Comptonization and coronal emission processes in accreting black holes

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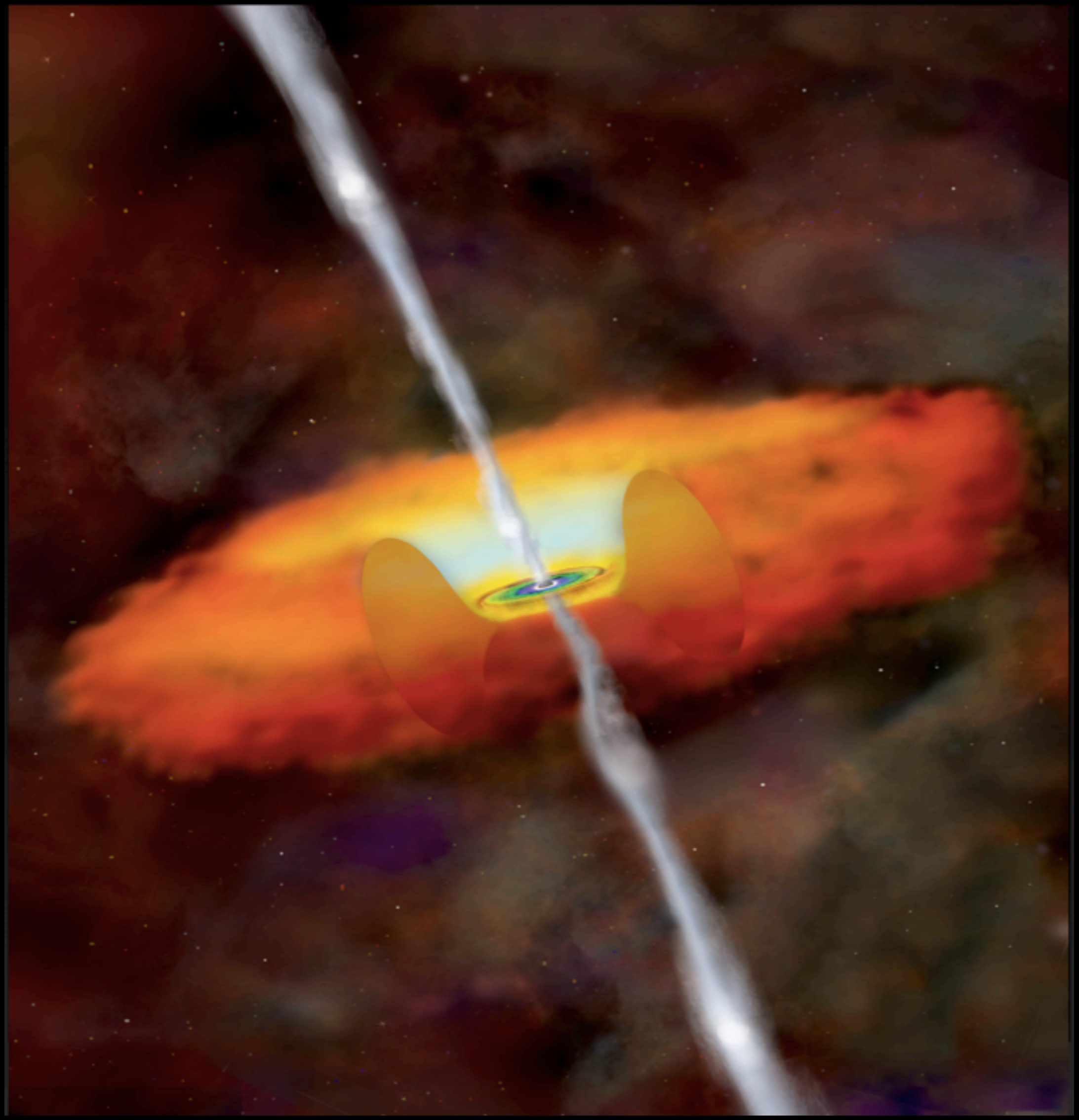
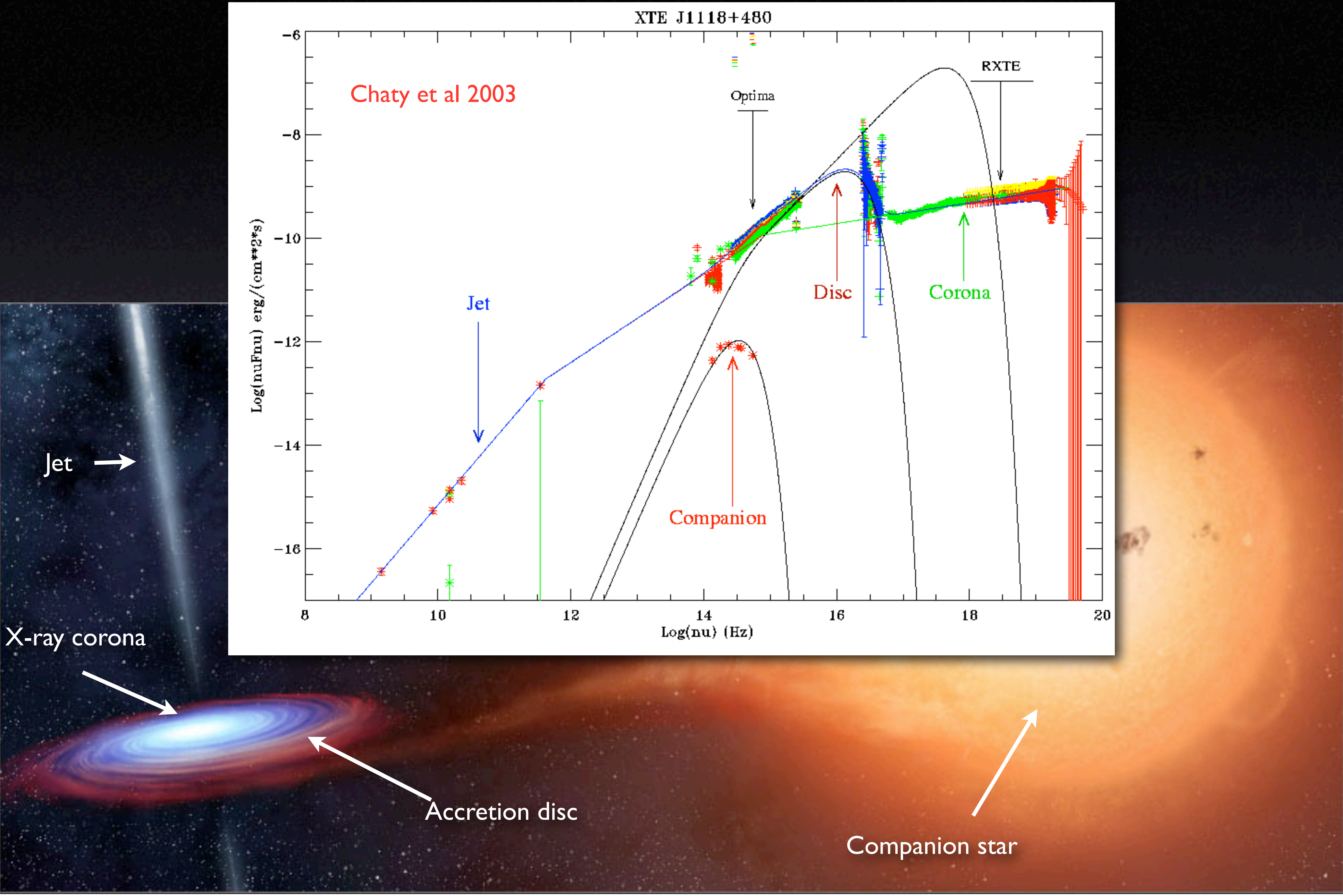
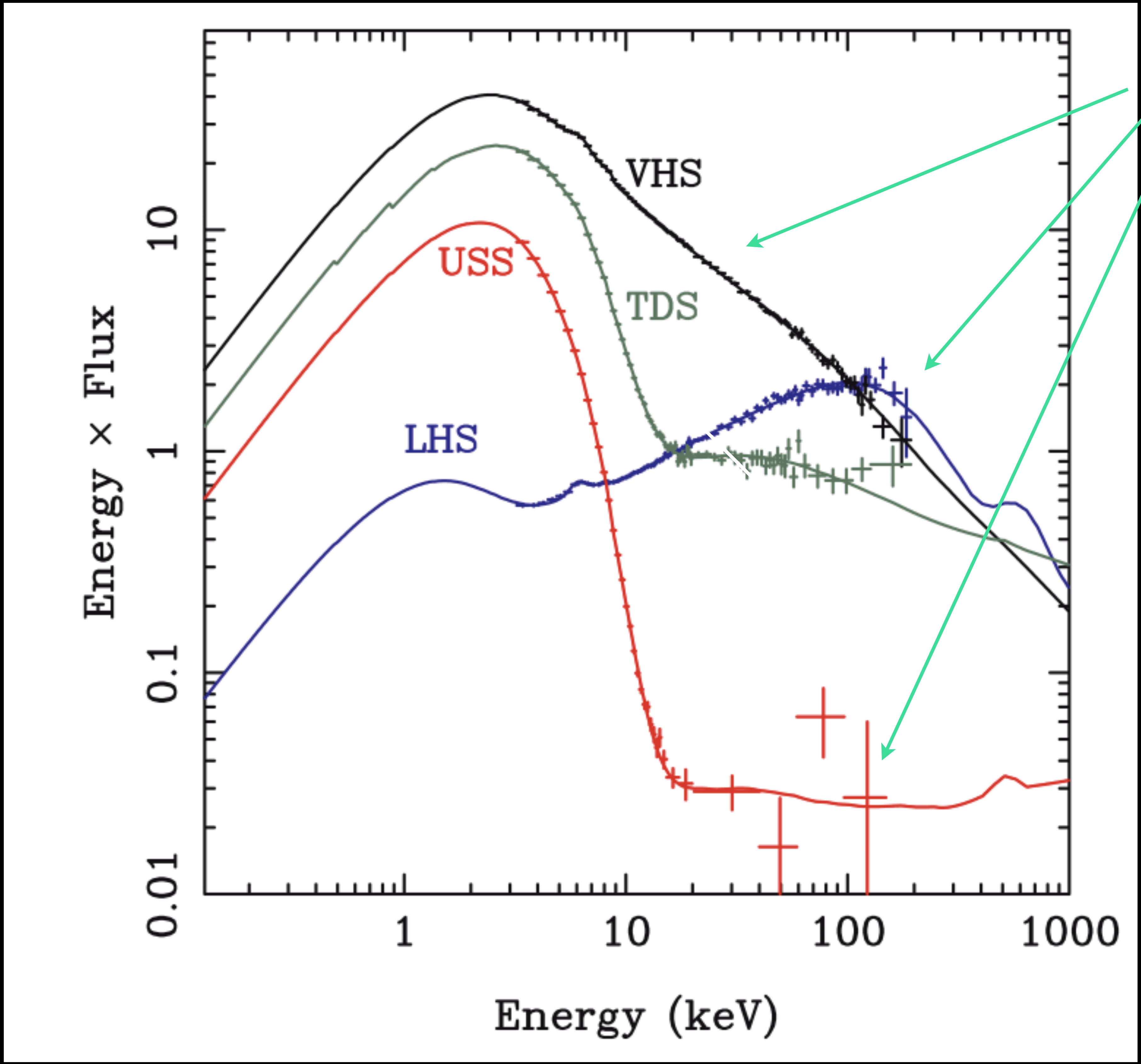


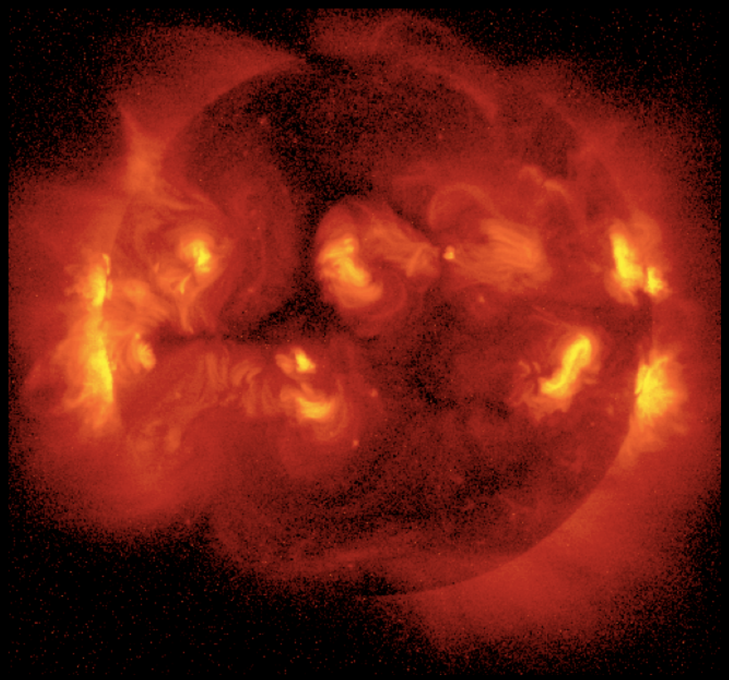
Black hole binaries



Broad band spectra of BH binaries

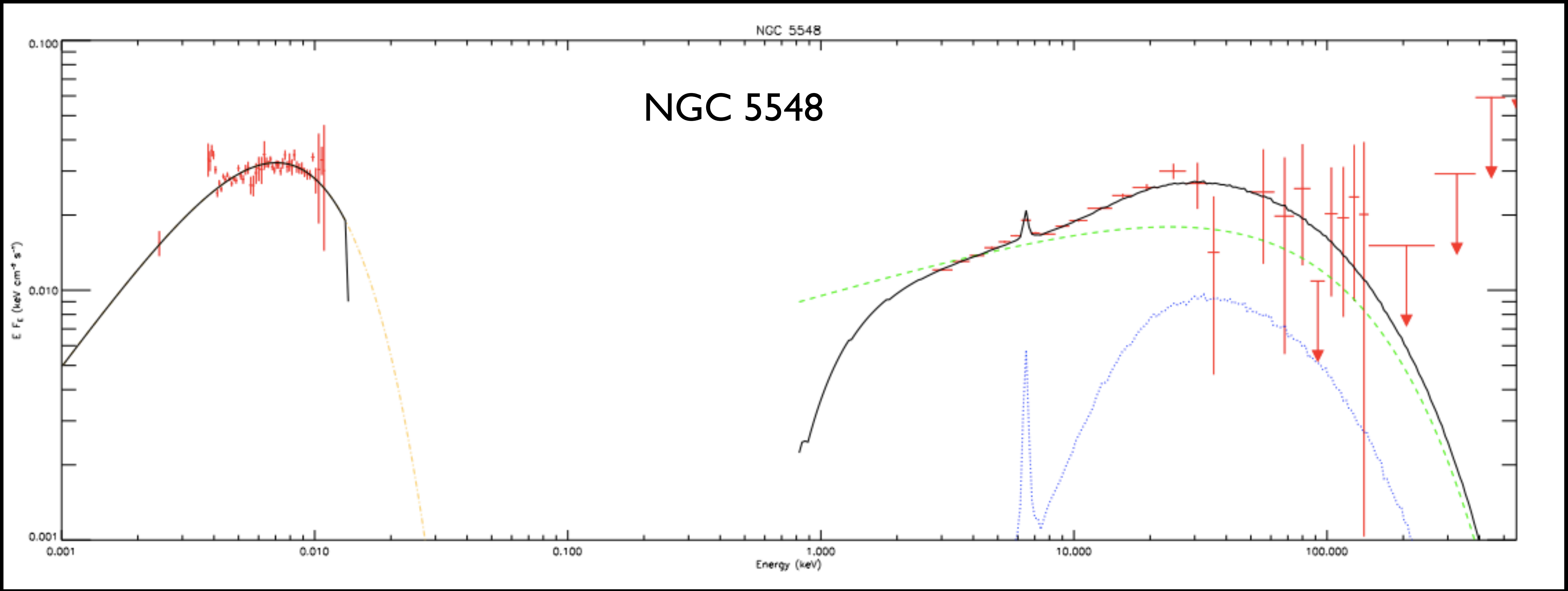


Non-thermal
emission:
'the corona'



from Done et al. 2007

Hard X-ray emission in AGN



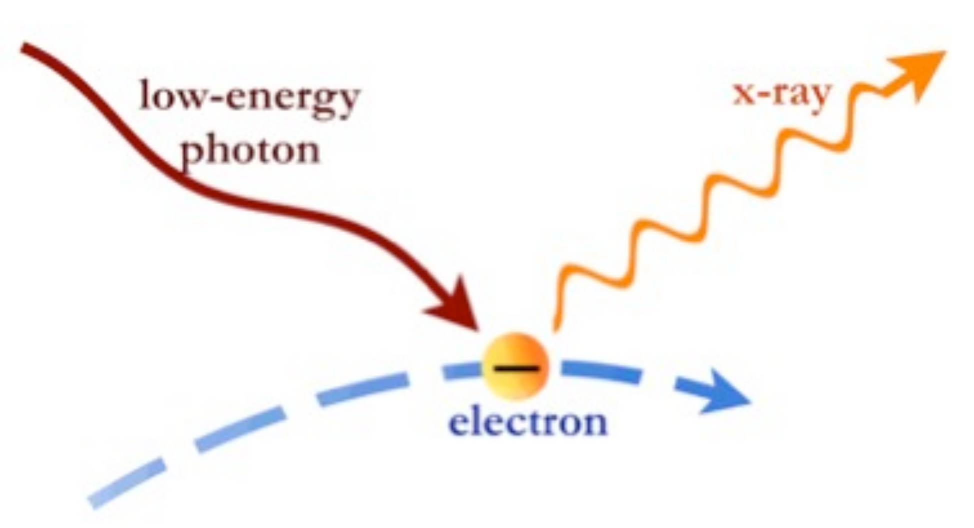
data from Magdziarz et al. 1998

Radiation processes in the corona

- Inverse Compton

➡ X-ray radiation

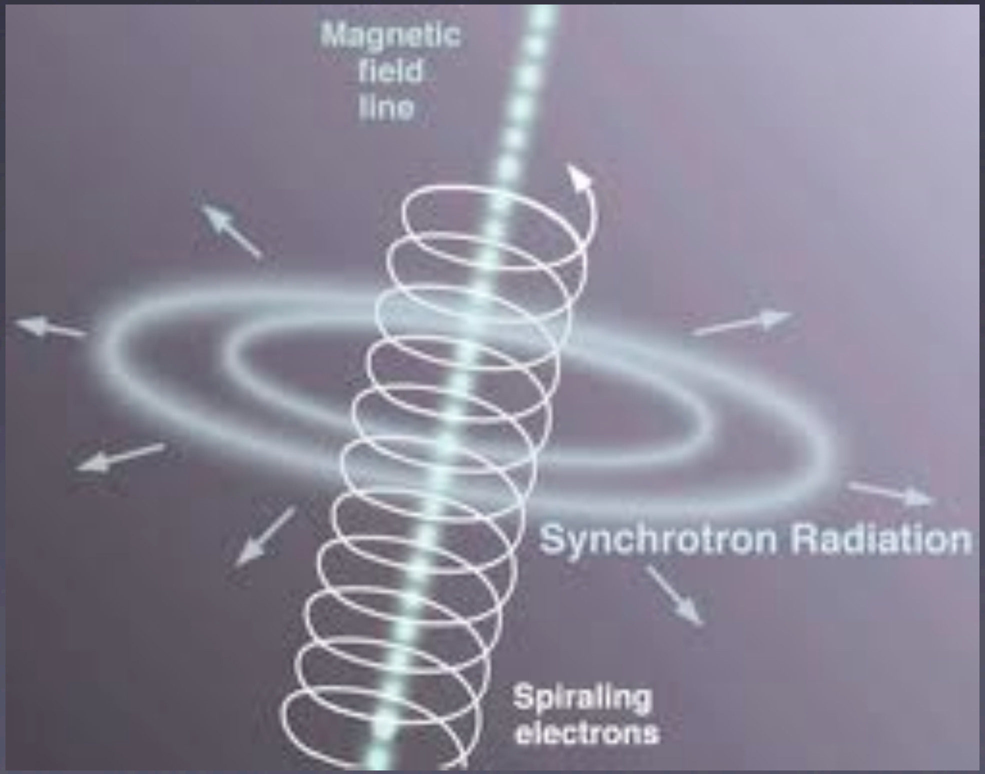
If $\tau_T \geq 1$: Comptonisation



- Soft seed photons ?

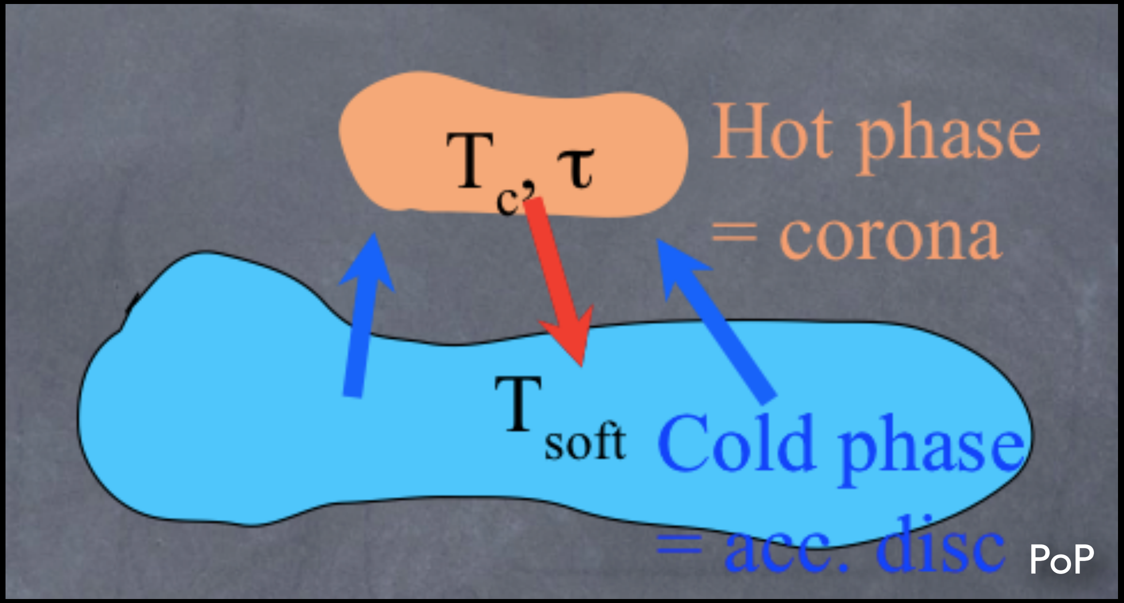
✓ blackbody emission from accretion disc

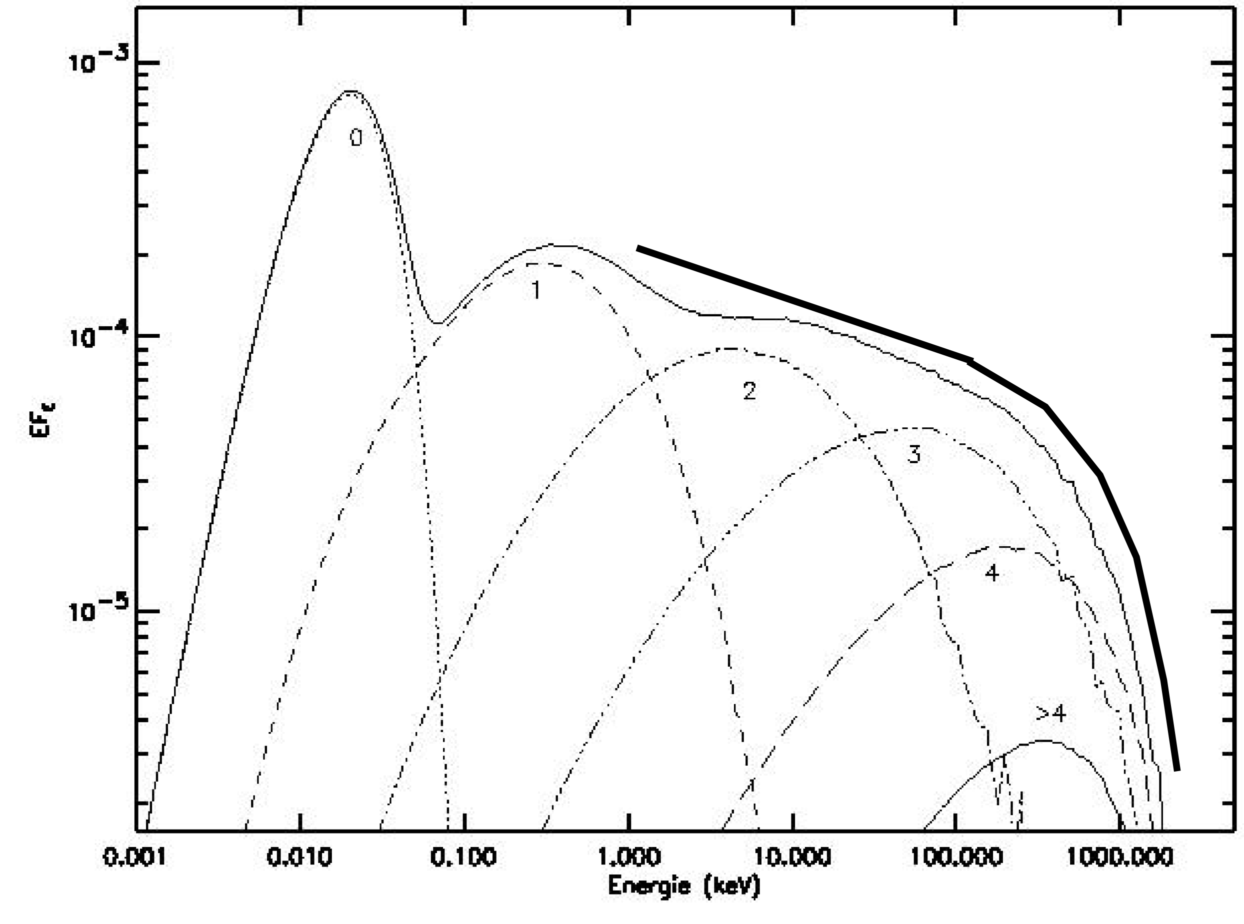
✓ synchrotron emission



Thermal Comptonization

- Comptonization of soft photon on a thermal plasma of electrons (Maxwellian energy distribution)
- Parametrized by temperature T and Thomson optical depth $\tau = n_e \sigma_T R$





$$F_E \propto E^{-\Gamma(kT,\tau)} \exp\left(-\frac{E}{E_c(kT,\tau)}\right)$$

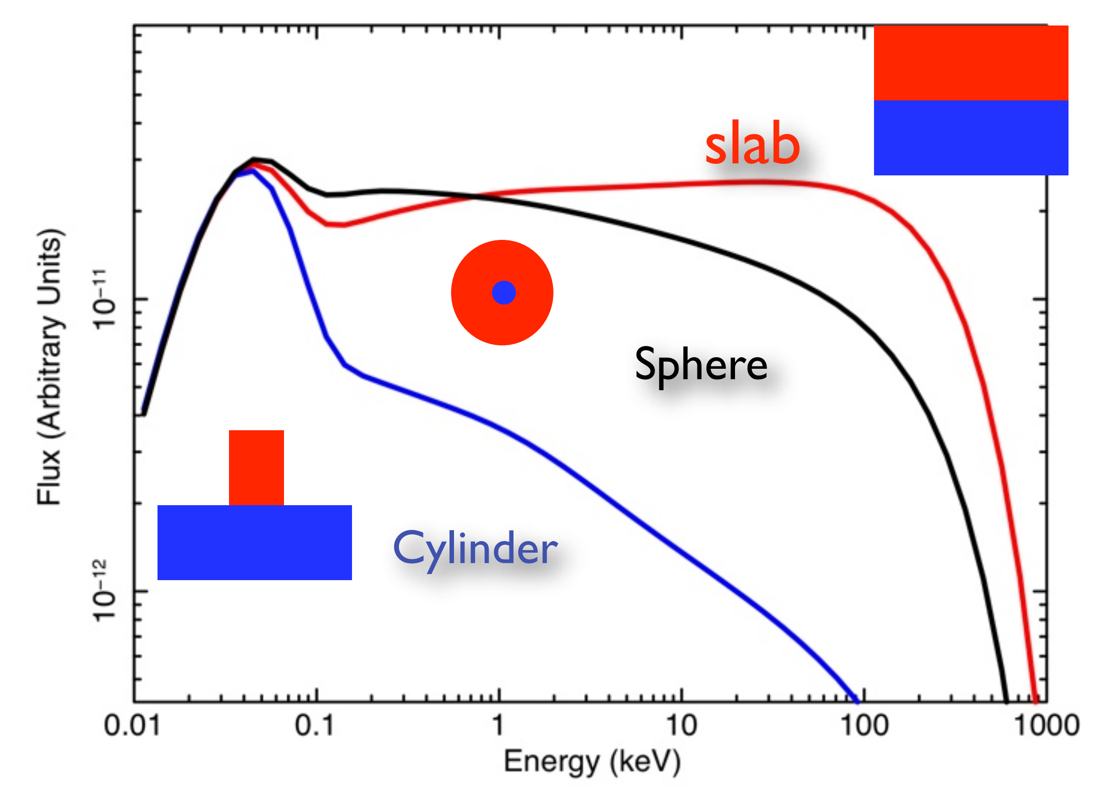
$$E_c \simeq kT$$

$$\Gamma(kT_{\mathrm{e}}, \tau)$$

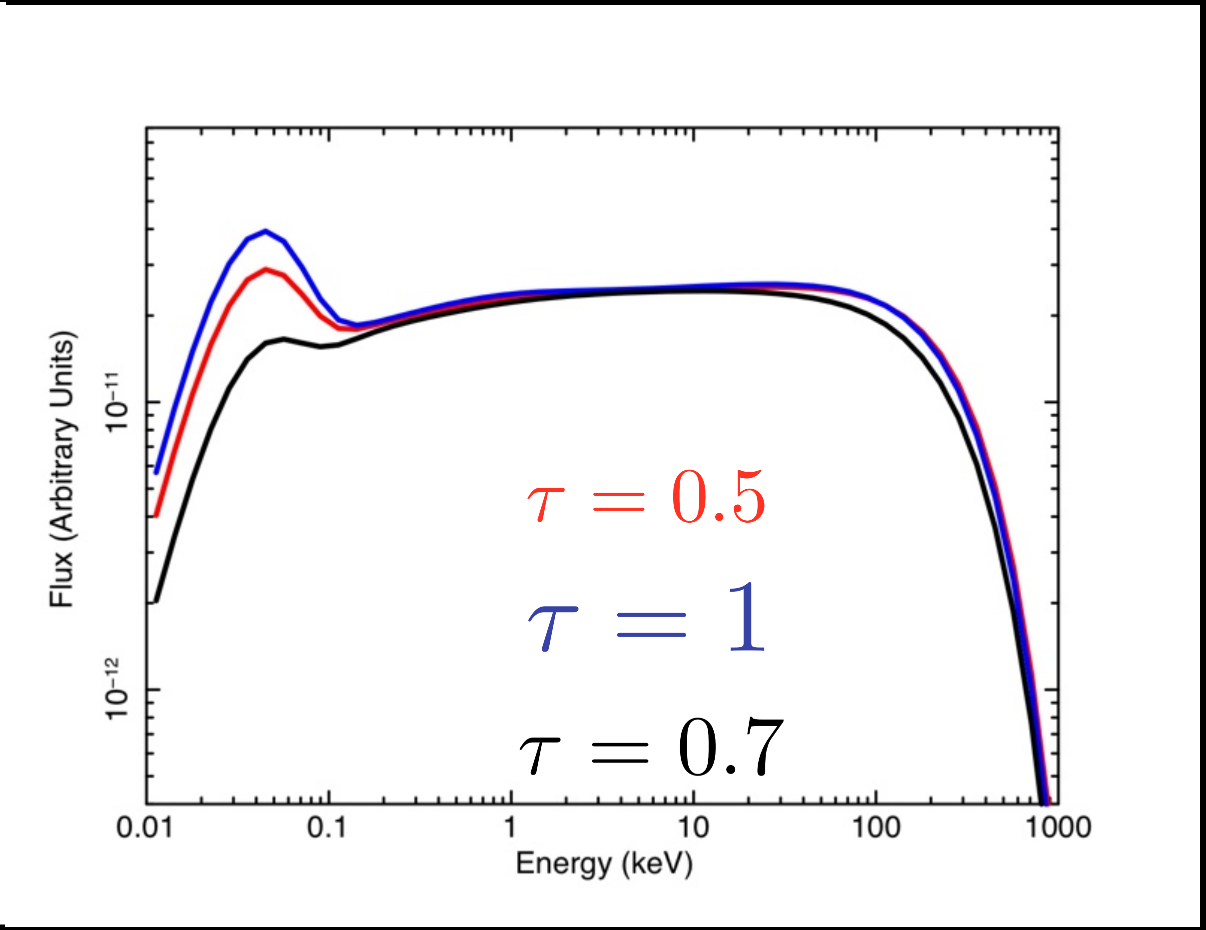
Spectral degeneracy: different T_{e} and τ give same Γ

Geometry dependence

$kT_{\mathrm{e}} = 100\,\mathrm{keV}, \tau = 0.5$



$kT_{\mathrm{e}} = 100\,\mathrm{keV}$



P.O. Petrucci

Geometric degeneracy

Radiative balance

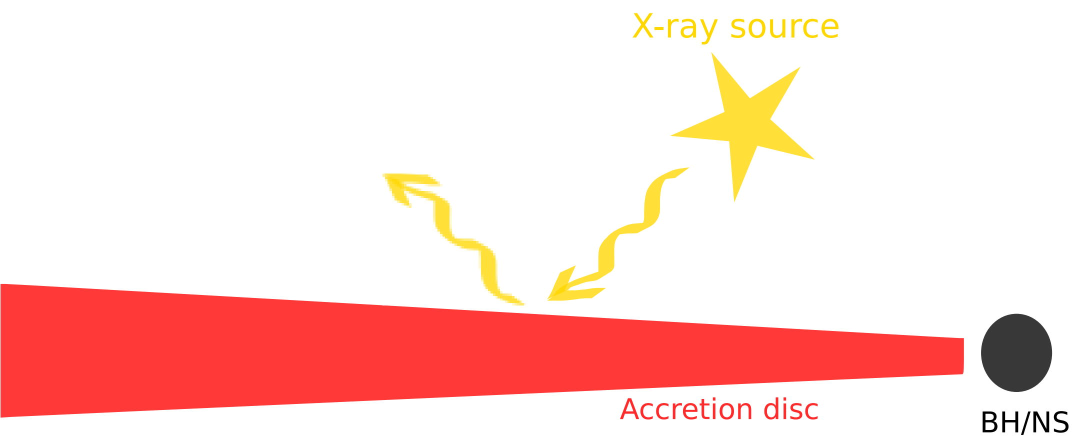
- In soft photon field of bright compact sources electrons radiate away their energy on time scales <R/c. Need continuous reheating/ acceleration to keep them energized. (Merloni & Fabian .2000)

- Depending on underlying physical scenario, this heating could be shocks or MHD wave acceleration, magnetic reconnection, Coulomb interactions with a population of hot ions ....

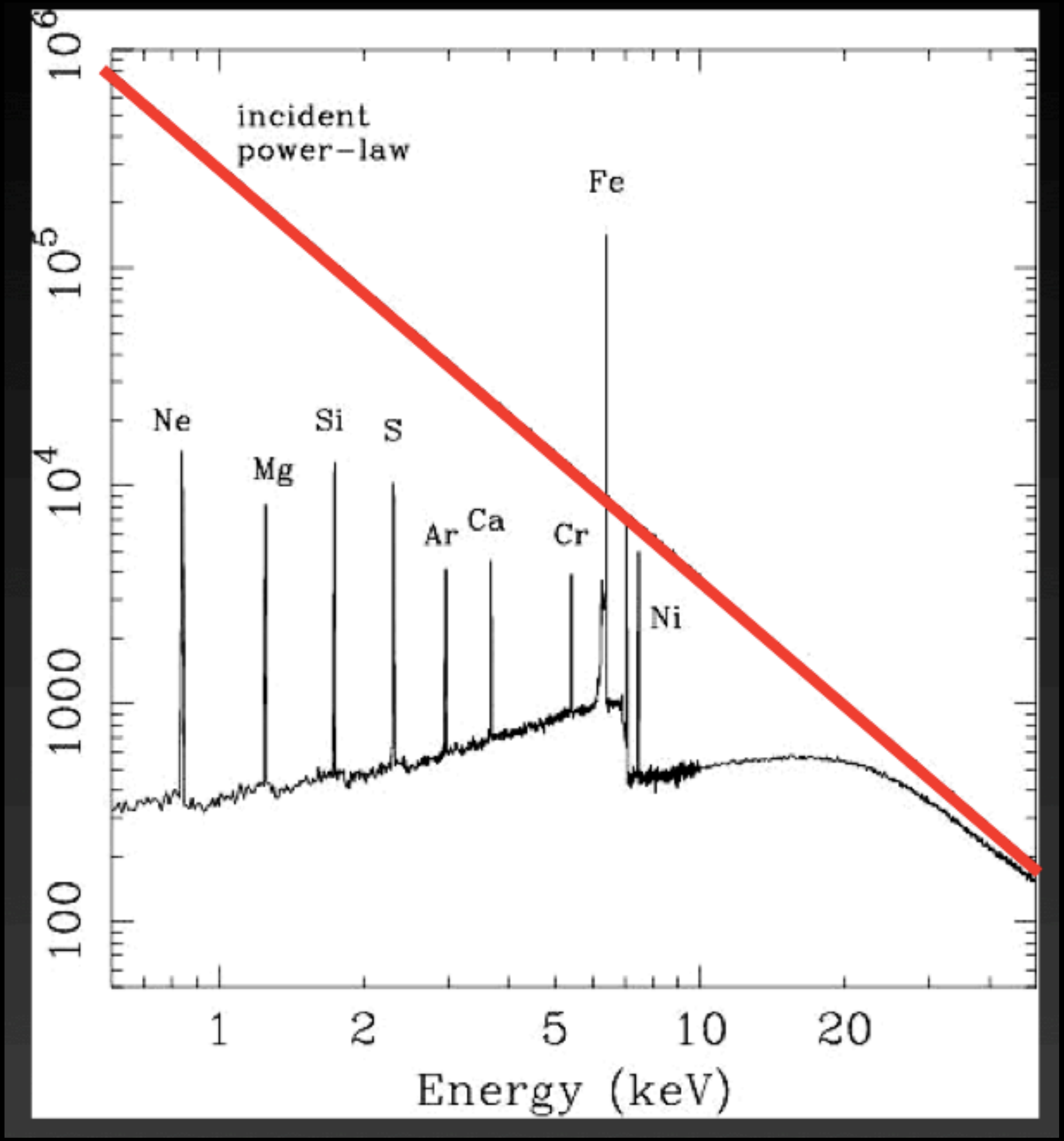
- Electron temperature controlled by heating= radiative cooling, cooling rate $\propto L_s$

- $\Gamma \propto \left(\frac{L_{heating}}{L_s}\right)^{-\delta}$ (see Belodorov 1999; Malzac et al 2001)

Disc reflection



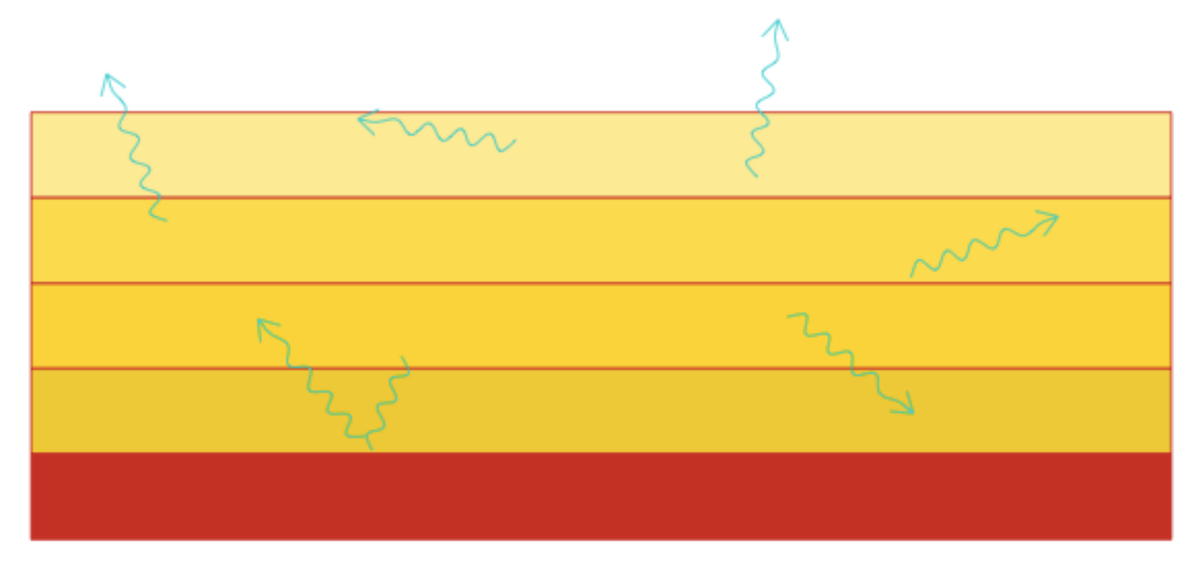
- At soft X-ray energies, reflection is small because of photoabsorption by the metals in the disc
- At hard X-ray energies, incident X- rays are Compton back-scattered from the disc
- A spectrum of fluorescent emission lines arises from photoionization of metals in the slab
- Iron Kα line at 6.40 keV is the most prominent because of its high fluorescent yield and large cosmic abundance.



- Relative amplitude of reflection features depends on geometry:

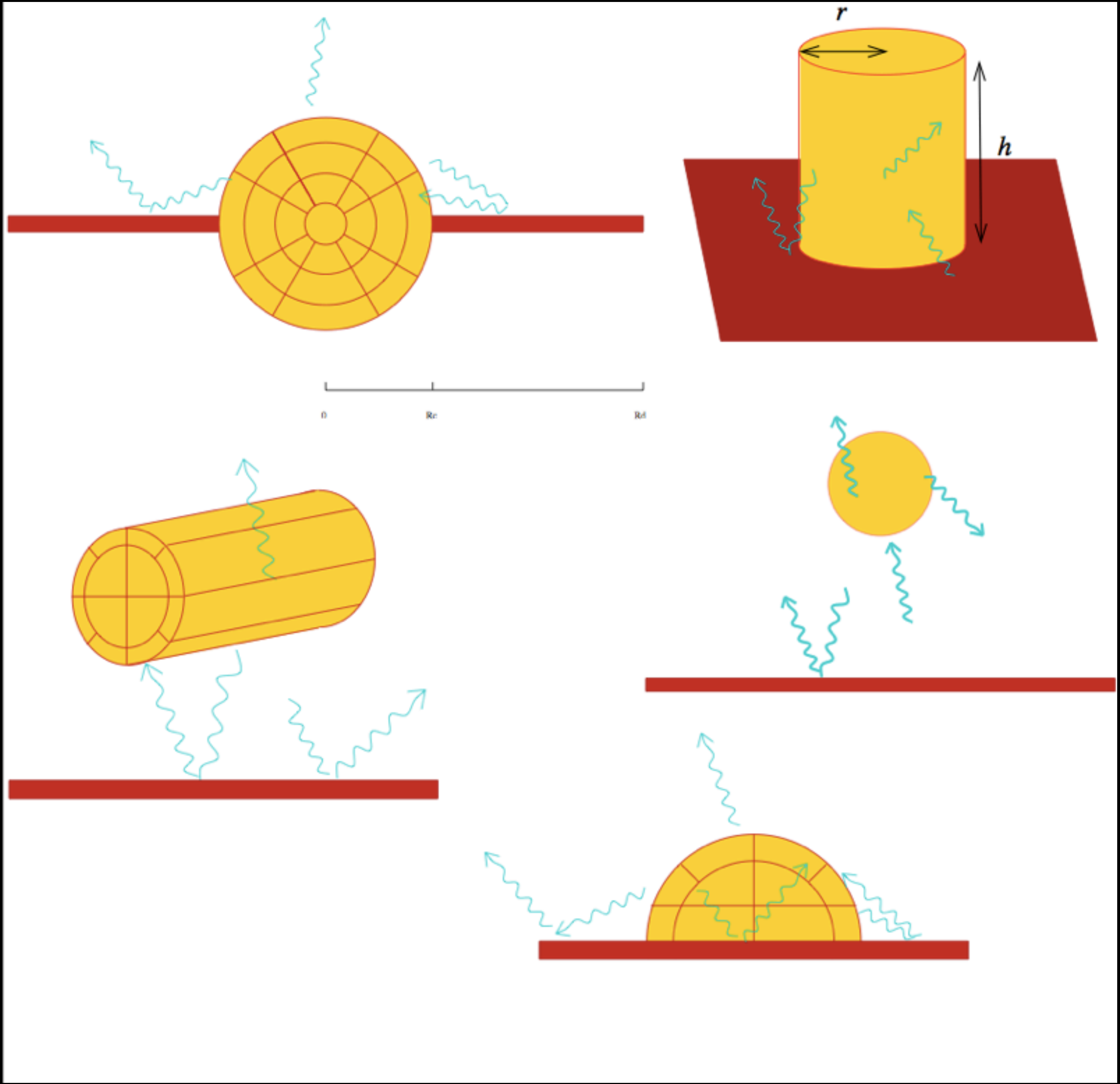
$$R = \Omega/2\pi$$

Radiation feedback

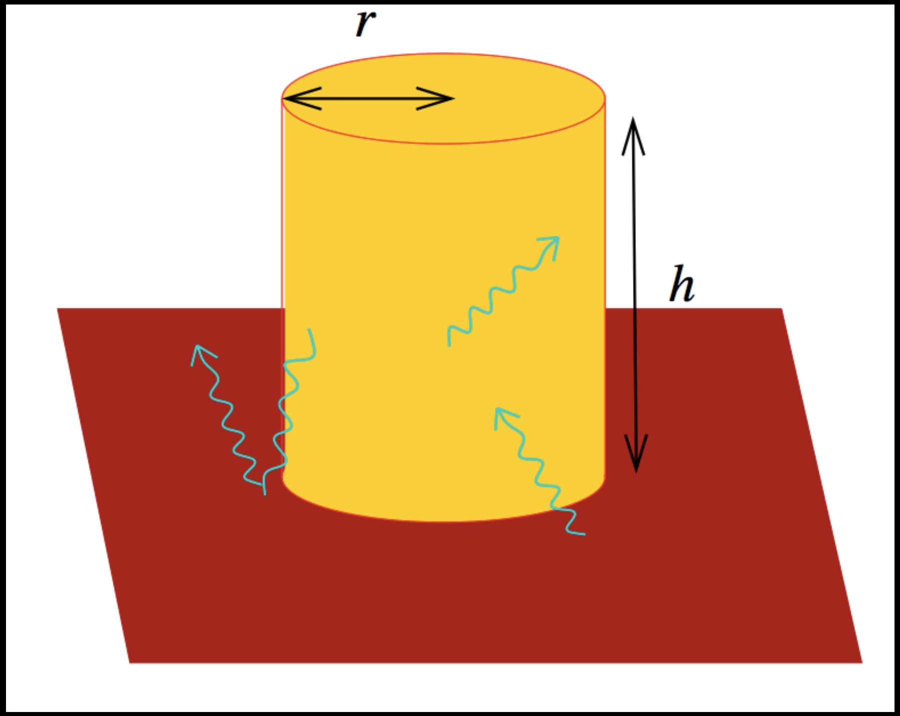


- Cold phase (accretion disc) illuminated by X-ray radiation-> reflection +absorption
- Absorbed radiation heats up the disc. Energy reprocessed and reemitted as low energy (nearly) thermal radiation.
- Depending on geometry a fraction of the reprocessed radiation may illuminate the corona and provide seed photons for comptonization
- If reprocessing dominates over intrinsic disc emission $L_s \propto L_{heating}$
- Then electron temperature and $\Gamma \propto \left(\frac{L_{heating}}{L_s}\right)^{-\delta}$ are determined by geometry

(Haardt & Maraschi 1993; Haardt Maraschi Ghisellini 1994)

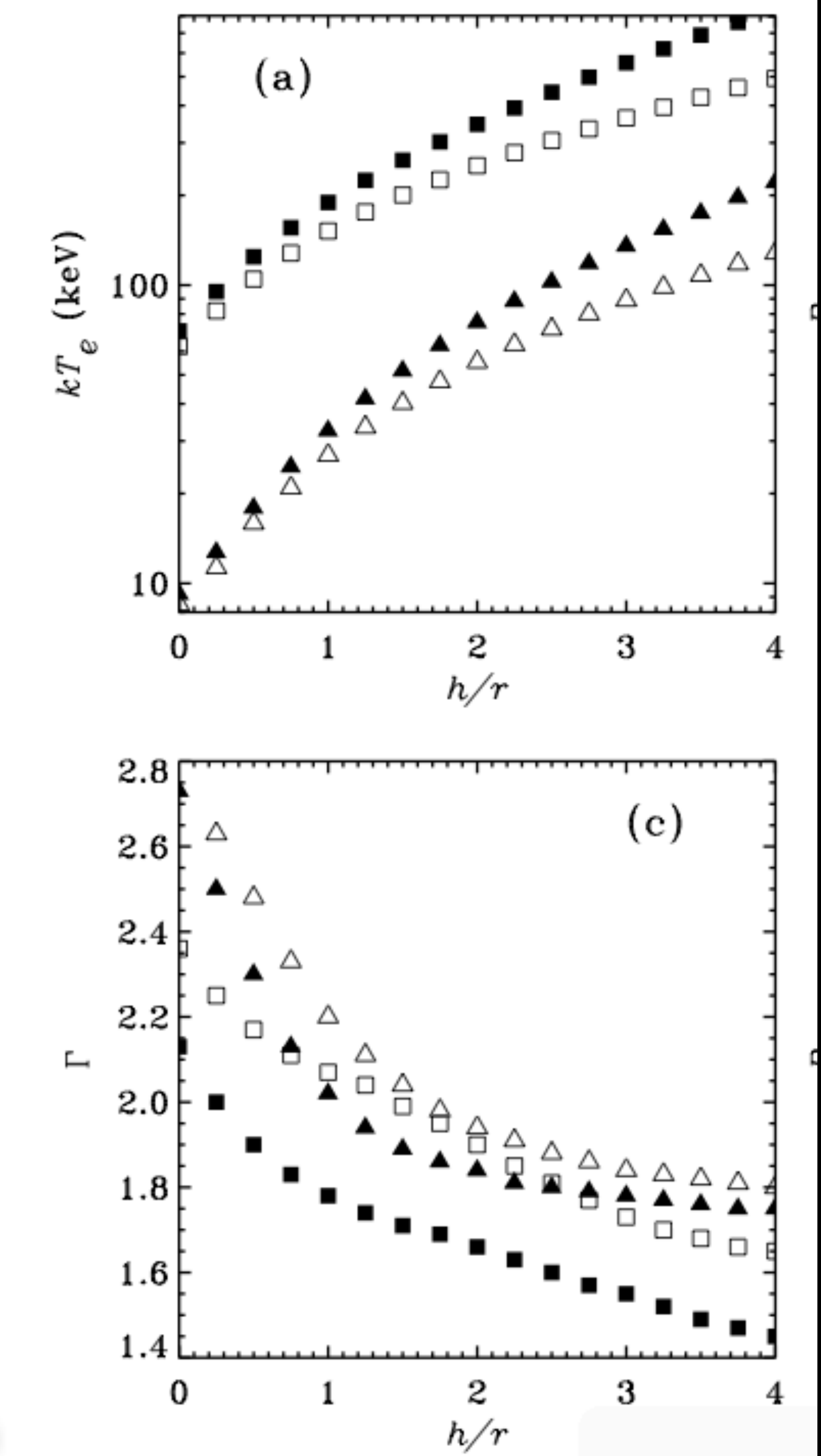

r
h
0
Rc
Rd

Dependence of spectral parameters on geometry



▲ BHB
△ AGN
} $\tau = 3$

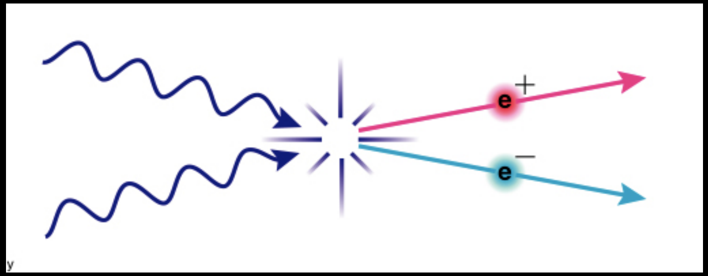
■ BHB
□ AGN
} $\tau = 0.5$



Malzac, Beloborodov, Poutanen 2001

The e^+-e^- pair thermostat

- Photons above 511 keV may interact with X-ray radiation field to produce e+-e- pairs

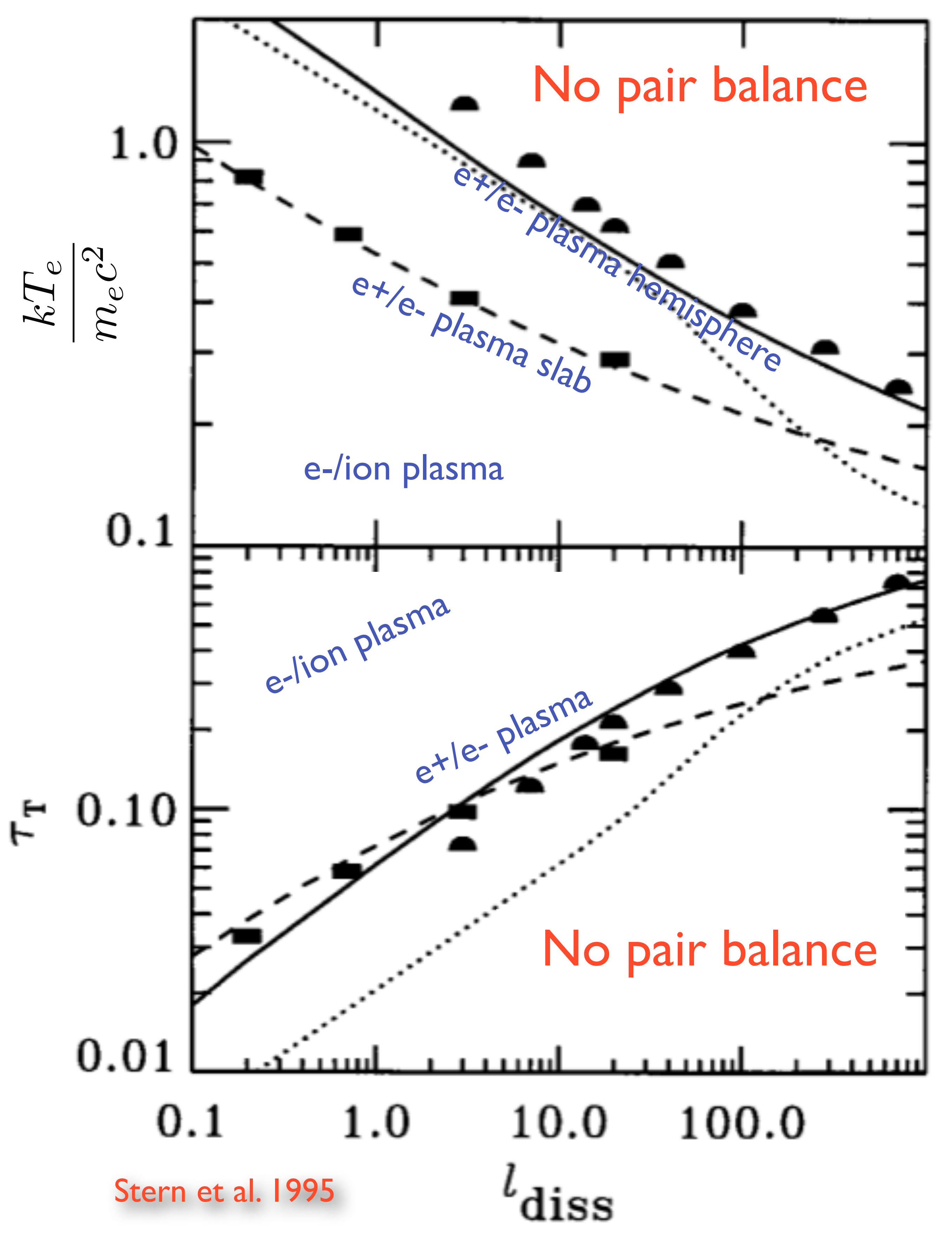


- The pair production rate increases with source compactness:

$$l_{dis} = \frac{L_h \sigma_T}{R m_e c^3}$$

- Pairs annihilate. At equilibrium, Thomson depth regulated by: production rate = annihilation rate

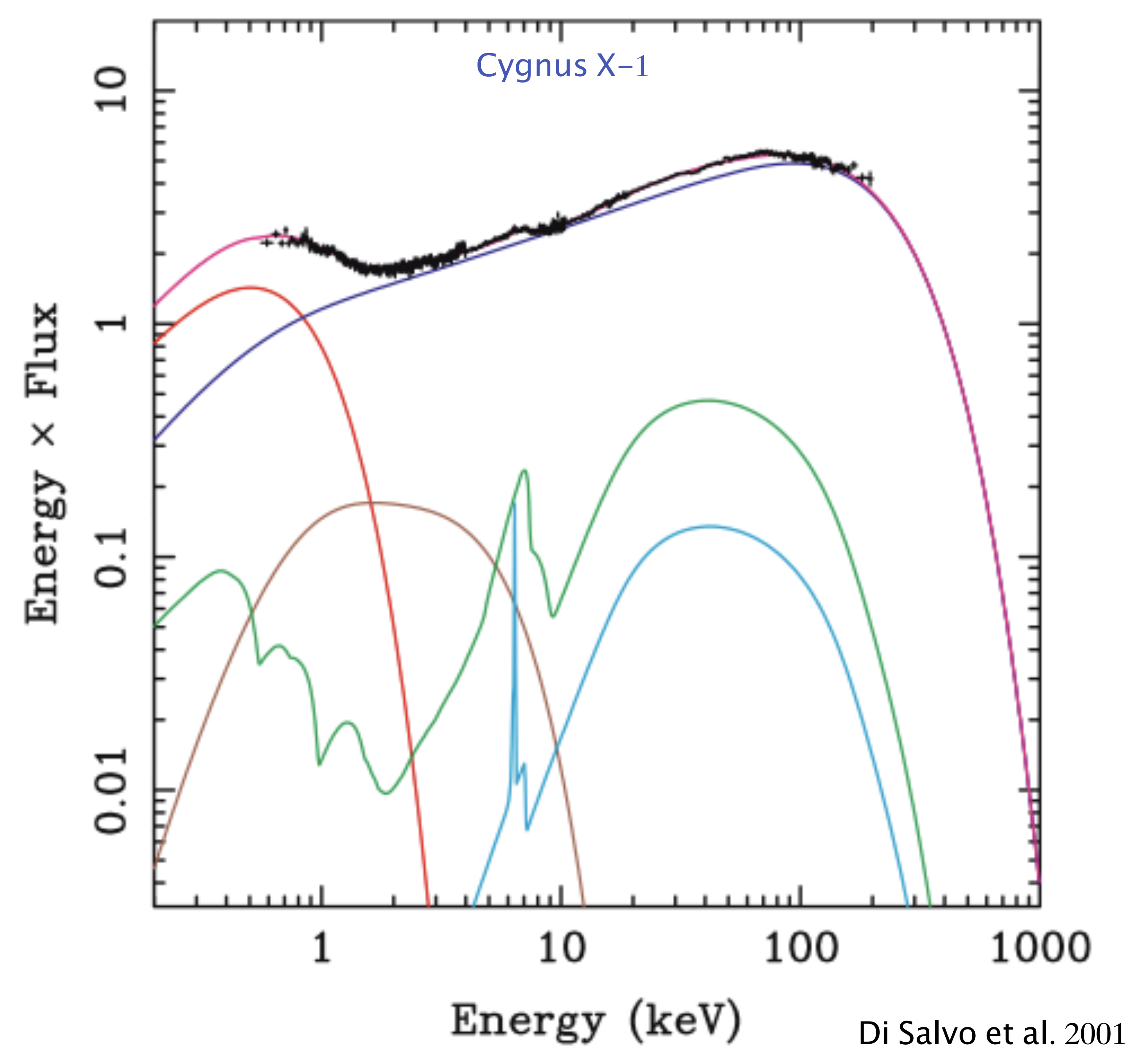
- This sets a minimum optical depth (and Maximum temperature) achievable for a given geometry



Stern et al. 1995

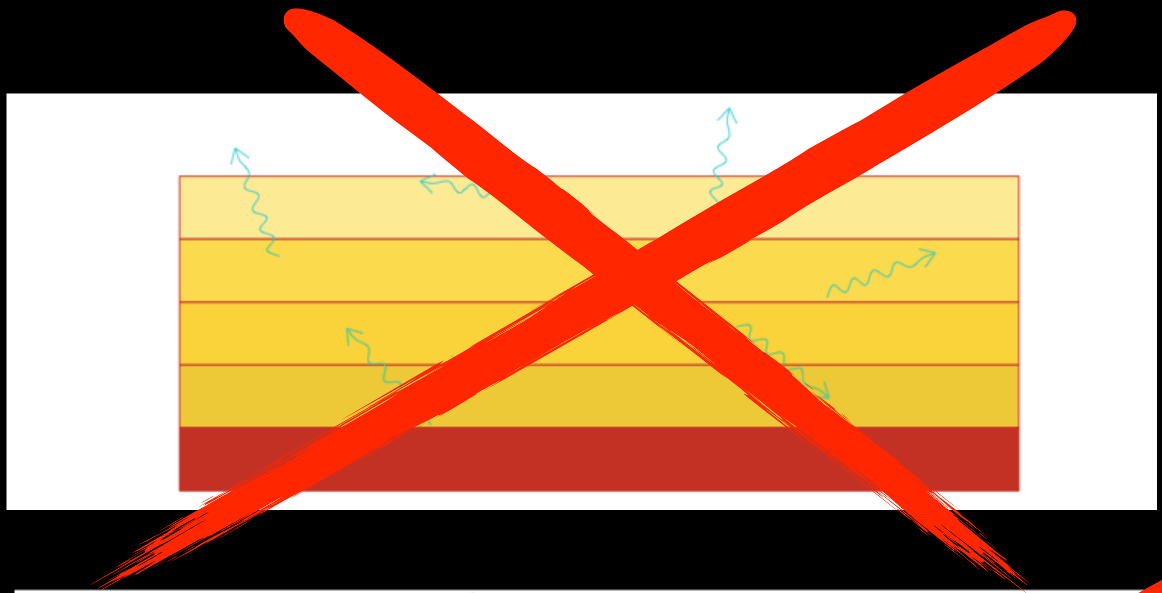
Application to BHBs in hard state

- Observed up to L<0.3 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:
  $\tau \simeq 1-3,\ kT_e \simeq 50-200\,\mathrm{keV}$
- Reflection amplitude is small R~0.3
- Associated with the presence of a compact radio jet



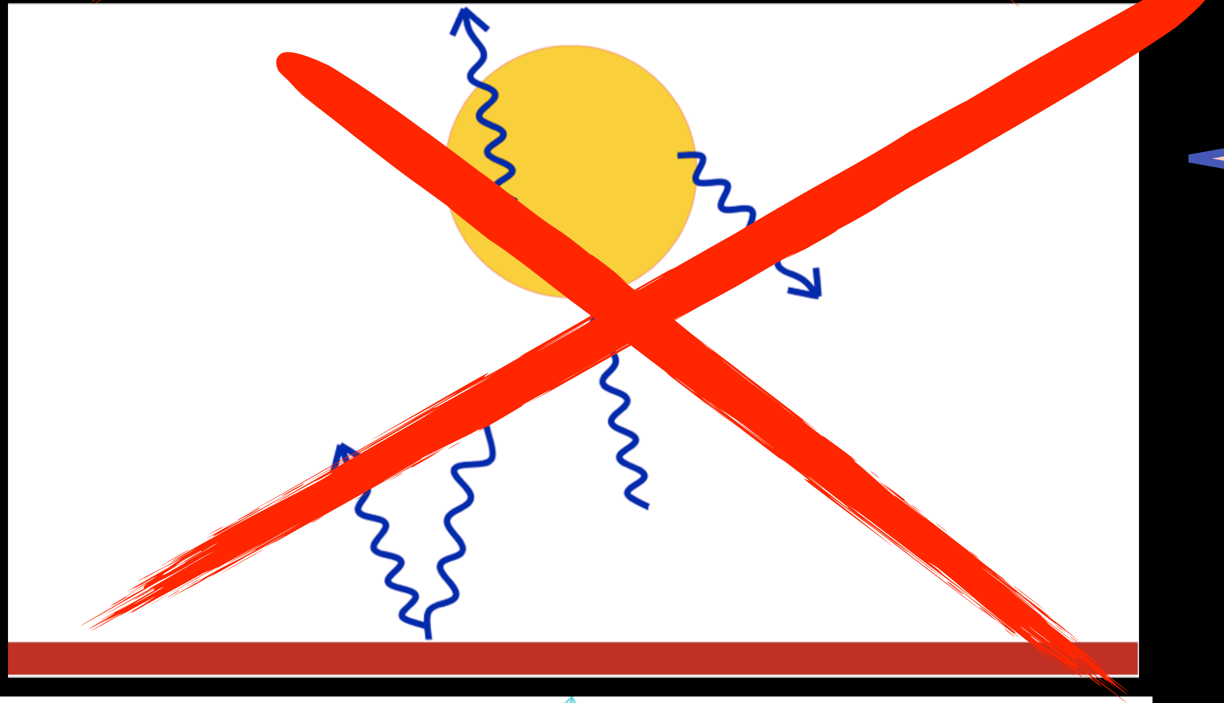
Di Salvo et al. 2001

Observed range of slopes and temperatures imply a `photon starved' geometry

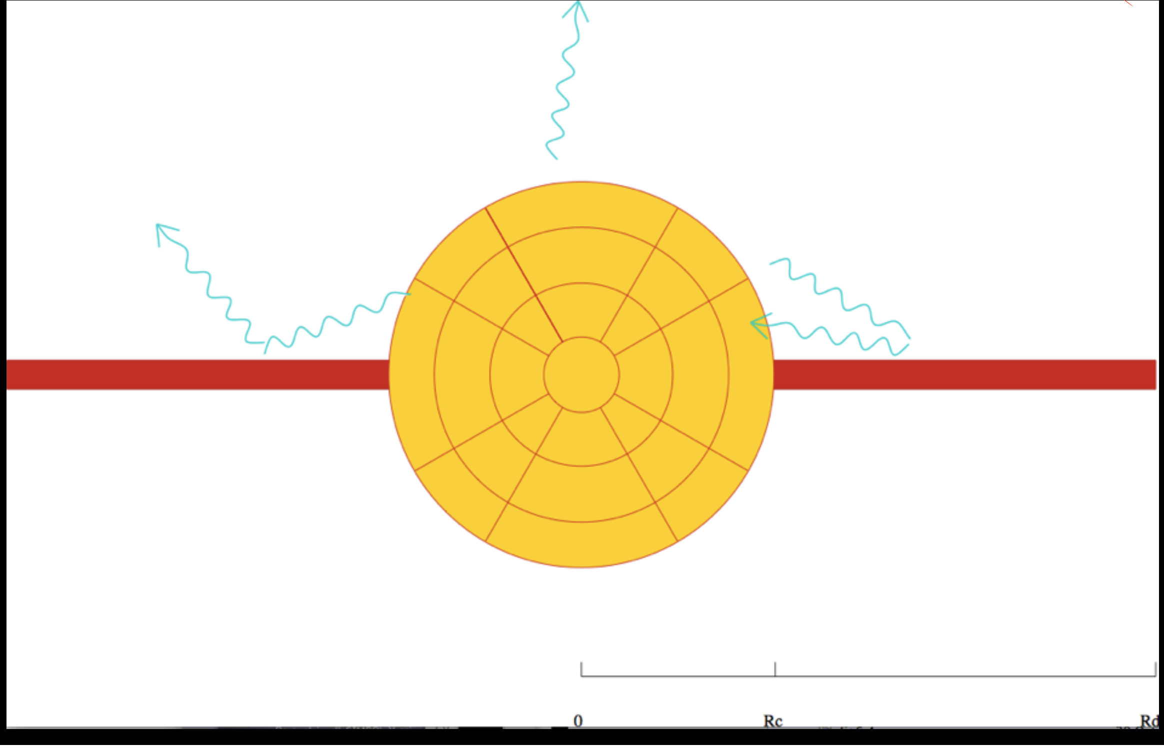


-Te too small

-Γ too large



- Te and Γ ok
- but R~1 expected



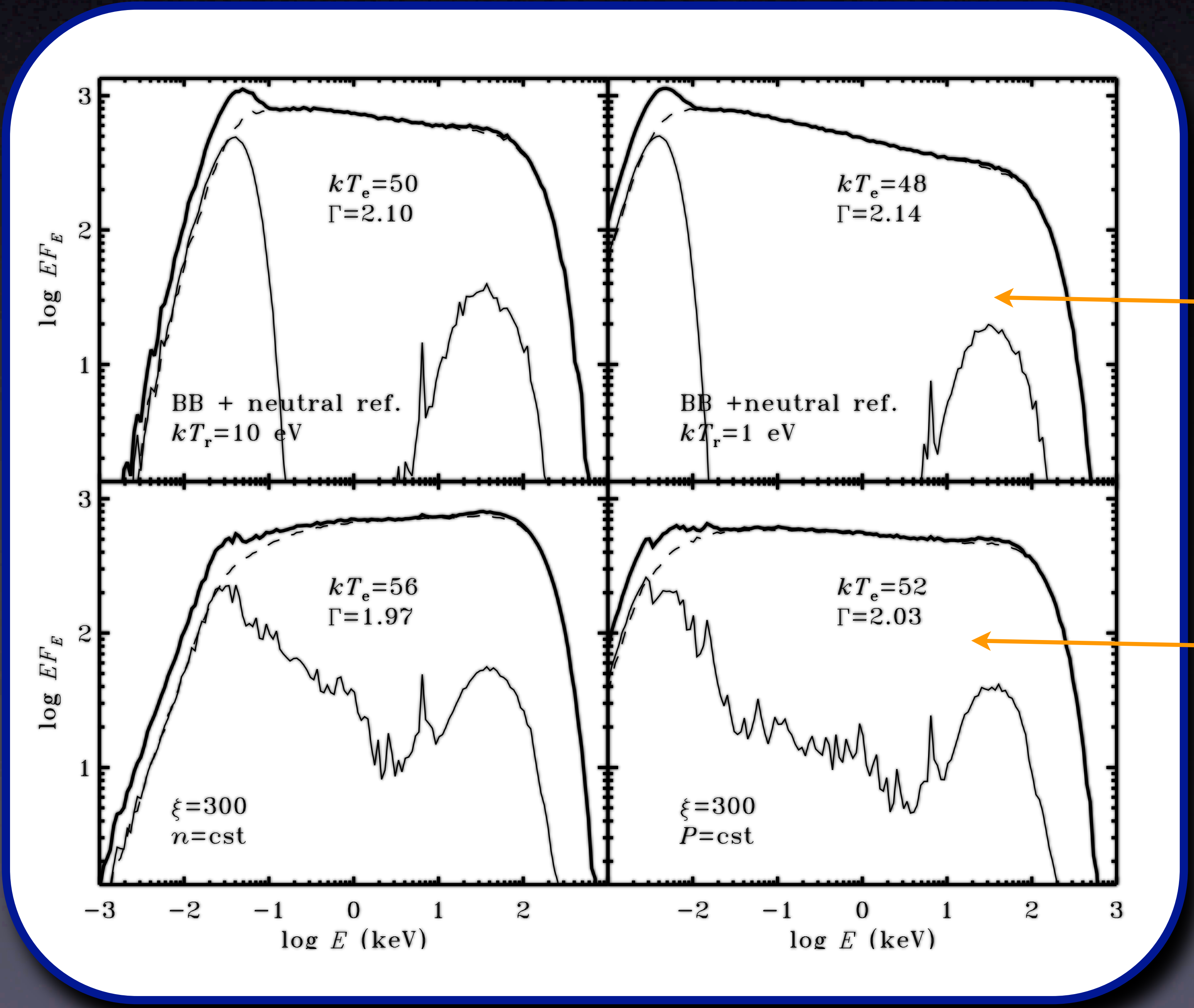
- Te and Γ
- R~0.3 expected

What if the accretion disc is ionised ?

- All calculations of ADC assumed neutral reflection on the accretion disc

If disc ionised ⇒X-ray albedo increased⇒ higher temperature ⇒harder spectrum

- Is it enough to relax constraints on ADC models ? NO



slab corona

neutral reflection

ionised reflection

(Malzac, Dumont & Mouchet 2005)

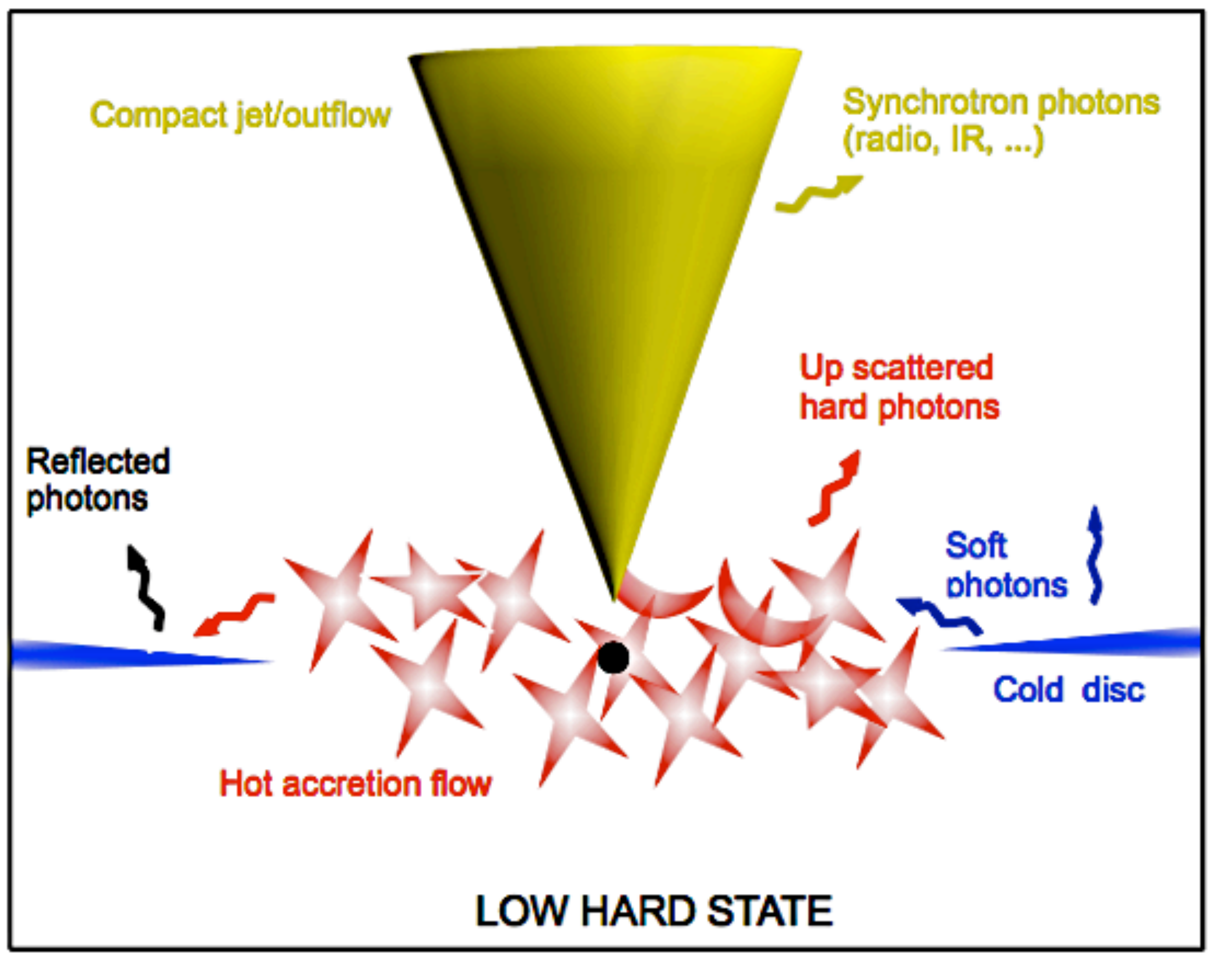
Truncated disc model

HARD STATE

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

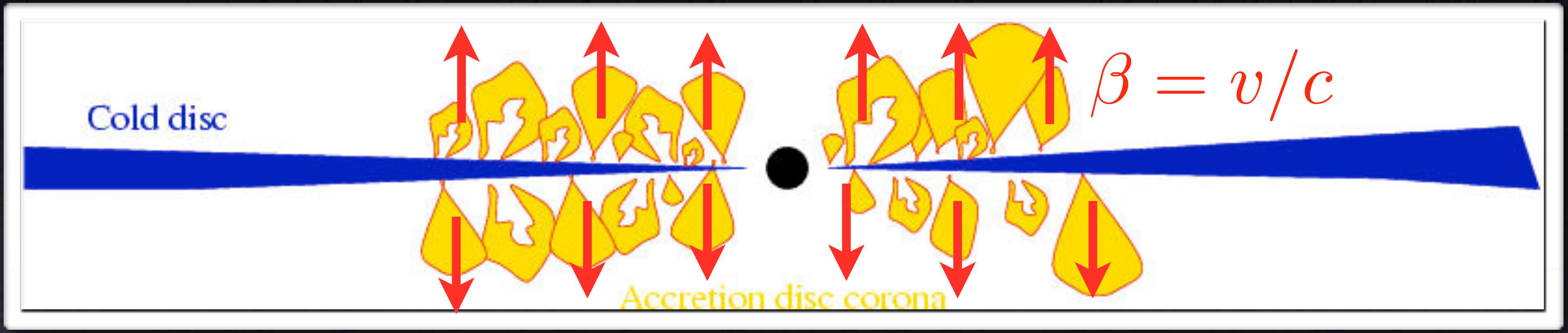
⇒ Thermal comptonisation
in the hot (10^9 K) plasma

(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...)



Alternative models for the hard state

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



(Merloni & Fabian 2001; Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

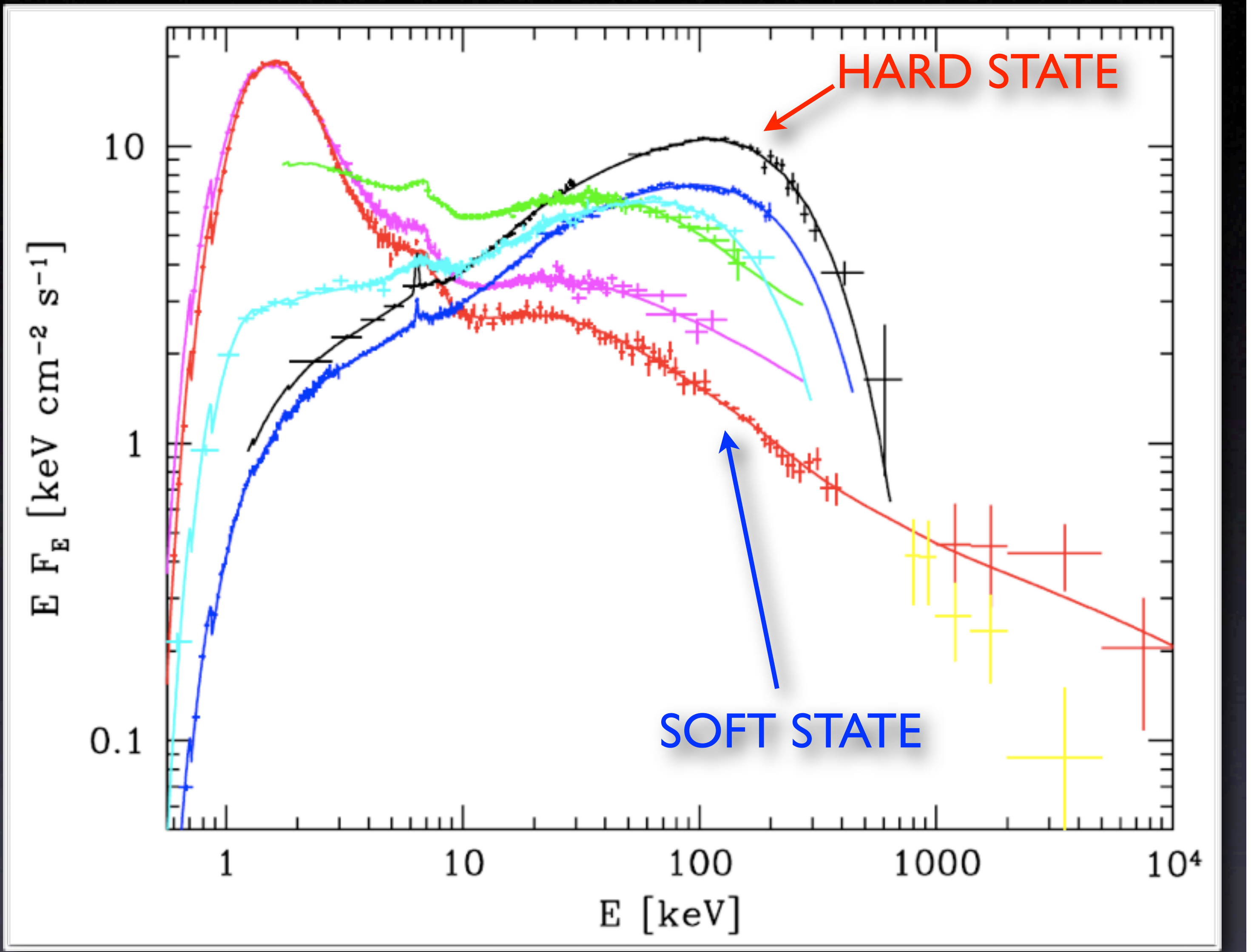
- X-ray Jet Models

(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)

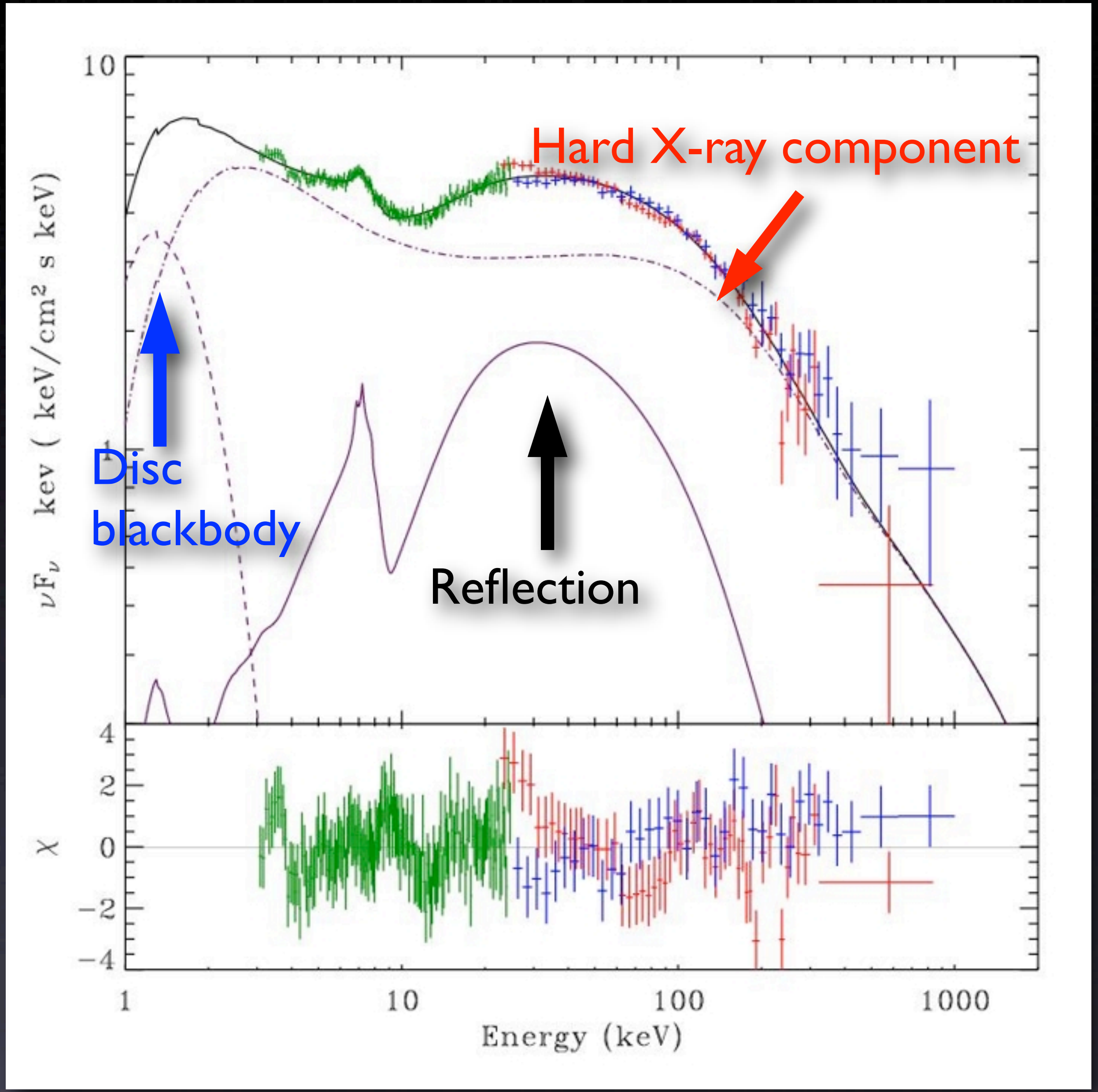
Spectral states



HARD STATE

SOFT STATE

Zdziarski et al 2003



Hard X-ray component

Disc blackbody

Reflection

Malzac et al. 2006

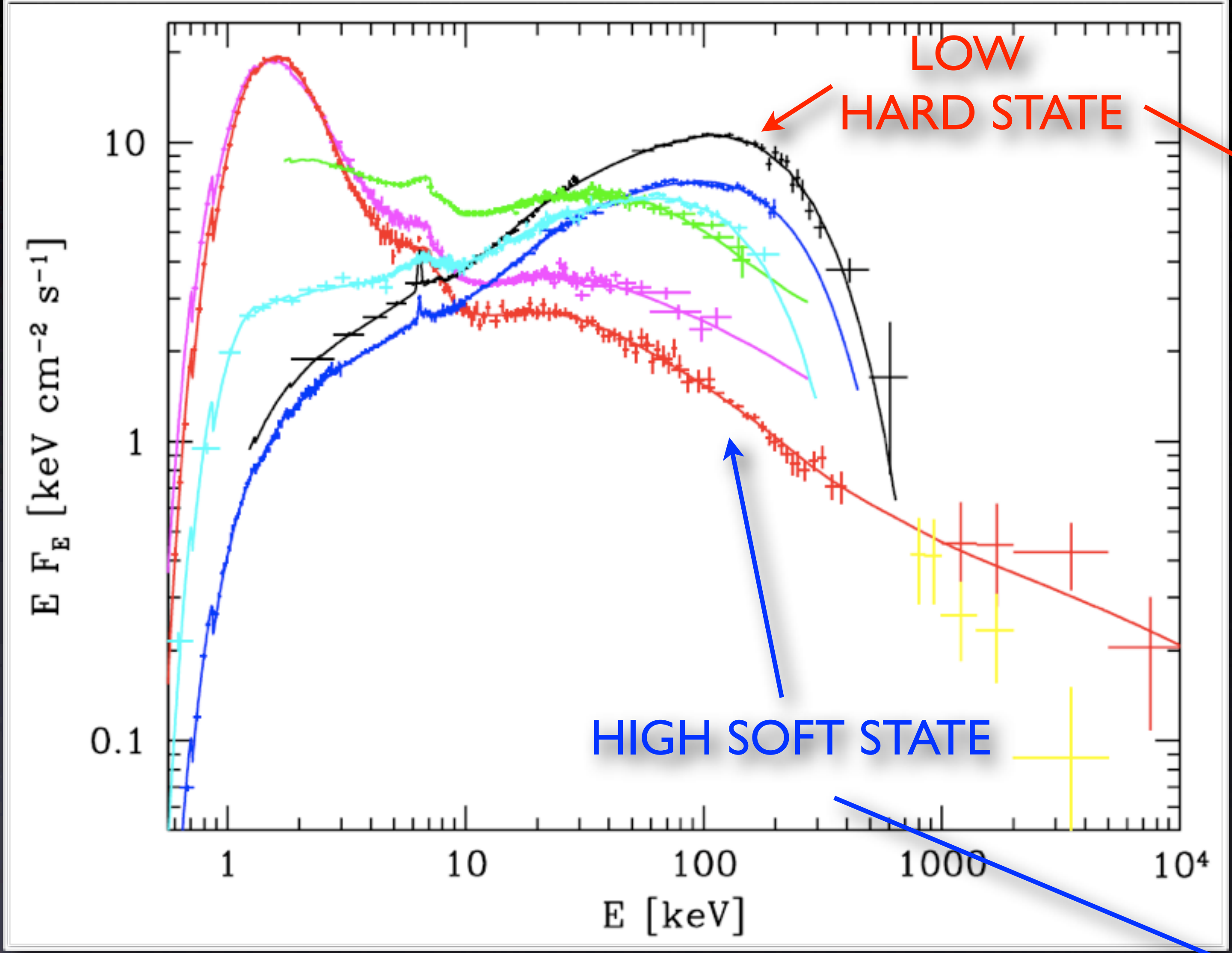
LOW HARD STATE: (compact radio jet)

disc blackbody and reflection: weak / Corona: THERMAL Comptonisation

HIGH SOFT STATE:

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

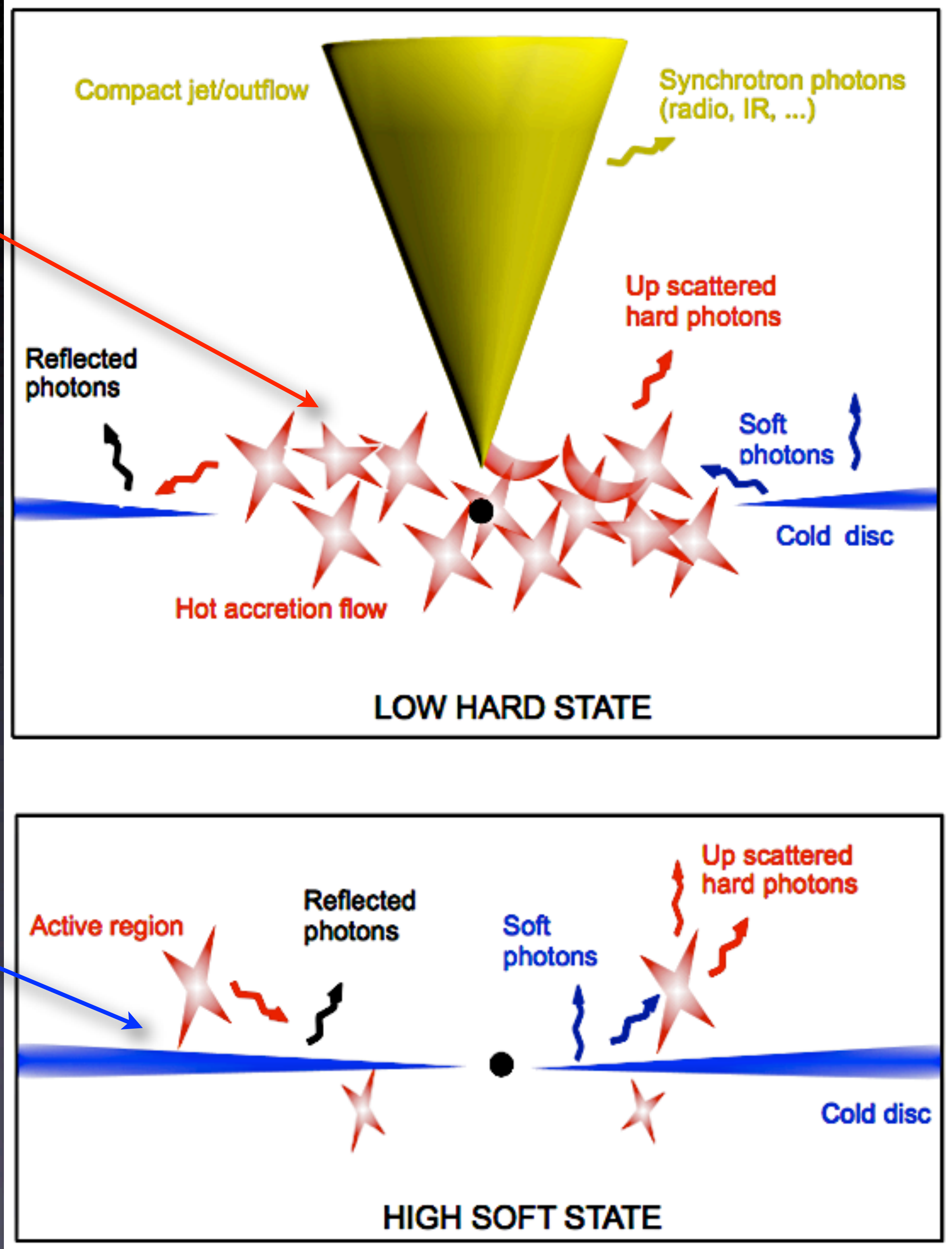
Standard picture: truncated disc model



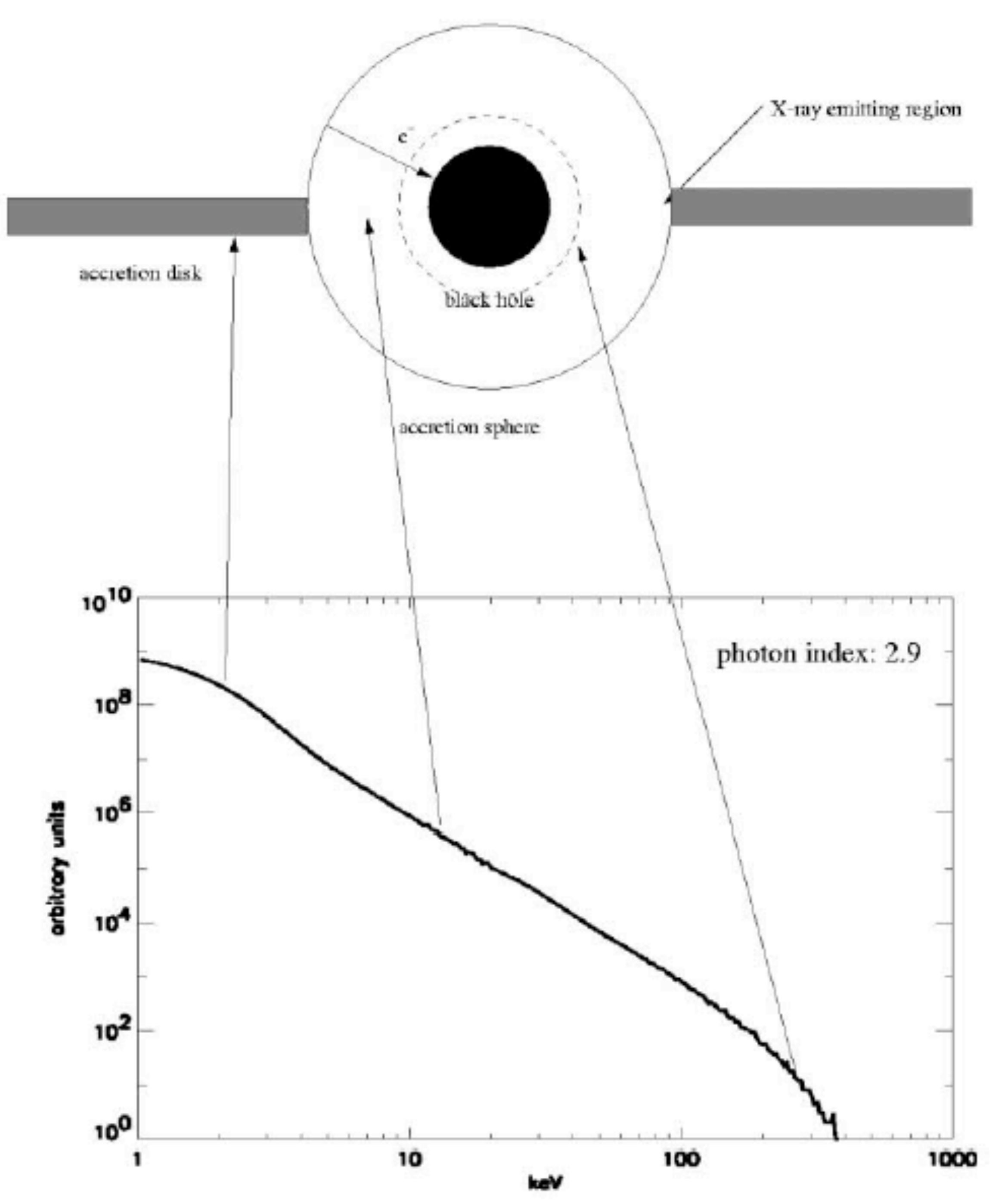
LOW HARD STATE

HIGH SOFT STATE

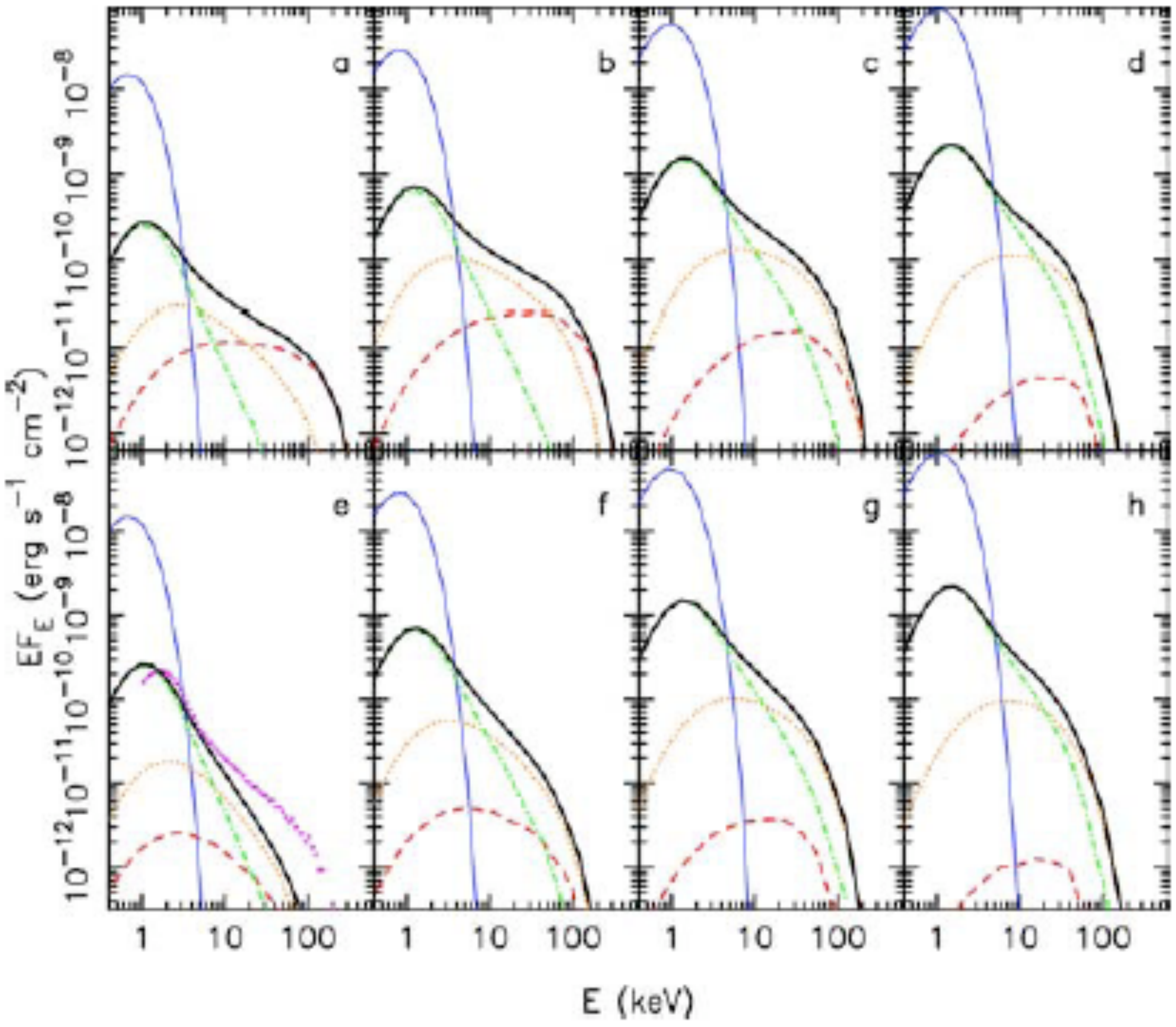
Zdziarski et al 2003



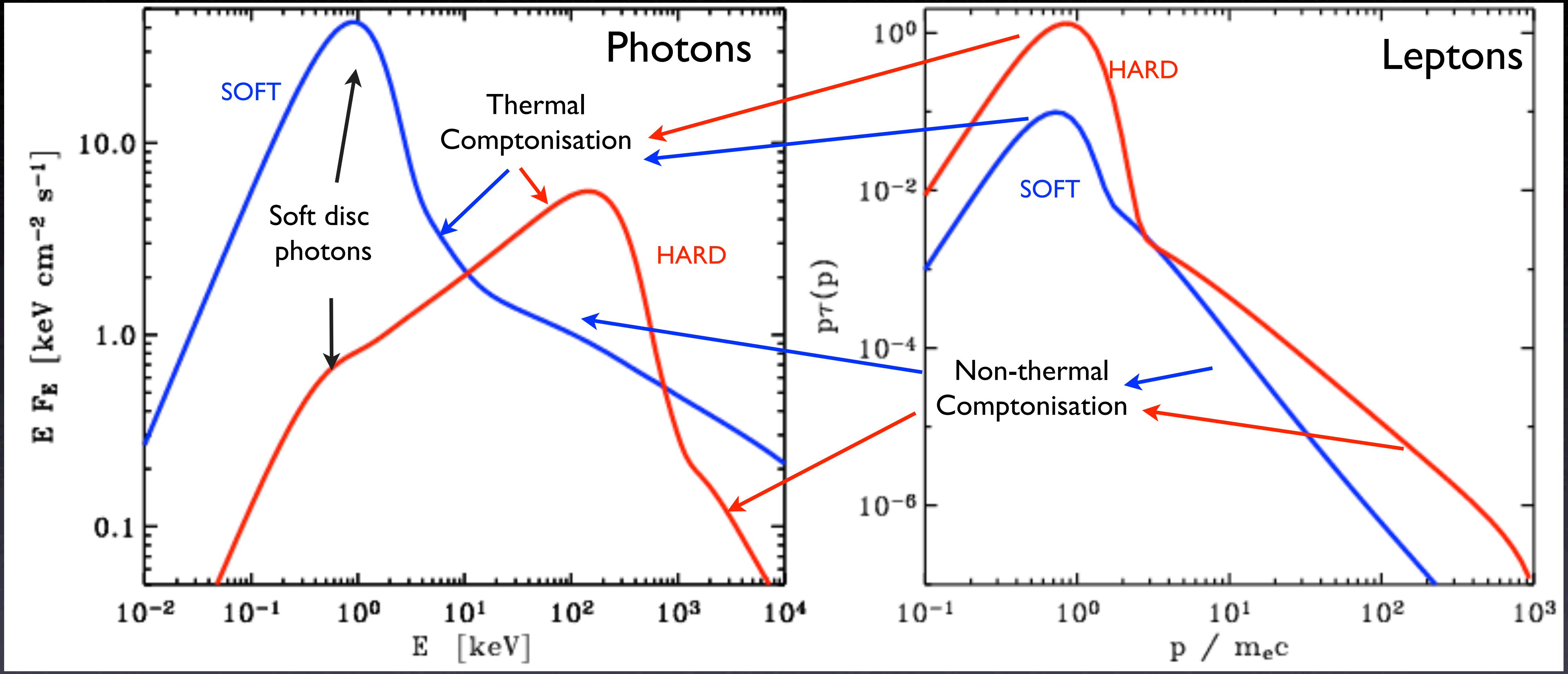
Alternative in the soft state: Inflowing bulk motion comptonisation



- produces correct X-ray slope and some features of the variability (Laurent & Titarchuk 2001, 2003)
- but predicts a high energy cut-off at 100 keV: not observed in the soft state (Niedzwiecki & Zdziarski 2006)



Hybrid thermal/non-thermal comptonisation models



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

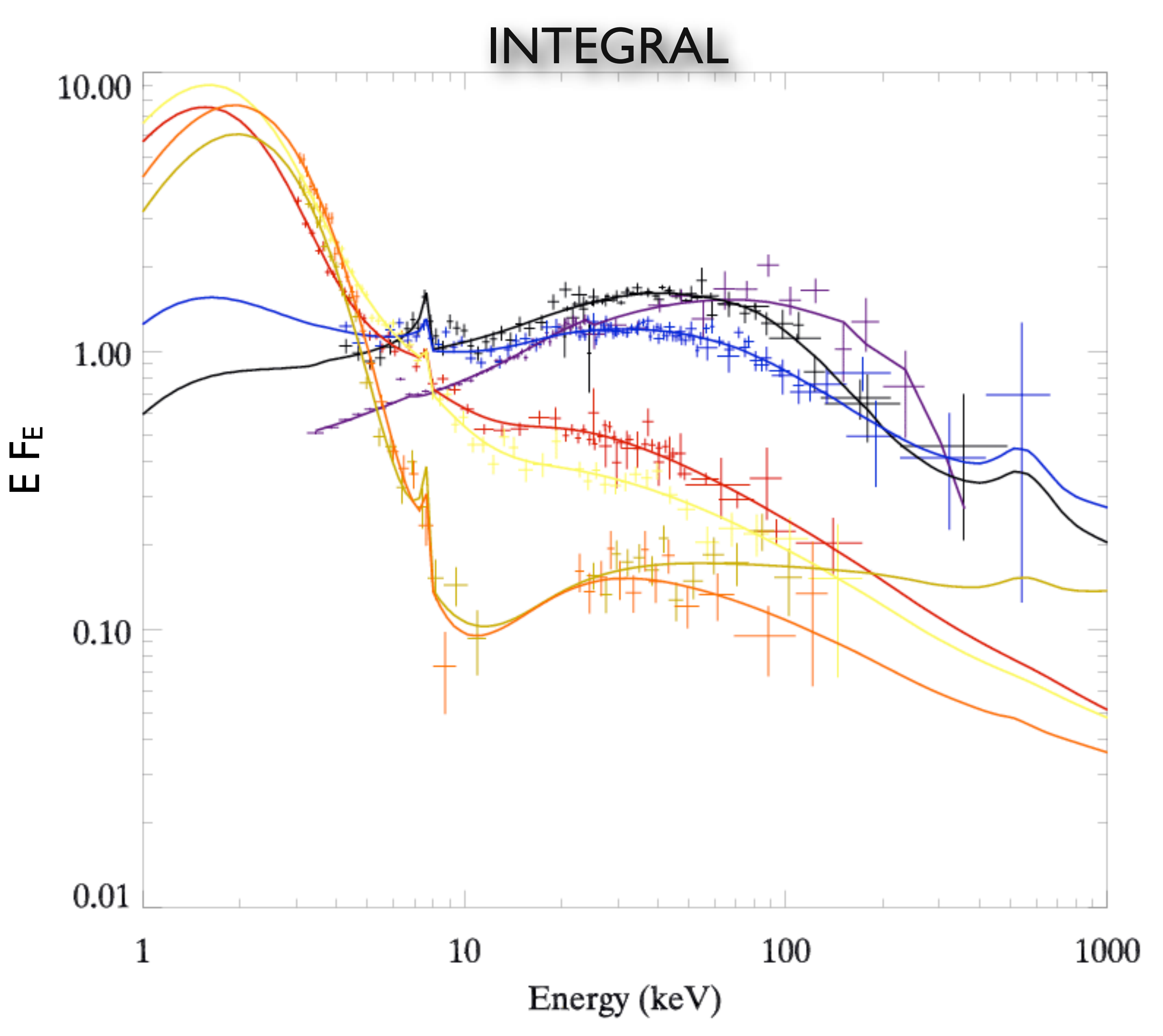
HARD STATE: kT~50-100keV, τ_T~1-3: Thermal comptonisation dominates

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

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

GX 339-4 during the 2004 state transition



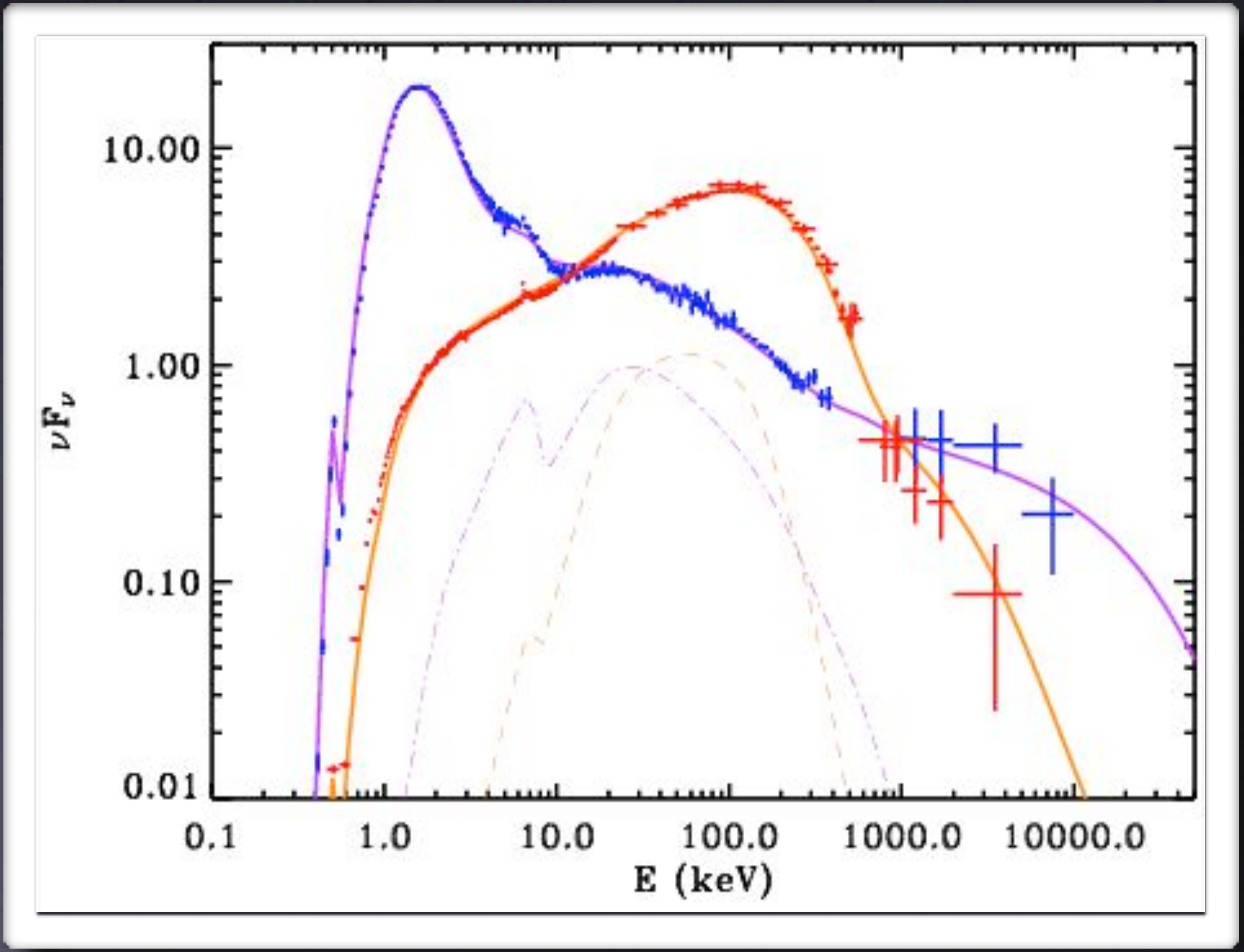
Del Santo, et al., MNRAS, 2008

- 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

Hybrid model with magnetic field

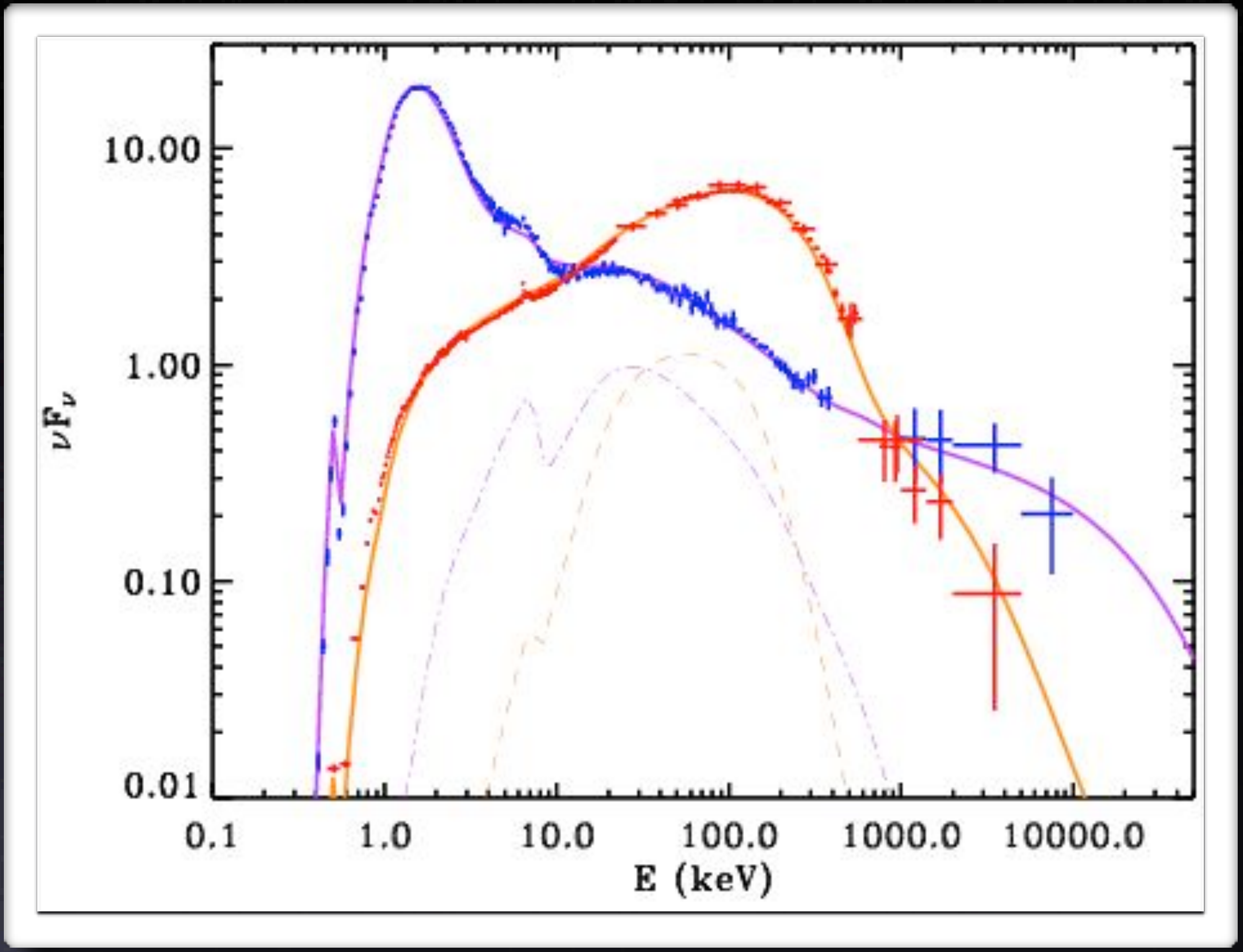
Effects of magnetic field:

- Cyclo-synchrotron radiation= seed photons for comptonization, enhanced cooling of the Maxwellian electrons
- Cyclo-synchrotron self-absorption= fast electron thermalisation
- Hard state consistent with pure SSC
- Different coronal temperatures in HS and SS due to more cooling by thermal disc photons in Soft state



(Belmont et al. 2008; Vurm et al. 2009; Malzac & Belmont 2009 ; Poutanen & Vurm 2009)

Constraint on coronal magnetic field



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; Droulans et al. 2010)

Hybrid models with hot protons

Electrons heated through Coulomb interactions with a population of hot thermal protons (two-temperature plasma)

➡Constraint on ion temperature in the corona in bright HS:

- Temperature of hot protons in hard state:

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

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

➡ consequence of $\tau_{\rm T} \geq 1$ in hard state:

Coulomb coupling is efficient,
larger Ti would imply higher luminosities than observed

(Malzac & Belmont 2009; Droulans et al. 2010)

Can hot accretion flows explain the bright hard state sources?

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

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

➡ standard hot flow solutions cannot be applied

- A possible fix:

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

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

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

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

- 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:

➡non-thermal electrons generate too much synchrotron

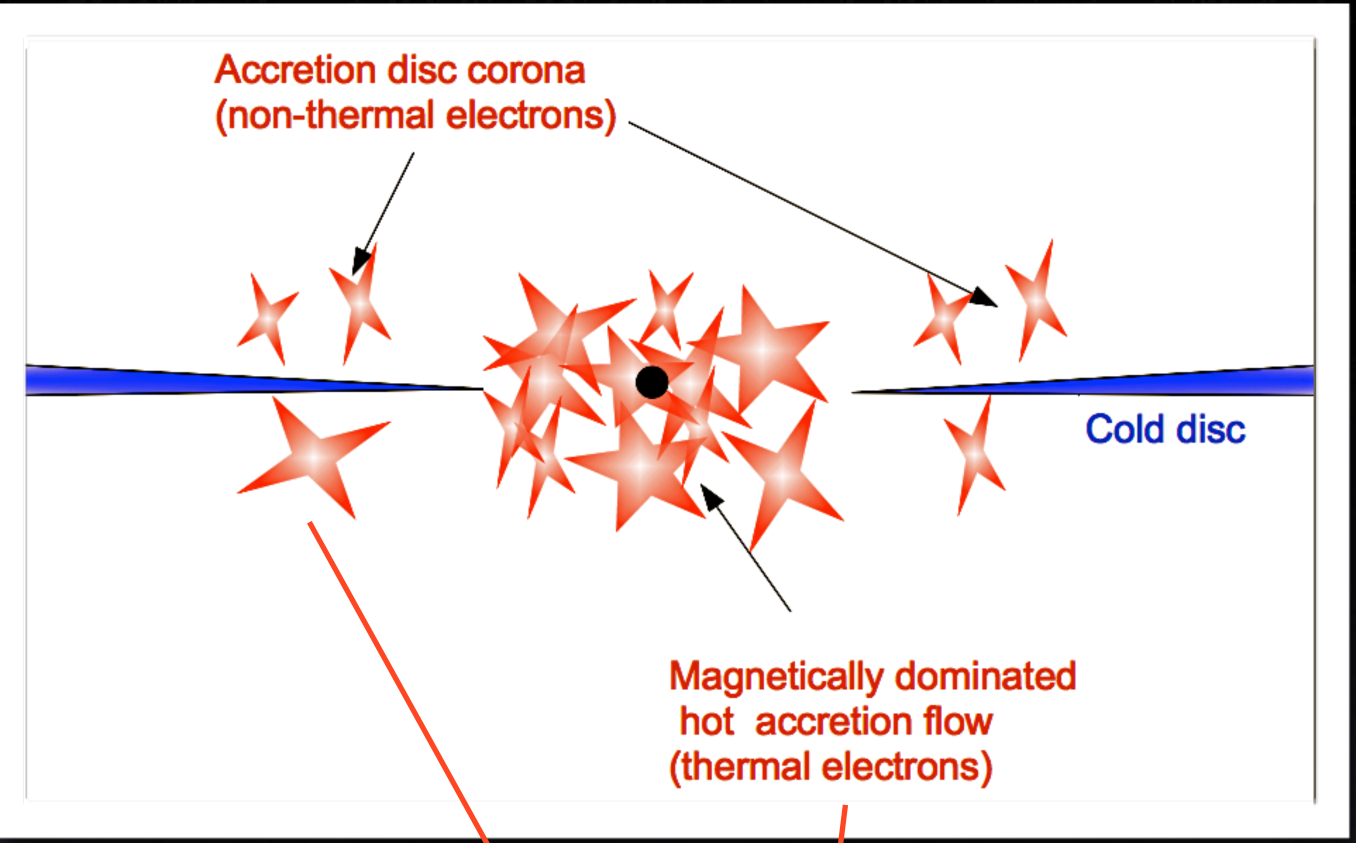
➡Maxwellian electrons are too cold

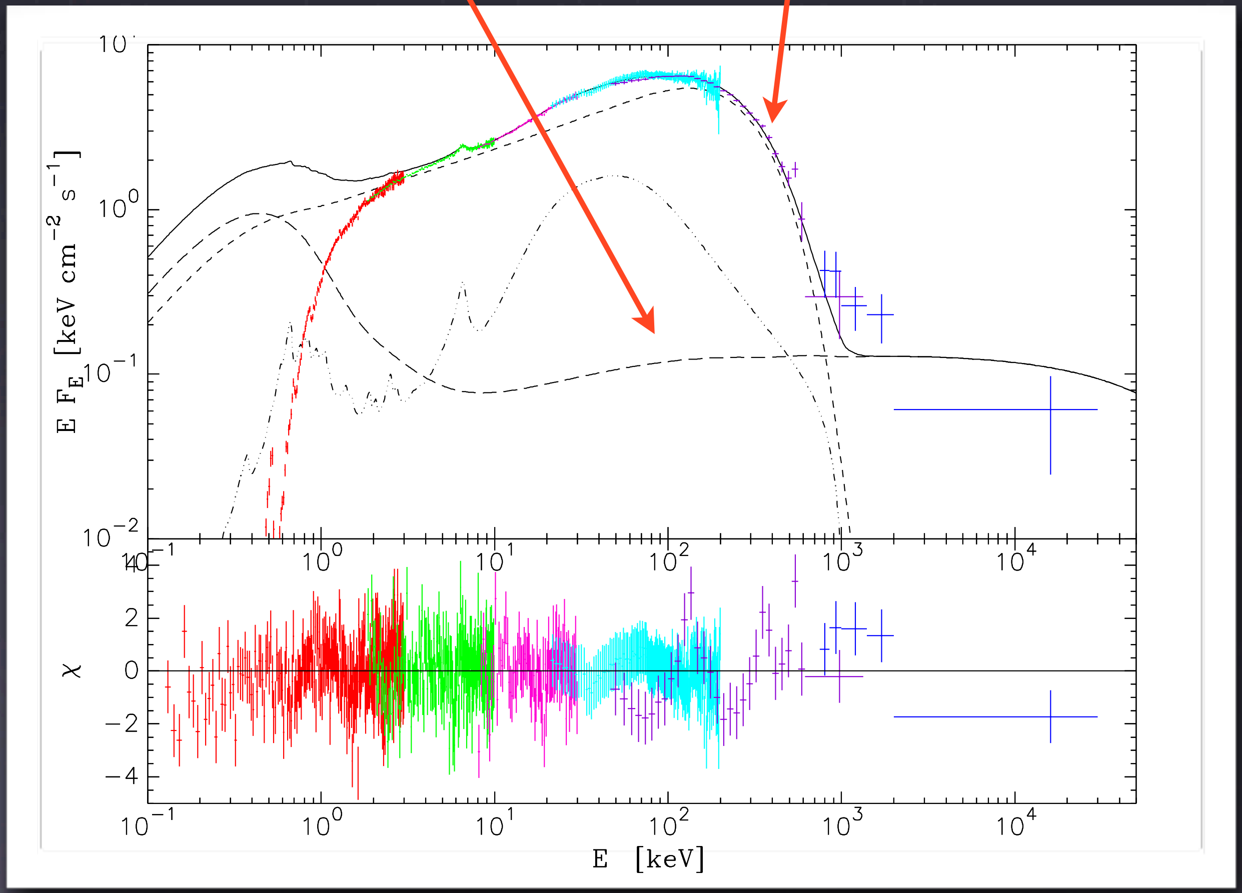
????

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

➡ multi-zone corona ?

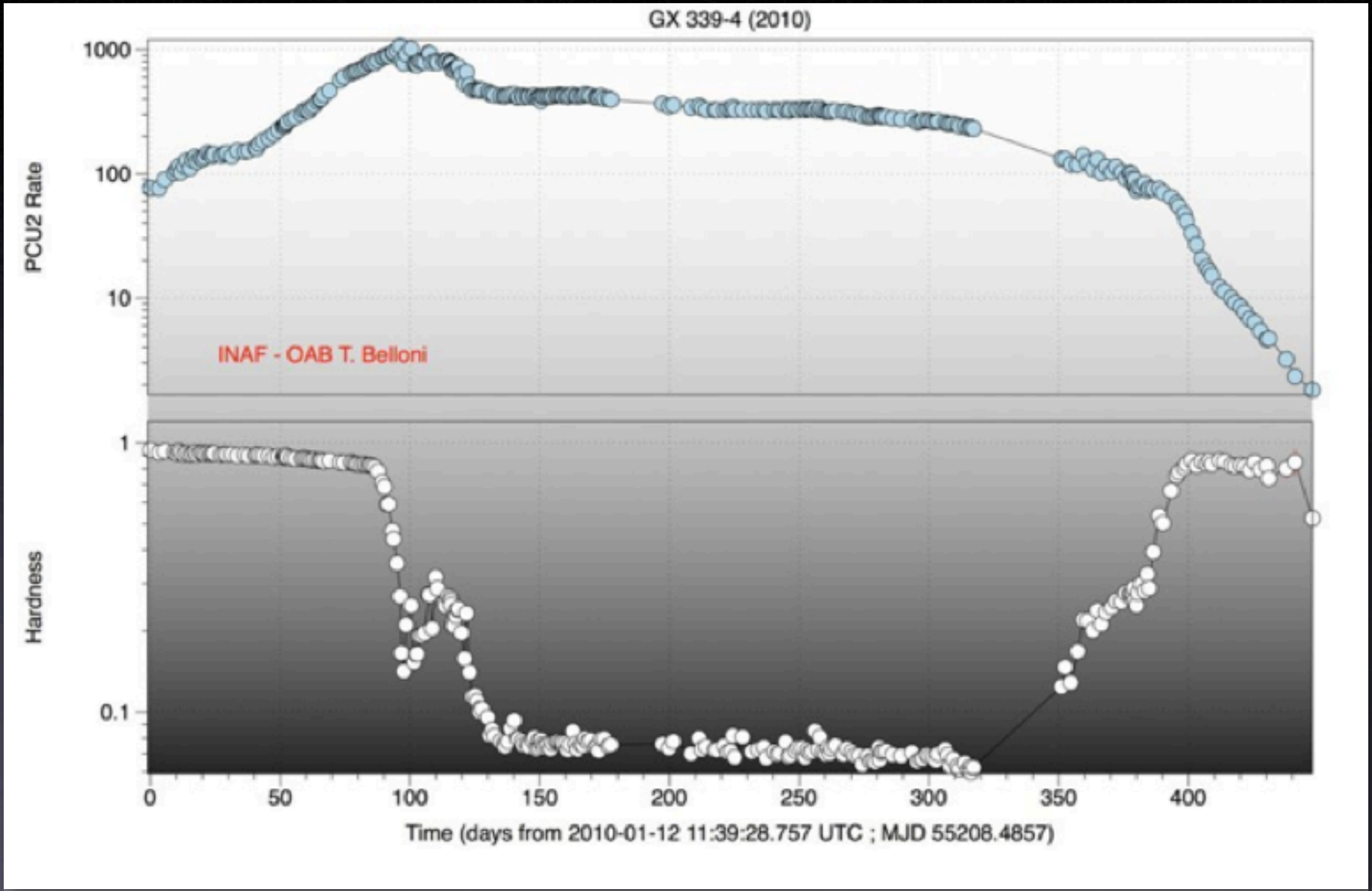
A two-component model for the LHS



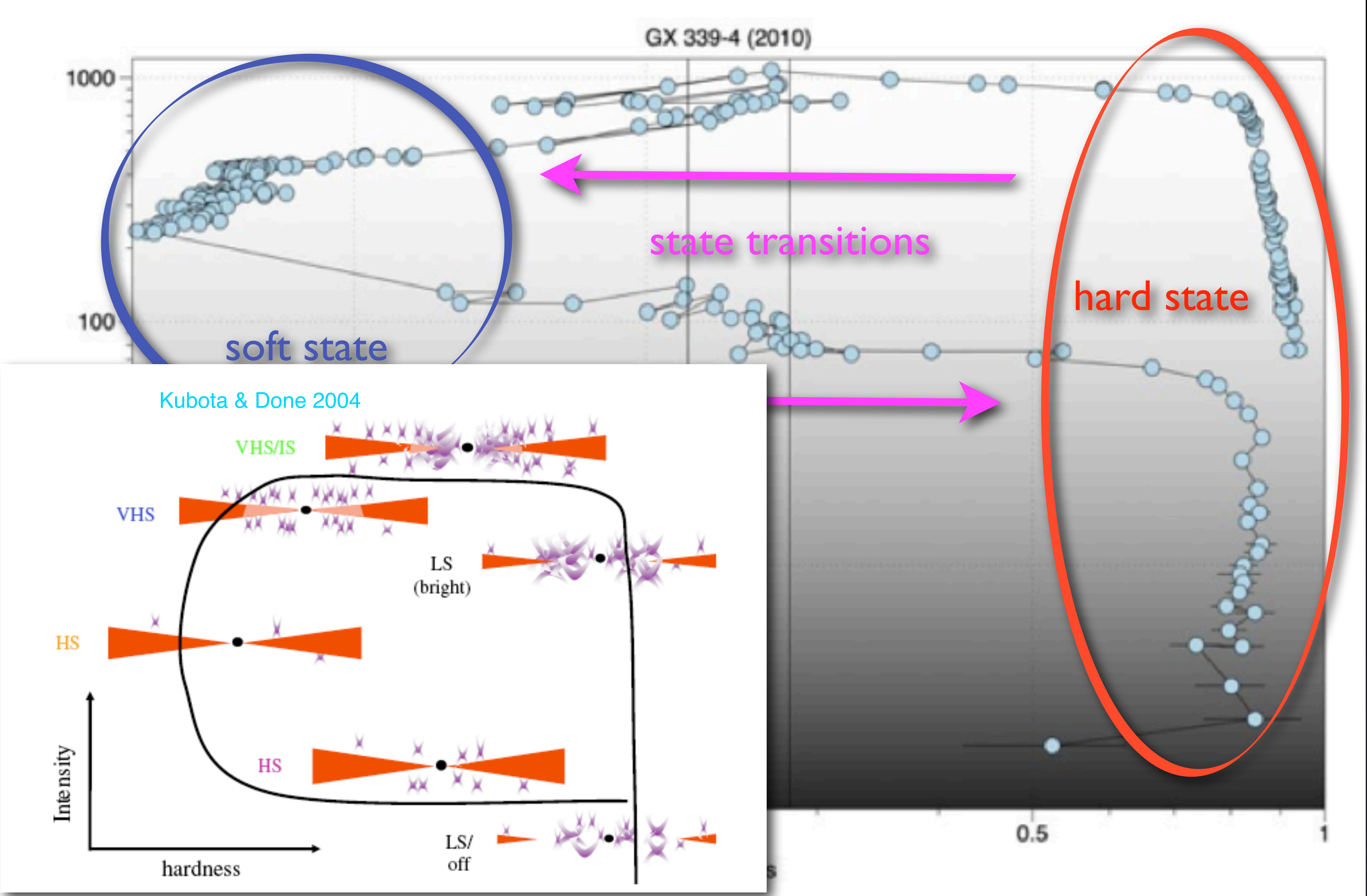


- Thermal comptonisation component dominates hard X-ray emission
- Non-thermal component reproduces soft X-ray excess and MeV emission
- Changes in the relative luminosity of thermal and non-thermal regions lead to state transitions

Spectral evolution during outbursts of BHBs



Spectral evolution during outbursts of BHBs

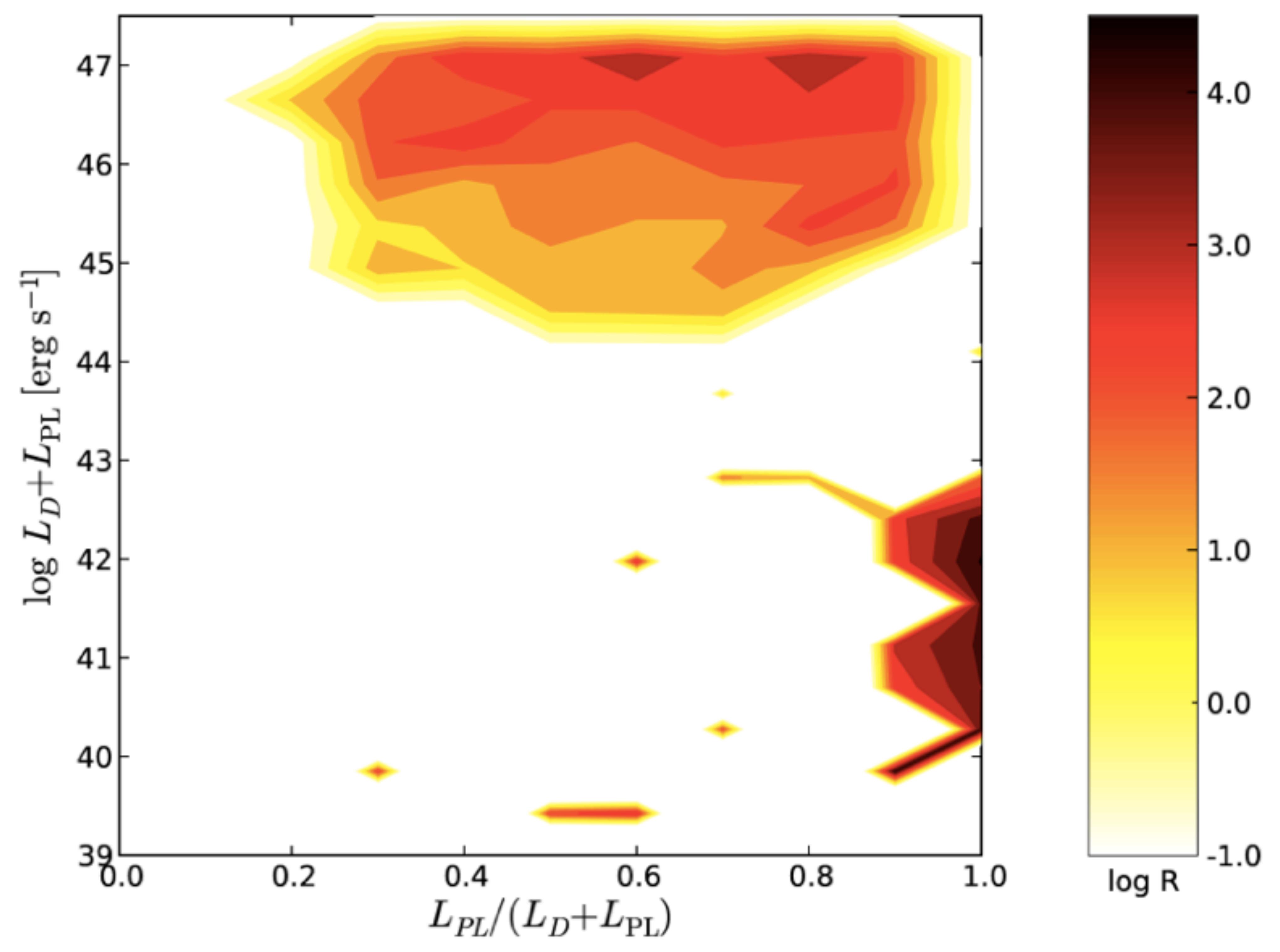


soft state

state transitions

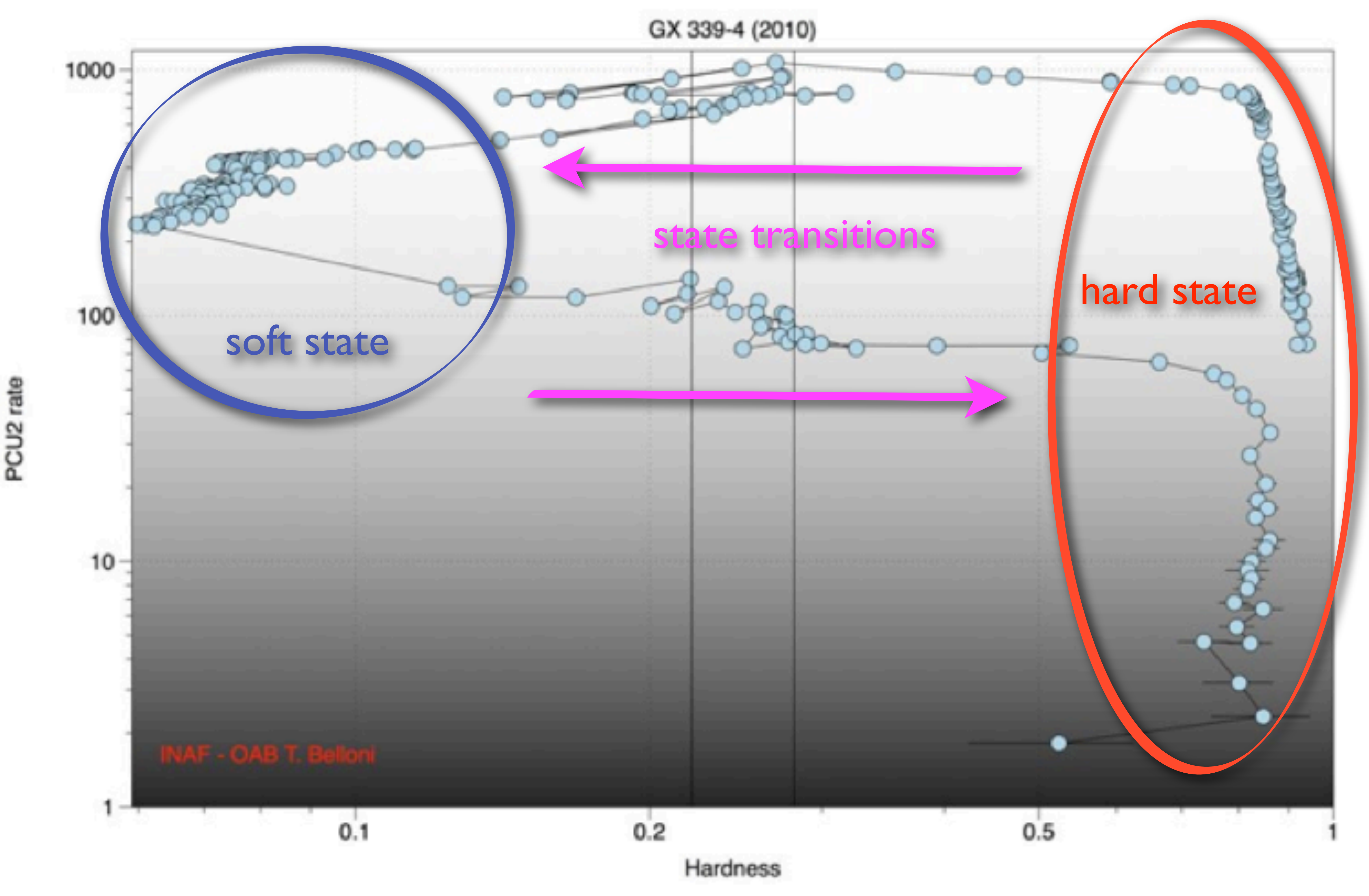
hard state

Kubota & Done 2004



Körding, Jester, Fender 2006

Spectral evolution during outbursts of BHBs



soft state

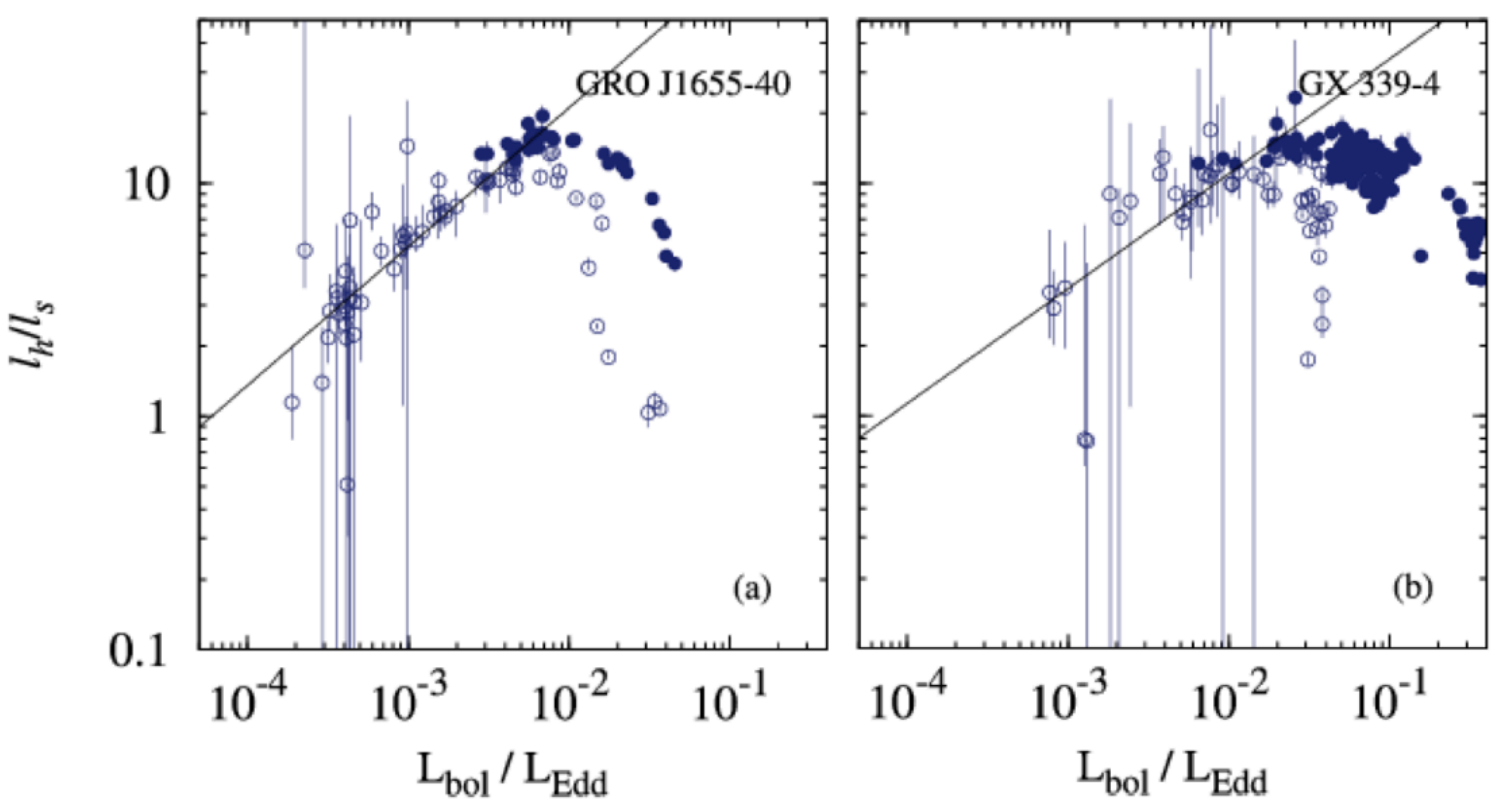
state transitions

hard state

Spectral evolution in hard state during outbursts

Now use compactness ratio l_h/l_s instead of hardness or photon index

$$\Gamma \propto (l_h/l_s)^{-\delta} \qquad \delta \sim 0.1$$

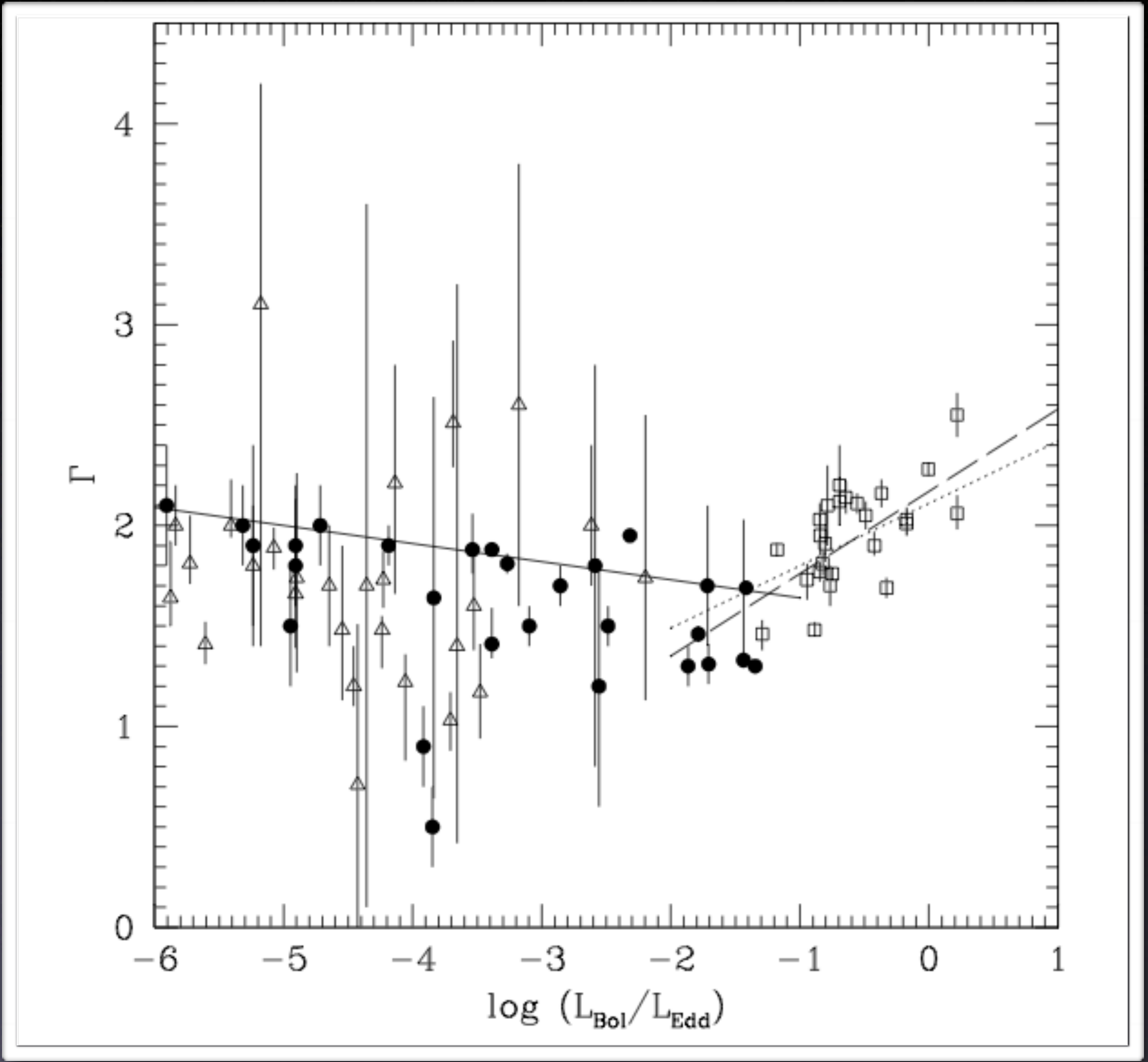


(Sobolewska et al. 2011)

$L/L_E < 0.01$ ⇒ X-ray spectrum harder when brighter (2.1<Γ<1.5)

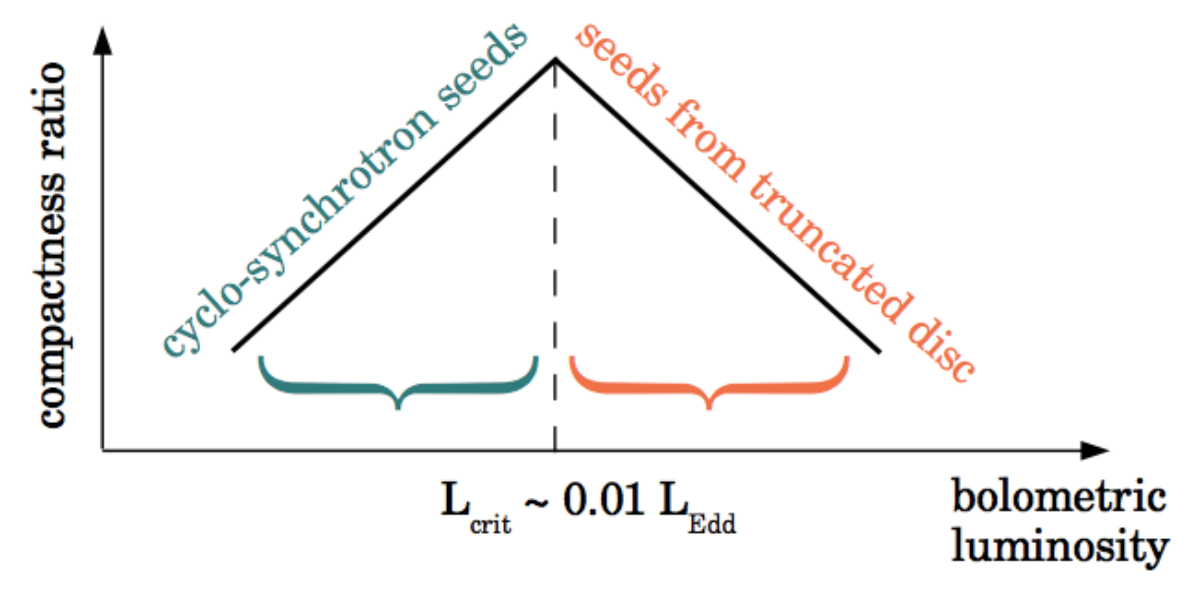
$L/L_E > 0.01$ ⇒ X-ray spectrum softer when brighter, hysteresis

Spectral index versus luminosity in AGN

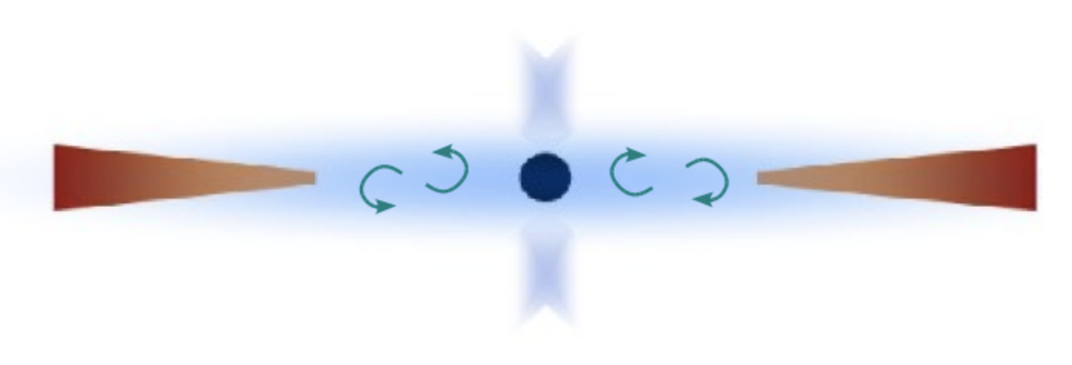


(Gu & Cao 2009)

Interpretation

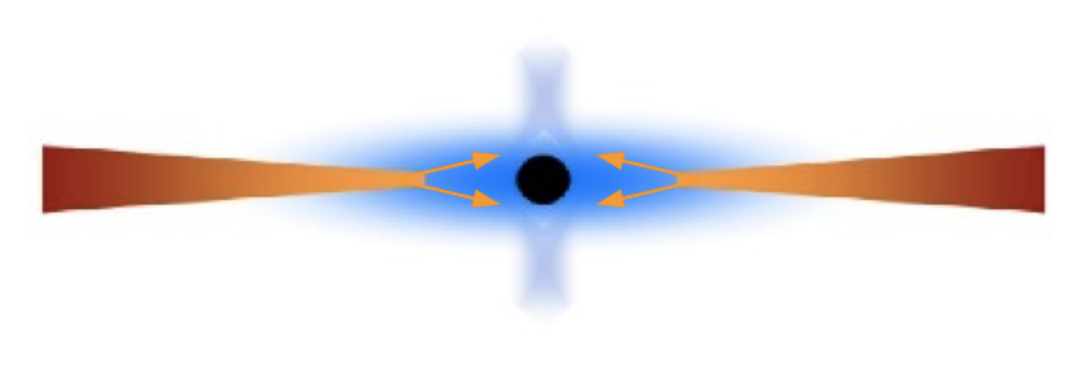


- A change in X-ray radiation mechanism



- $L/L_E < 0.01$: soft seed photons from cyclo-synchrotron radiation

➡ $l_h/l_s \propto L^{1.1}$ (radiatively inefficient + thermal electrons)



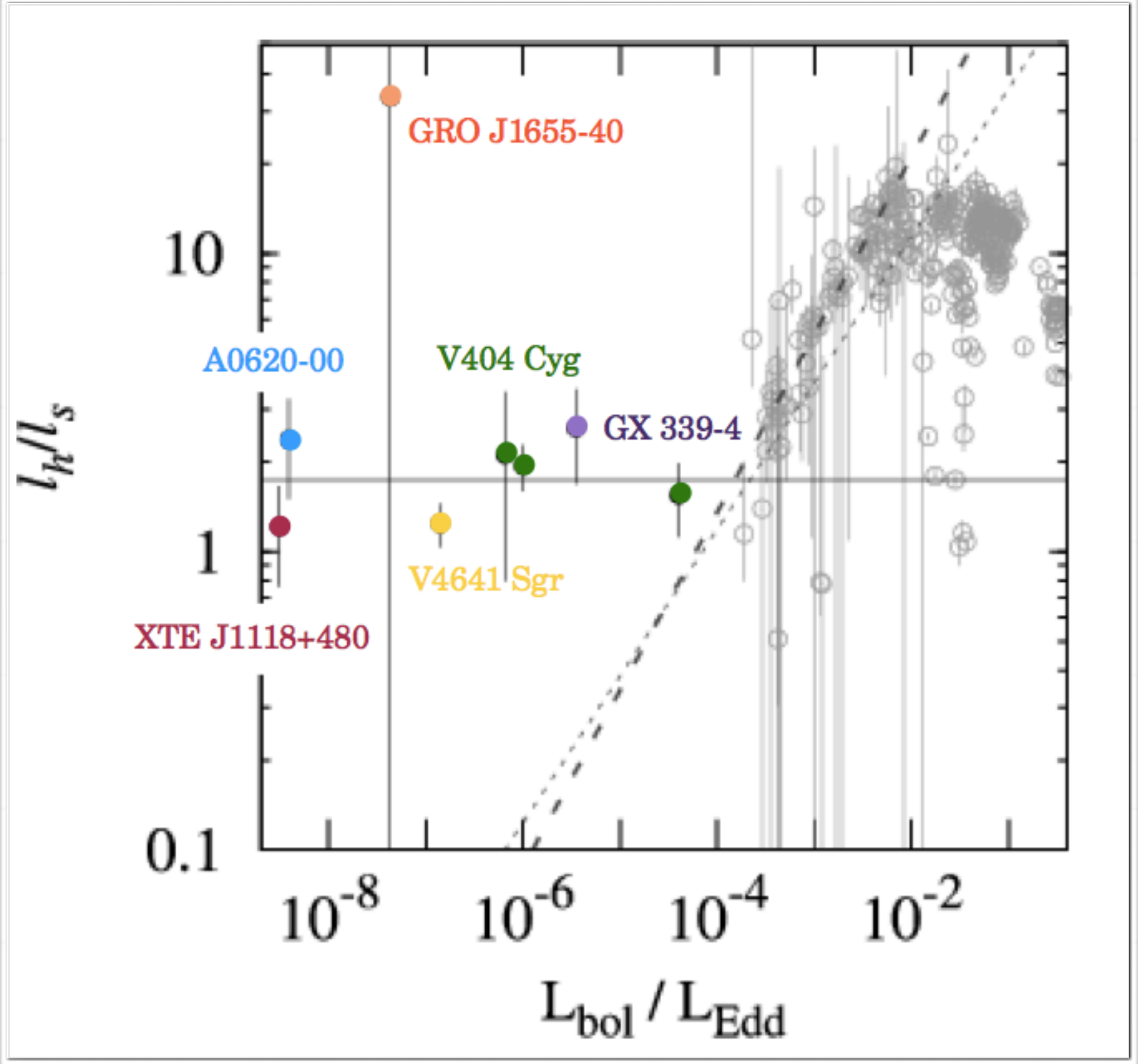
- $L/L_E > 0.01$: soft seed photons from accretion disc:

➡ $l_h/l_s \propto L^{-3/2}$ (radiatively efficient)

➡ $l_h/l_s \propto L^{-1/4}$ (radiatively inefficient)

Saturday, 23 July 2011

Quiescence



At very low L, ($L/L_E < 10^{-4}$), spectral index saturates around Γ ~ 2.1

(from Sobolewska et al. 2011)

➡ radiation by non-thermal electron distribution ?

- τ<<1 → emission dominated by non-thermal particles

or

- X-ray emission dominated by synchrotron emission in jet (Yuan et al. 2004, Russell et al. 2011)

Conclusions:

- In the best documented sources (bright BHBs), 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
- Radiation processes depend on mass accretion rate

Thanks !