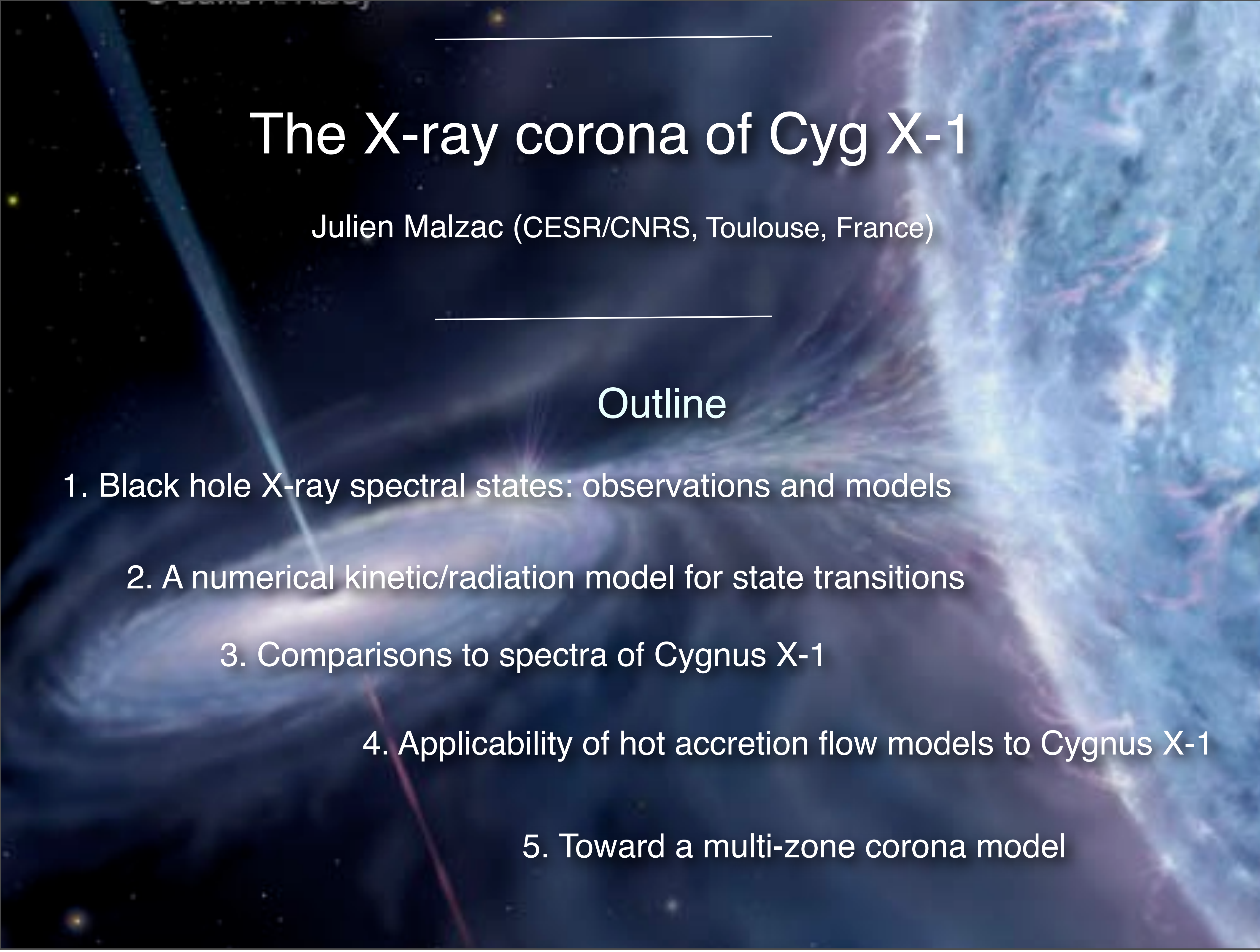


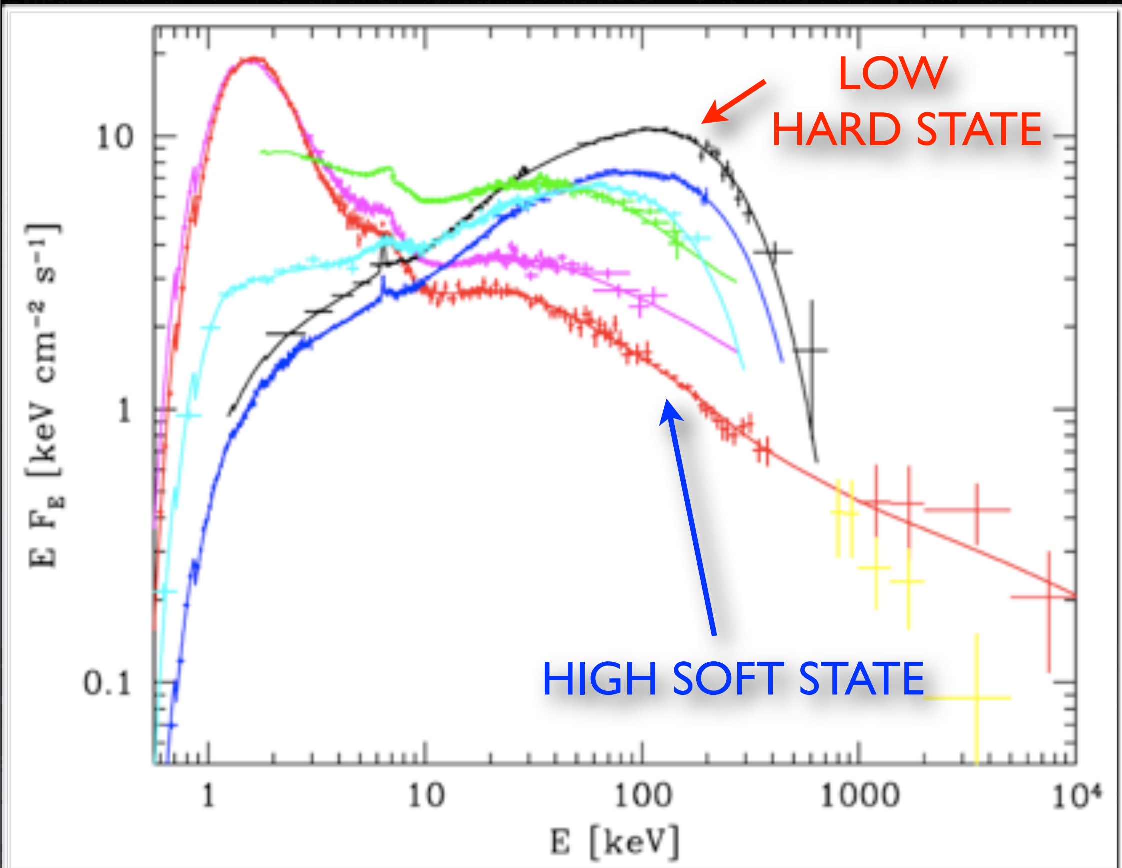
The X-ray corona of Cyg X-1

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. Applicability of hot accretion flow models to Cygnus X-1
5. Toward a multi-zone corona model

High energy emission of Cygnus X-1



Zdziarski et al 2003

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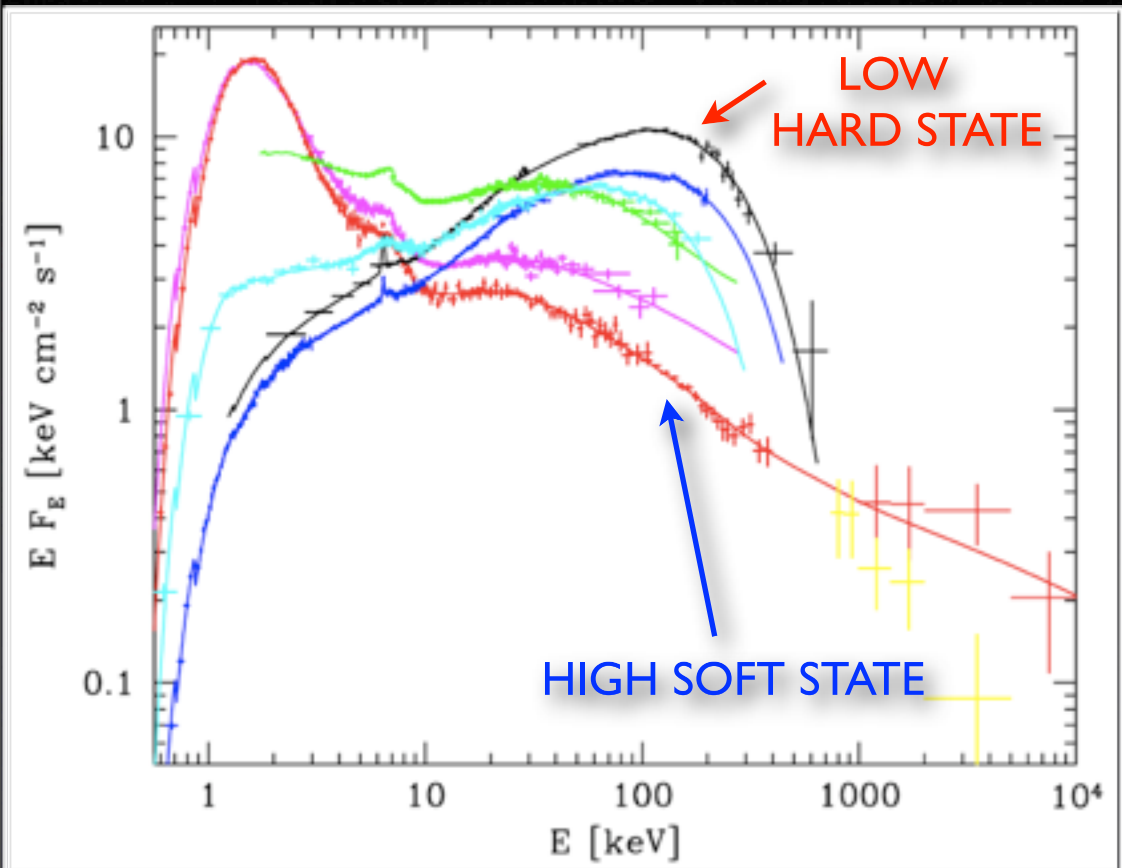

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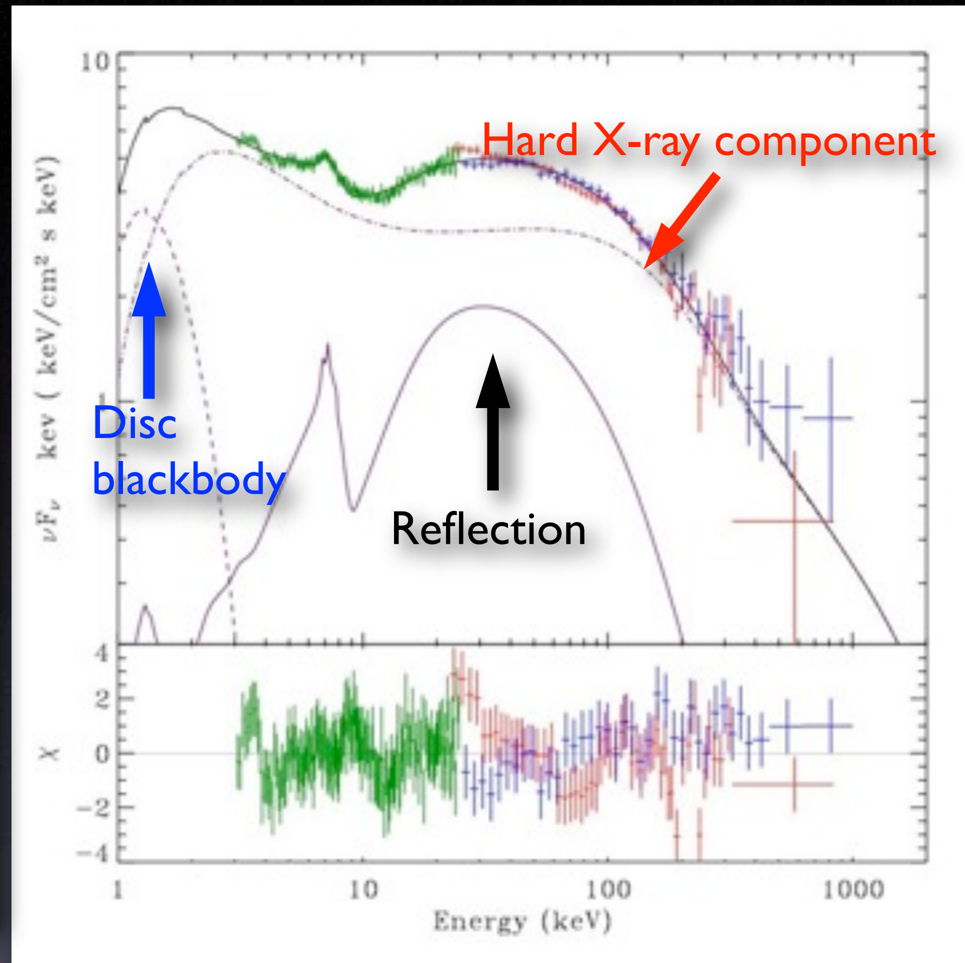


Malzac et al. 2006

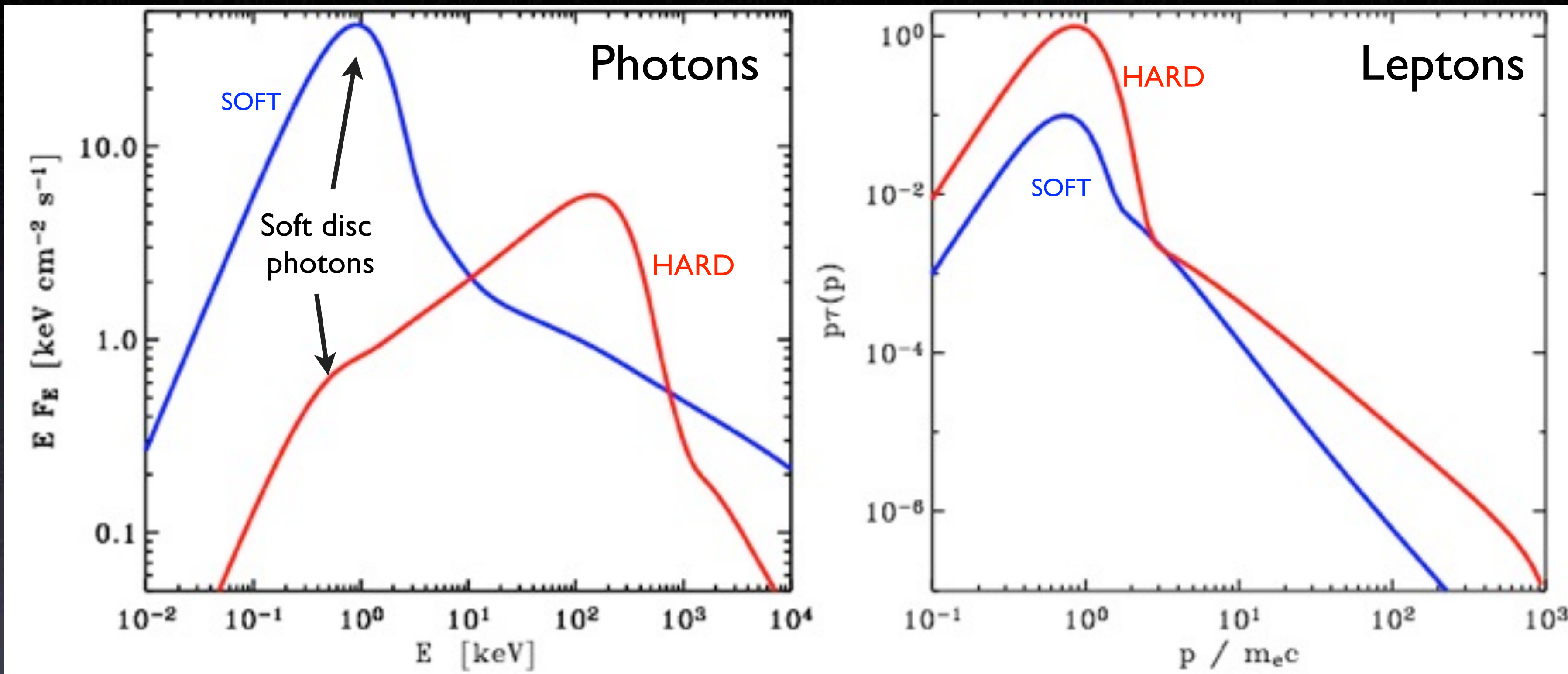
LOW HARD STATE: (compact radio jet)

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



- 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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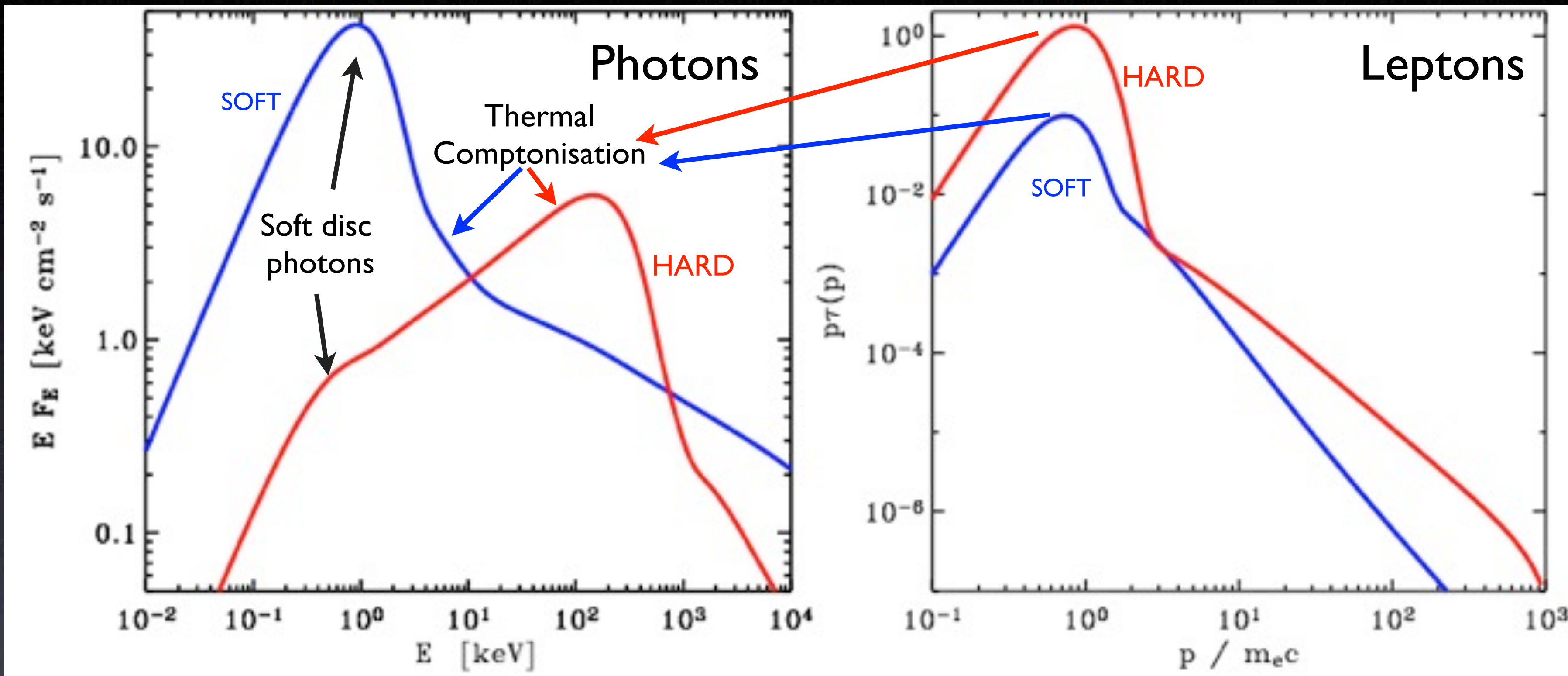

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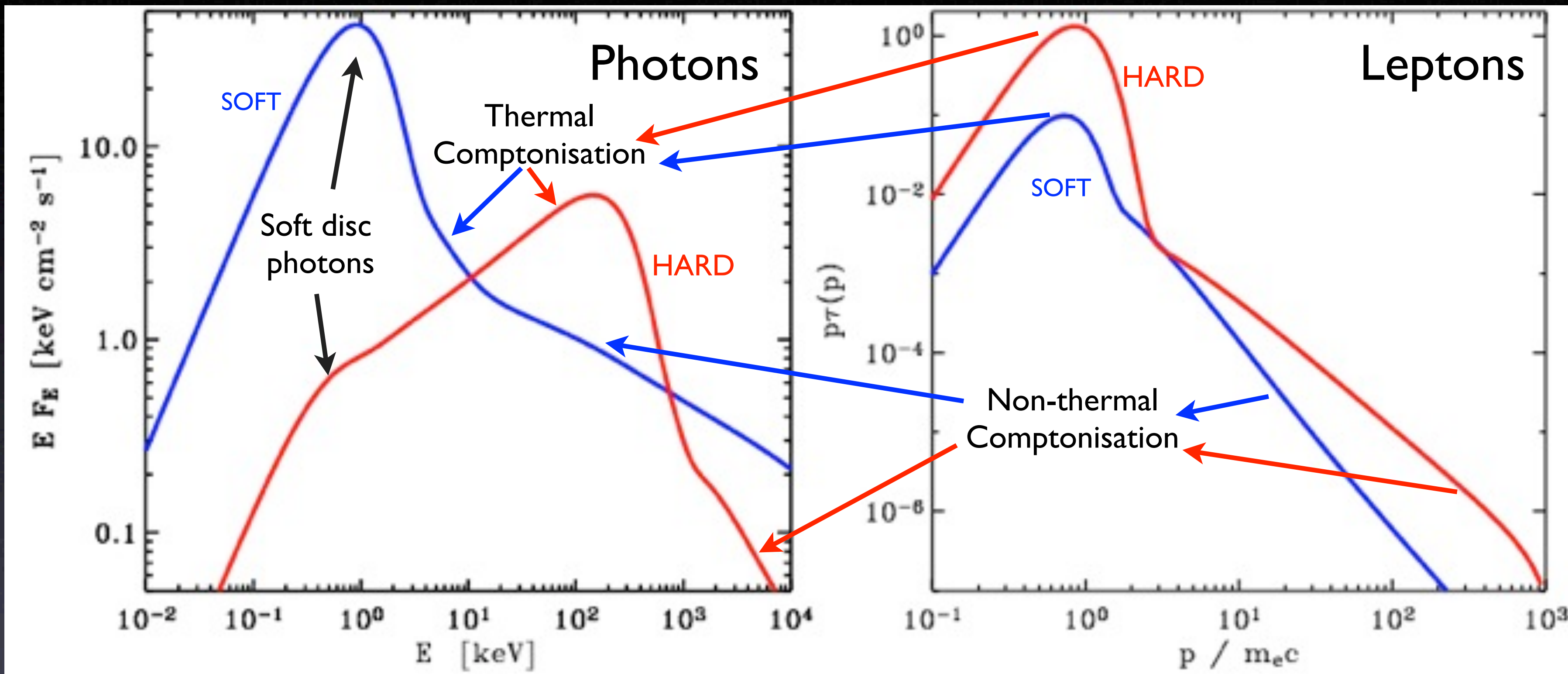

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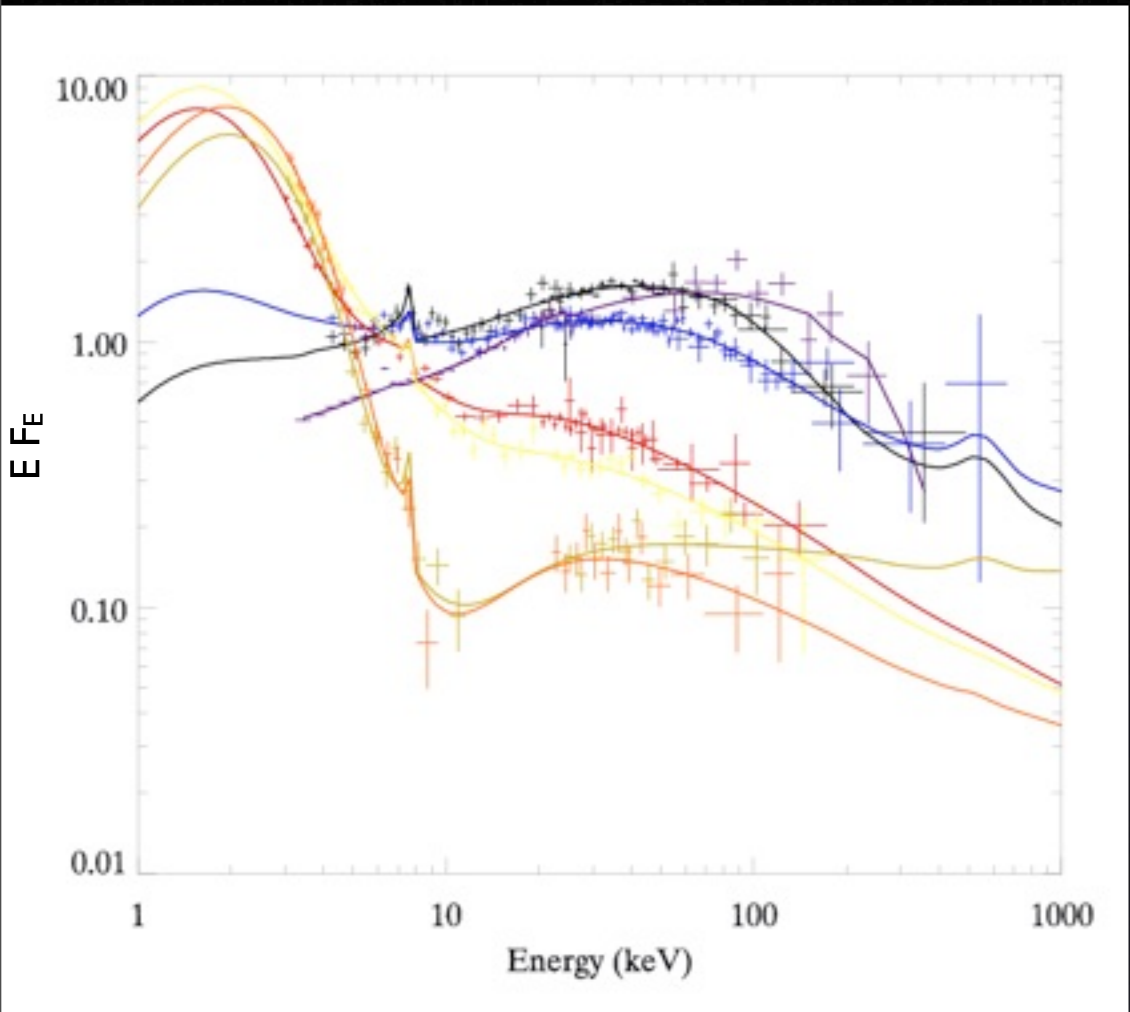
GX 339-4 during the 2004 state transition



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...)

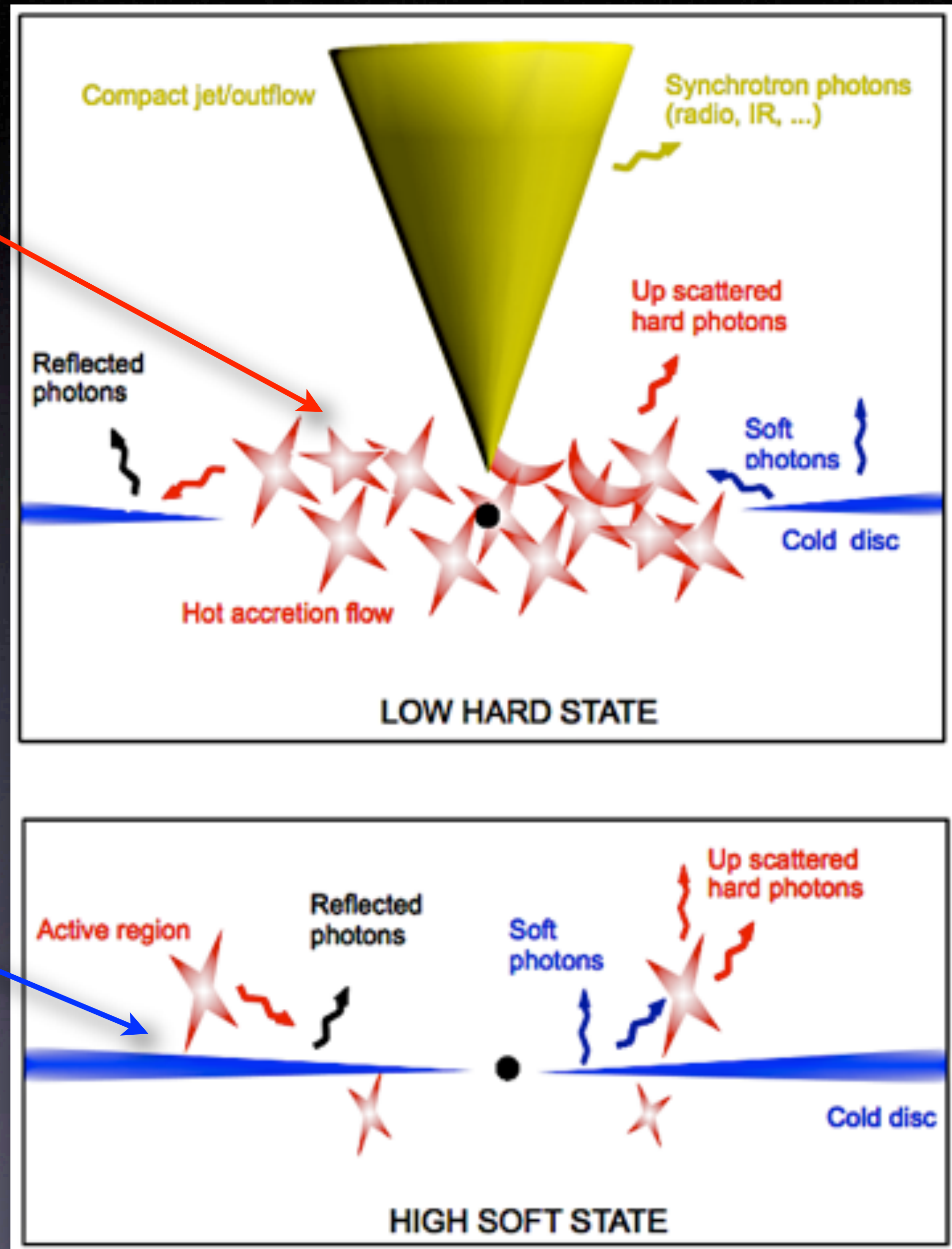
HIGH SOFT STATE

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

⇒ dominant thermal disc emission

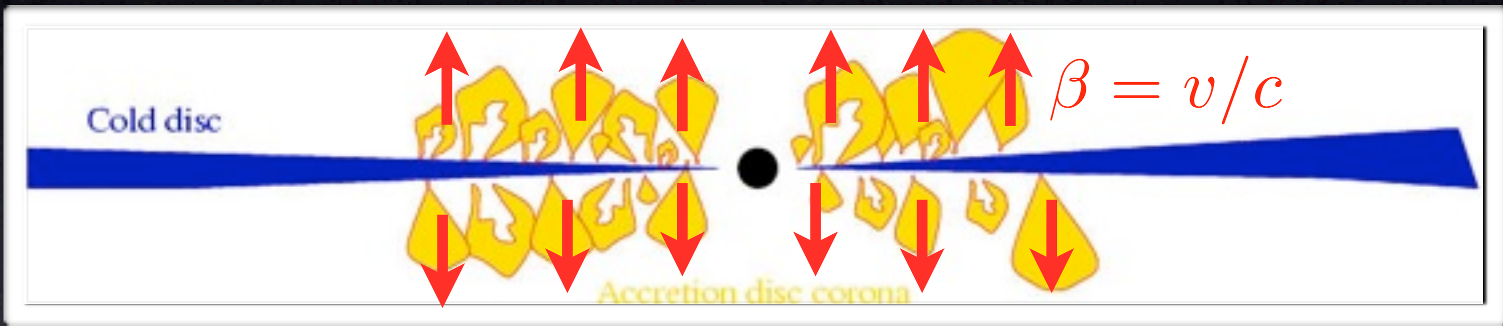
+ non-thermal comptonisation

(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)

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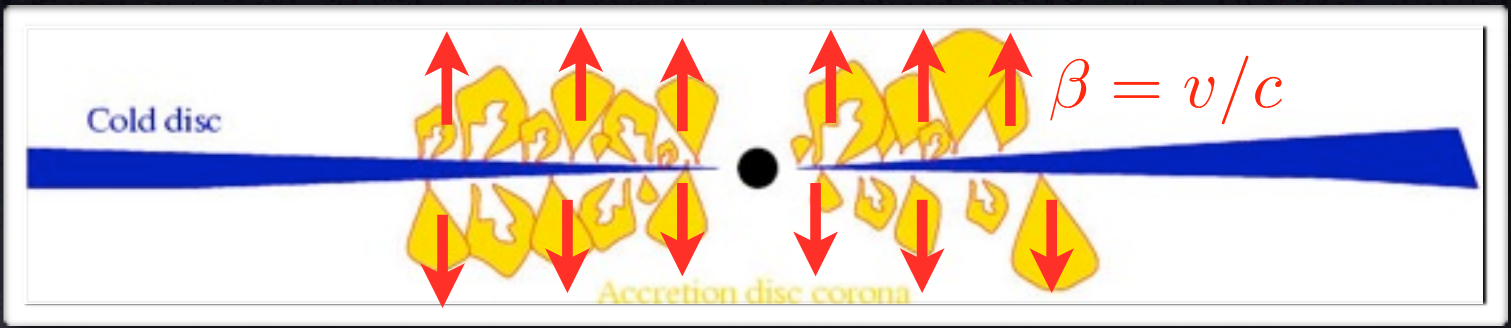


(Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

- X-ray Jet Models

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

although X-ray jet seems unlikely in Cyg X-1
(see 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)

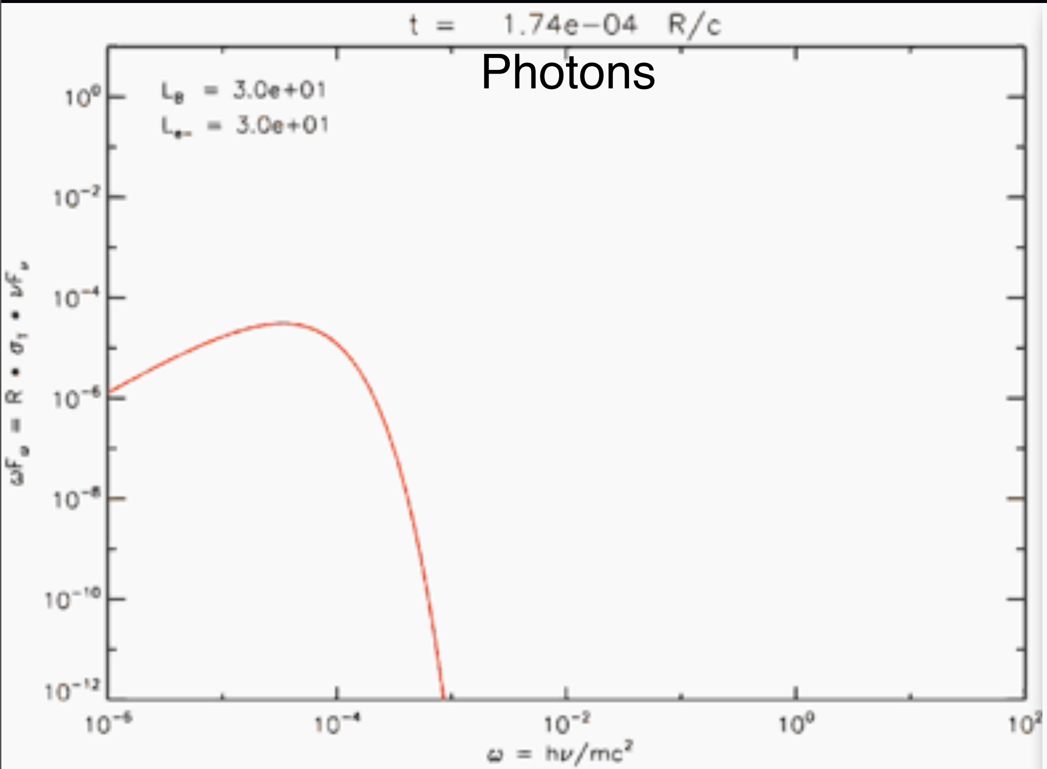
- Solve coupled time-dependent kinetic equations for leptons and photons (no assumption on the shape of the electron distributions)

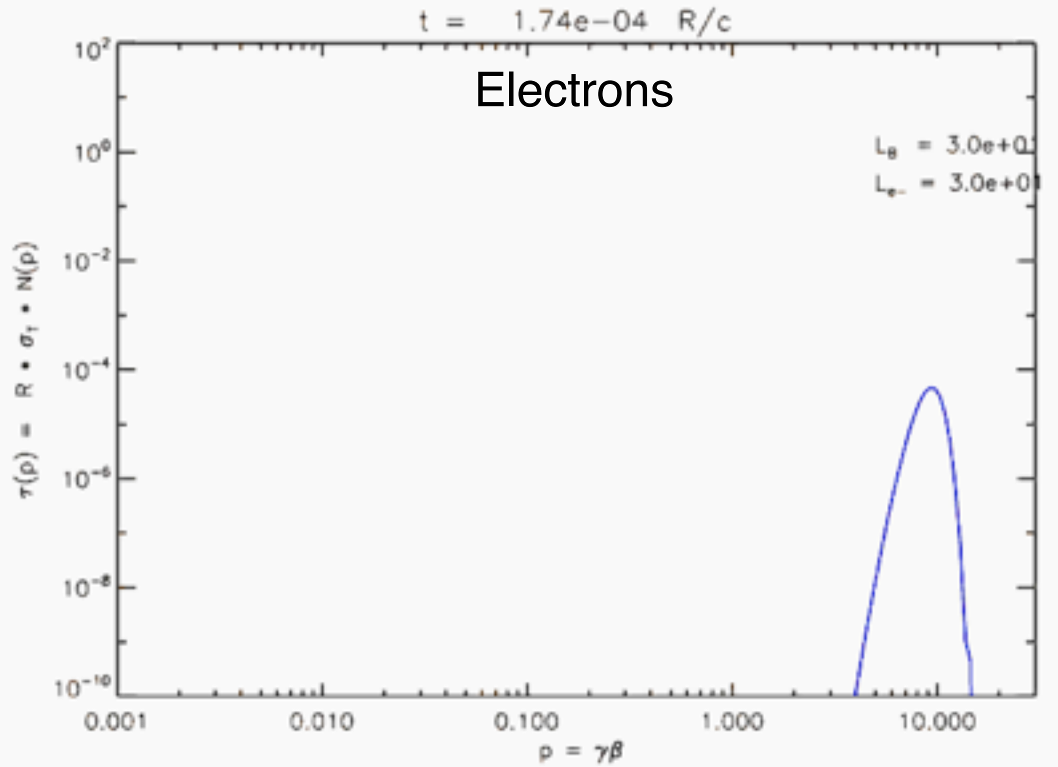
- Compton, Synchrotron emission and absorption, e-e and e-p Coulomb, e+-e- pair production/annihilation, e-p bremstrahlung

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

The Synchrotron boiler

(Ghisellini, Guilbert and Svensson 1988)

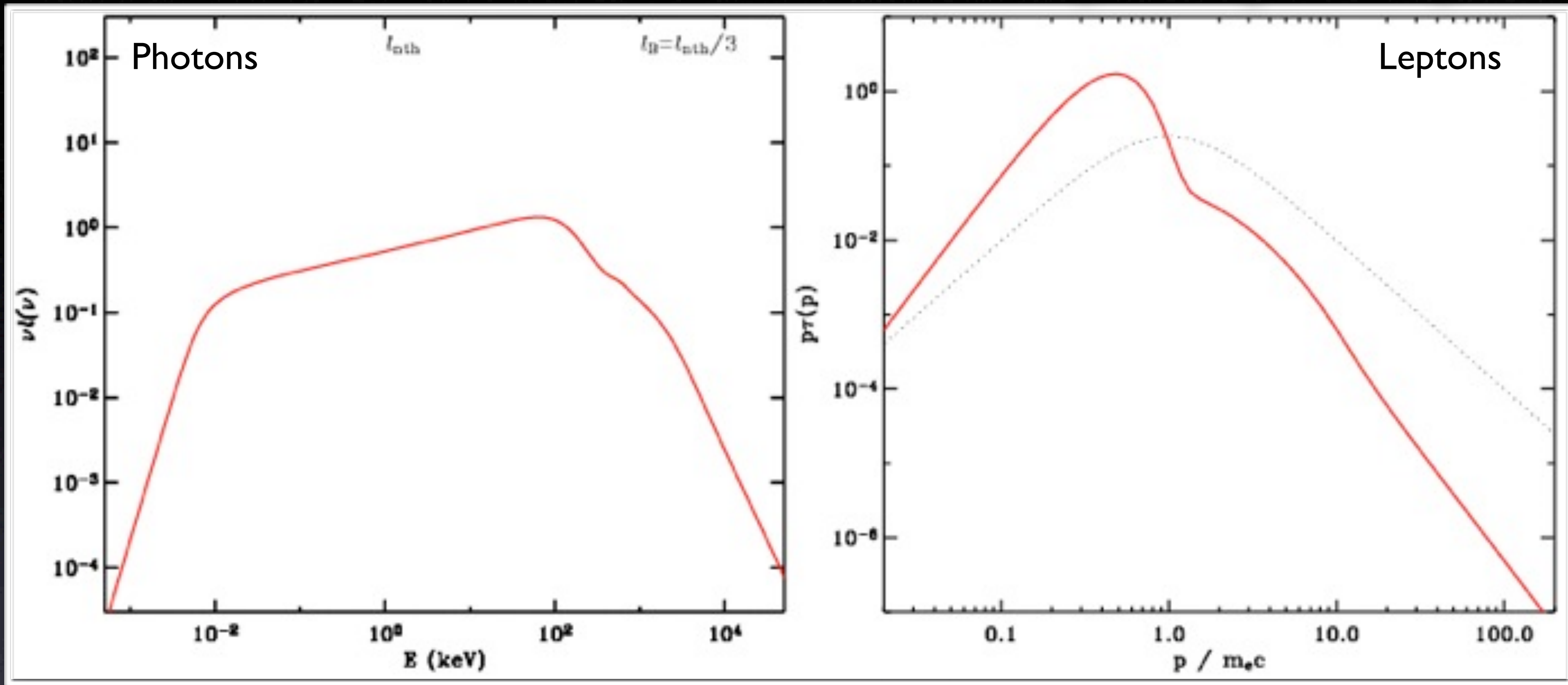




- Electrons injected with γ =10 in an empty (but magnetised) region
  Synchrotron self-Compton emission
- High energy e- → synchrotron photons → self-absorbed by lower energy e-
  ➡ transfer of energy between particles
  - ➡ 'thermalizing' effect on the electron distribution
  - ➡ At steady state: hybrid 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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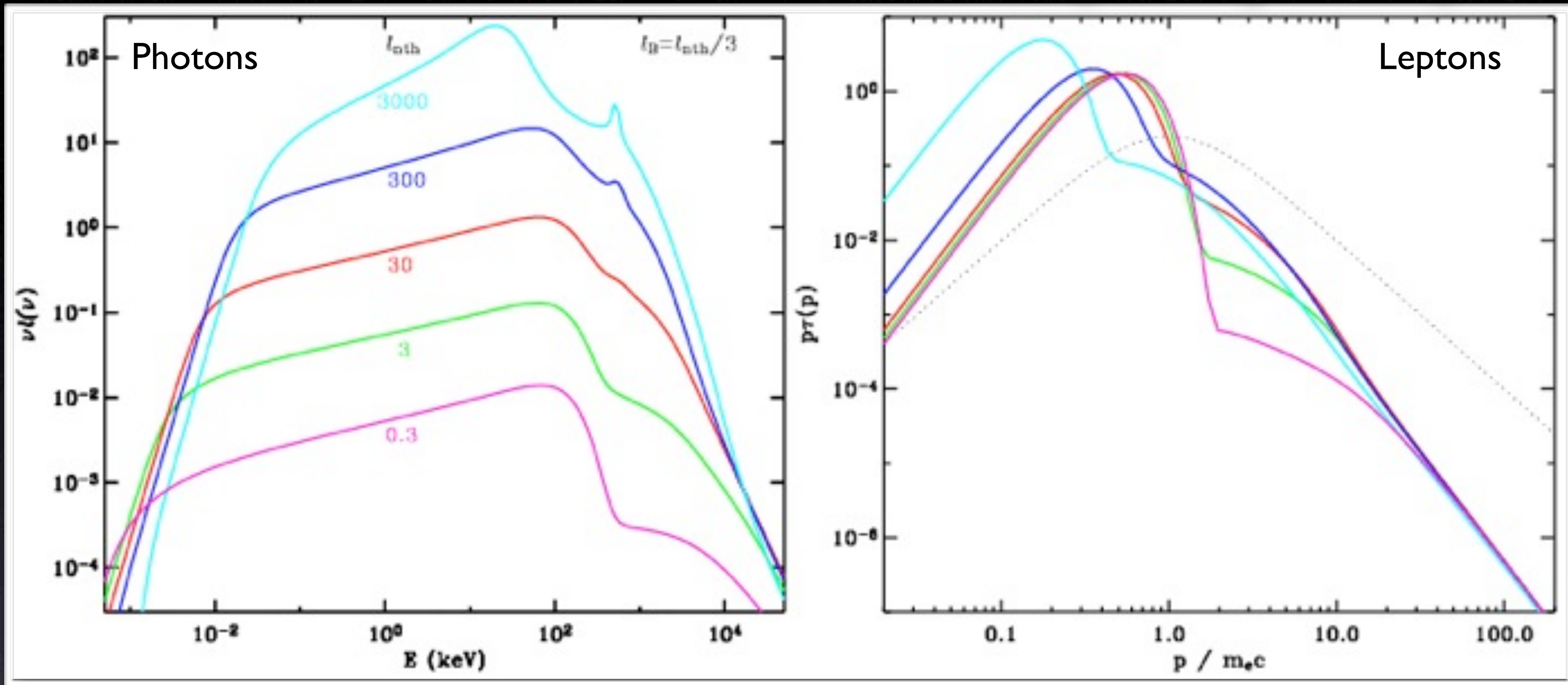

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Effect of external soft photons

- Add soft thermal photons:

➡ temperature of Maxwellian electrons decreases

➡ Compton emission increasingly dominated by non-thermal electrons

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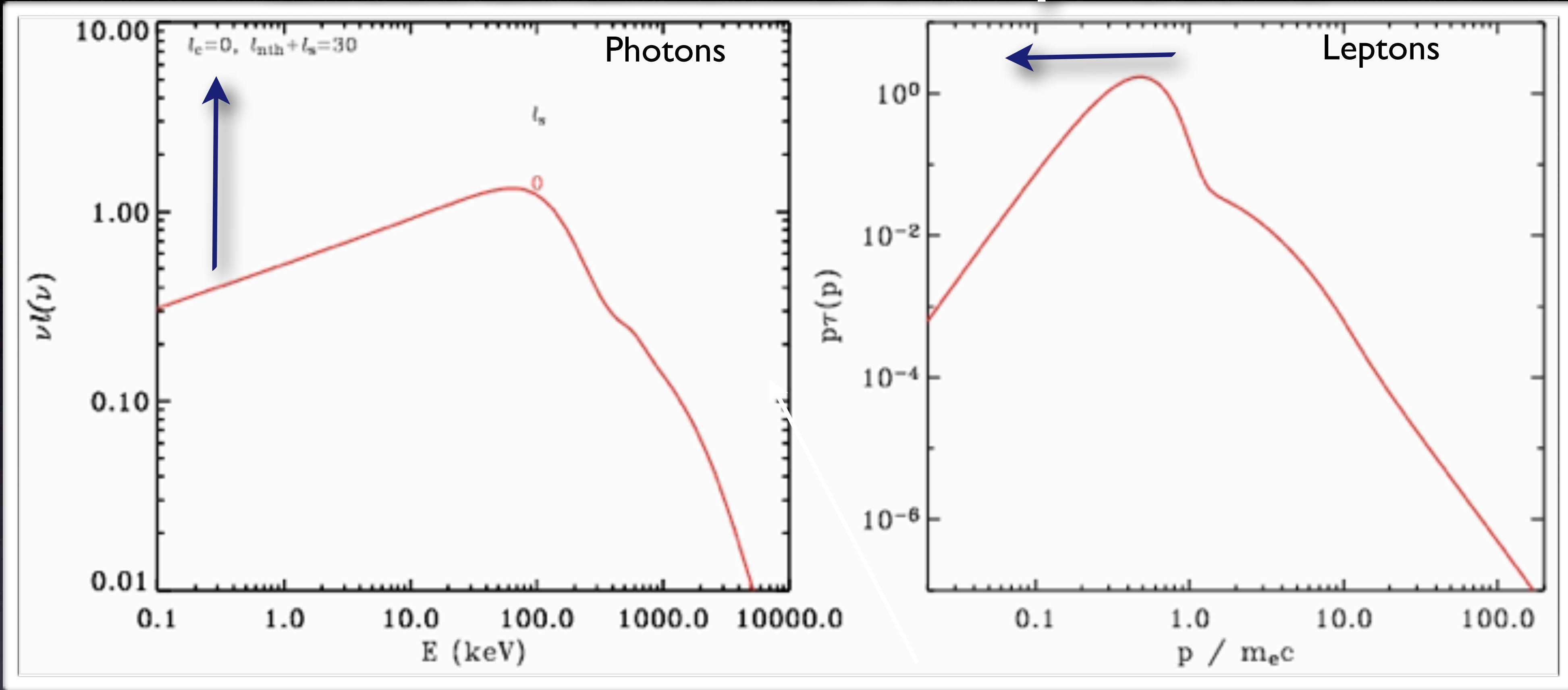

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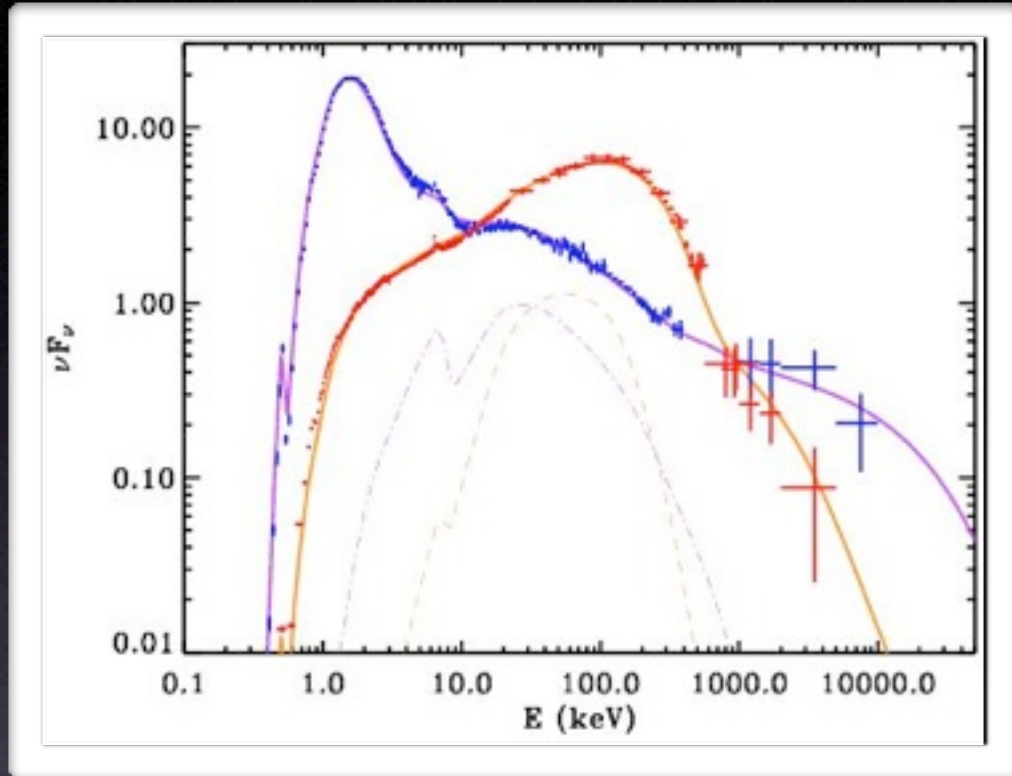
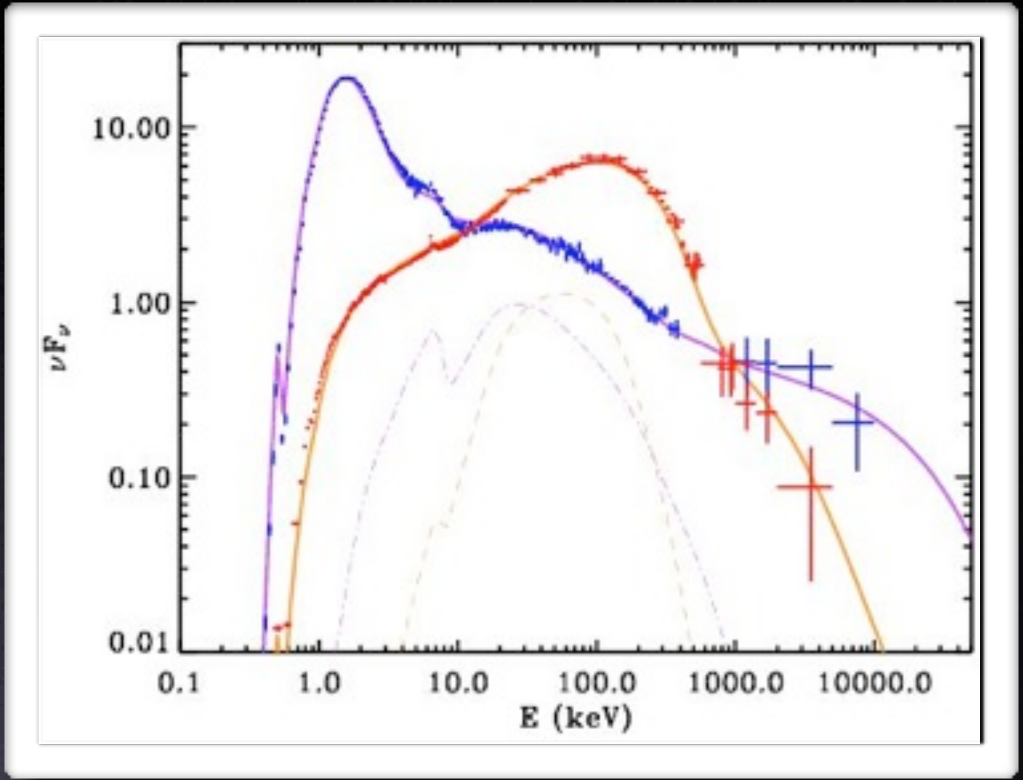


(Malzac & Belmont MNRAS 2009 ; Poutanen & Vurm 2009)

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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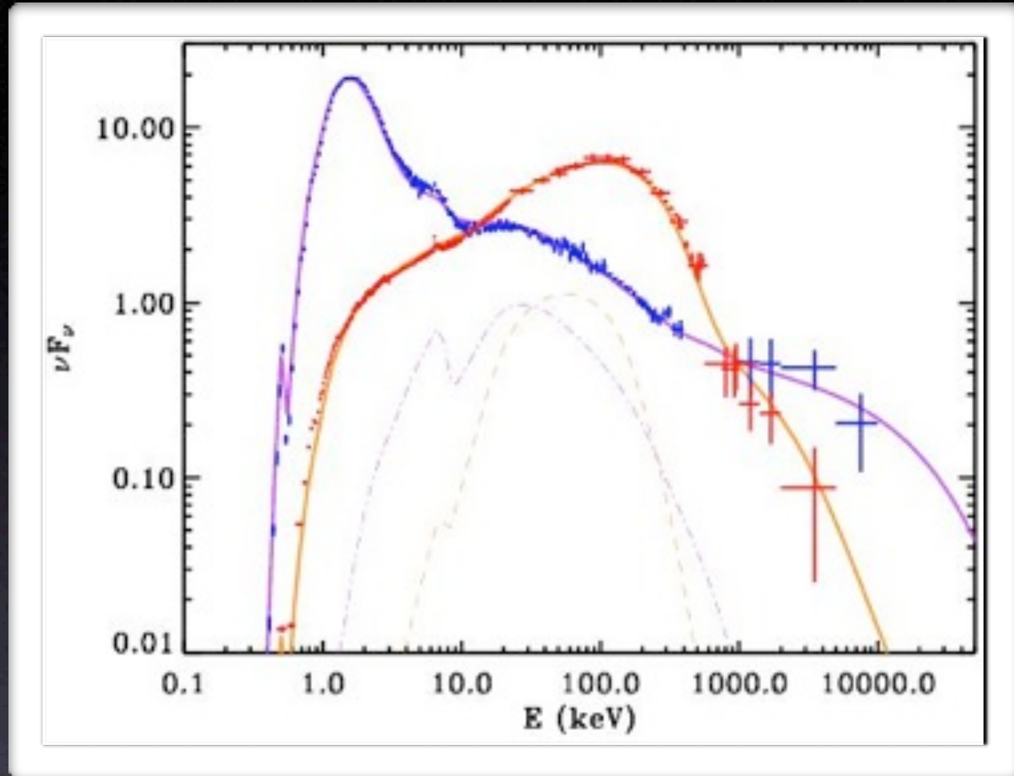

If B is large:

➡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 MNRAS 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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- Similar constraints on B and T_i obtained for GX339-4 in a bright hard state (Droulans et al. 2010)

Do hot accretion flows really fit the Hard State ?

- Local flow thermal balance: $Q_{\rm vis} = Q_{\rm ie} + Q_{\rm adv}$

Viscous heating

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

Coulomb losses

Advection

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  Viscous heating → $Q_{\rm vis}$; Coulomb losses → $Q_{\rm ie}$; Advection → $Q_{\rm adv}$

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- $Q_{\rm vis}(\tau_T, T_{\rm e}, T_{\rm i}, R), Q_{\rm ie}(\tau_T, T_{\rm e}, T_{\rm i}, R)$

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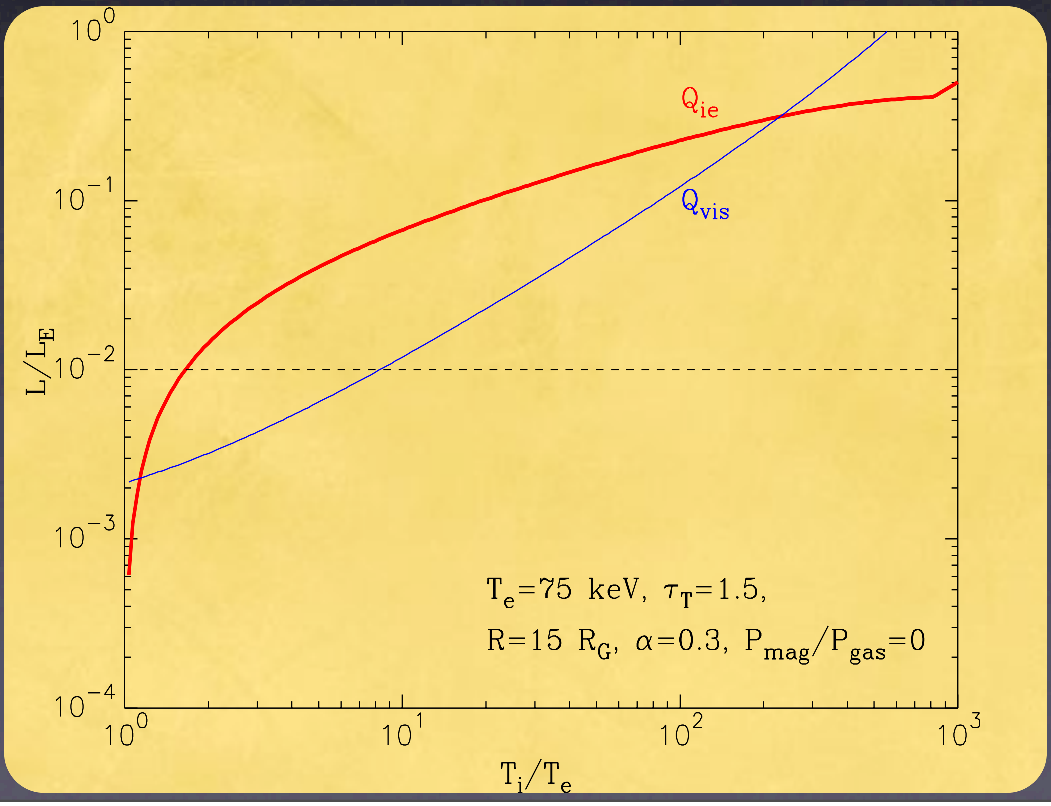

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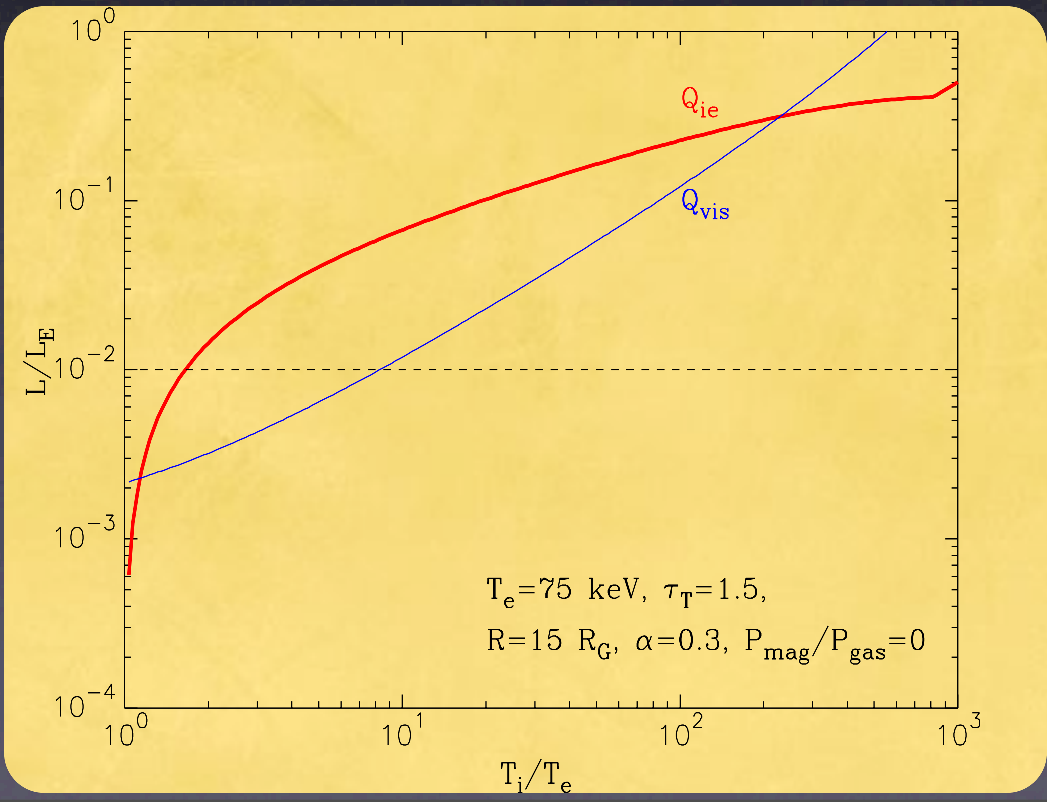

For typical X-ray luminosity of Cyg X-1 in LHS:

$$Q_{\rm ie} > Q_{\rm vis}$$

⇨ No solution!

Do hot accretion flows really fit the hard state?

- A possible solution:

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

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

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

- $Q_{\rm vis}(\tau_T, T_{\rm e}, T_{\rm i}, R, P_{\rm mag}), Q_{\rm ie}(\tau_T, T_{\rm e}, T_{\rm i}, R, P_{\rm mag})$

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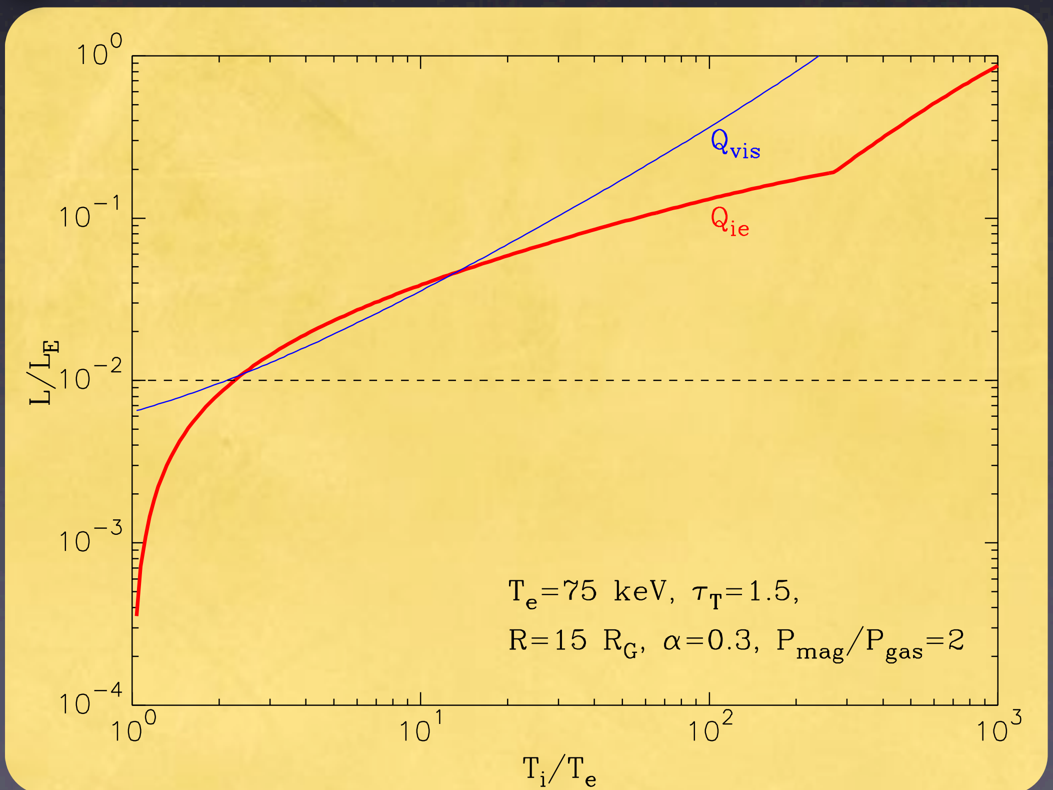

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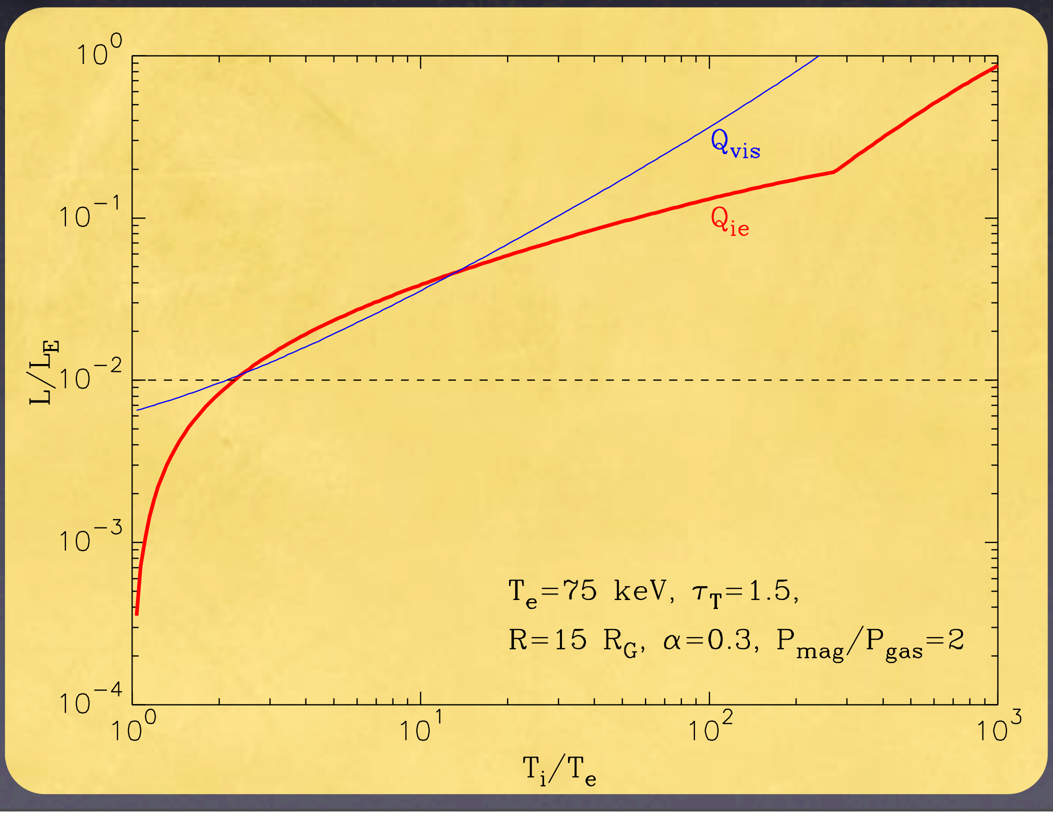

For typical X-ray luminosity of Cyg X-1 in LHS, possible solutions with:

$$P_{\rm mag}/P_{\rm gas} \sim 2$$

$$Q_{\rm adv} \sim 0$$

$$T_{\rm i}/T_{\rm e} \sim 2 - 10$$

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

➡ strong magnetic field

but...

- Non-thermal high energy excess ➡ weak magnetic field

If B is large:

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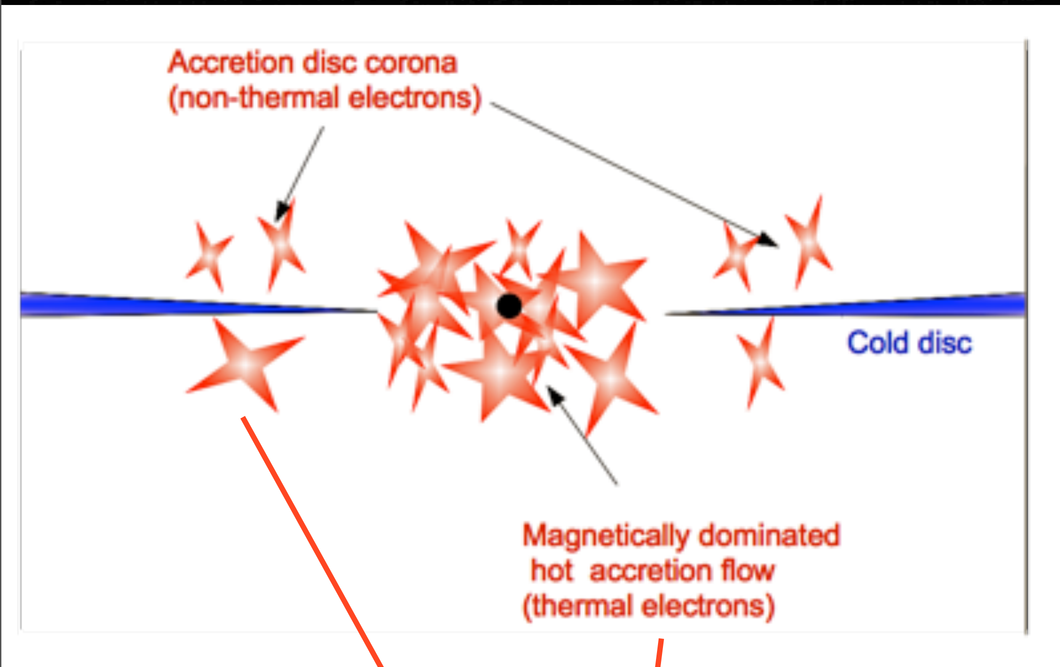
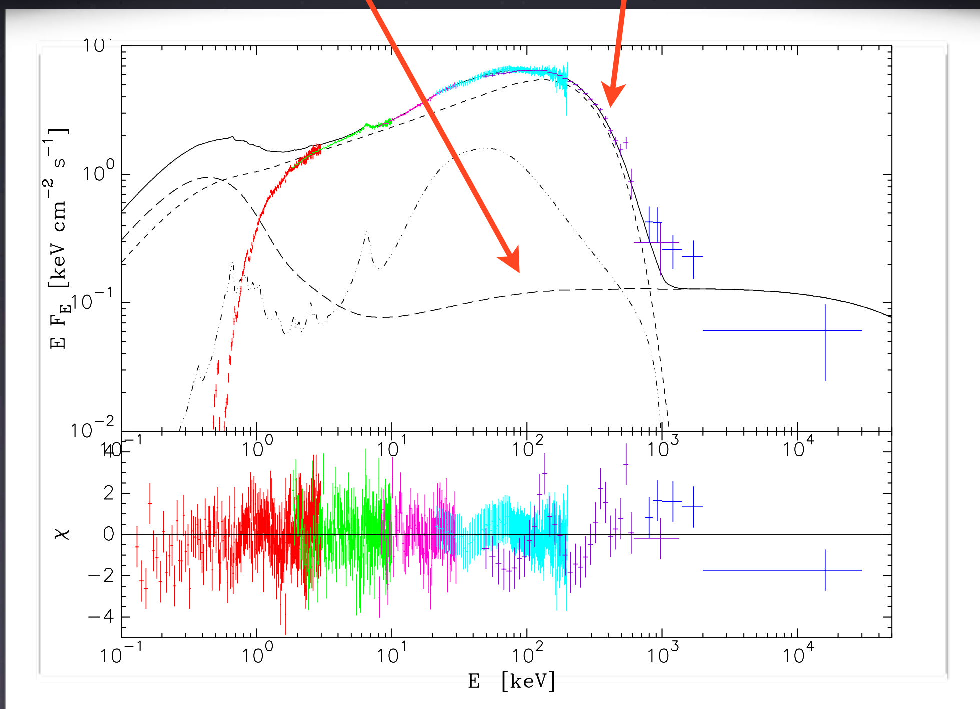
????

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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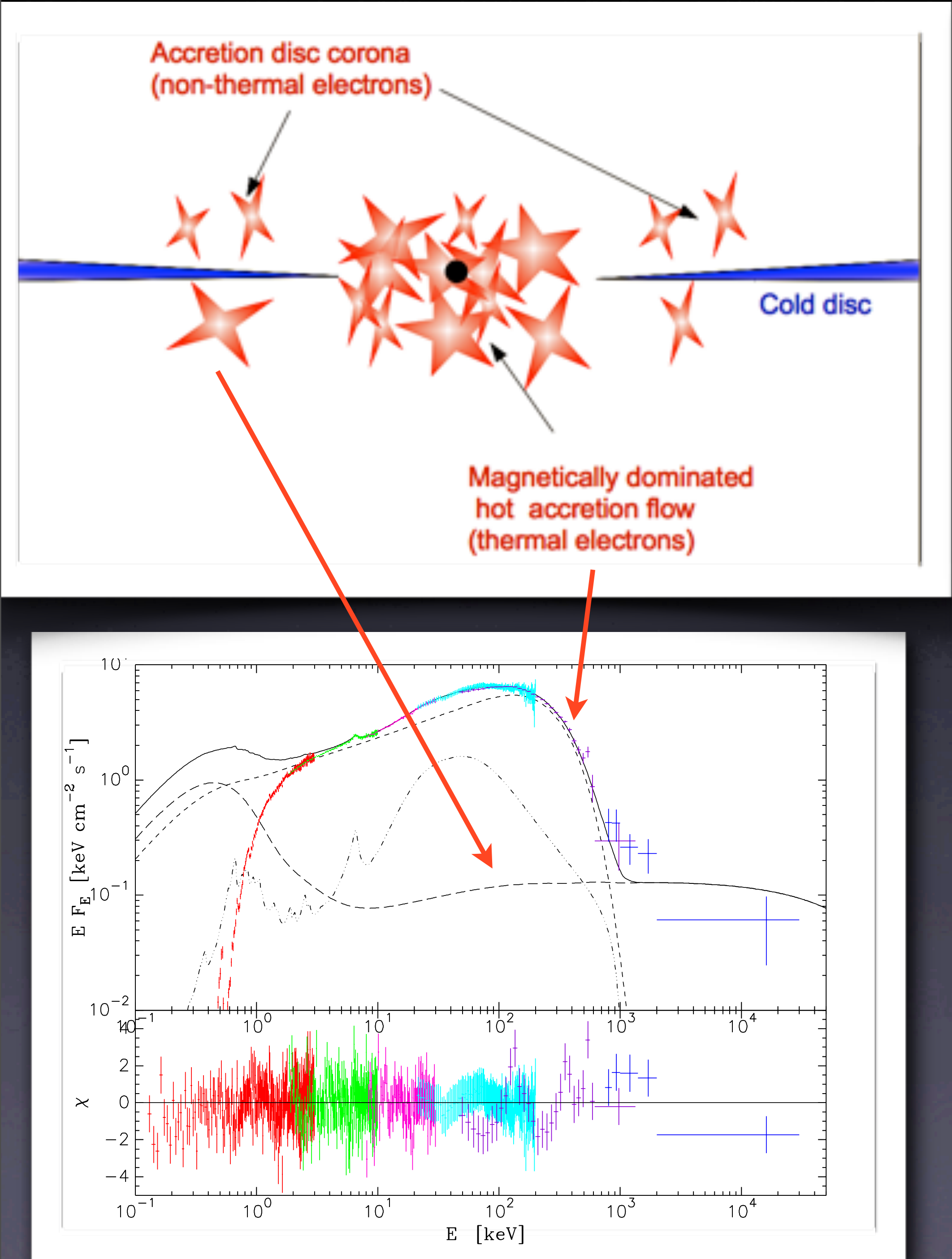

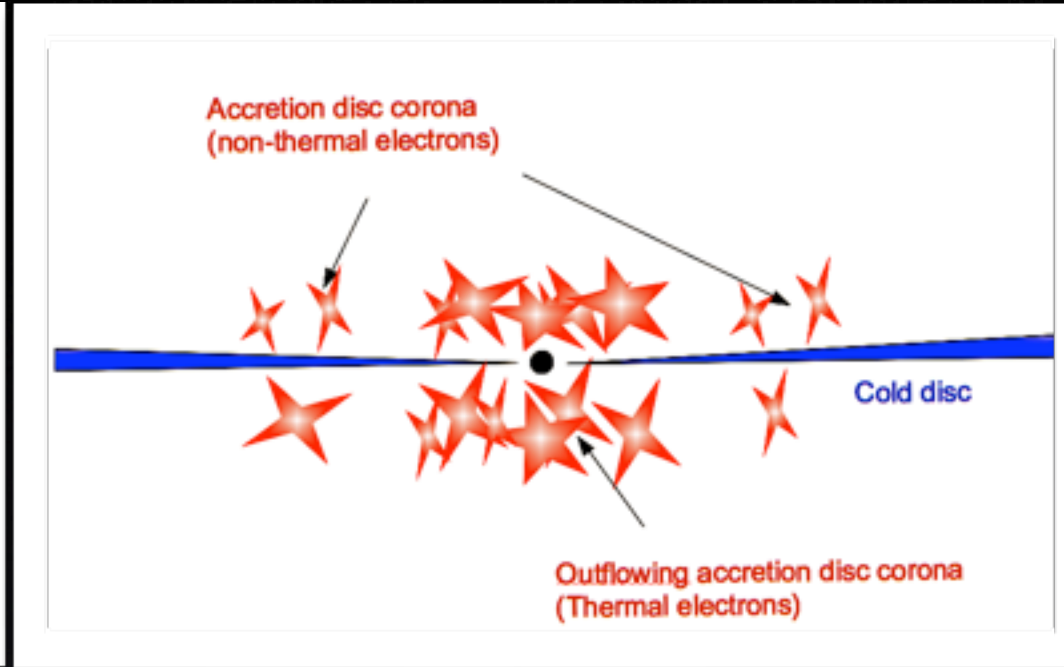

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Conclusions:

- Magnetic field likely to be strong, effects on

  -accretion flow dynamics

  -particle thermalisation / cooling

  -radiation

- Magnetically dominated hot flow models reproduce the observations of Cygnus X-1

- The structure of the corona appears complex: multi-zone models seem required