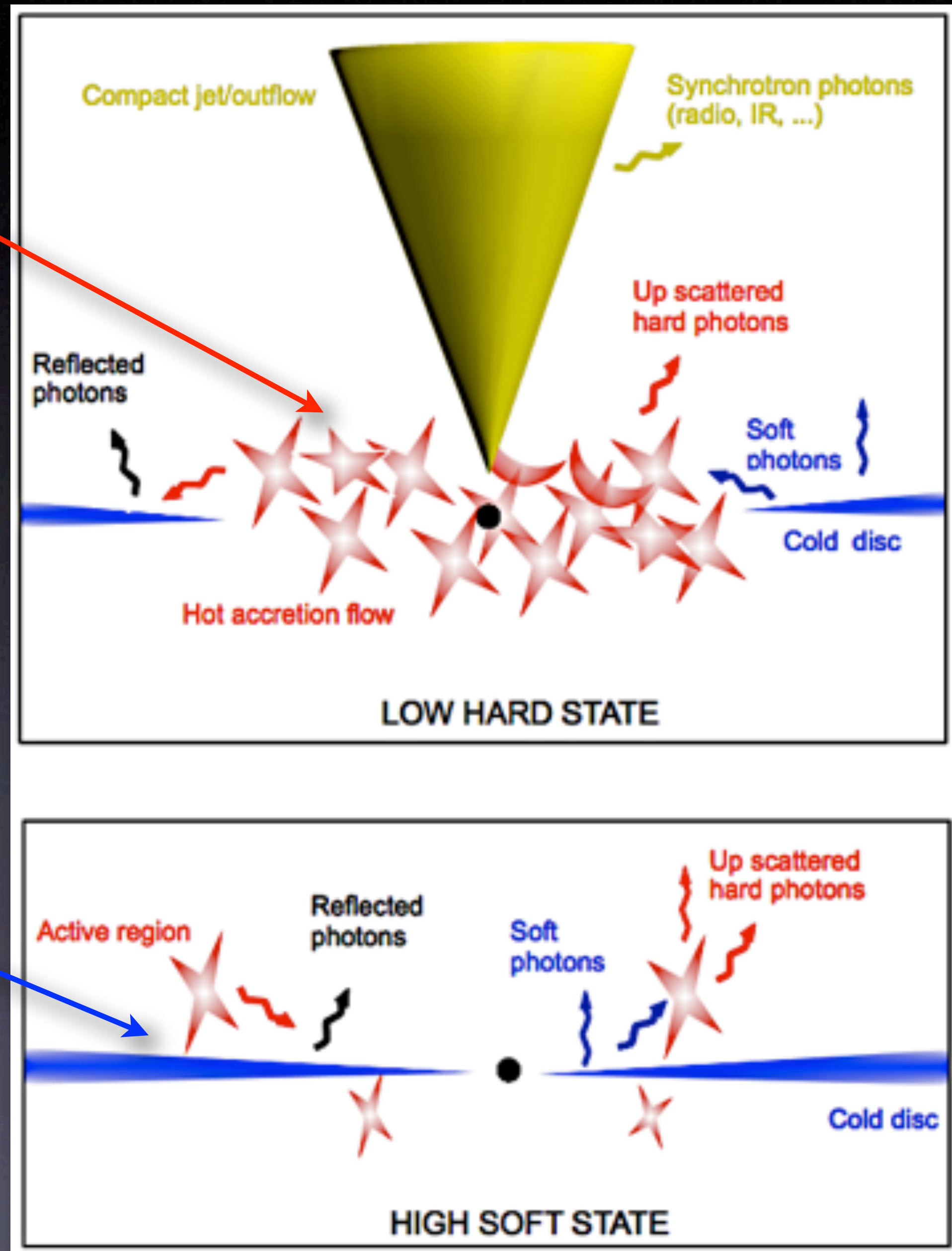
Standard picture: truncated disc model

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. 2010...)



HIGH SOFT STATE

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

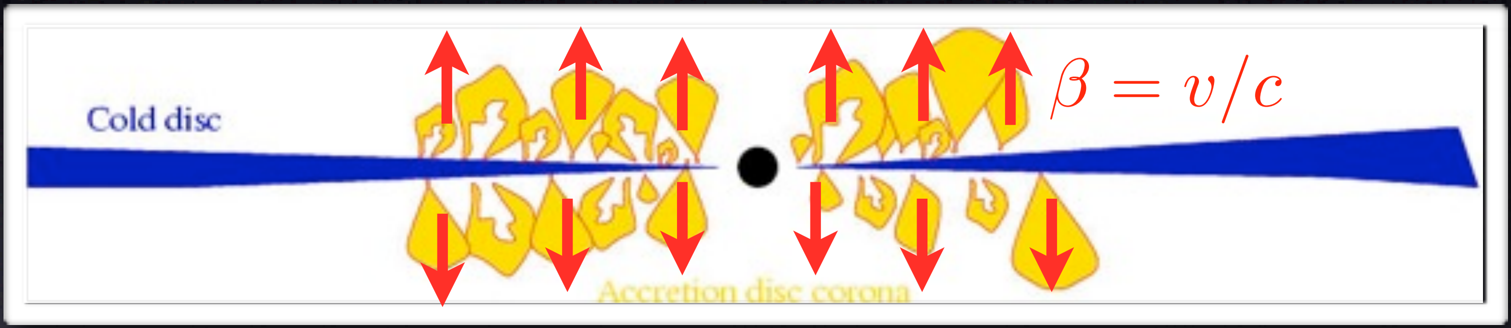
⇒ dominant thermal disc emission

+ non-thermal comptonisation

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

Alternative models for the hard state

- Accretion disc corona outflowing with midly relativistic velovity 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: $P_{\rm j} \simeq L_{\rm X} \simeq 2 \times 10^{37}$ erg s^{-1} (Gallo et al. 2005, Russell et al. 2007)

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➡ accretion proceeds efficiently in the hard state

➡ cannot be strongly advection dominated

➡ not enough power to eject corona with $\tau_{\rm T} > 1$ to infinity with relativistic speed

➡ X-ray corona $\neq$ Jet

Malzac, Belmont & Fabian, MNRAS, 2009

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)

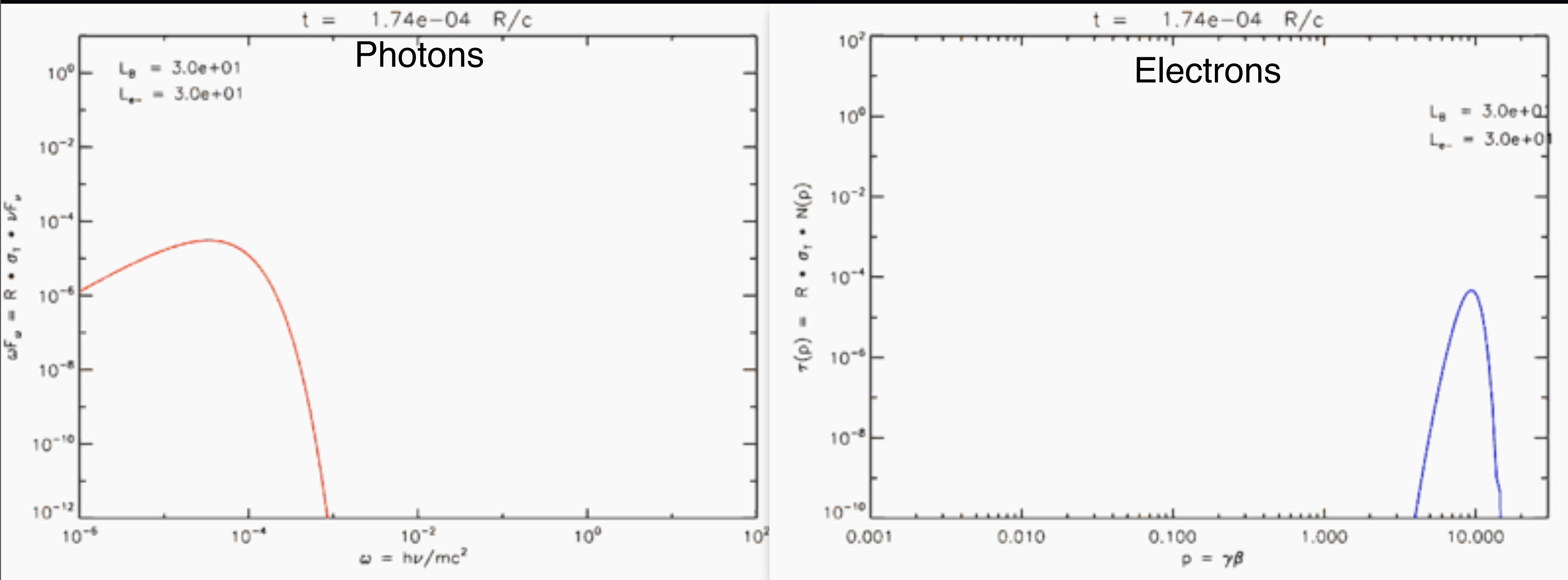
- Solve coupled time-dependent kinetic equations (one zone) for leptons and photons (no assumption on the shape of the electron distributions)

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

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

The Synchrotron boiler

(Ghisellini, Guilbert and Svensson 1988)



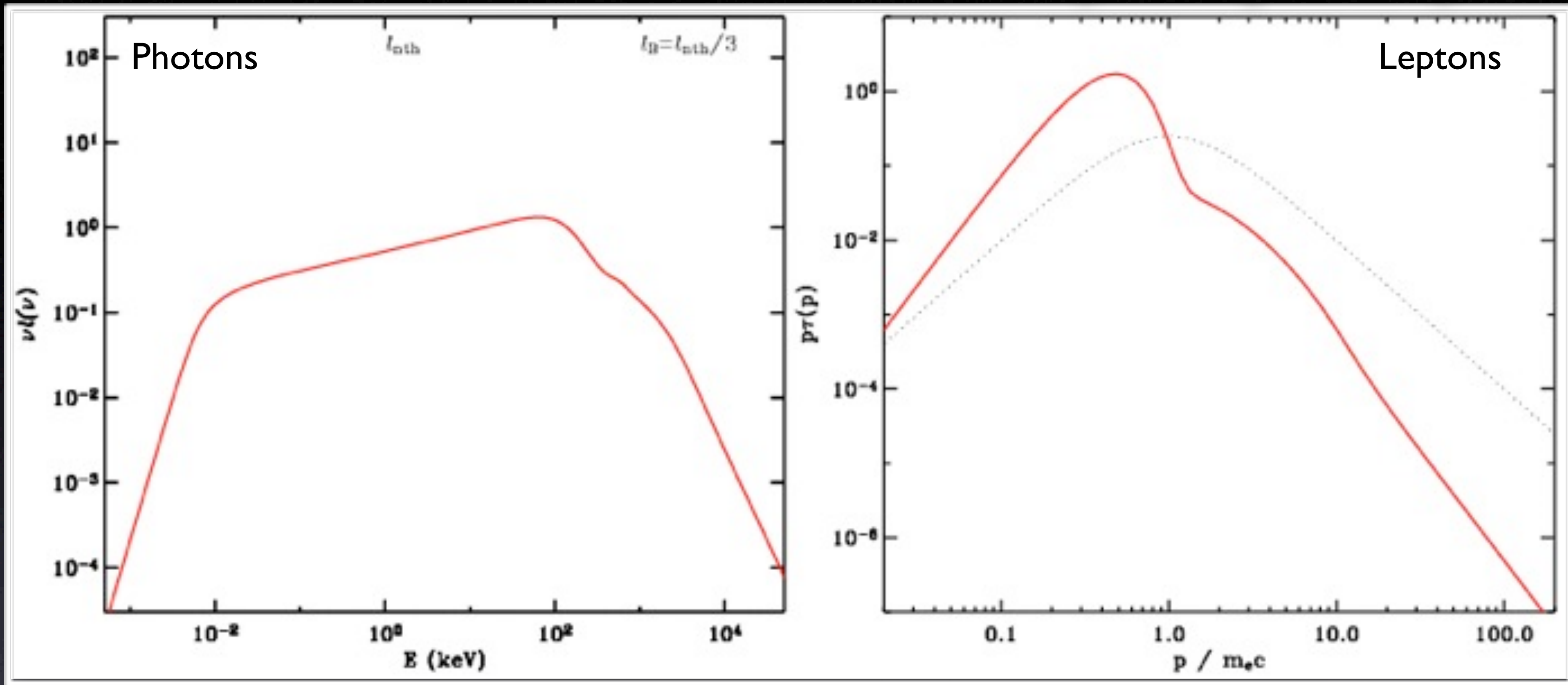
- Electrons injected with γ =10 in an empty (but magnetised) region

  Synchrotron self-Compton emission

- High energy e- ➙ synchrotron photons ➙ 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)

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/(8π)
- 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)

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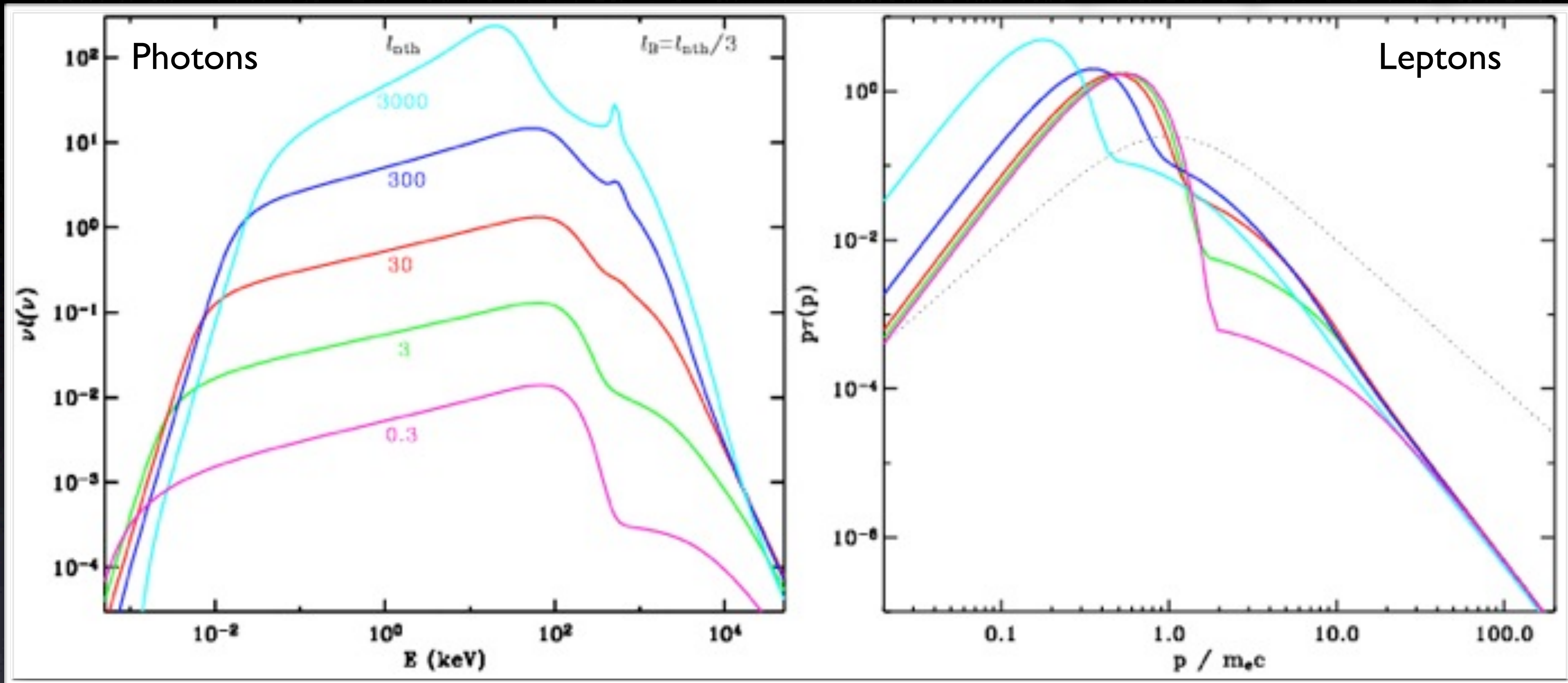

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Effect of external soft photons

- Add soft thermal photons:

➡ temperature of Maxwellian electrons decreases

➡ Compton emission increasingly dominated by non-thermal electrons

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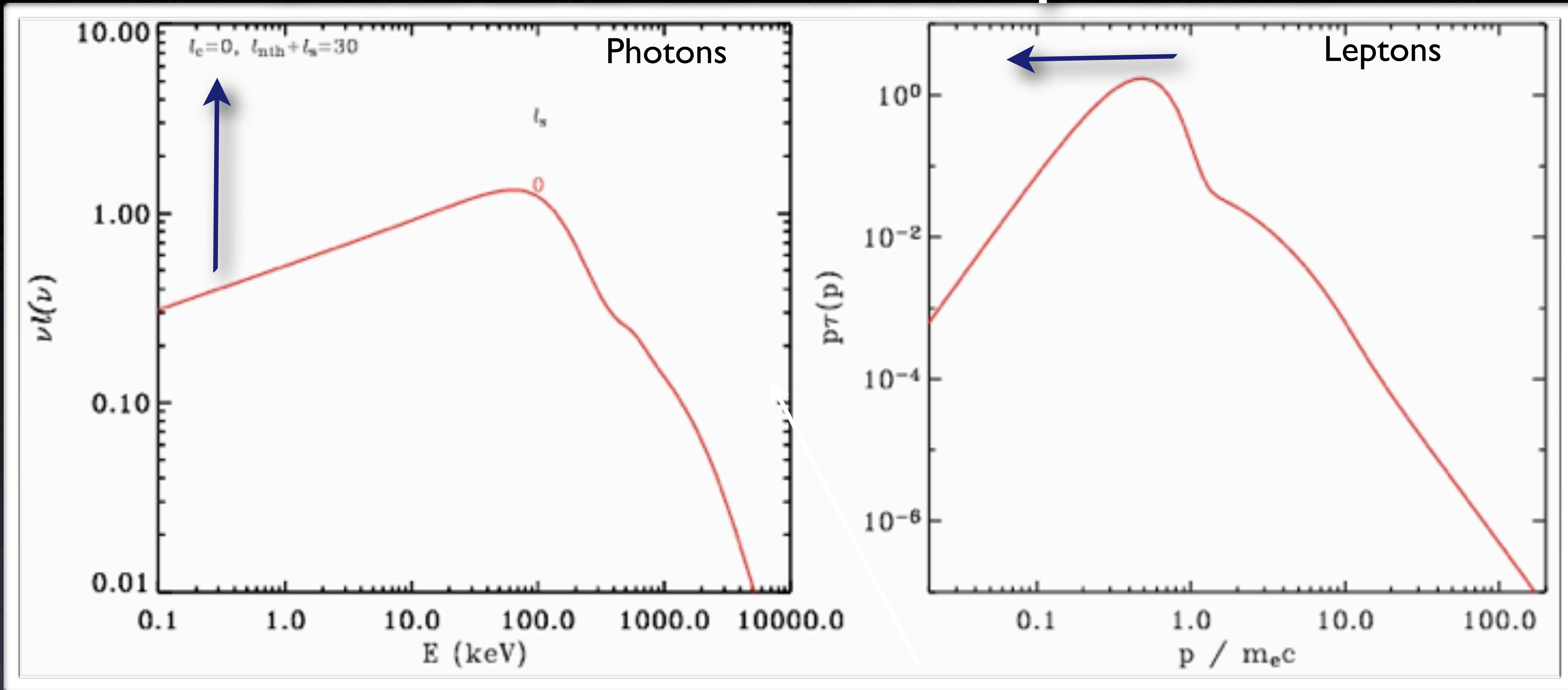

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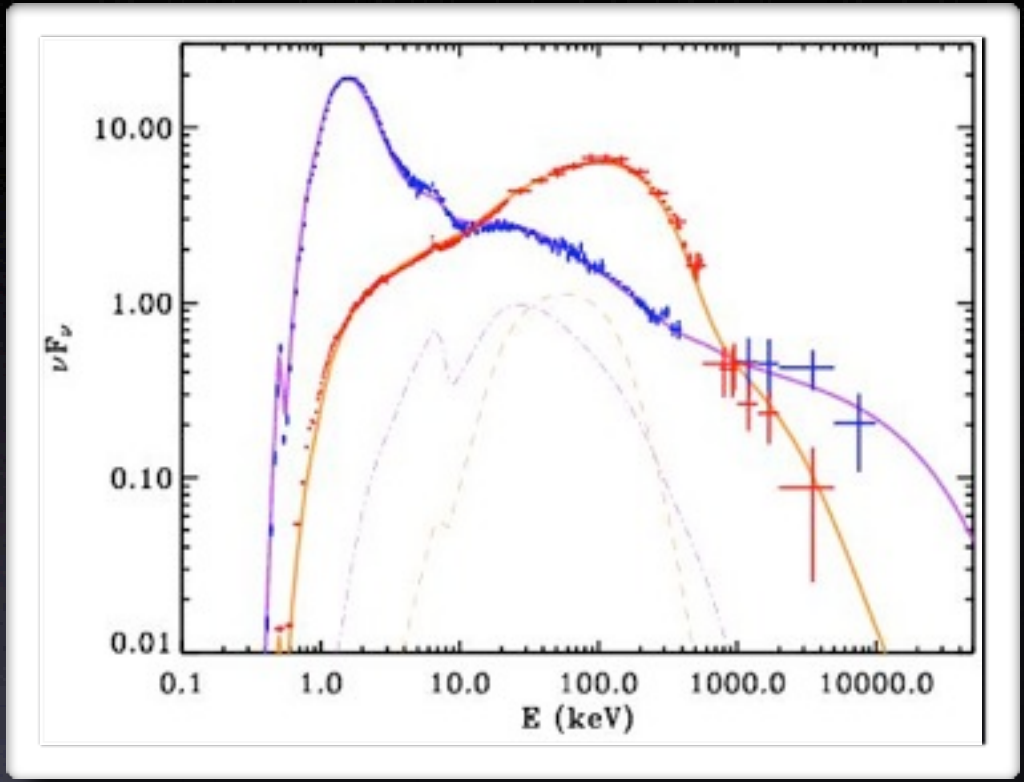
Comparisons to Cygnus X-1 spectra

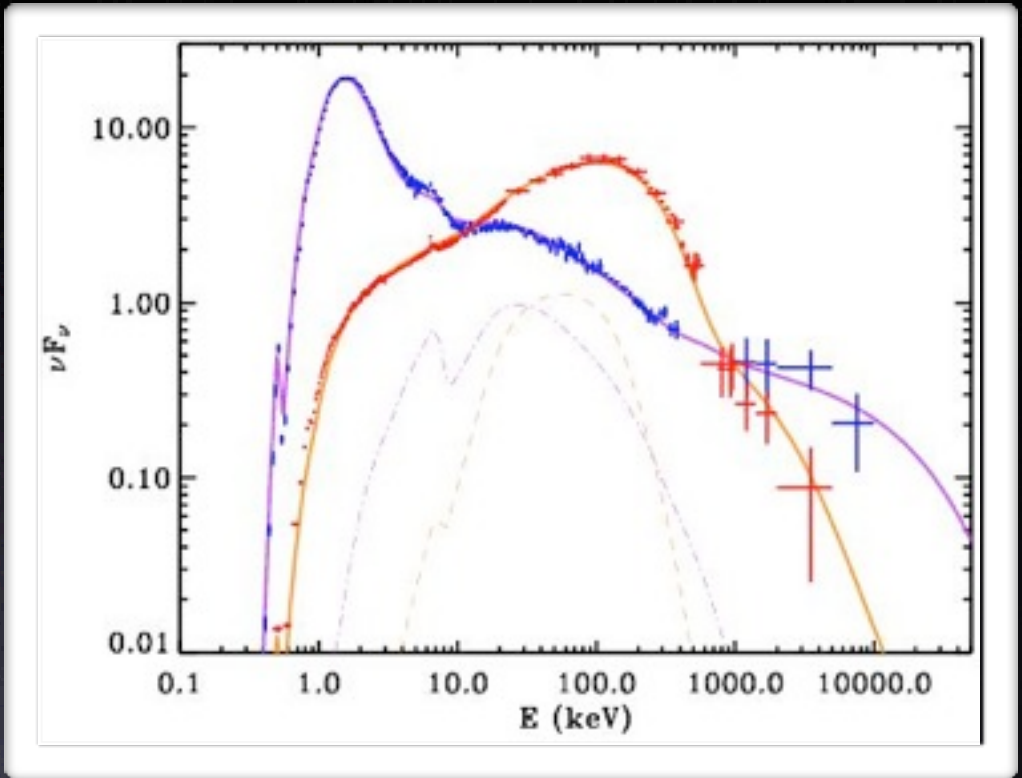


(Malzac & Belmont 2009 ; Poutanen & Vurm 2009)

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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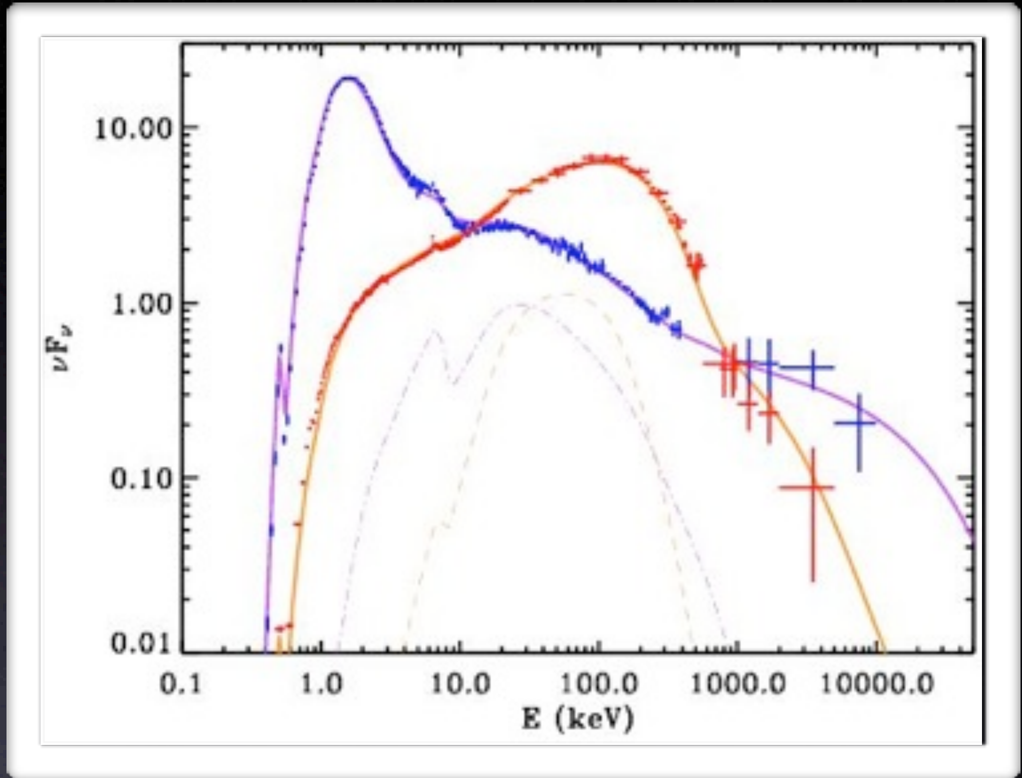

If B is large:

➡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):

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- Temperature of hot protons in hard state:

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

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

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- 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. $Q_{\rm vis} = -\alpha P_{\rm gas} R \frac{d\Omega}{dr}$),

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

➡ standard ADAF solution cannot be applied

- A possible fix:

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

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

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

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

- Hot accretion flow solutions
- Accretion disk coronae
- MHD jet models

➡ strong magnetic field

but...

- Non-thermal high energy excess ➡ weak magnetic field

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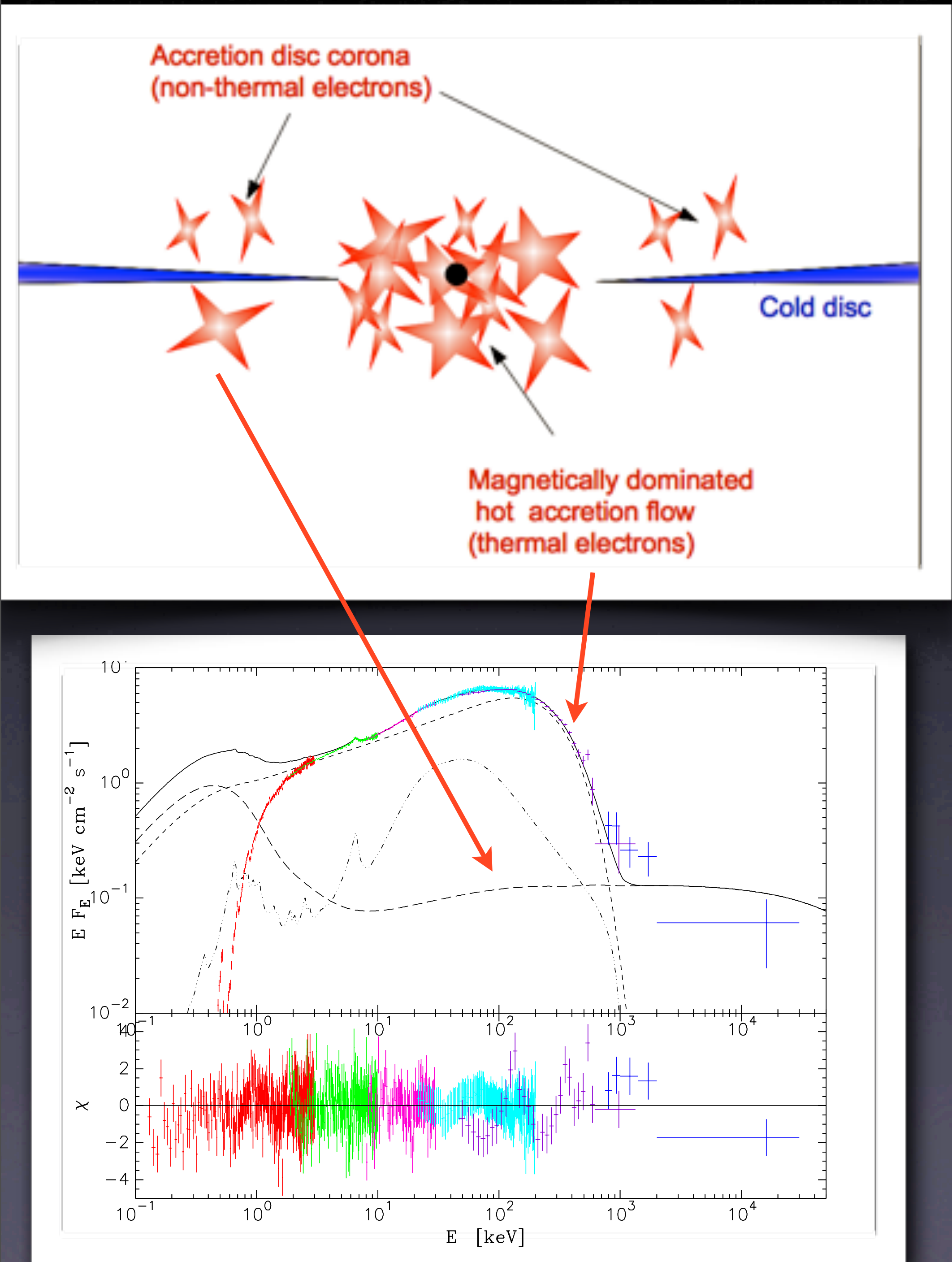
Constraint of low B removed if thermal and non-thermal Comptonisation produced in different locations

➡ 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

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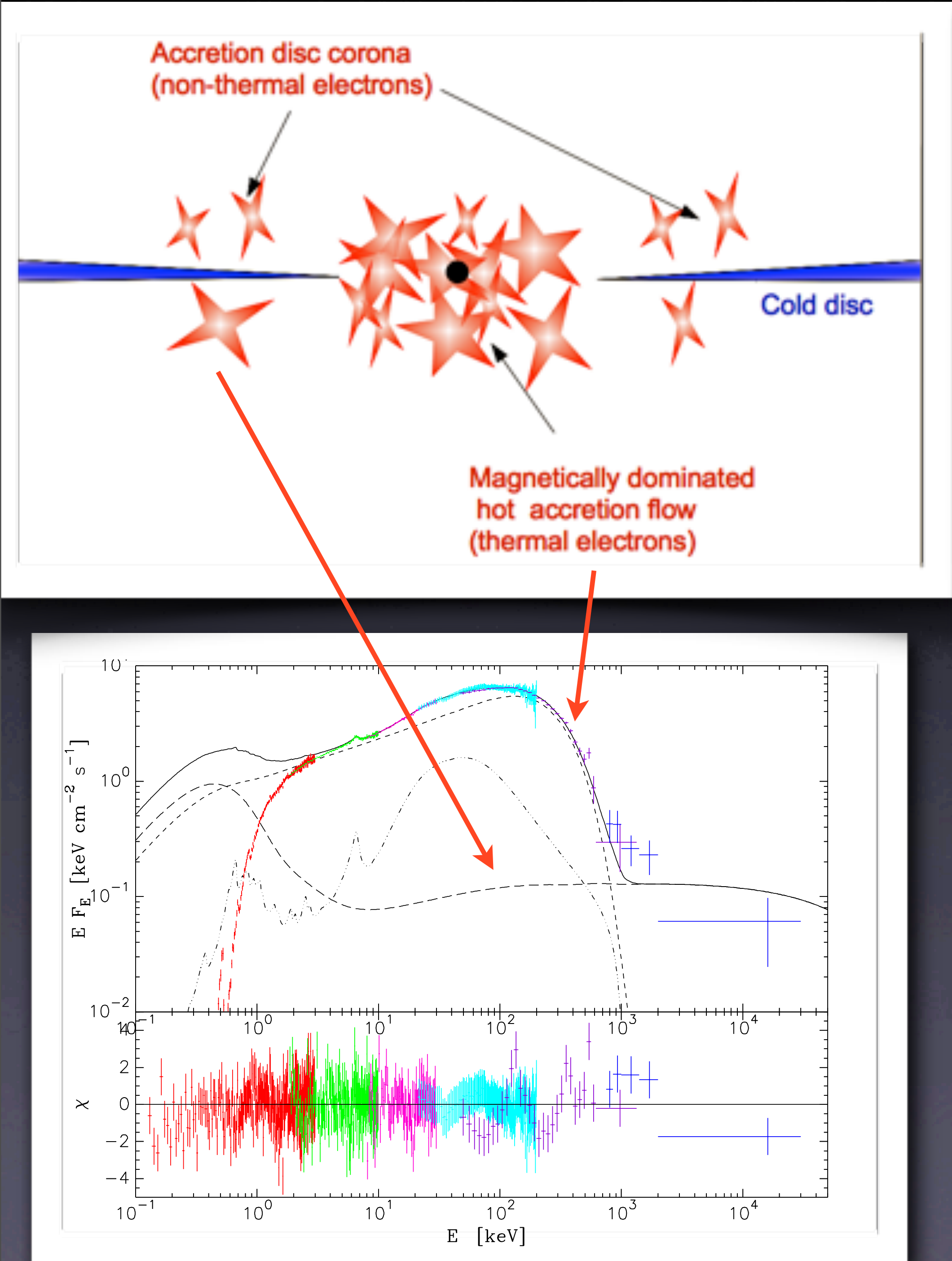

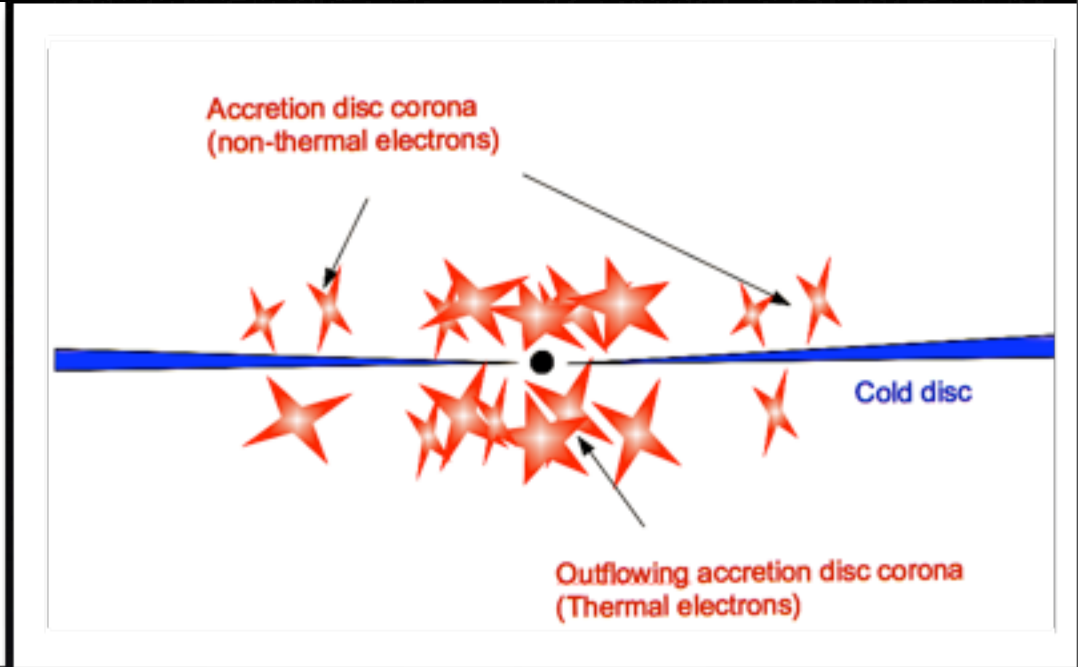

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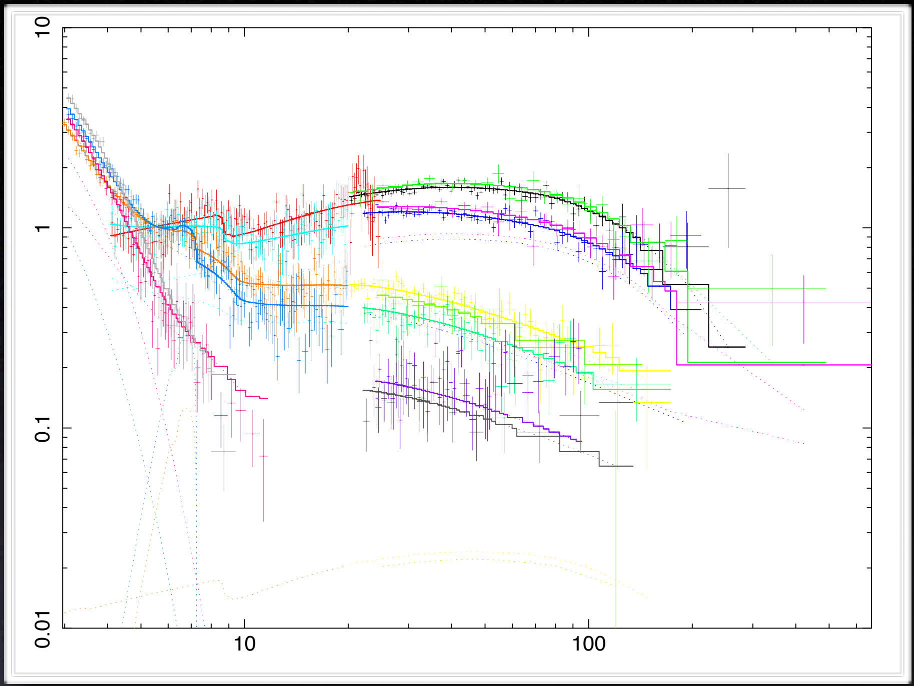
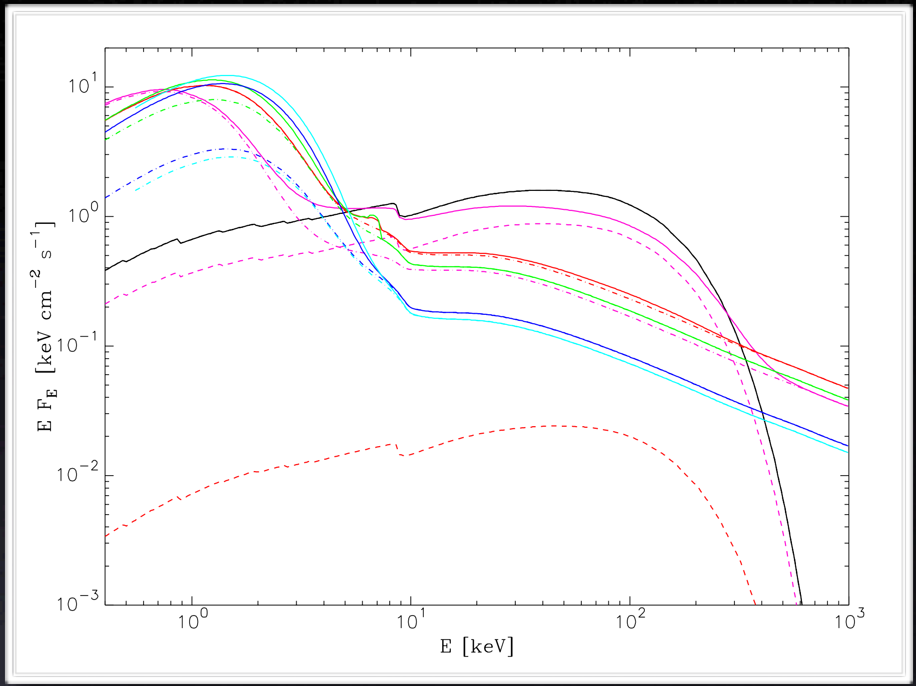
Spectral state transitions revisited





- 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:

- We still do not know what the corona is ...
- In the best documented sources, none of the ‘usual’ corona models really fits the data
- However, magnetically dominated hot flow models seem promising for bright hard state sources.
- 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