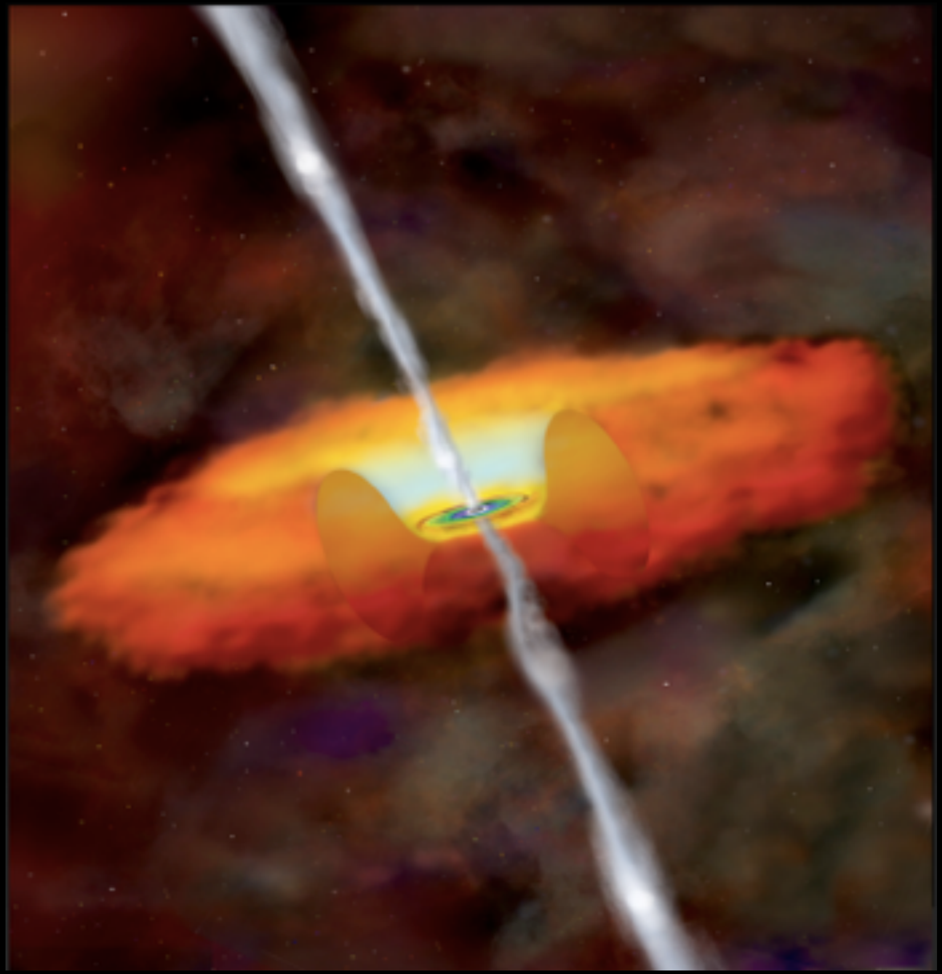
X-ray corona
of X-ray binaries (and AGN)



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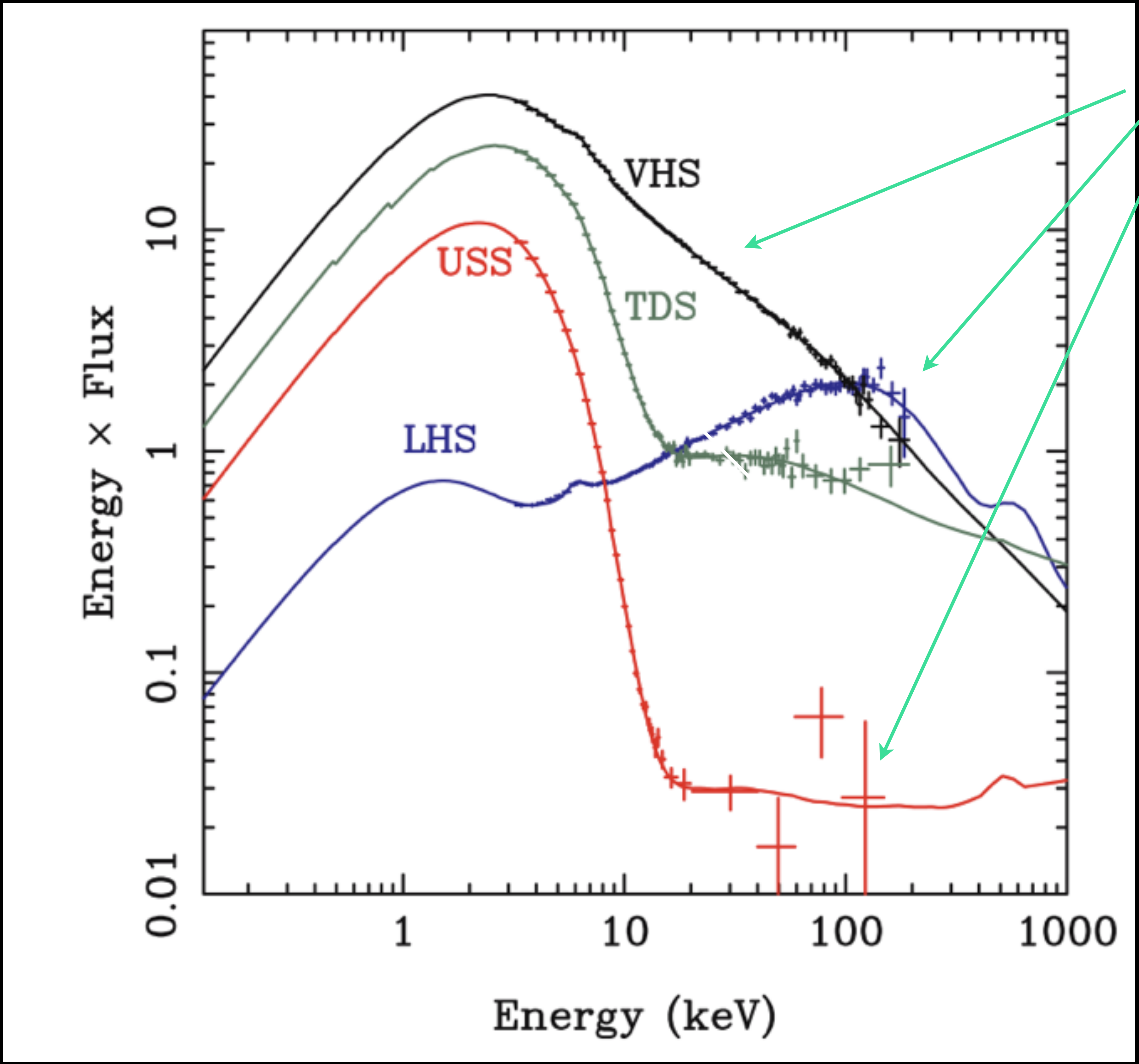
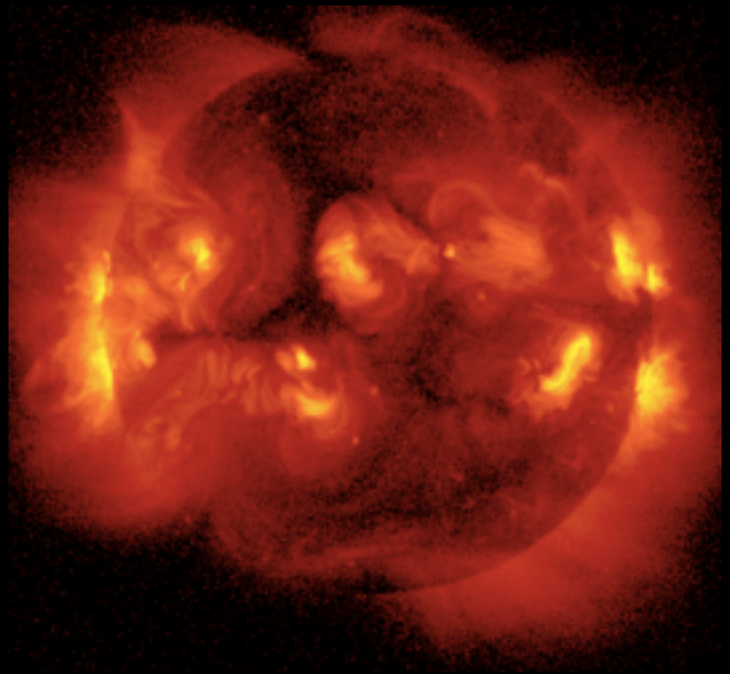
Julien Malzac

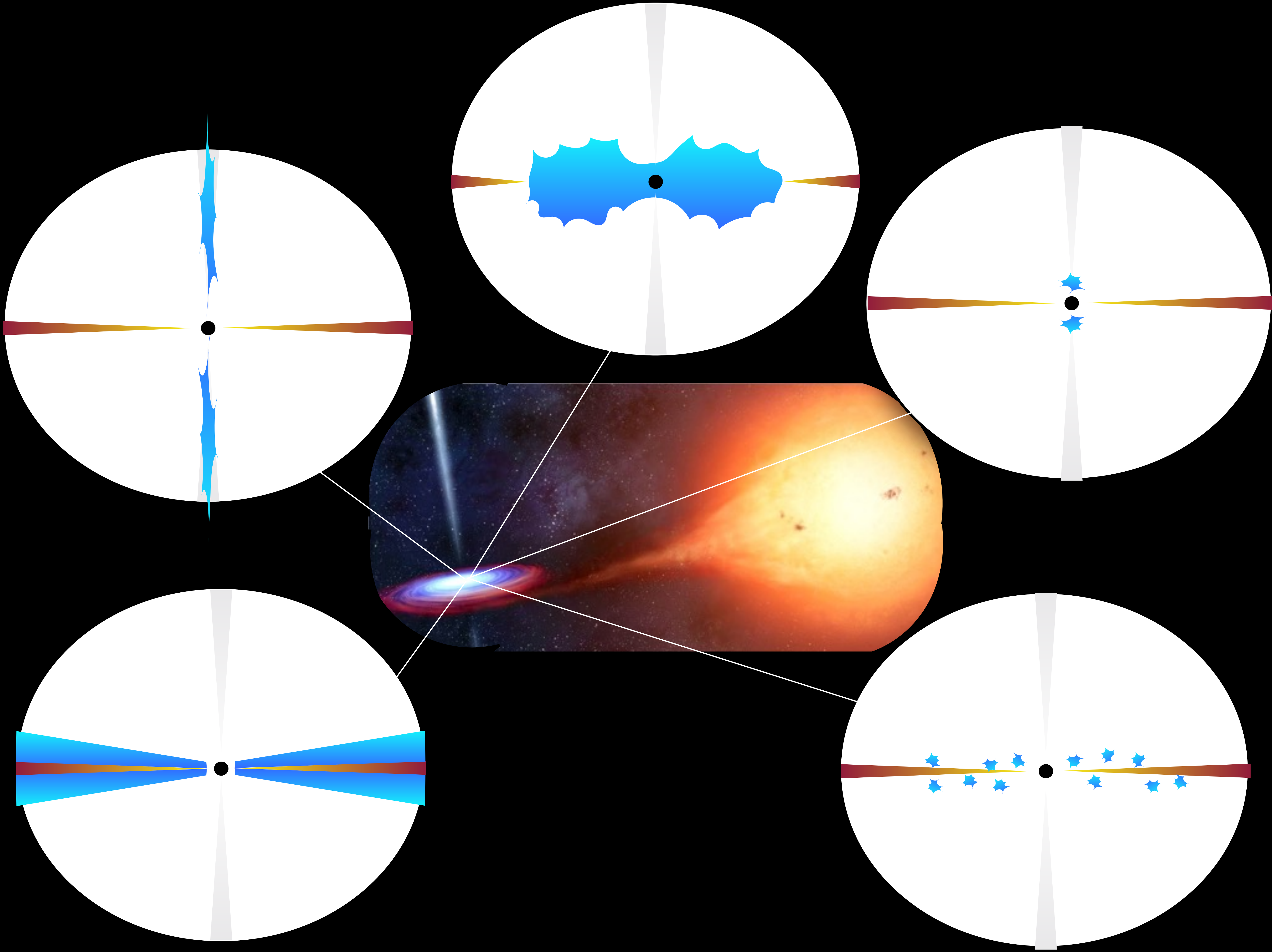
Broad band spectra of BH binaries



Non-thermal emission: 'the corona'



from Done et al. 2007

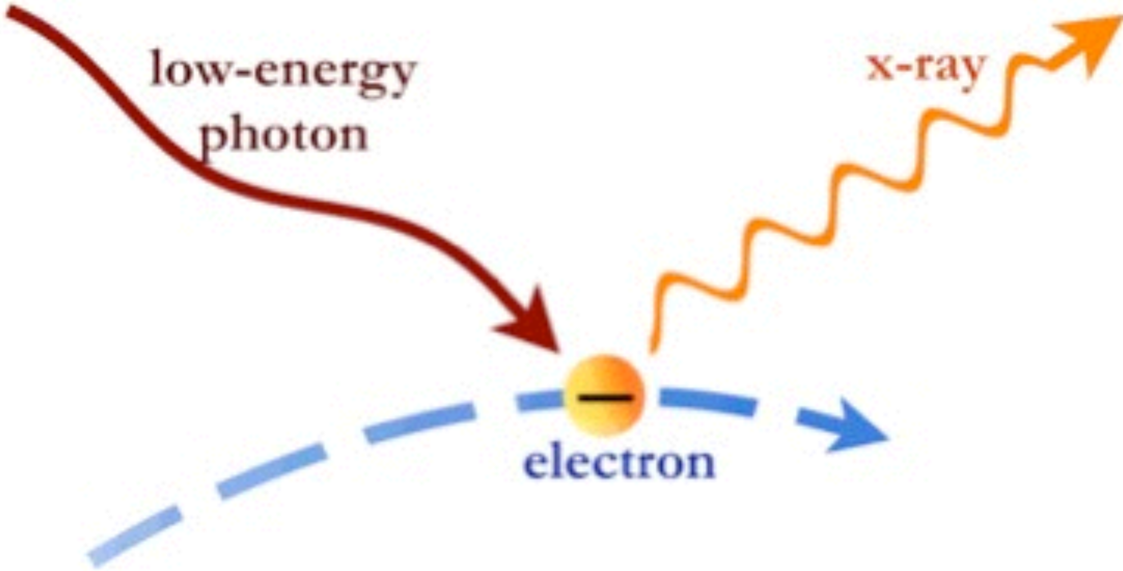


Radiation processes in the corona

- Inverse Compton

➡ X-ray radiation

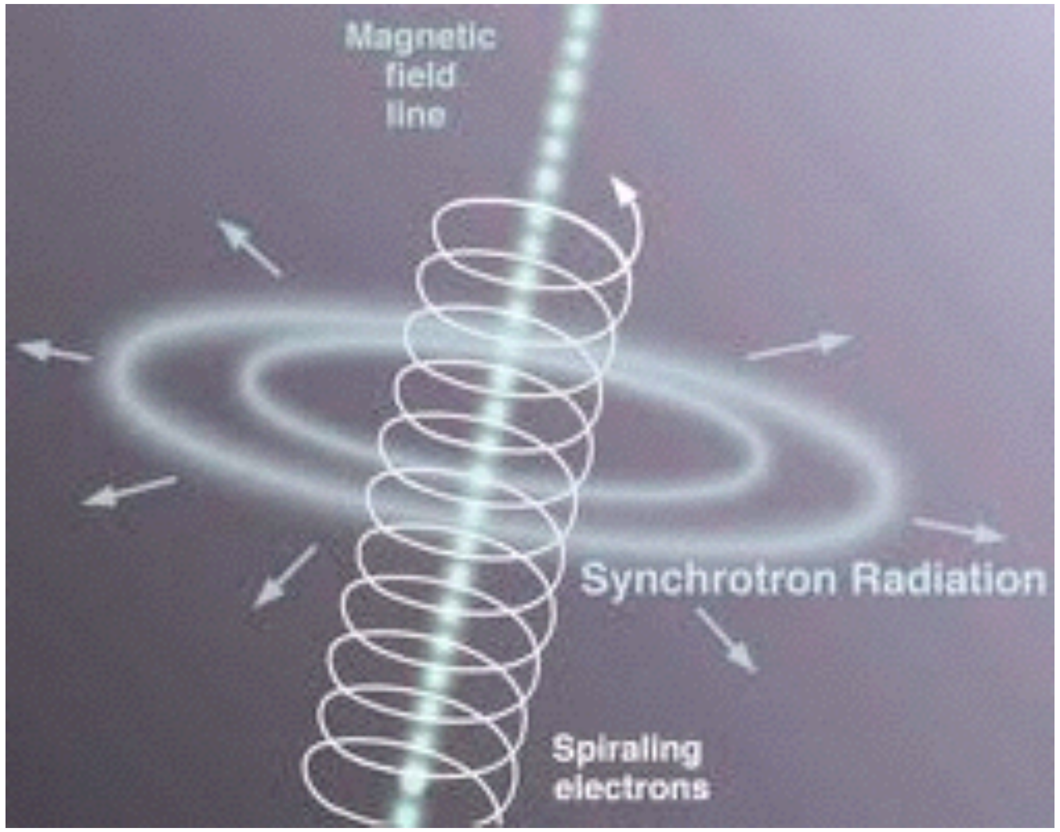
If $\tau_T = n_e \sigma_T R \geq 1$: Comptonisation



- Soft seed photons ?

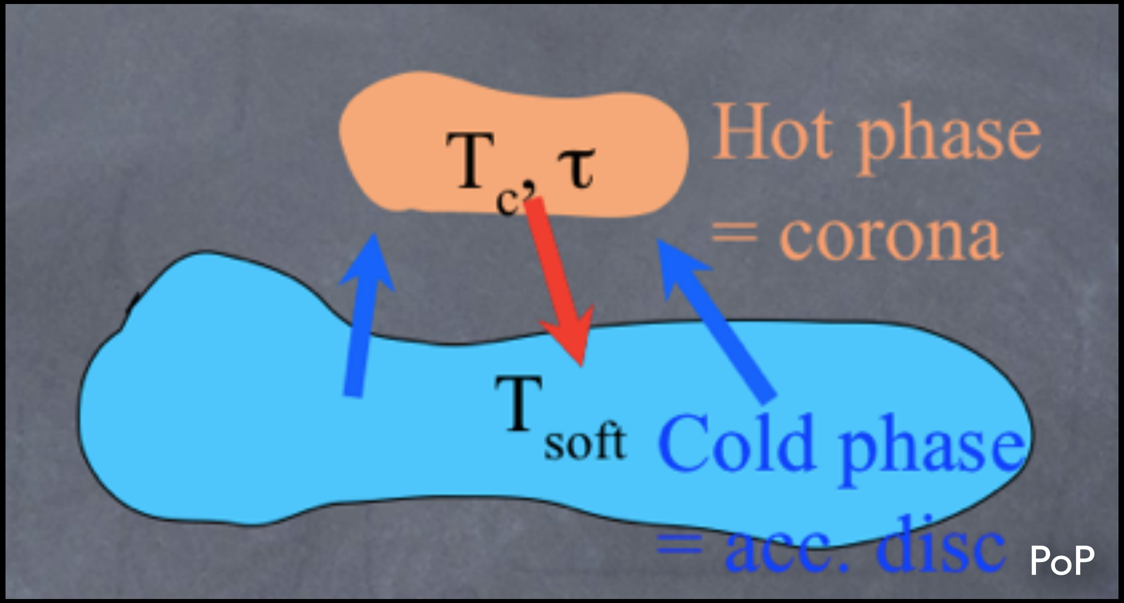
  ✓ blackbody emission from accretion disc

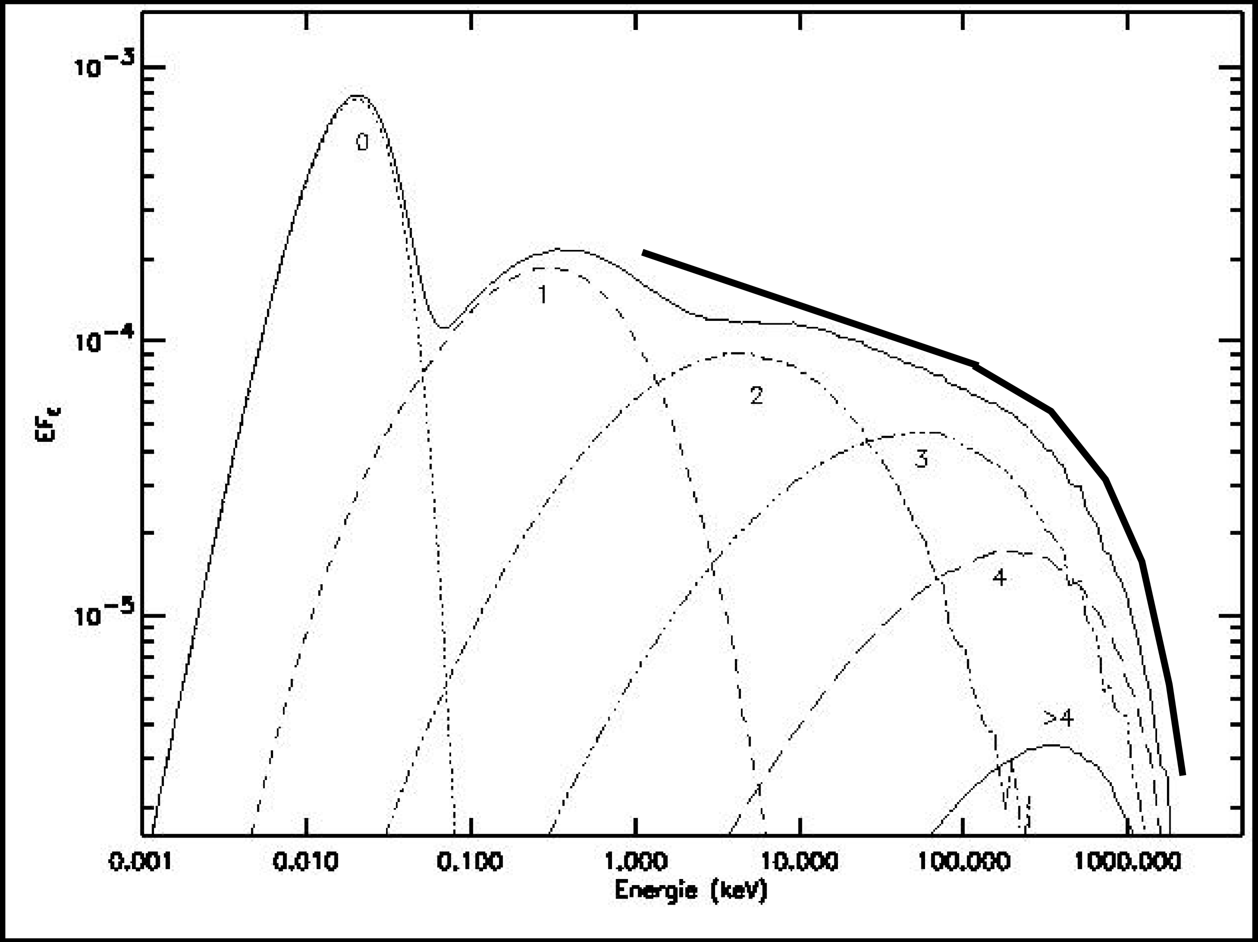
  ✓ synchrotron emission



Thermal Comptonization

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





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

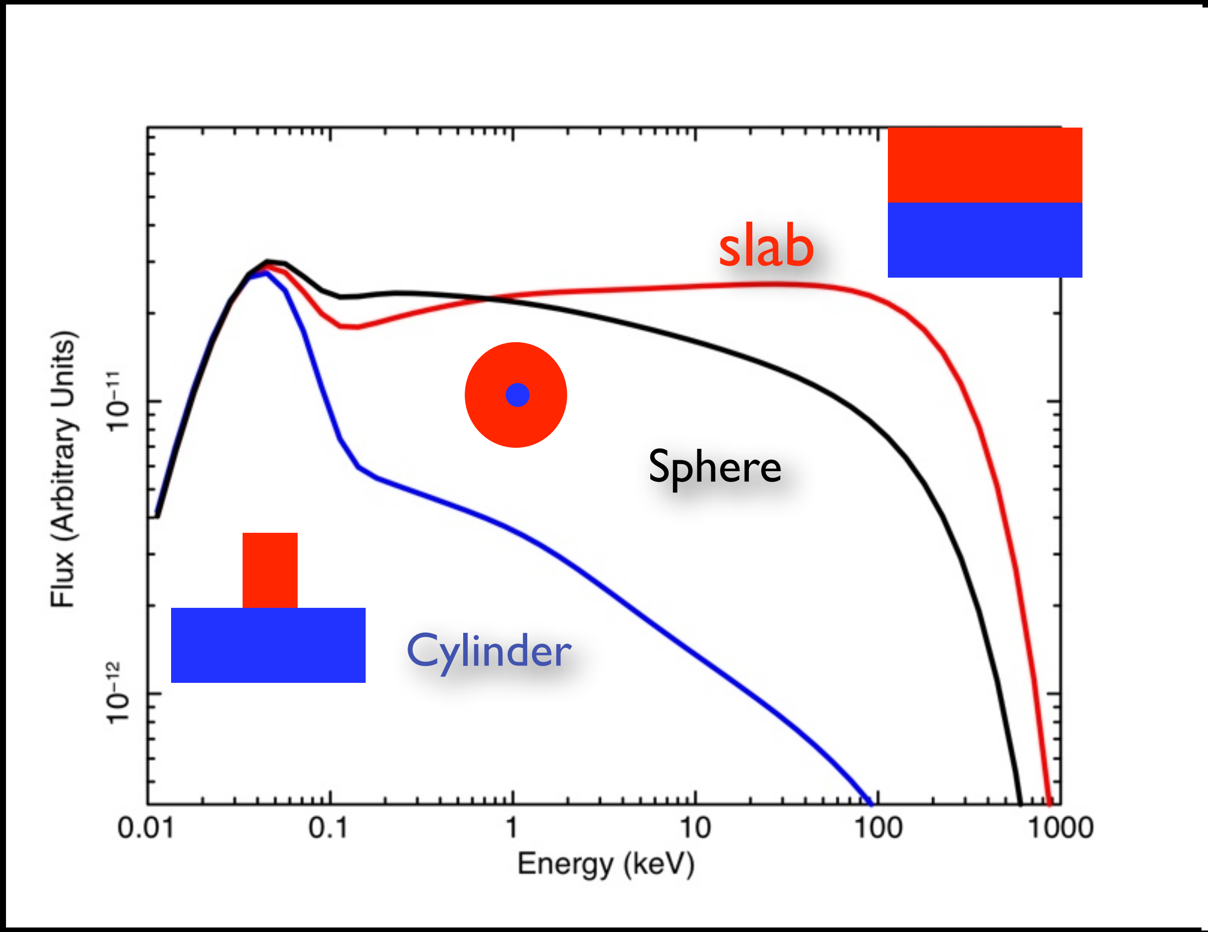
$$E_c \simeq kT$$

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

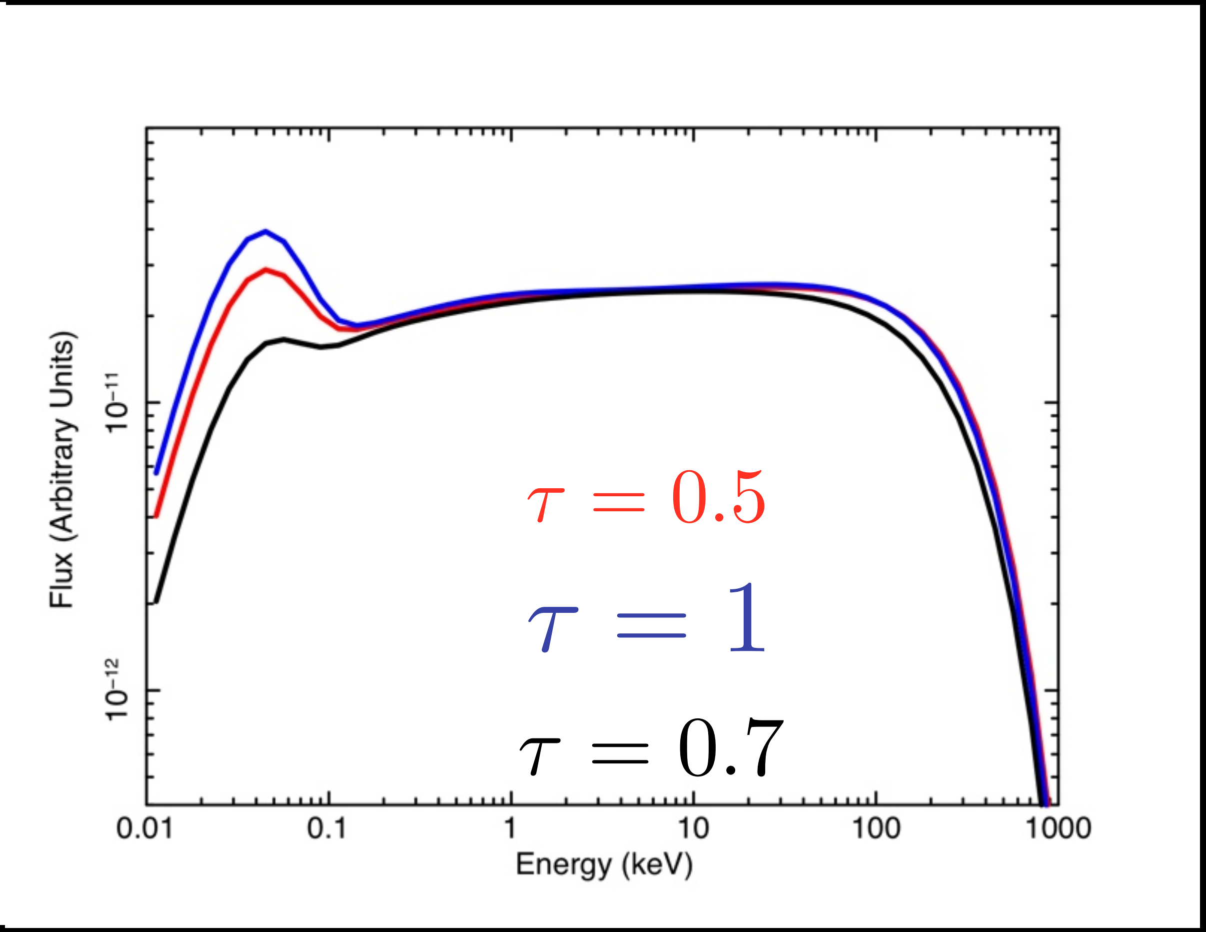
Spectral degeneracy: different T_{e} and τ give same Γ

Geometry dependence

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



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



P.O. Petrucci

Geometric degeneracy

Radiative balance

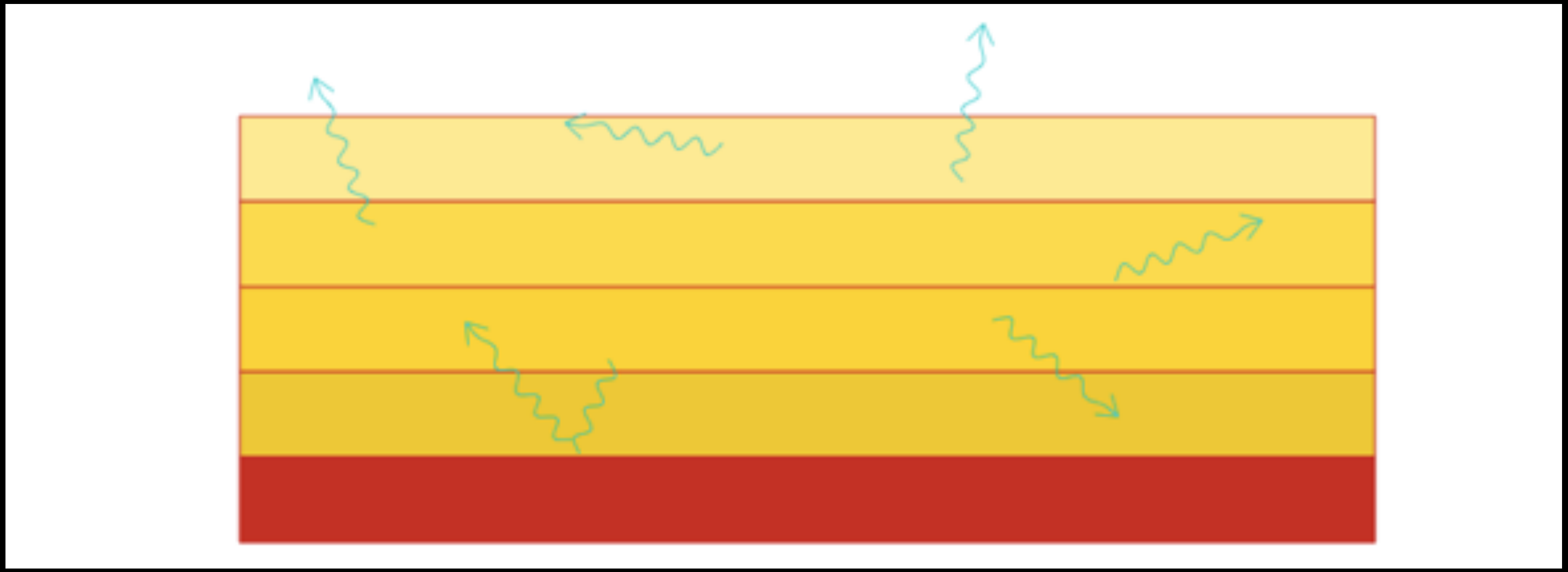
- In soft photon field of bright compact sources electrons radiate away their energy on time scales <R/c. Need continuous reheating/acceleration to keep them energized. (Merloni & Fabian .2000)

- 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 $\propto L_s$

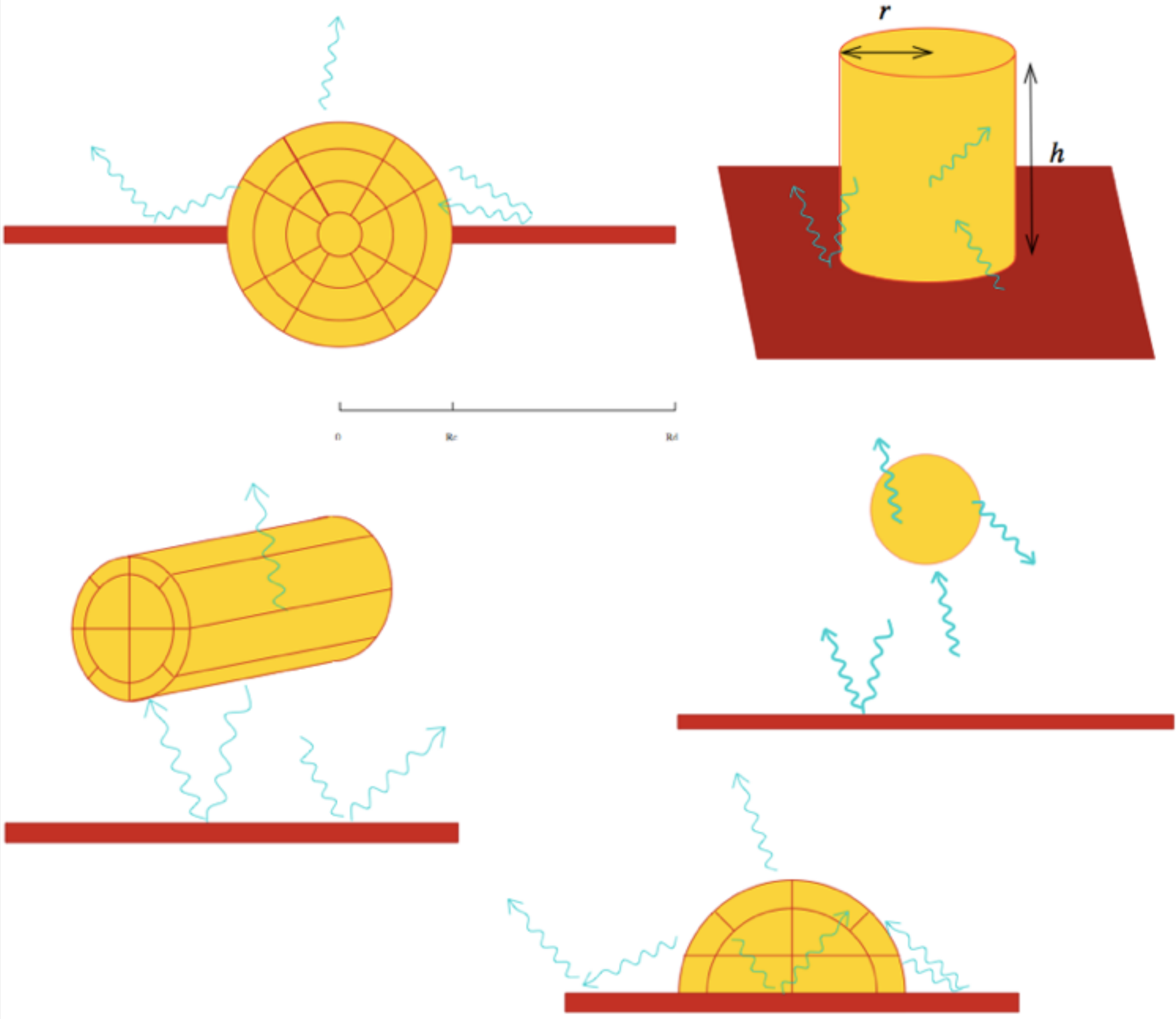
- $\Gamma \propto \left(\frac{L_{heating}}{L_s}\right)^{-\delta}$ (see Belodorov 1999; Malzac et al 2001)

Radiation feedback



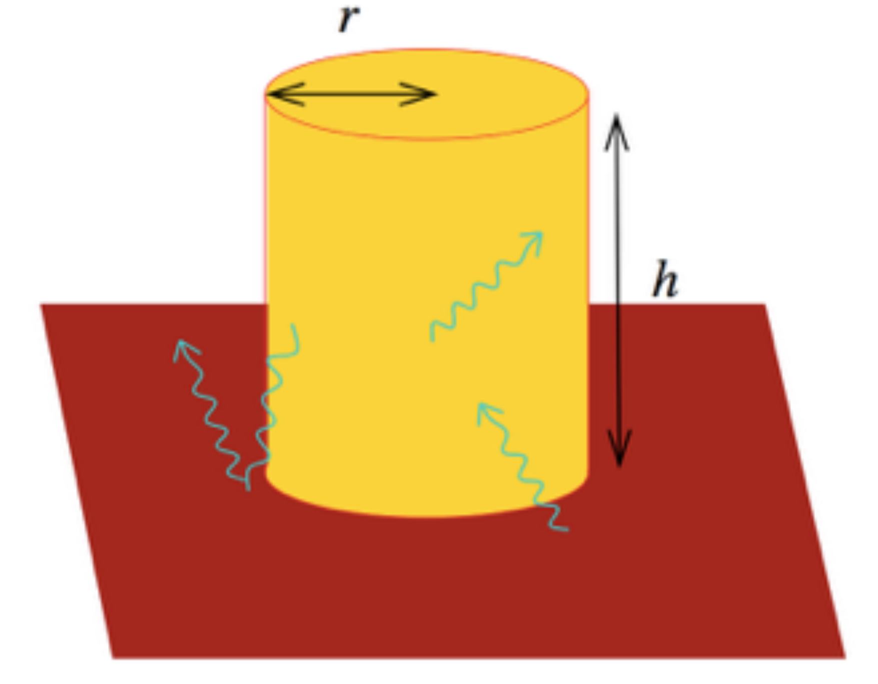
- Cold phase (accretion disc) illuminated by X-ray radiation-> reflection +absorption
- Absorbed radiation heats up the disc. Energy reprocessed and reemitted as low energy (nearly) thermal radiation.
- Depending on geometry a fraction of the reprocessed radiation may illuminate the corona and provide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

(Haardt & Maraschi 1993; Haardt Maraschi Ghisellini 1994)



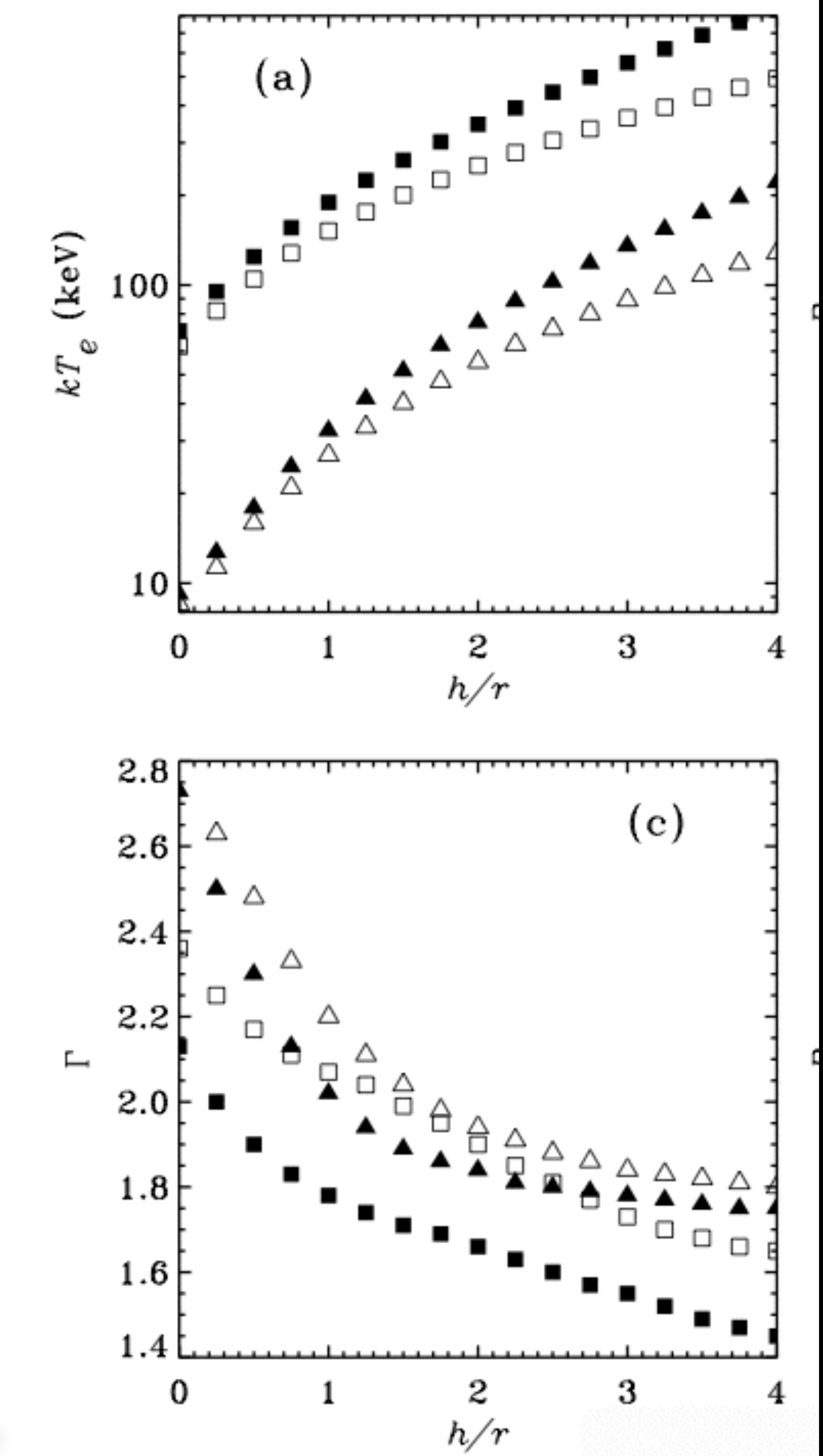
(Stern et al. 1995, Poutanen Svensson & Stern 1996)

Dependence of spectral parameters on geometry



▲ BHB
△ AGN
$\Big\}\ \tau = 3$

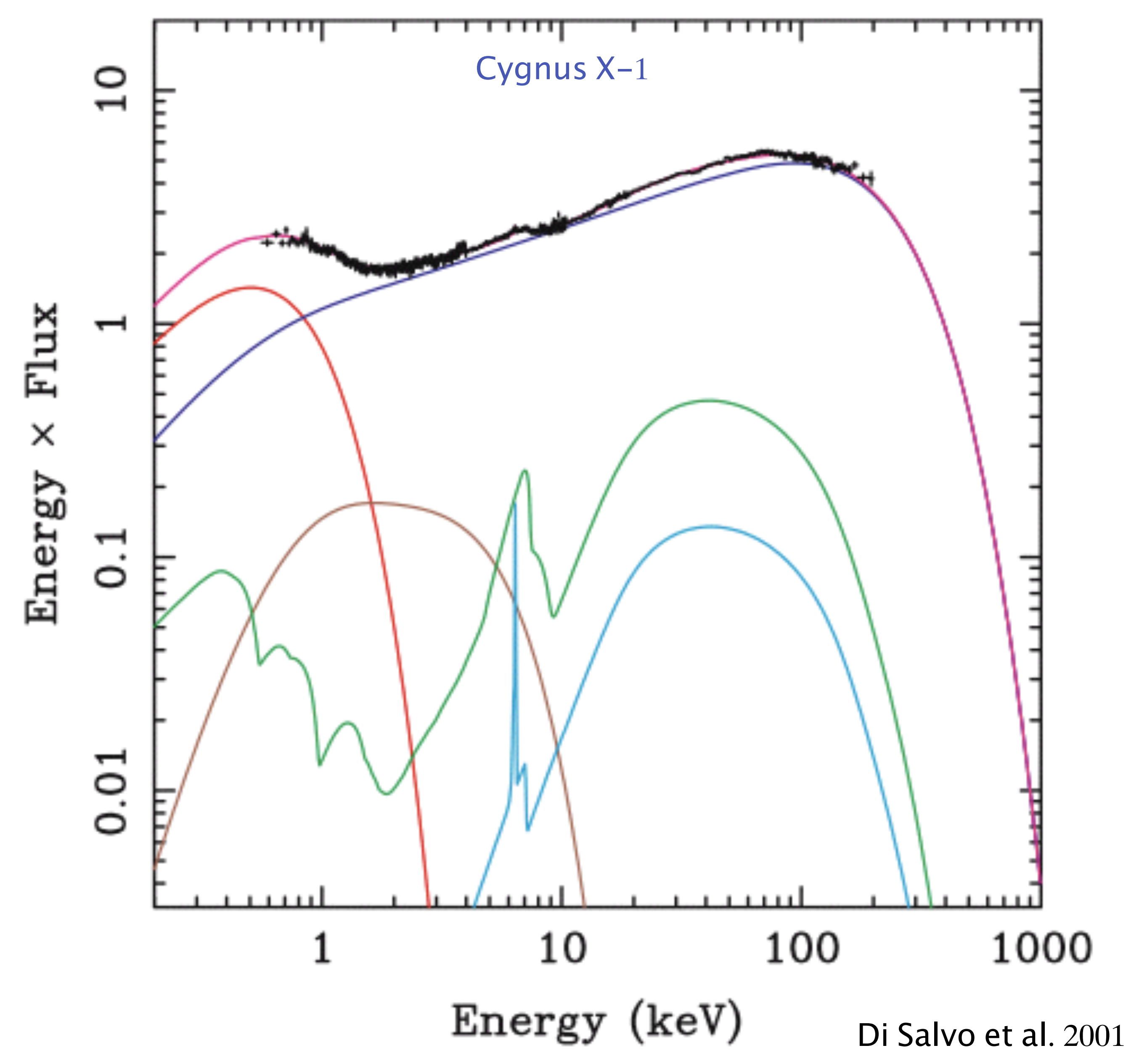
■ BHB
□ AGN
$\Big\}\ \tau = 0.5$



Malzac, Beloborodov, Poutanen 2001

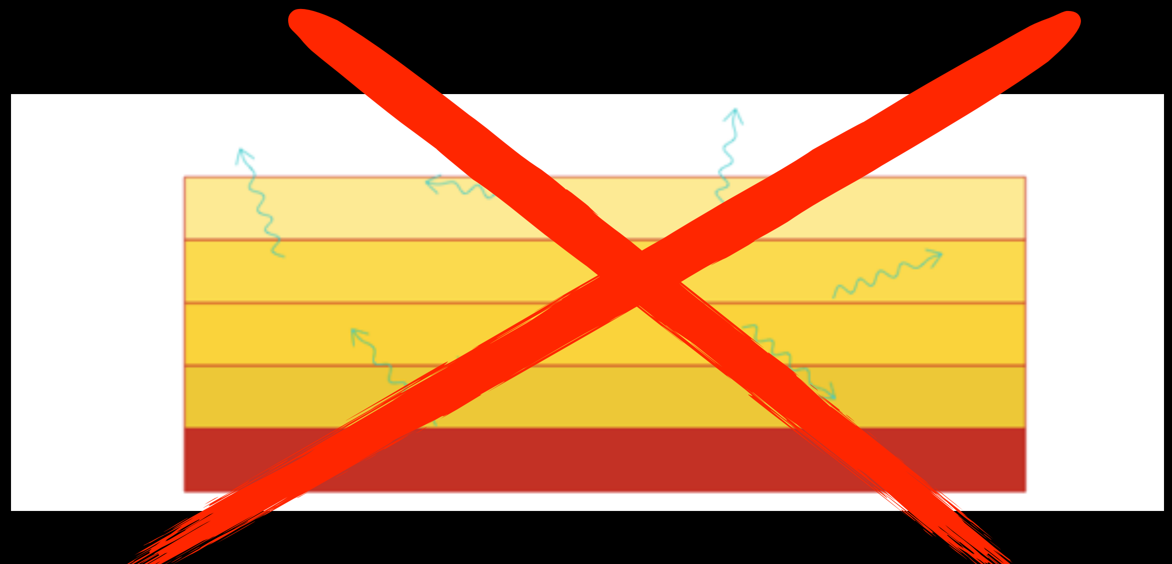
Application to BHBs in hard state

- 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 $\Gamma = 1.4 - 1.9$
- 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

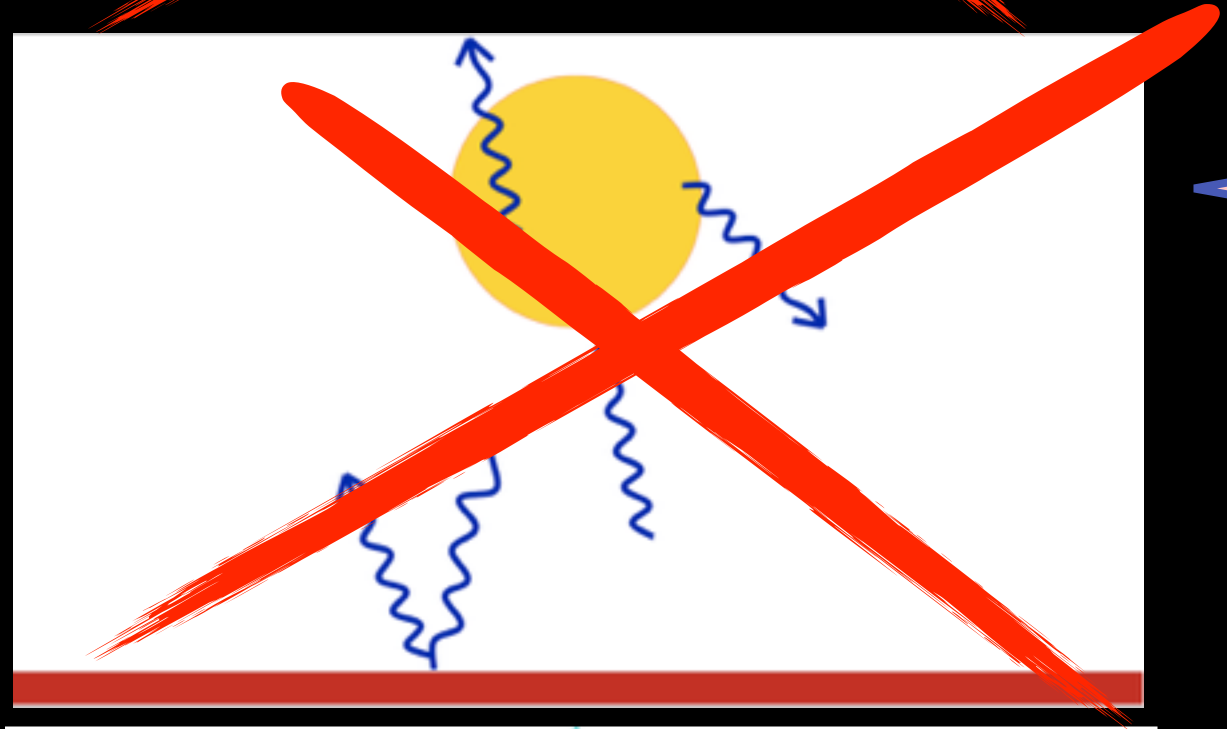


Di Salvo et al. 2001

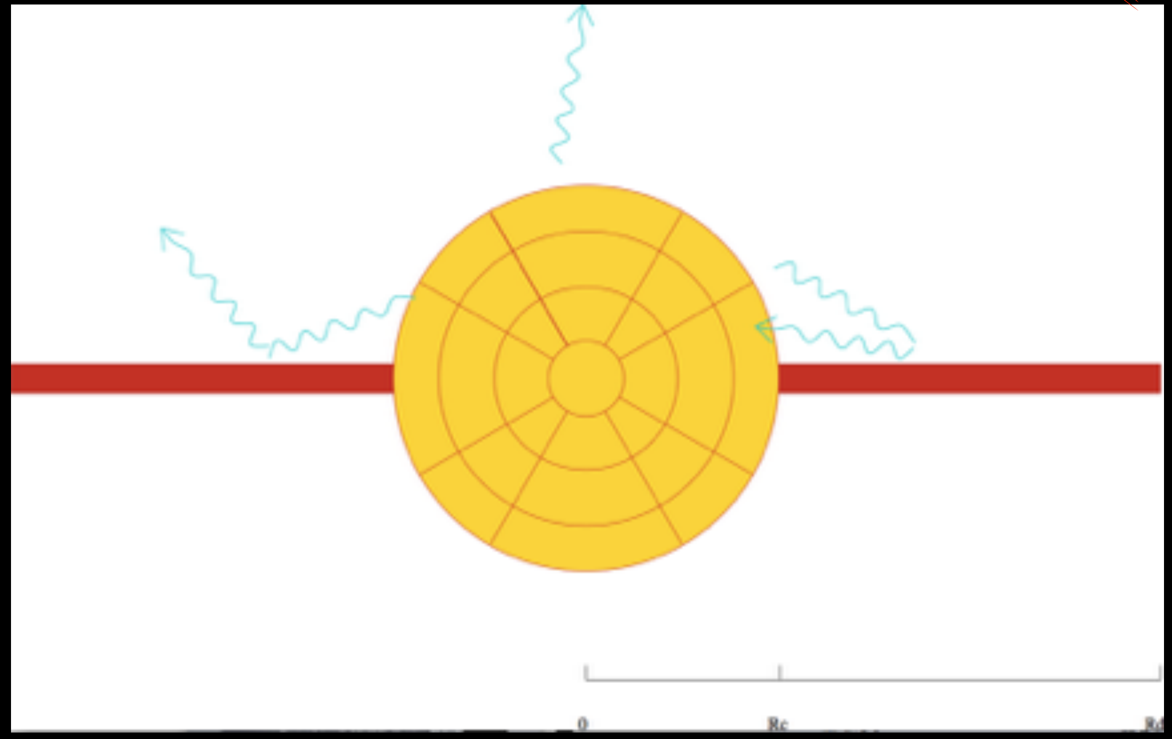
Observed range of slopes and temperatures imply a `photon starved' geometry



- Te too small
- Γ too large



- Te and Γ ok
- but R~1 expected



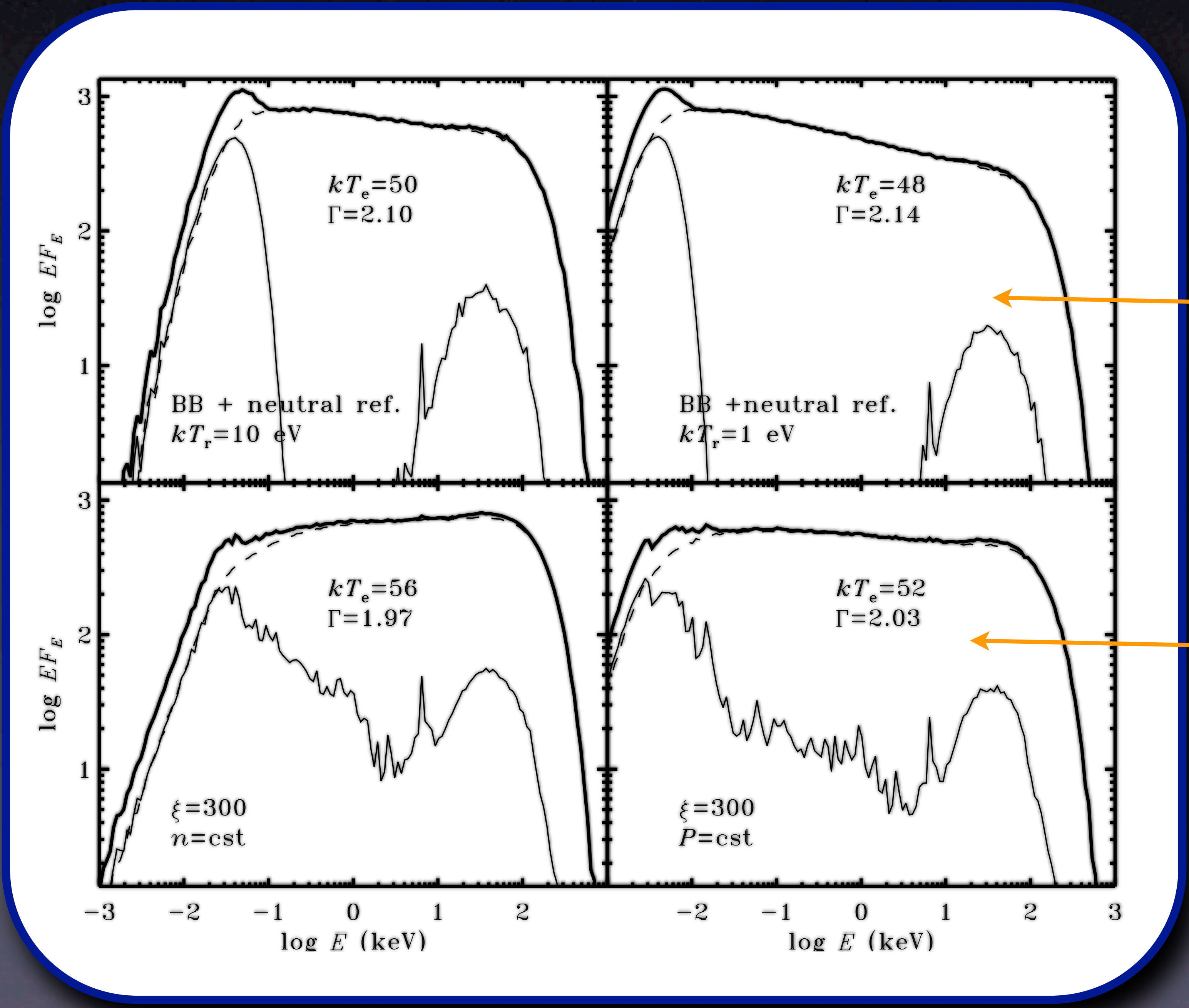
- Te and Γ
- R~0.3 expected

What if the accretion disc is ionised ?

- All calculations of coupled corona+disc
  assumed NEUTRAL reflection of the accretion disc

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

- Is it enough to relax constraints on geometry ? NO



slab corona

neutral reflection

ionised reflection

Malzac, Dumont & Mouchet 2005,
see also
Poutanen, Veledina & Zdziarski 2018
for recent calculations

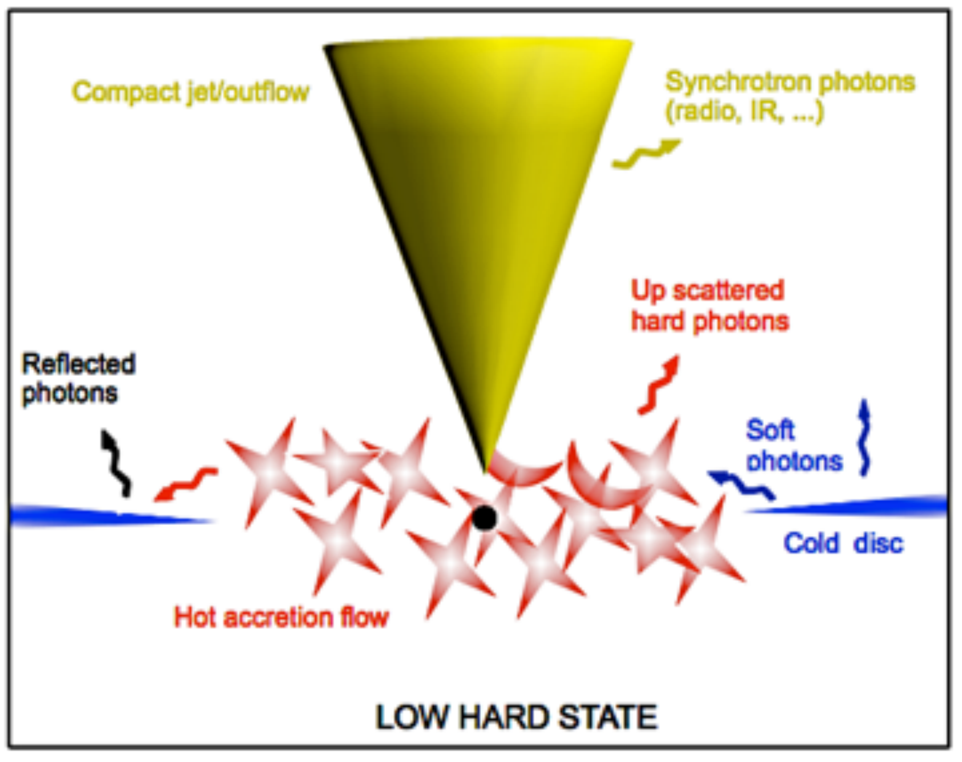
Truncated disc model

HARD STATE

- Cold disc truncated at ~ 100-1000 Rg
  + hot inner accretion flow
- Corona=hot accretion flow

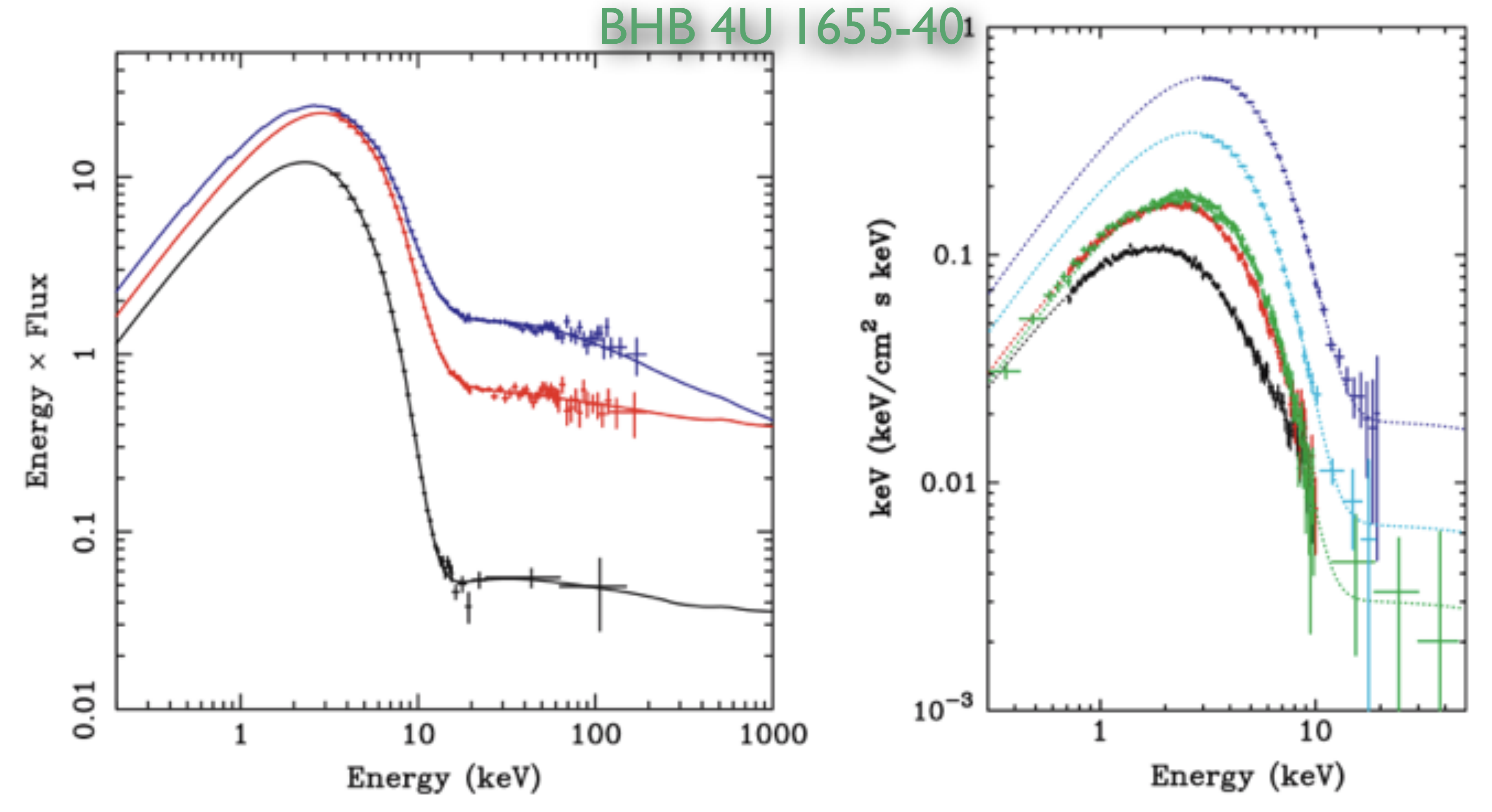
  (ADAF, CDAF, RIAF, JED,….

  Esin et al. 1997, Poutanen et al. 1997, Yuan & Zdziarski 2004, Petrucci et al. 2010., Meyer-Hofmeister et al. 2018)



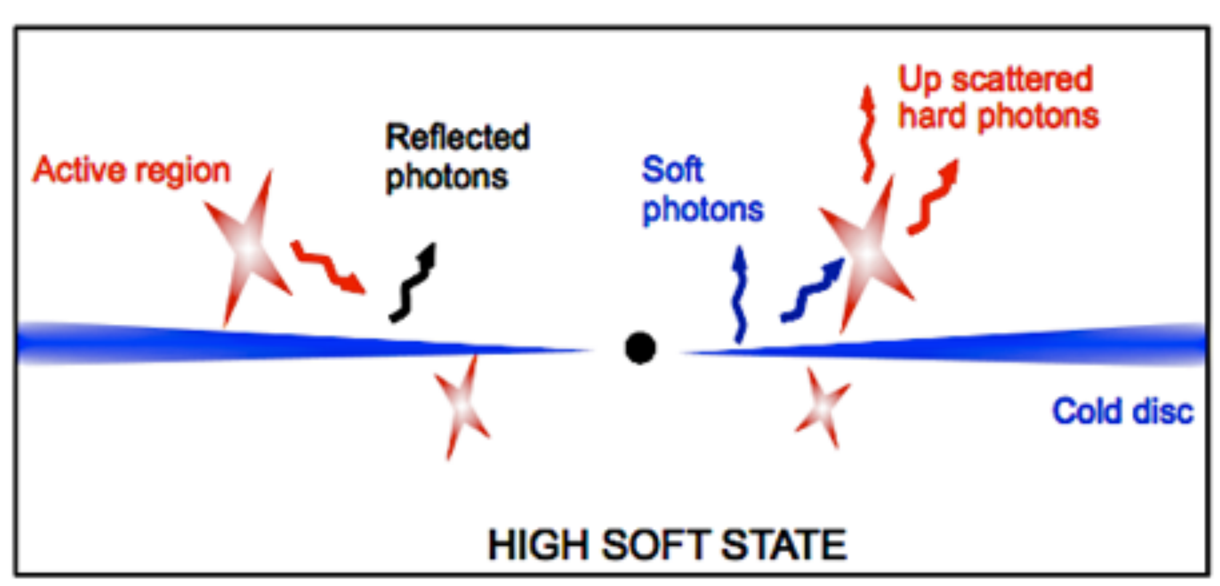
- Variations of truncation radius also explain qualitatively:
  - spectral evolution with luminosity in hard state in XRBs and AGN (Gamma vs luminosity)
  - hardness intensity diagram evolution of XRBs (and AGN ?)
  - rms-flux correlation, hard lags (propagation of fluctuations)
  - reflection lags
  - evolution of QPO frequencies (LT precession of hot flow)…

Soft state of Black Hole binaries

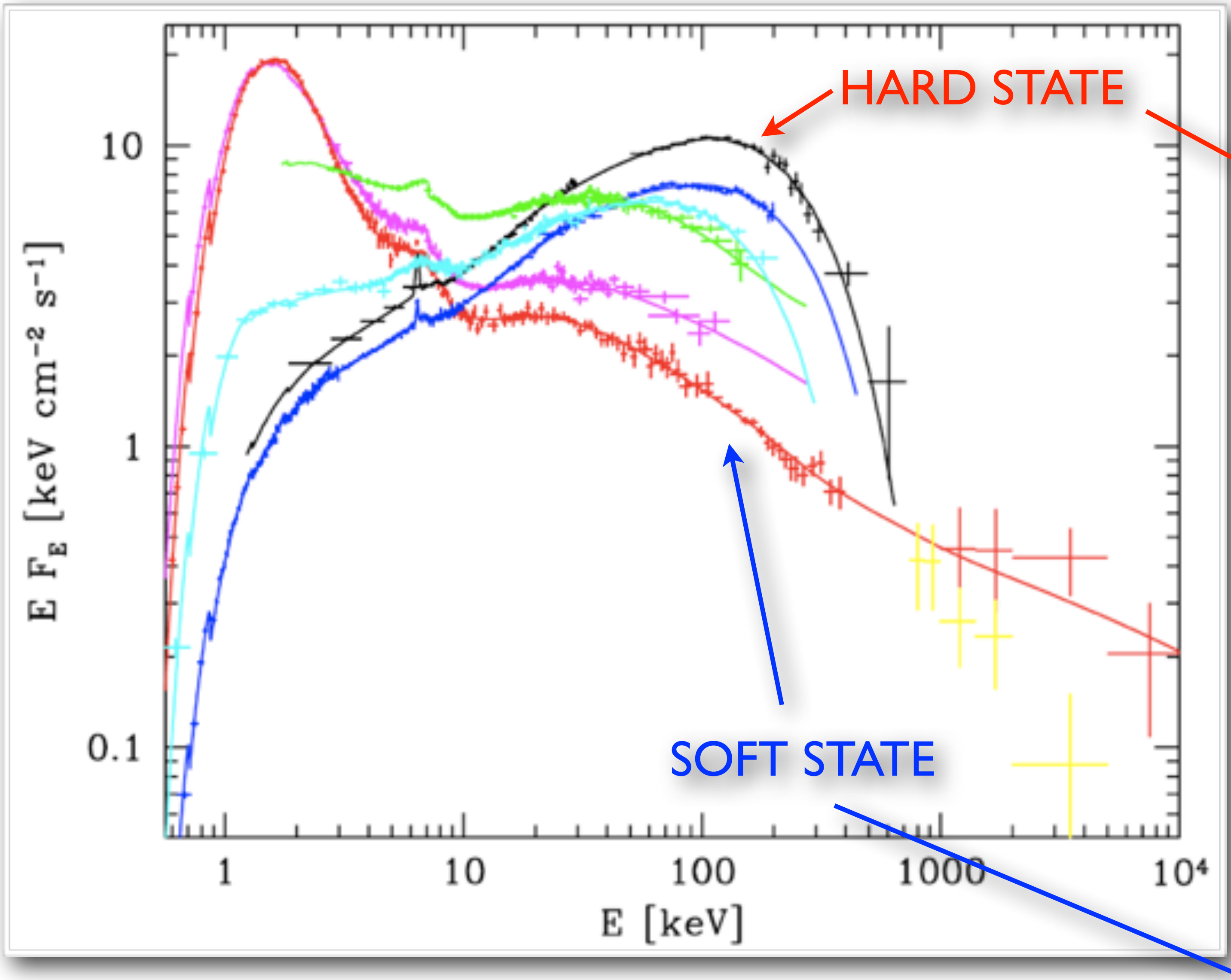

BHB 4U 1655-40

Observed in a narrow range of luminosities (~0.01 -0.1 L_{Edd})

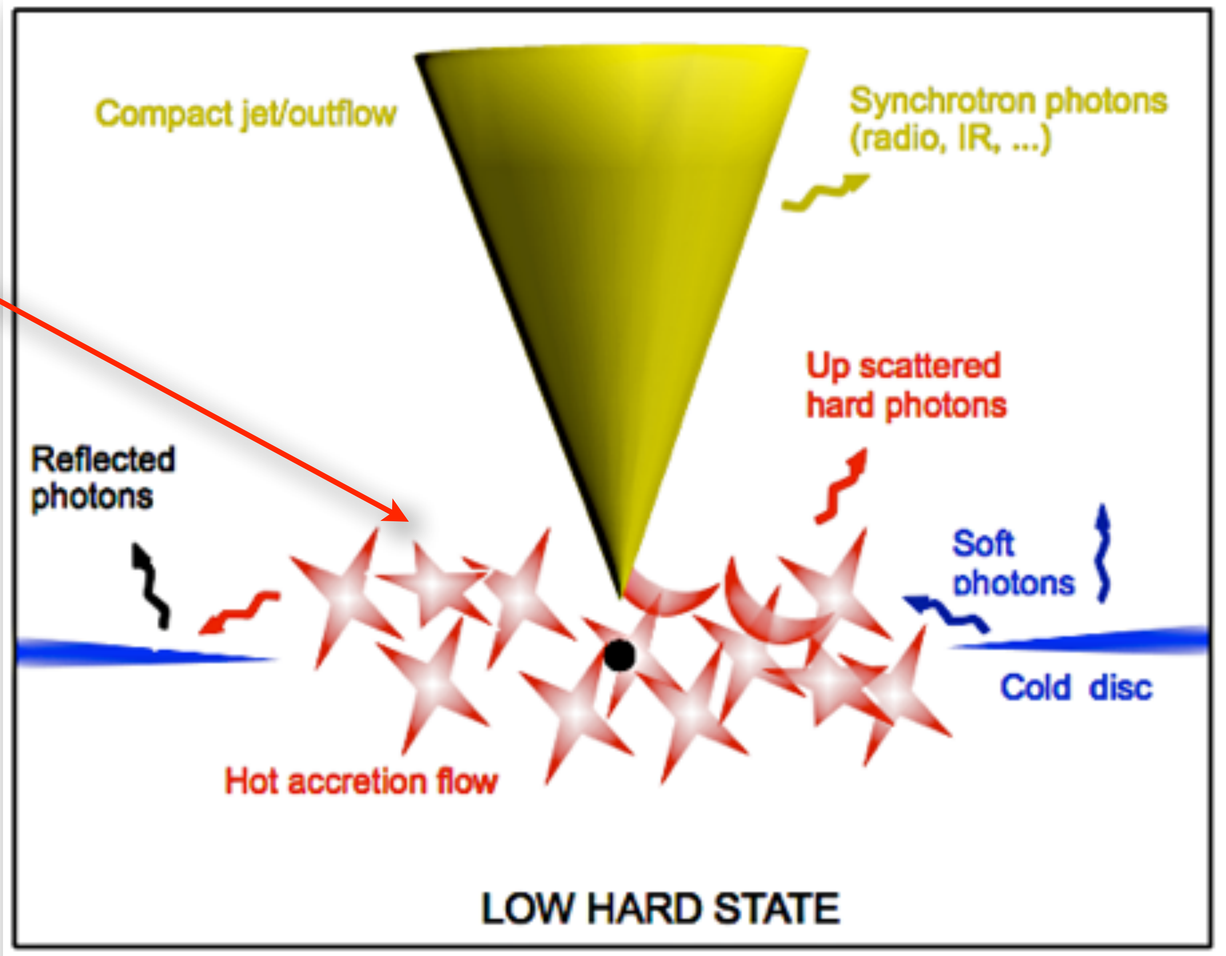
X-ray spectrum dominated by soft thermal emission: perfect for tests of accretion disc models and measurements of parameter of the inner accretion disc

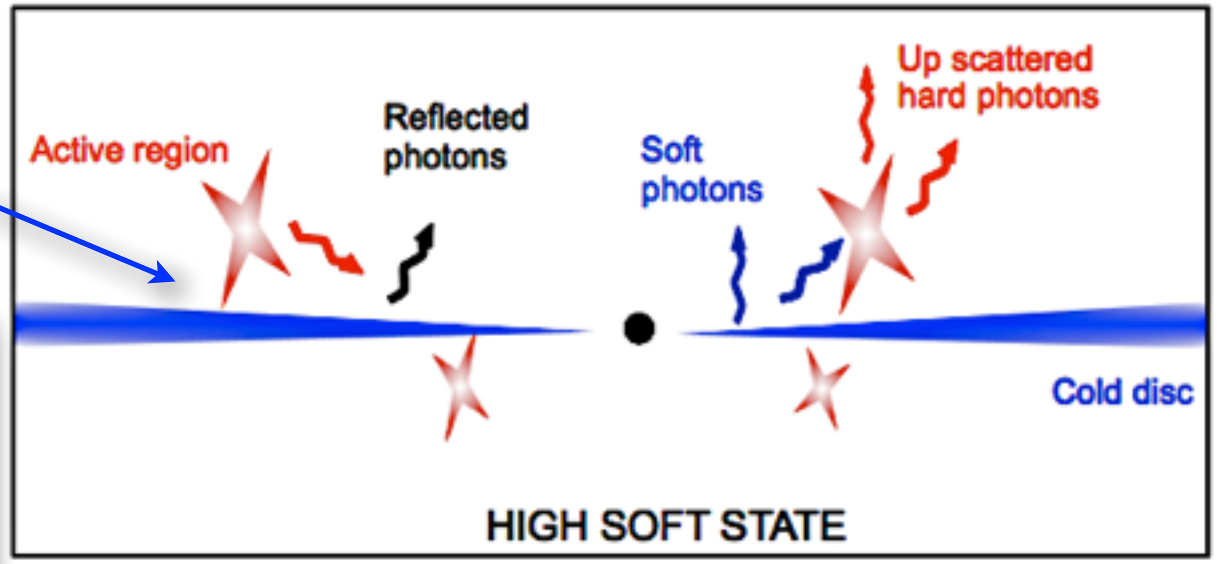


Emission from the accretion flow



Zdziarski et al 2003

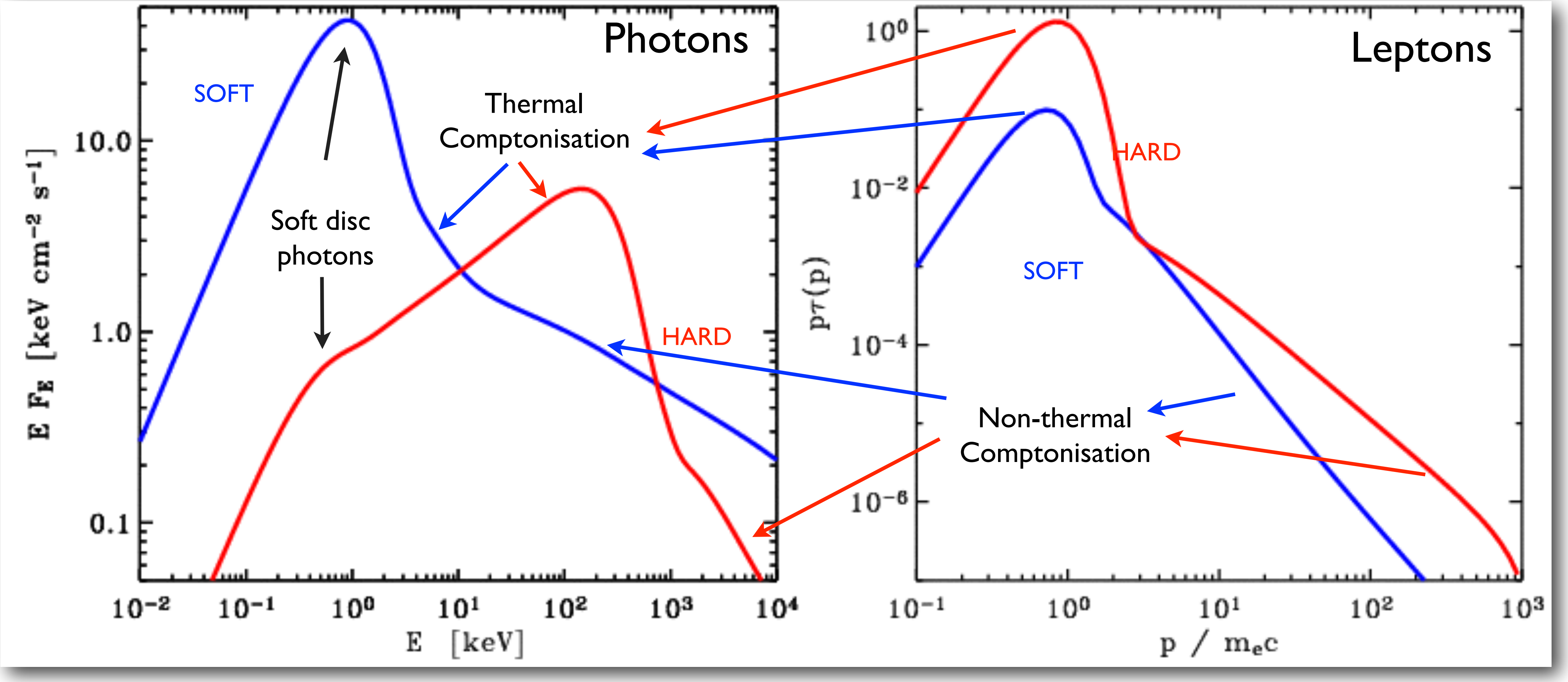




HARD STATE: (compact radio jet)
disc blackbody: weak / Corona: THERMAL electrons

SOFT STATE:
disc blackbody: strong / Corona: NON-THERMAL electrons

Hybrid thermal/non-thermal comptonization models



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

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

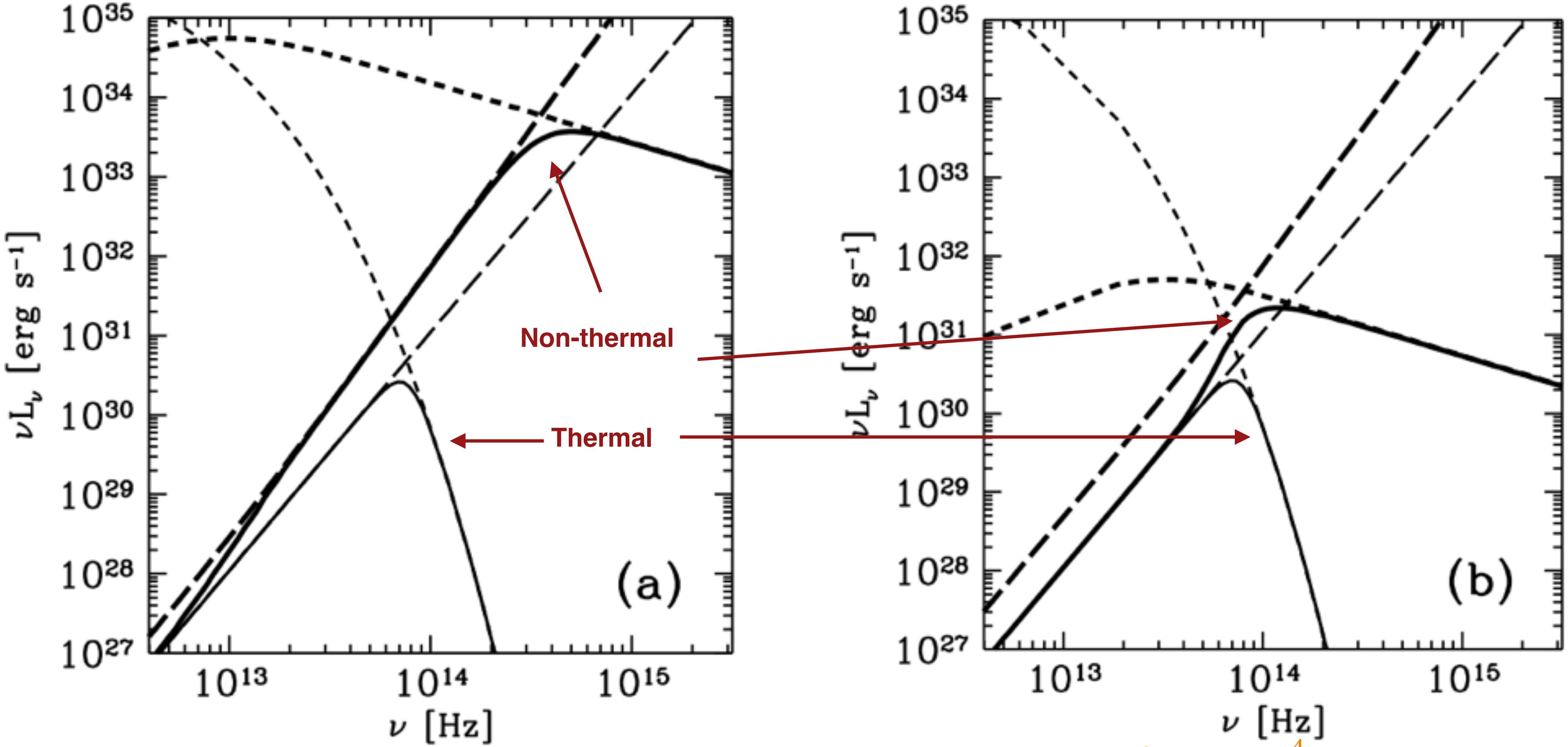
SOFT STATE: kT~10-50 keV, τ_T~0.1-0.3: Inverse Compton by non-thermal electrons dominates

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

- EQPAIR

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

Effect of magnetic field

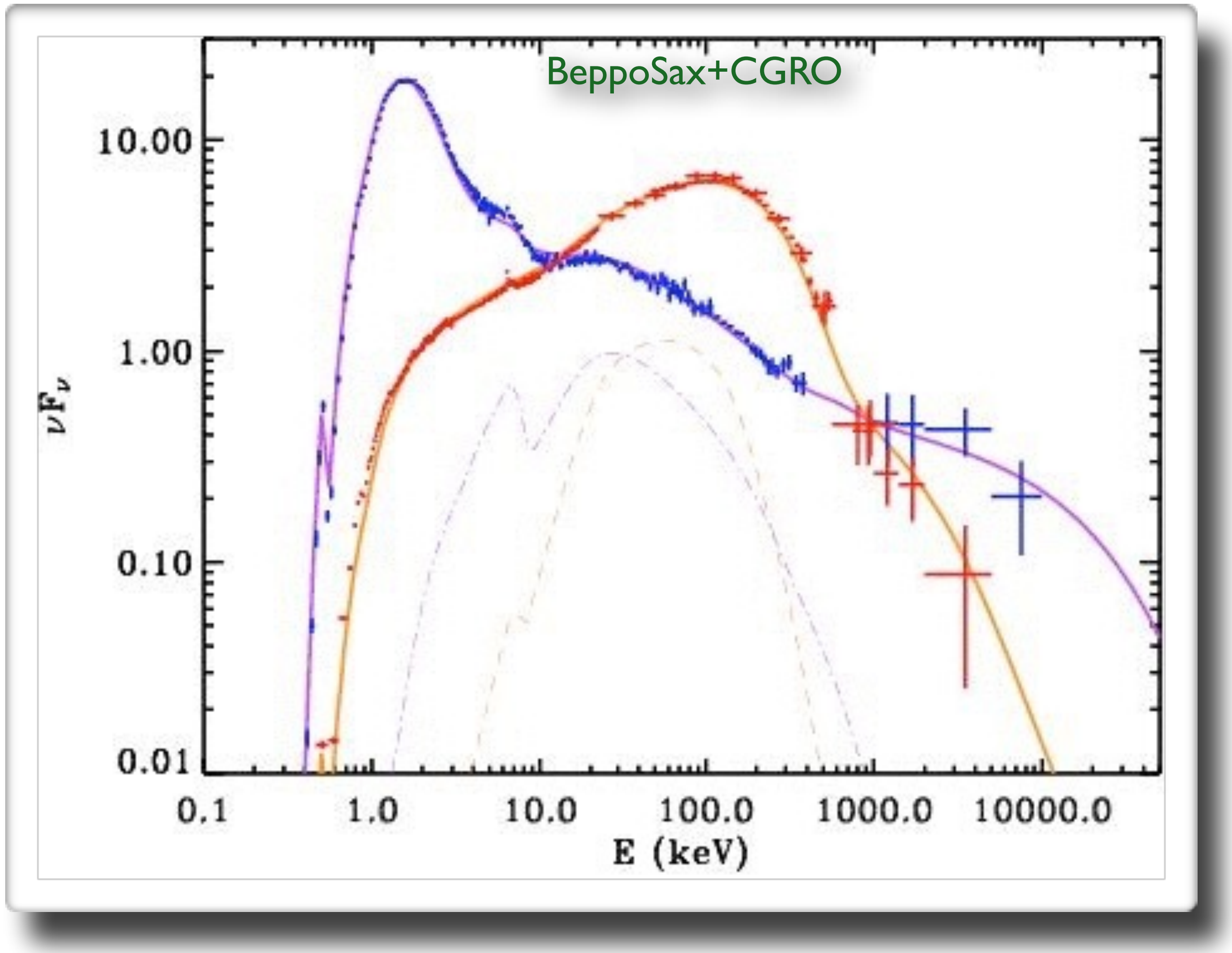


$\delta = 0.19$ $\delta = 10^{-4}$

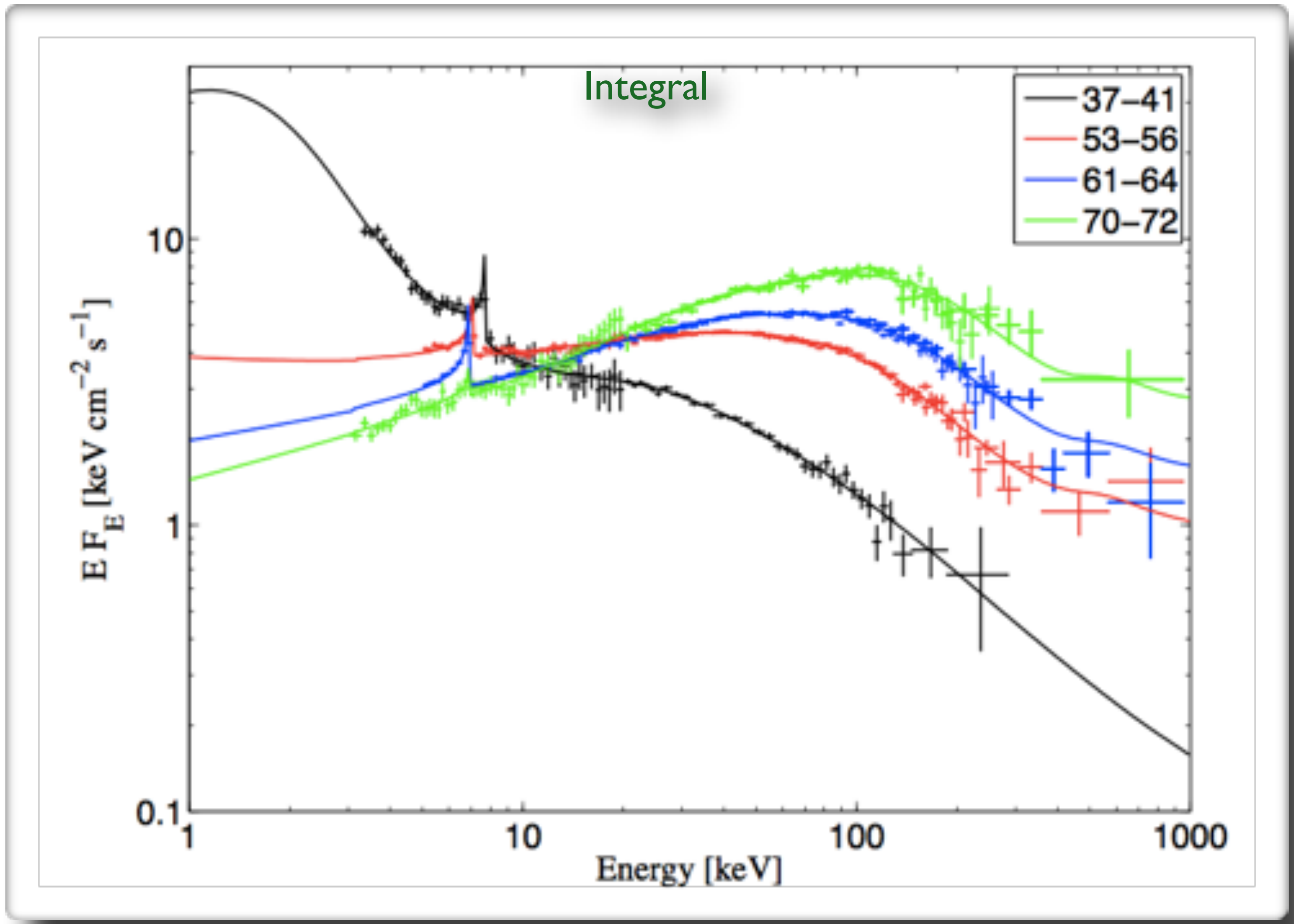
- Cooling: Optical synchrotron flux considerably increased by non-thermal particles Wardzinski & Zdziarski 2002
- Thermalization of electrons: the synchrotron boiler effect

(Ghisellini,Gilbert & Svensson 1988; Belmont, Malzac & Marcowith 2008; Vurm & Poutanen 2009)

Hybrid comptonization with magnetic field



Malzac & Belmont 2009; Poutanen & Vurm 2009



Droulans et al. 2010; Del Santo et al. 2013

- All spectral states consistent with pure non-thermal acceleration models,
- Hard state compatible with pure synchrotron Comptonization
- Spectral transitions: thermal disc photons cool down the corona in softer states
- Spectral fits with BELM: first constraints (upper limits) on coronal magnetic field B and ions temperature T_{ions} in all spectral states

➡ weak (i.e strongly sub-equipartition) magnetic field in hard state

Can hot accretion flows explain the bright hard state sources?

- Brighest hard sources reach $0.3L_{\rm Ed}$ with, with $\Gamma < 1.7$ $kT_e \simeq 30$ $\rm keV$, which implies $\tau_{\rm T} \geq 1$
- 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 hot flow solutions cannot be applied

- A possible fix: magnetically dominated accretion flow

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

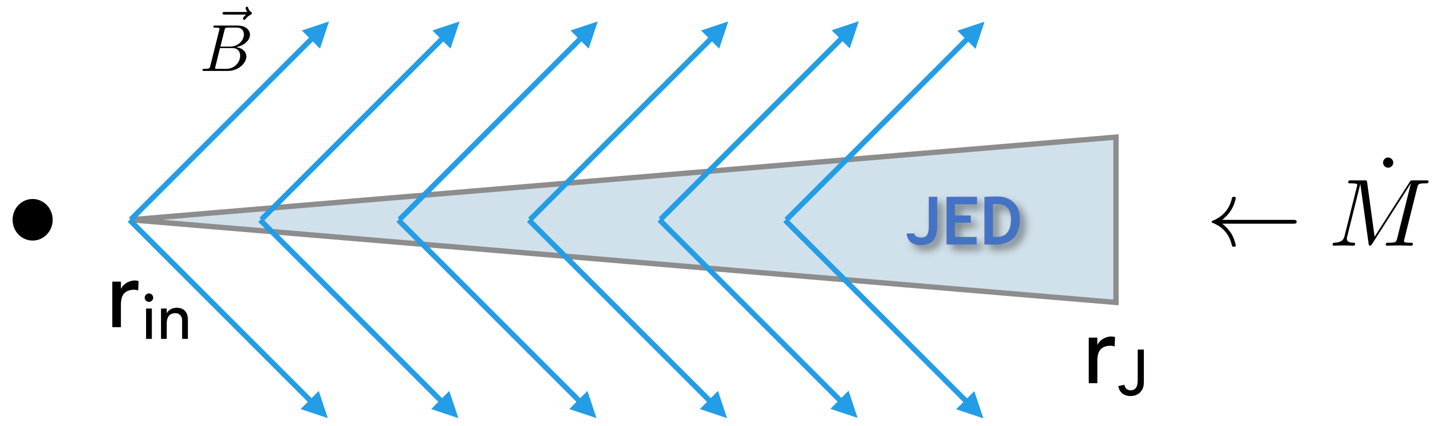
  2) Modified viscosity law: $Q_{\rm vis} = -\alpha (P_{\rm gas} + P_{\rm mag}) R \frac{d\Omega}{dr}$

➡ 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)

Jet Emitting Disk

Ferreira et al. 2006
Petrucci et al. 2008

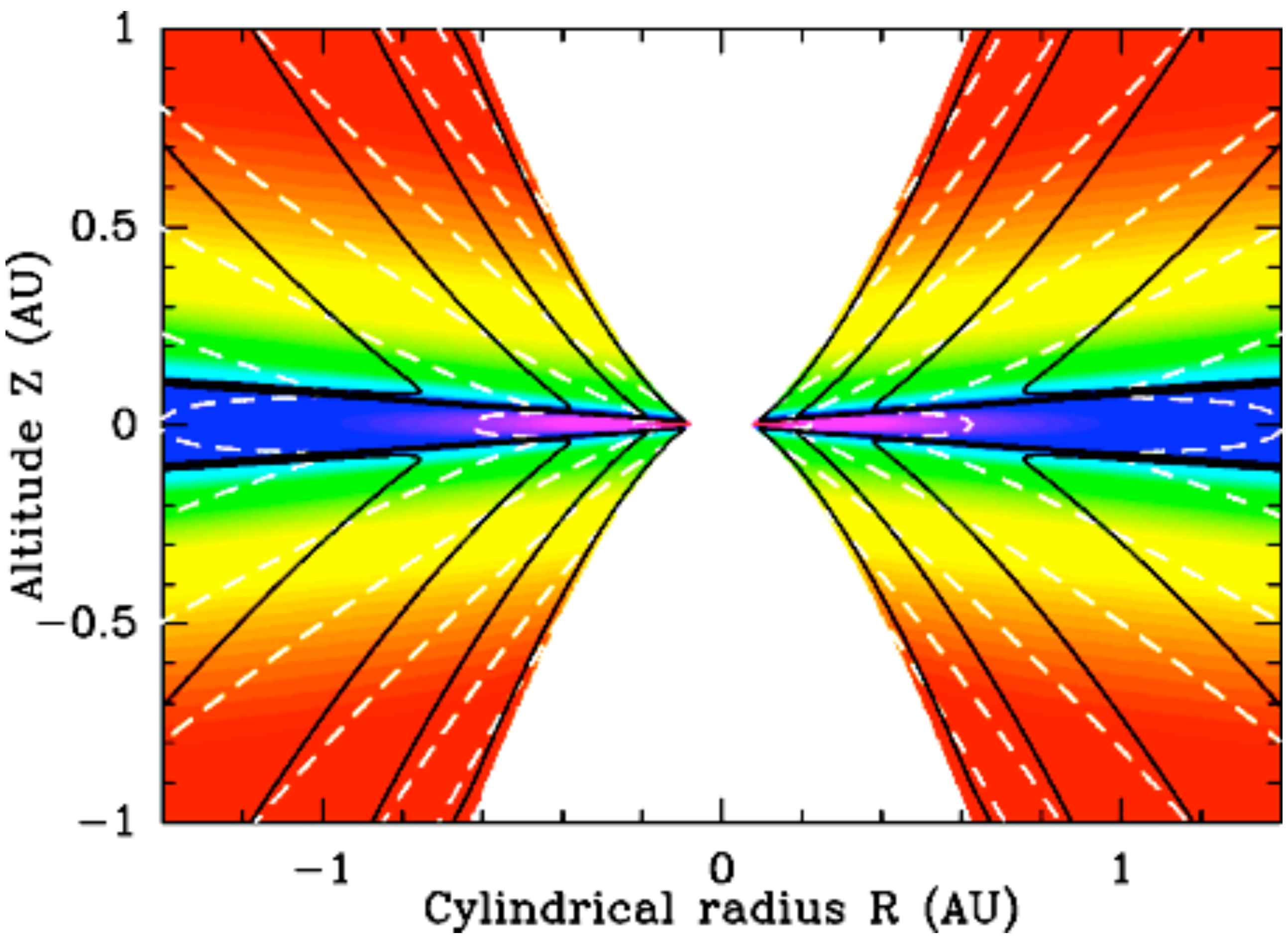


Jet Emitting Disk:

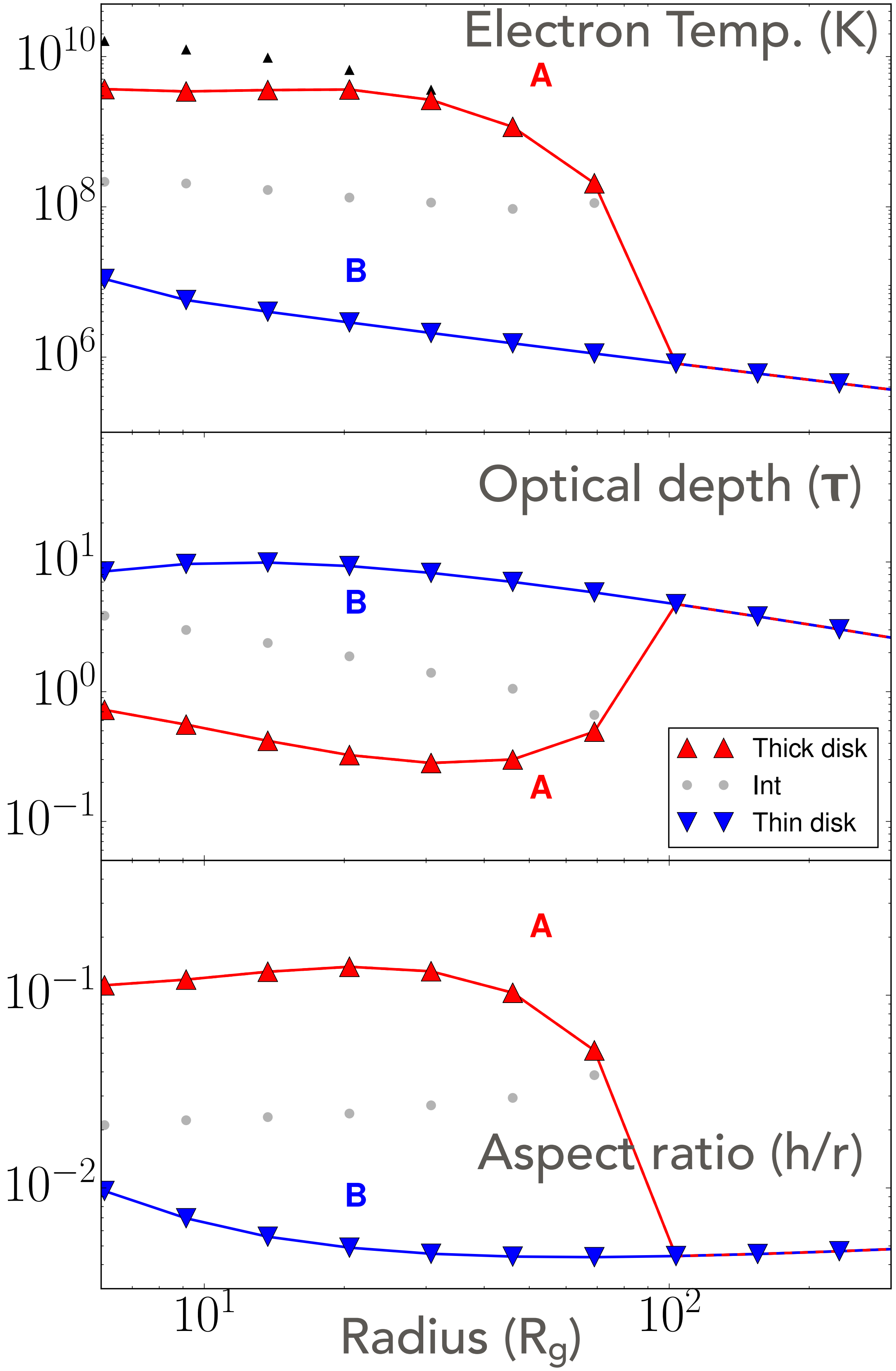
- Accretion due to magnetic torque,
- $P_{jets} = b\, P_{acc}$,
- $v_r \geq c_s$ —> Supersonic accretion flow

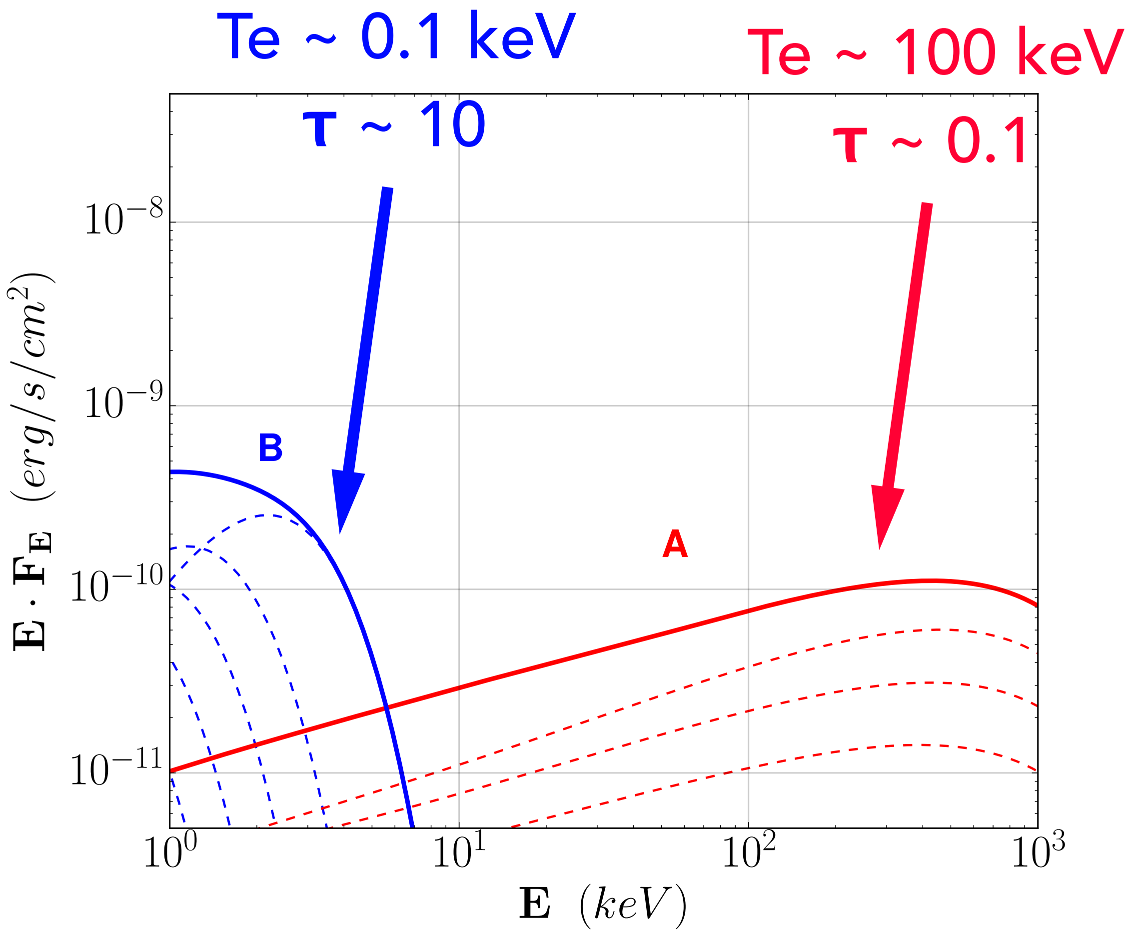
$$P_{jets} = b\, \frac{GM\dot{M}}{2r_{in}} \left(1 - \frac{r_{in}}{r_J}\right)$$

Ferreira 1997



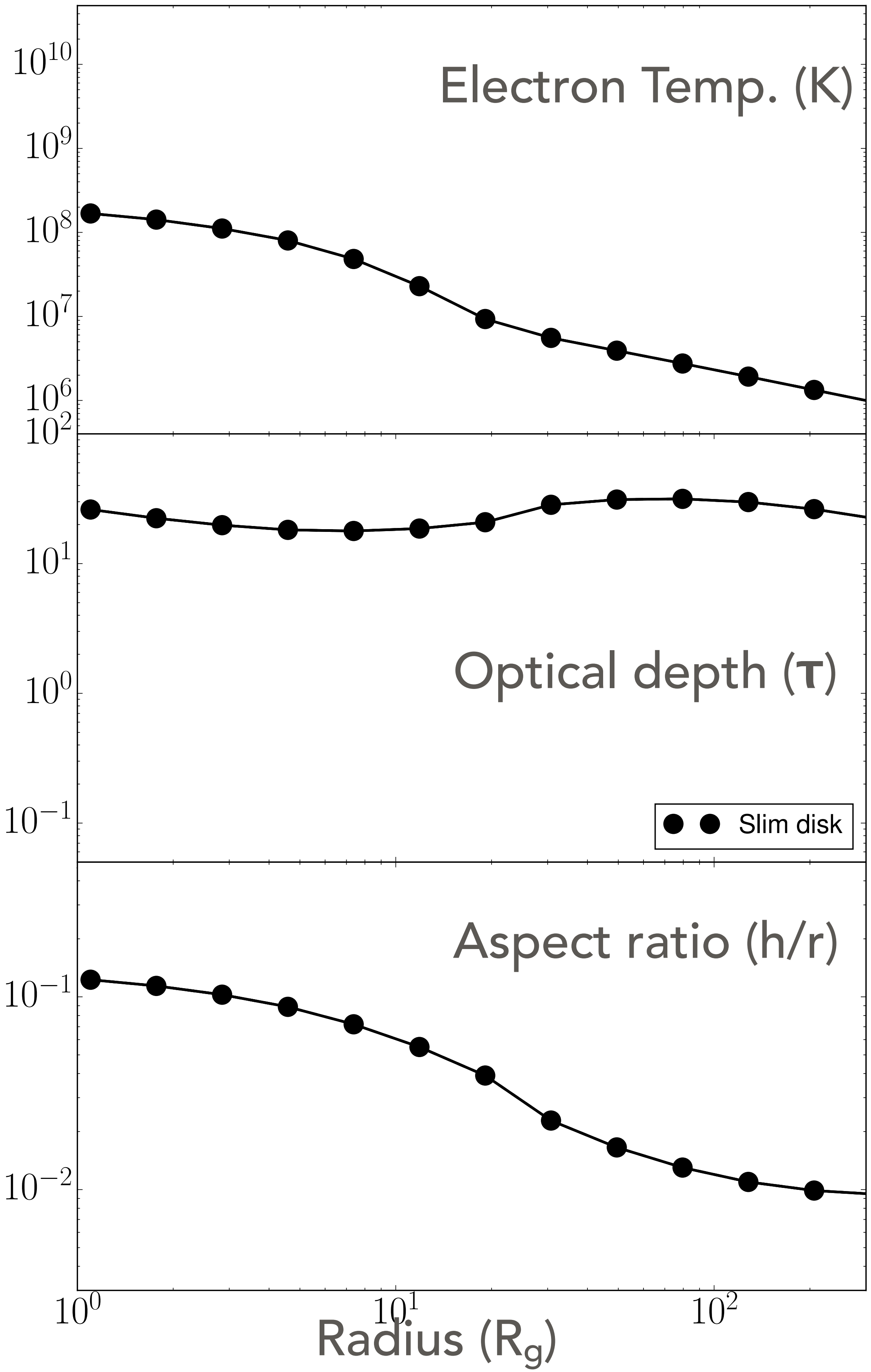
At low luminosity… L = 10^{-3} L_{Edd}



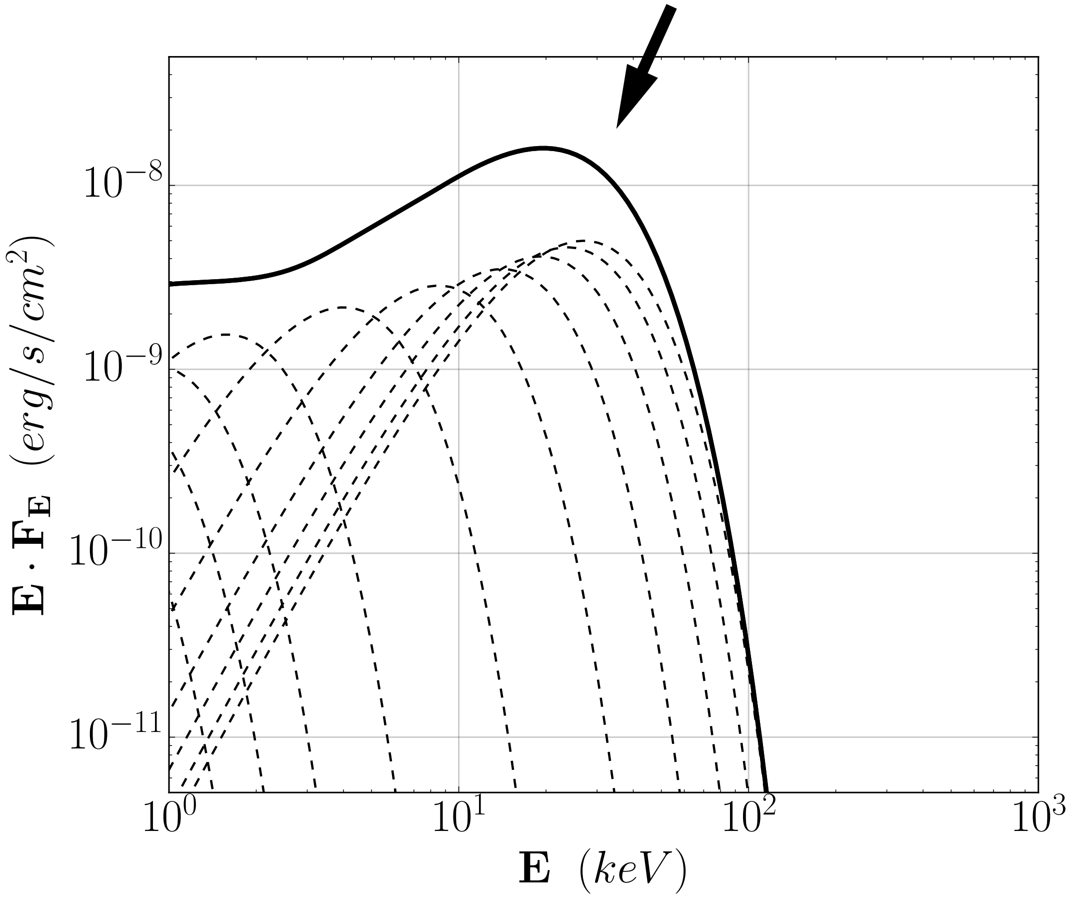


Marcel et al. 2018 A&A in press

Jet Emitting Disc solutions at L> 0.1 Led



- Solutions similar to slim disc but obtained at lower mdot
- Combination of local quasi-thermal spectra mimic high low-Te comptonization spectra

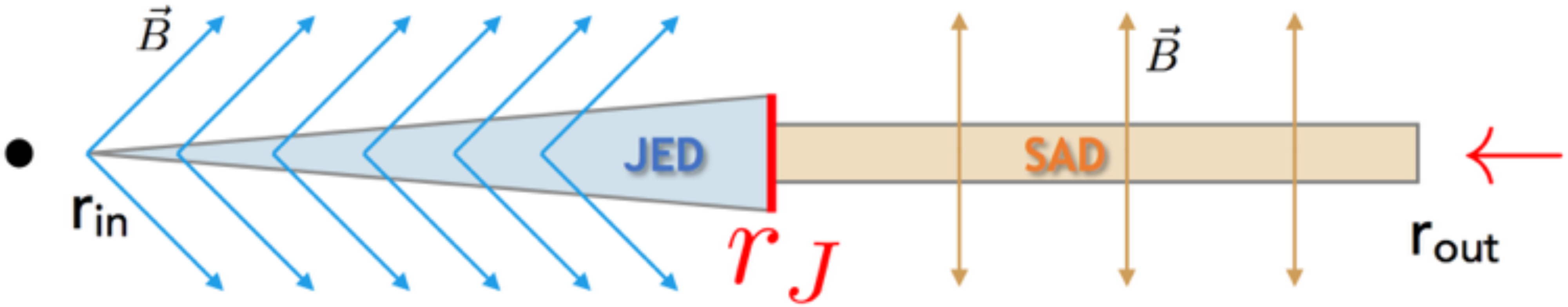


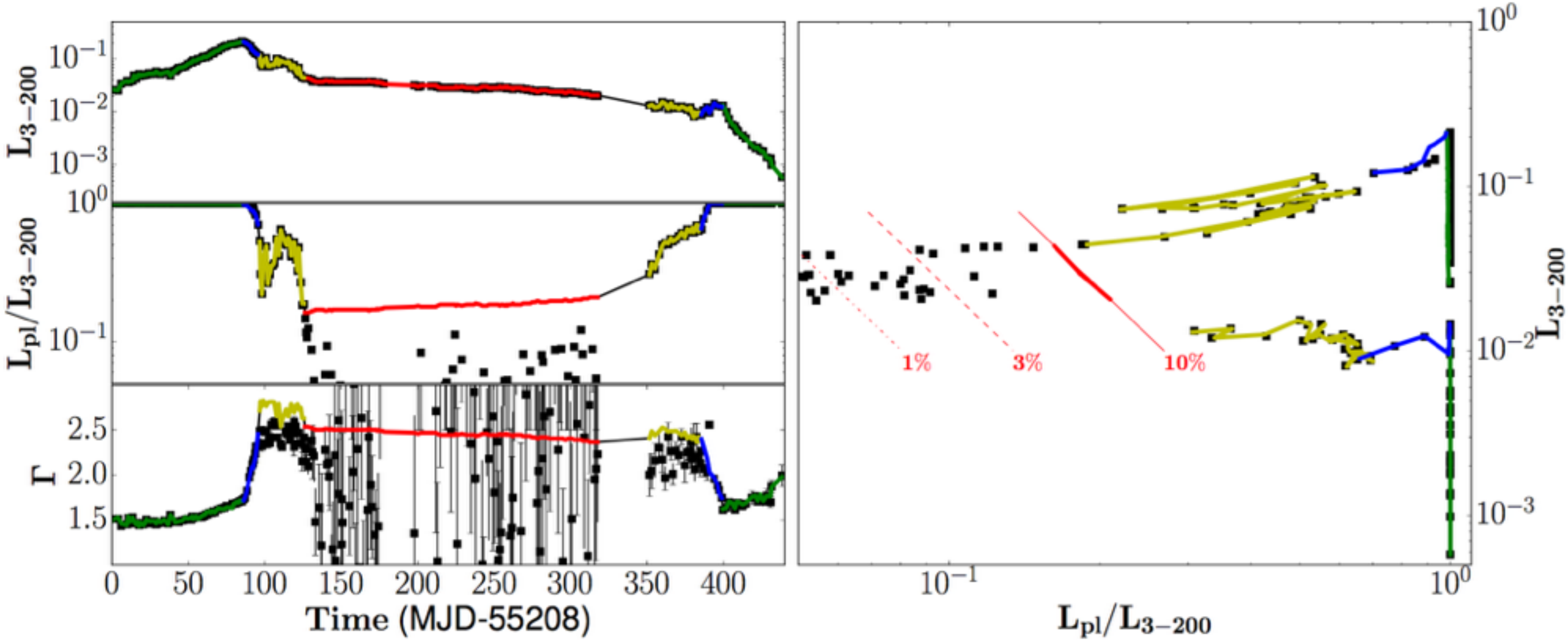
Γ ~ 1.7

E_{cut} < 100 keV

Marcel et al. 2018 A&A in press

Modelling an outburst of GX339-4

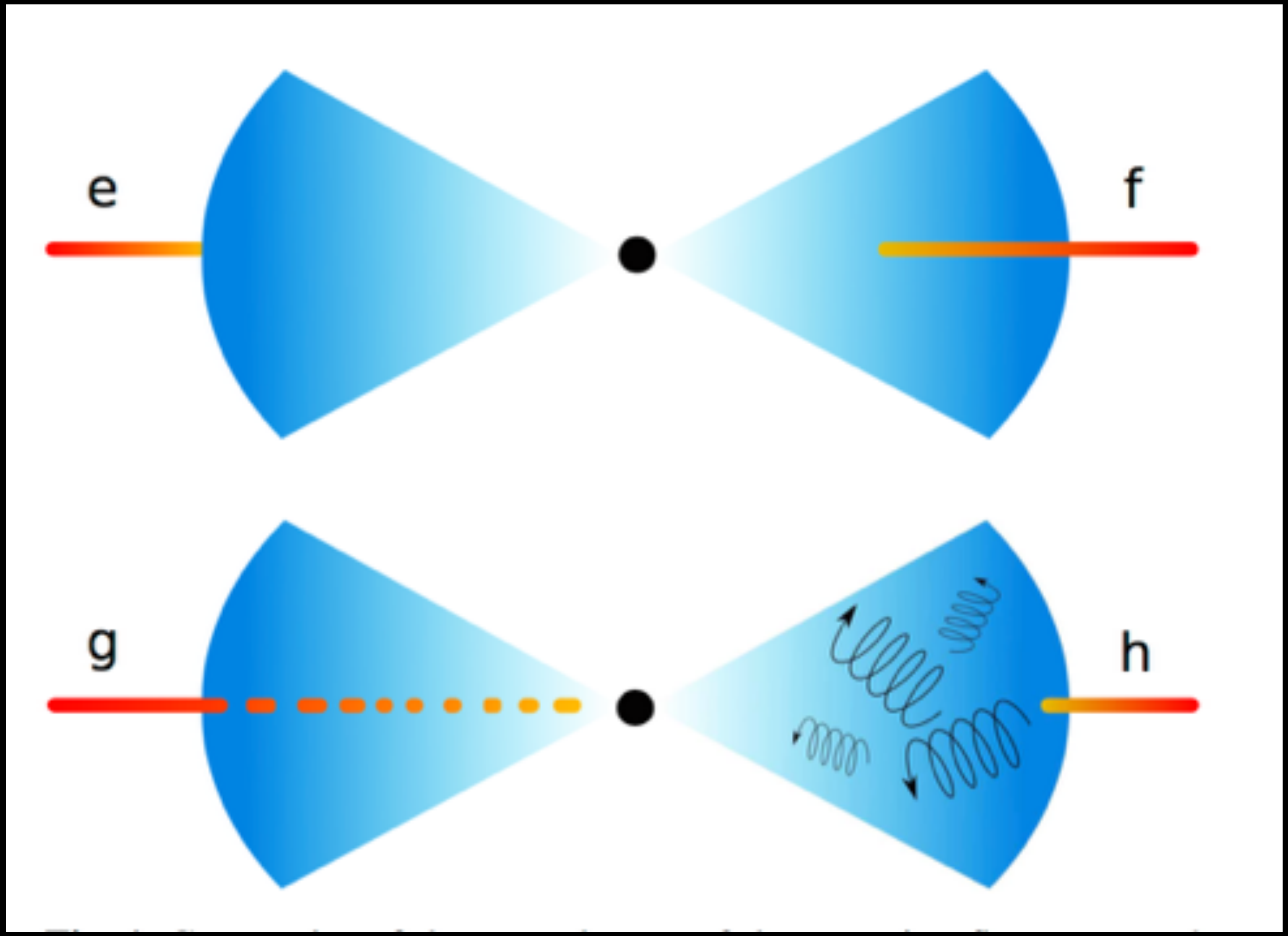




Marcel et al. 2018 in preparation

Radiation cooling
in truncated geometry

- Depends on exact geometry of hot flow
- Depends on details of disc to hot flow transition and other possible complications



Poutanen, Veledina & Zdziarski 2018

The e^+-e^- pair thermostat

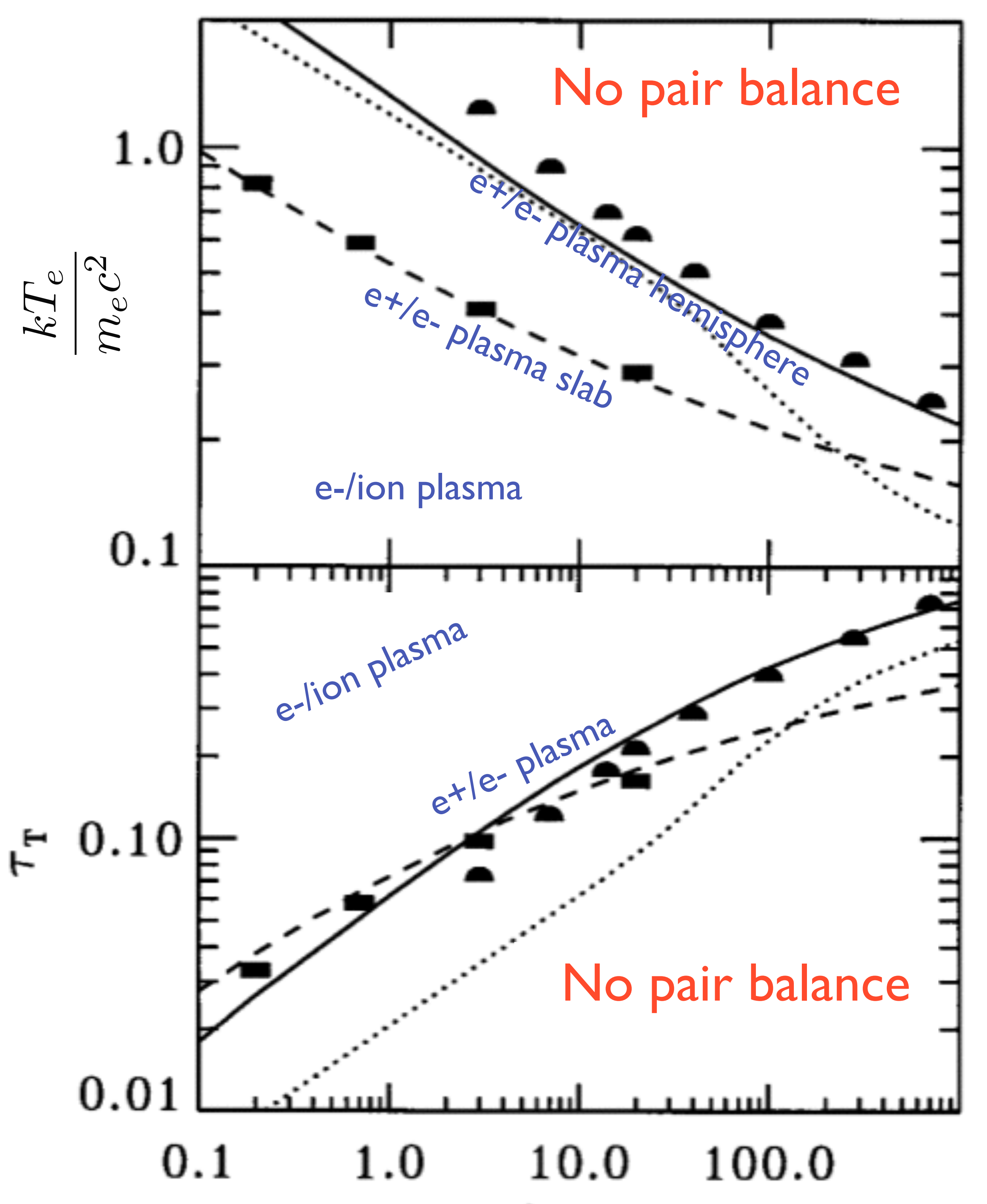
- Photons above 511 keV may interact with X-ray radiation field to produce e+-e- pairs

- 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

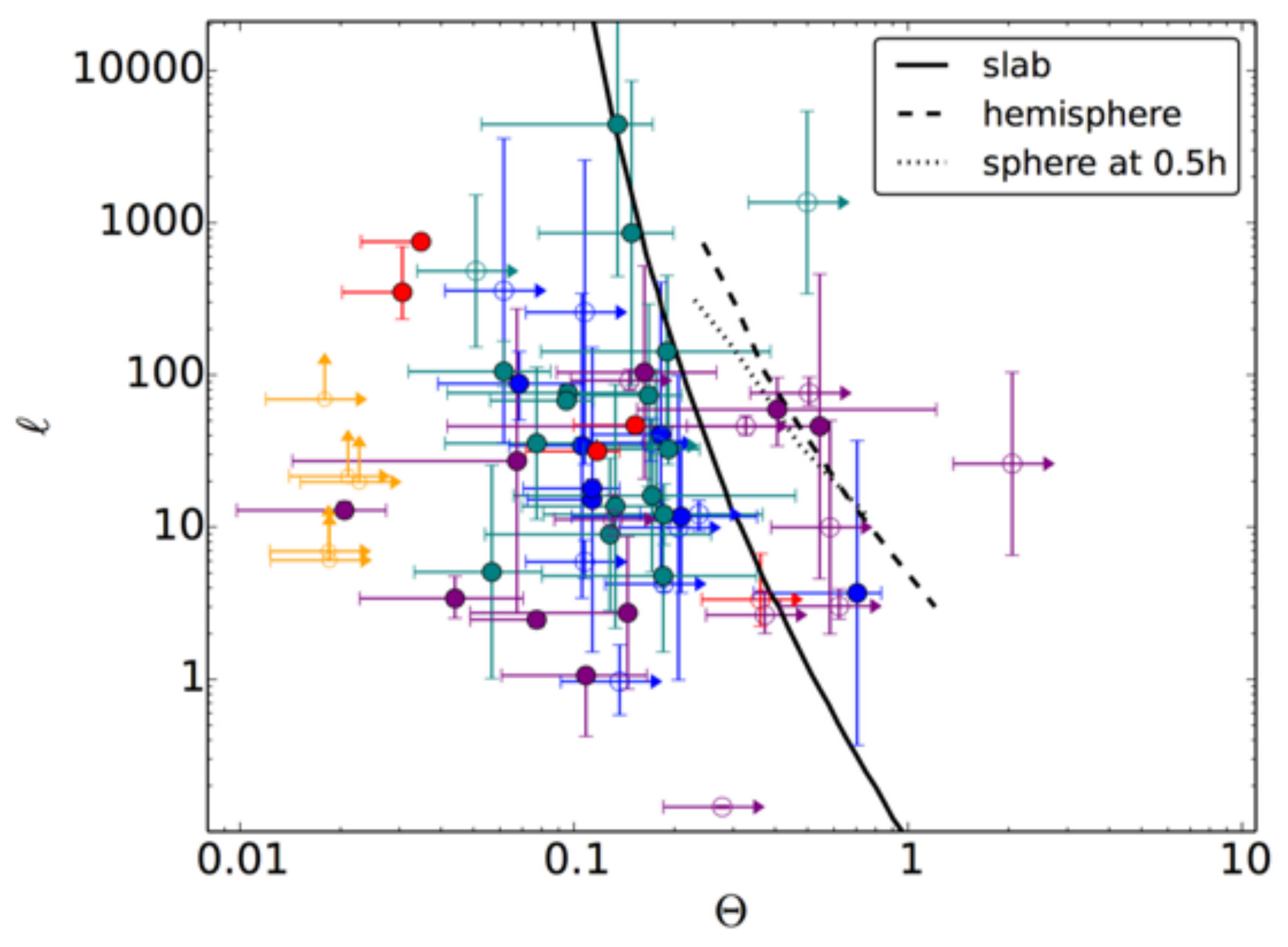
- This sets a minimum optical depth (and Maximum temperature) achievable for a given geometry



Stern et al. 1995

Evidence for pair dominated coronae

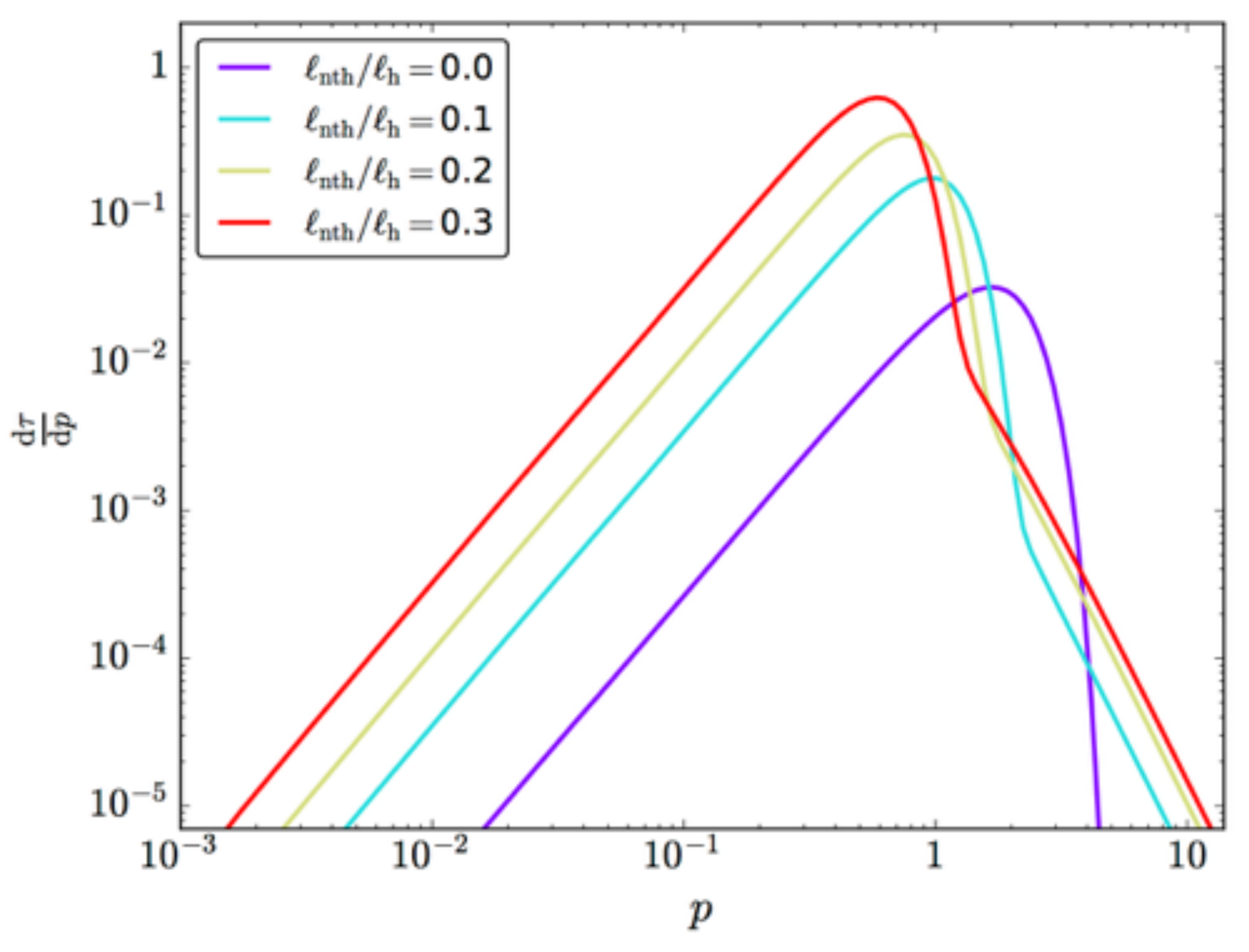
- Size of corona obtained from relativistic line profiles, disc reflection time-lags, or micro-lensing.
  + observed luminosity → estimates of compactness l_{dis}
- In many sources the data suggest compact coronae 2 Rg $<r_{co}<$ 10 Rg, implying $l_{dis}>10$.
- Plasma temperature estimated from high energy cut-off

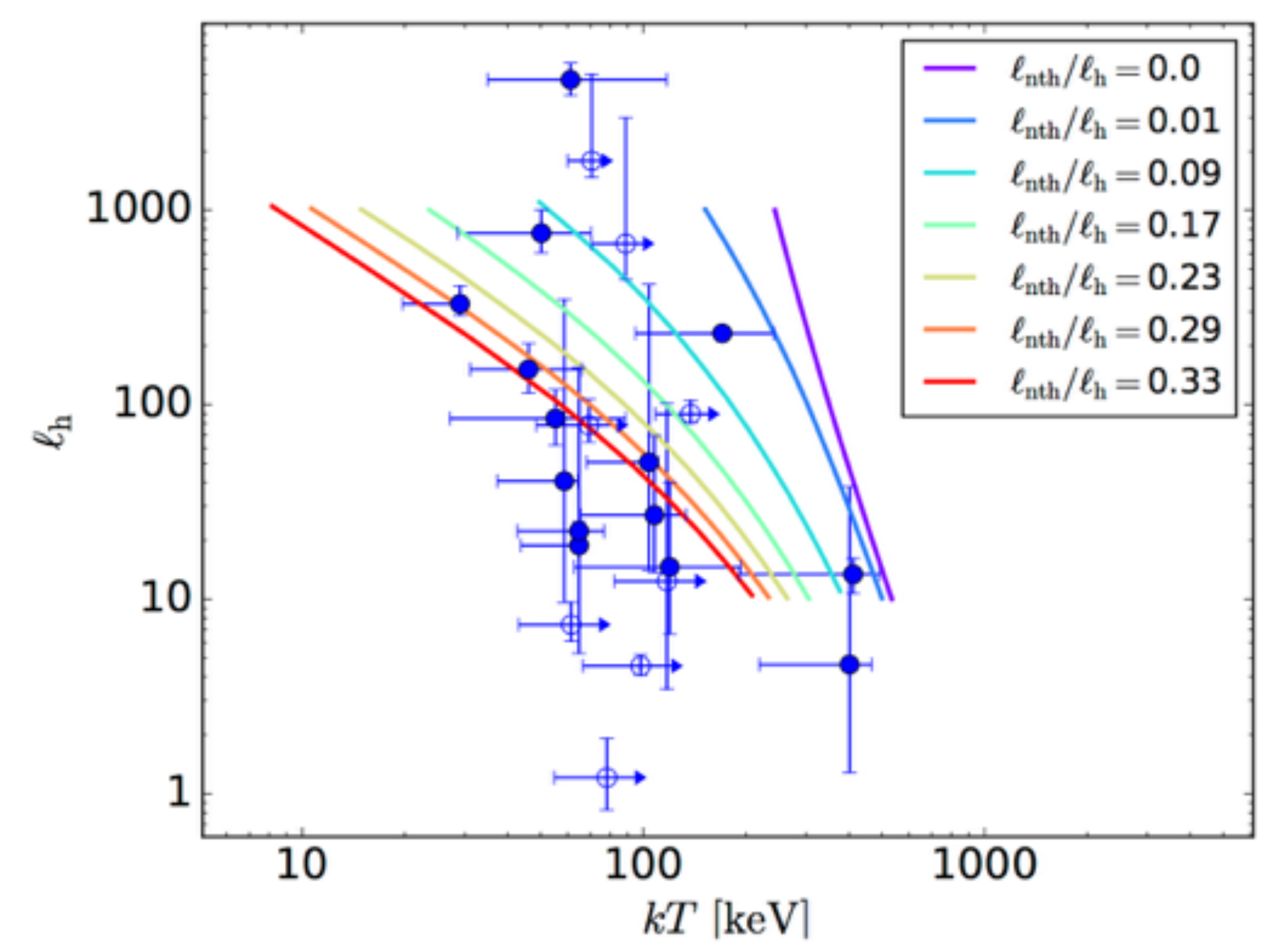


Fabian et al. 2016

Pair dominated hybrid thermal-non thermal model

- Pair yield dramatically increased by energetic non-thermal leptons
- —> lower Te for the same compactness



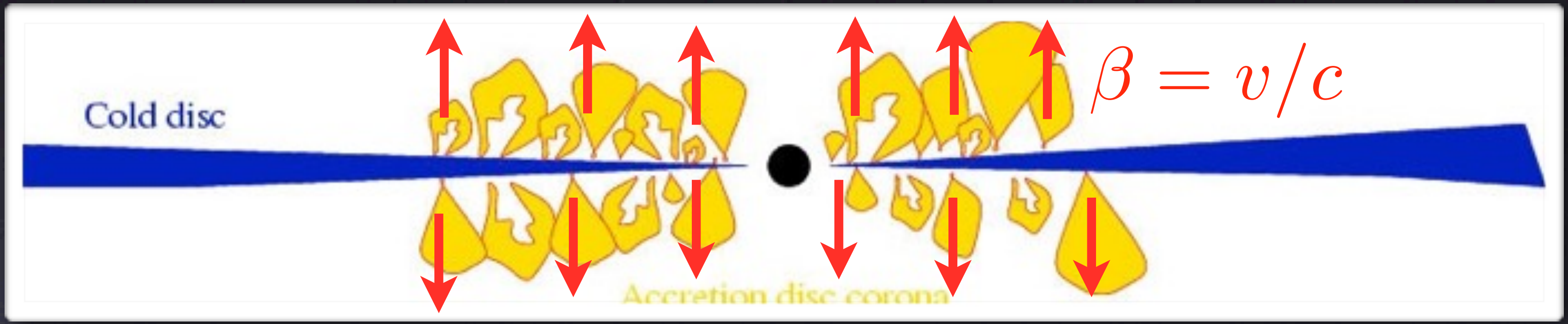


Coppi et al. 1999; Fabian et al. 2017

Consequences for coronal models

- Standard two-temperature hot accretion flow solutions cannot be pair dominated (Esin et al. 1999)

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



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

- If the corona is pair dominated, radiation pressure from the disc is enough to generate a bulk velocity v~c/2 (Beloborodov 1999)

Conclusions

- In X-ray binaries truncated disc geometry is favoured (physically motivated and observationally relevant)
- JED solutions solve the problem of luminous hard state sources (and account for jets)
- Pair production could be important in many sources