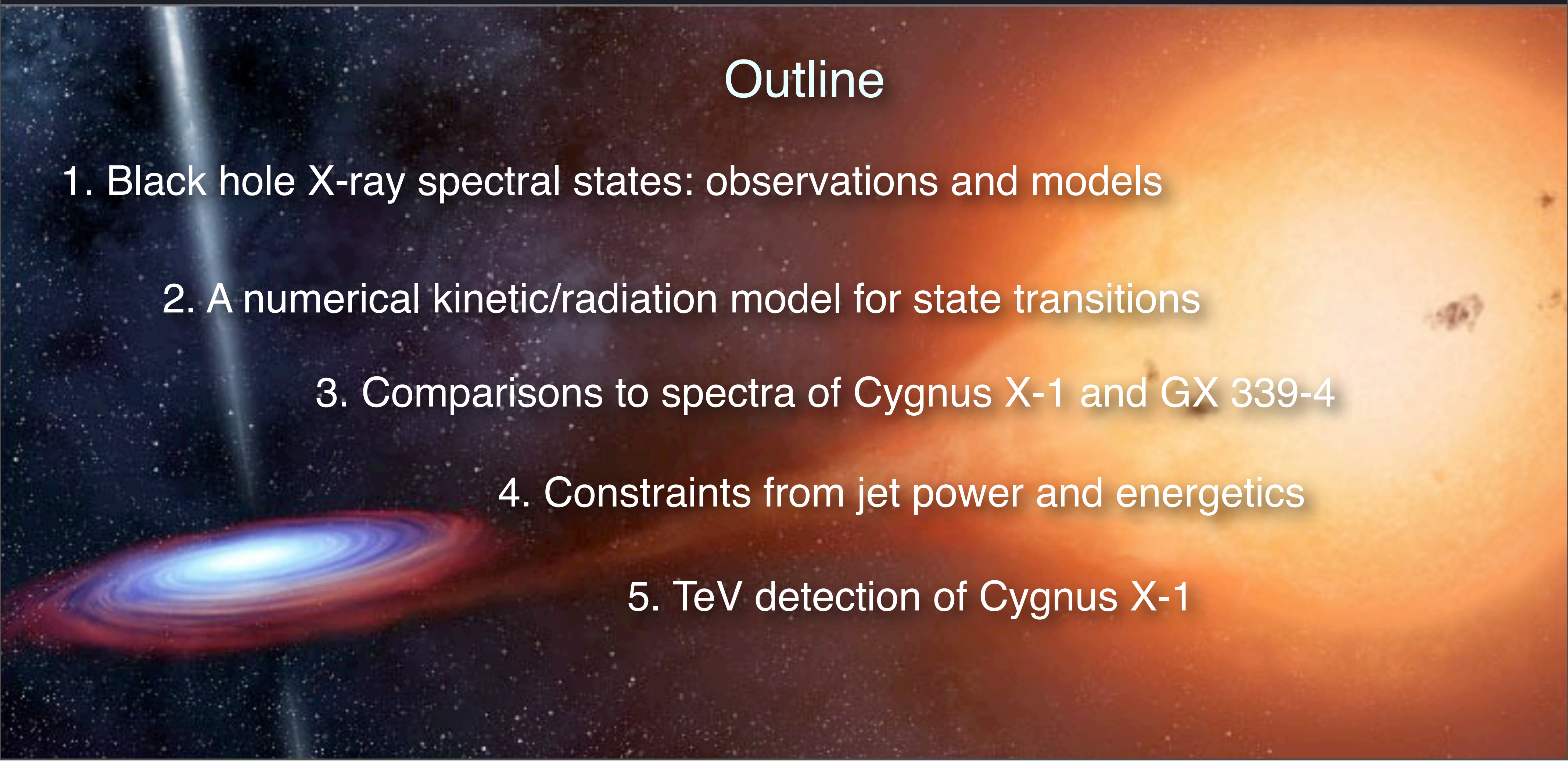
Jet and X-ray corona of Cygnus X-1

Julien Malzac (CESR/CNRS, Toulouse, France)

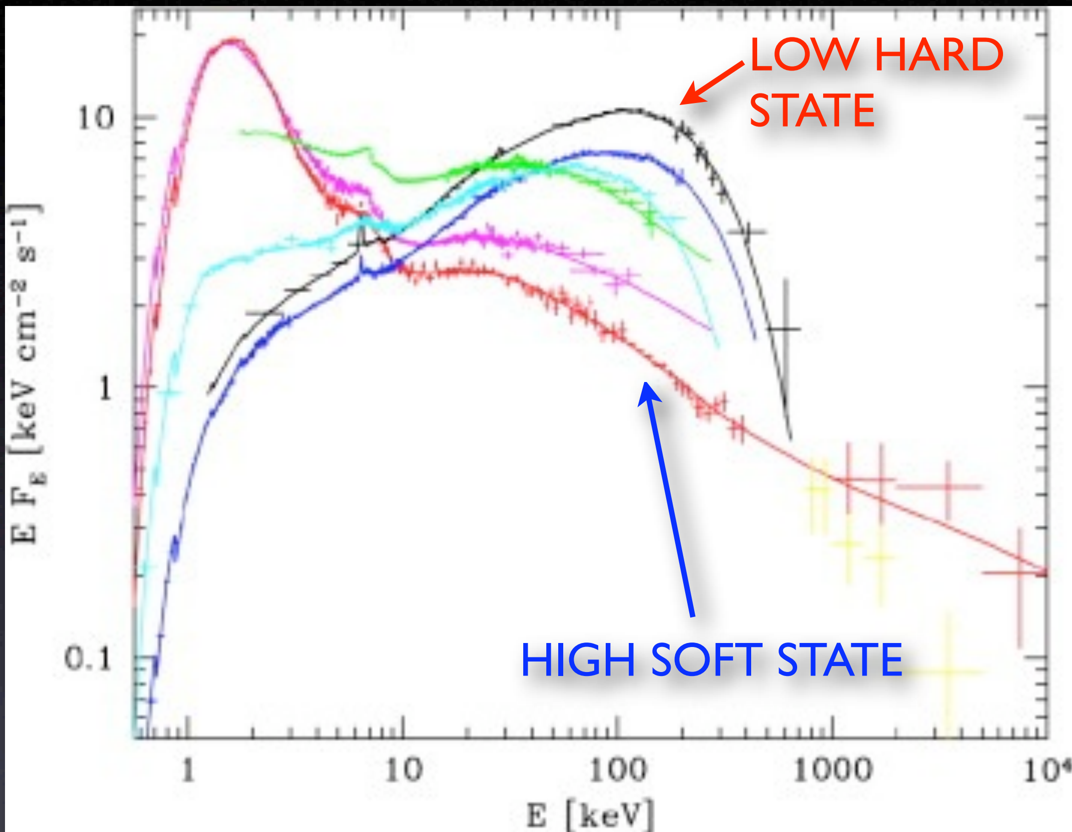


Outline

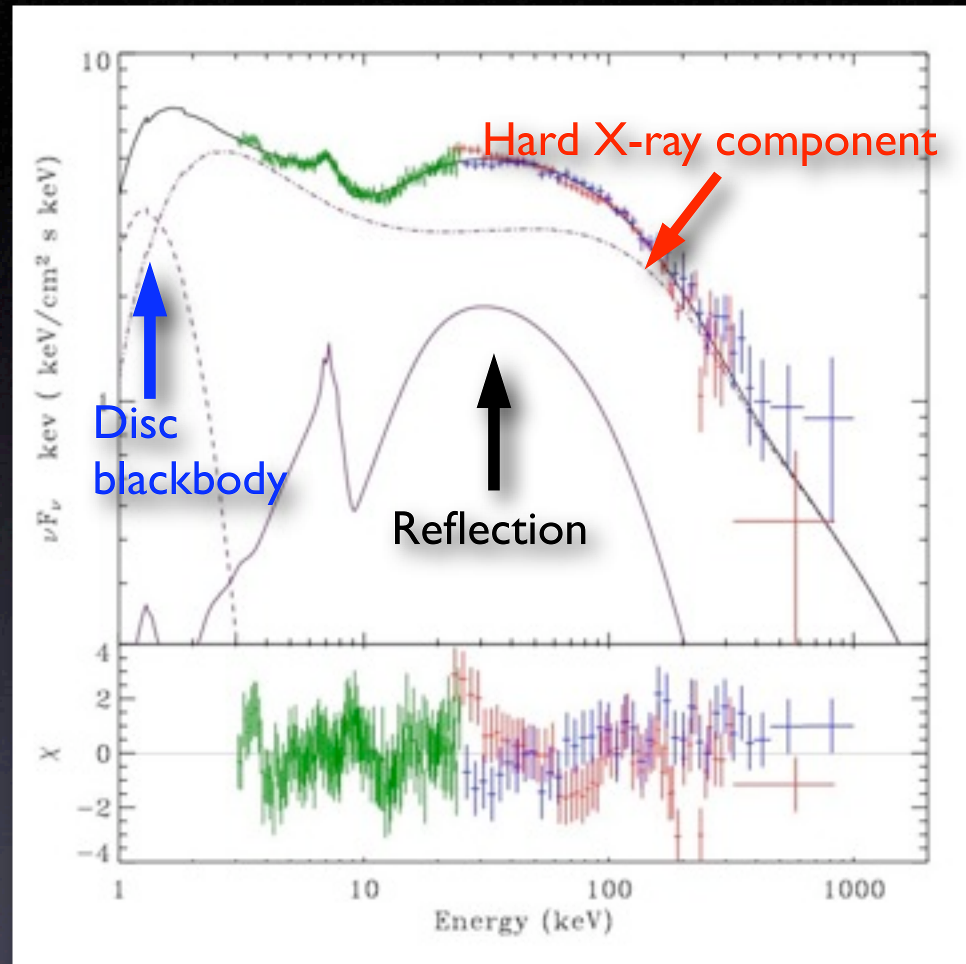
1. Black hole X-ray spectral states: observations and models
2. A numerical kinetic/radiation model for state transitions
3. Comparisons to spectra of Cygnus X-1 and GX 339-4
4. Constraints from jet power and energetics
5. TeV detection of Cygnus X-1

High energy emission of accreting black holes

Cygnus X-1



Zdziarski et al 2003



Malzac et al. 2006

LOW HARD STATE:
disc blackbody and reflection: weak / Corona: THERMAL Comptonisation

HIGH SOFT STATE:
disc blackbody and reflection: strong / Corona: NON-THERMAL (or hybrid) Comptonisation

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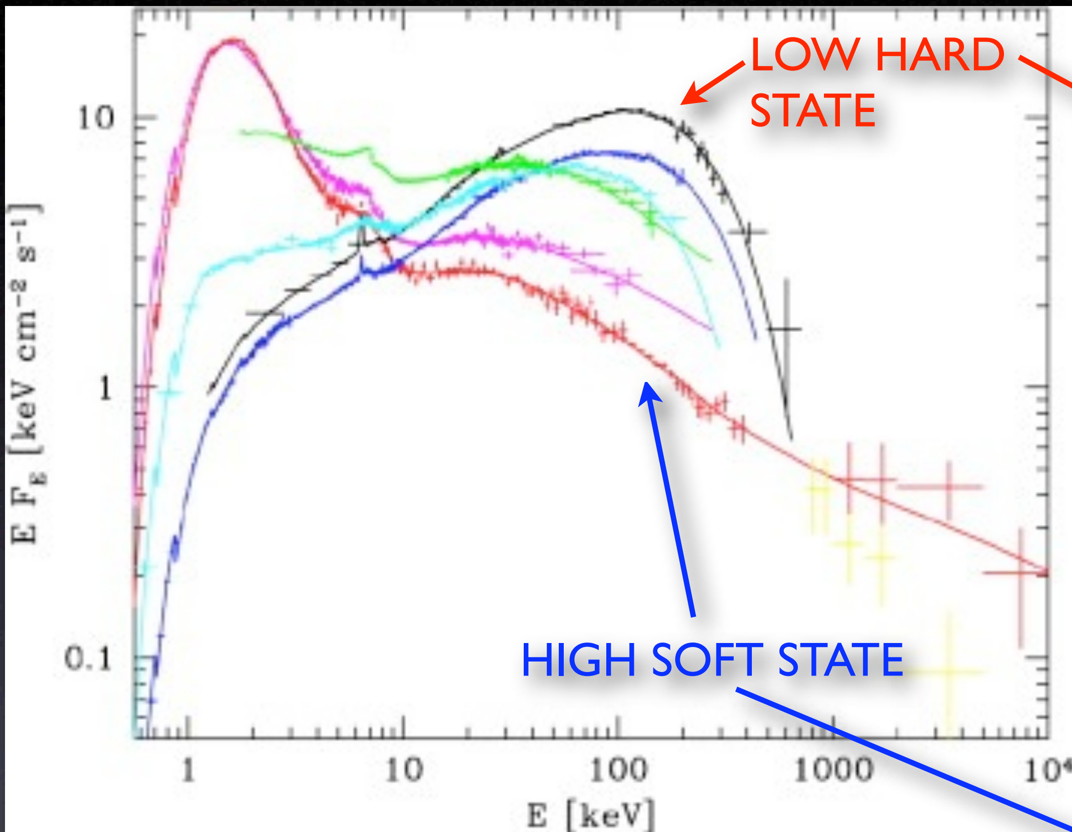

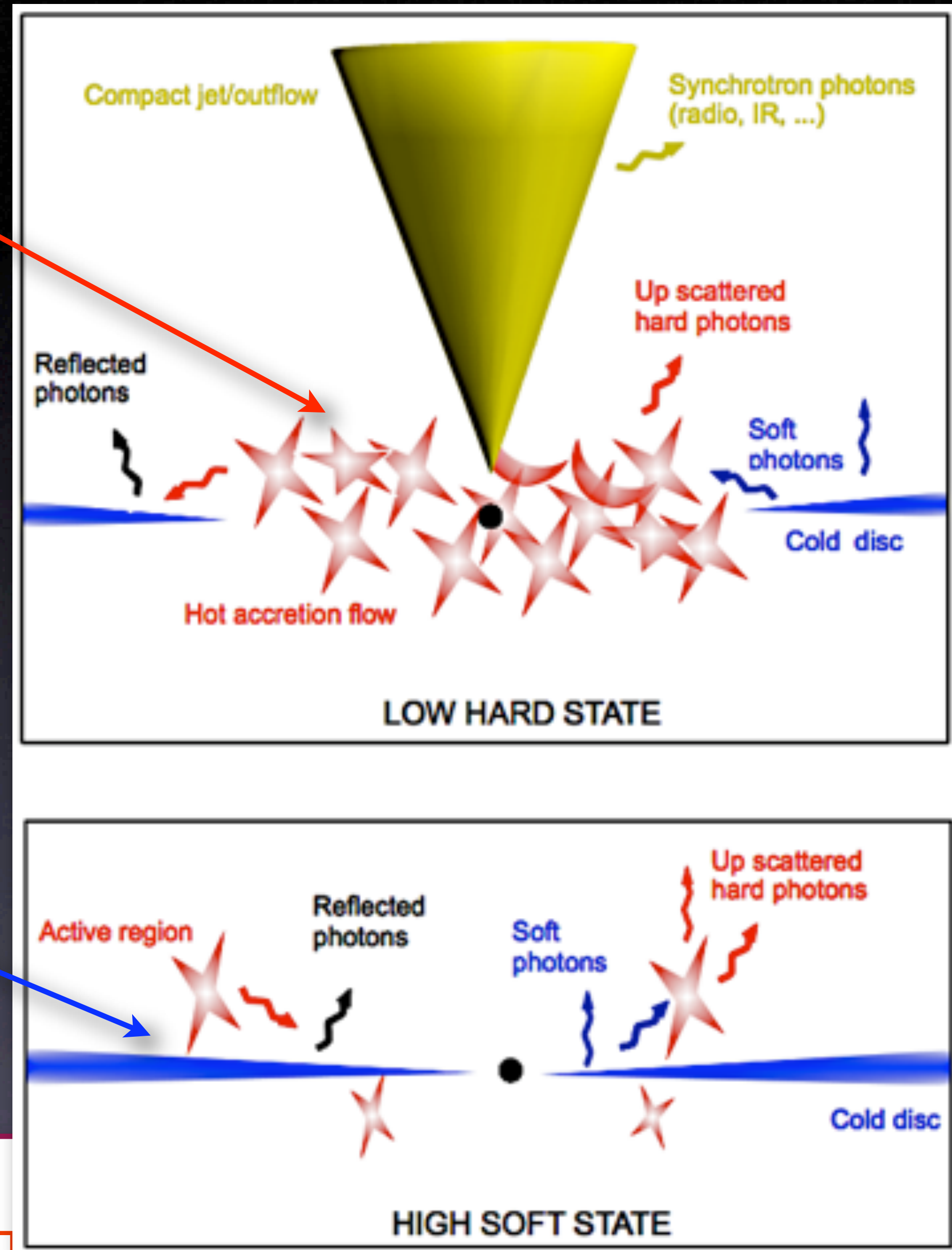

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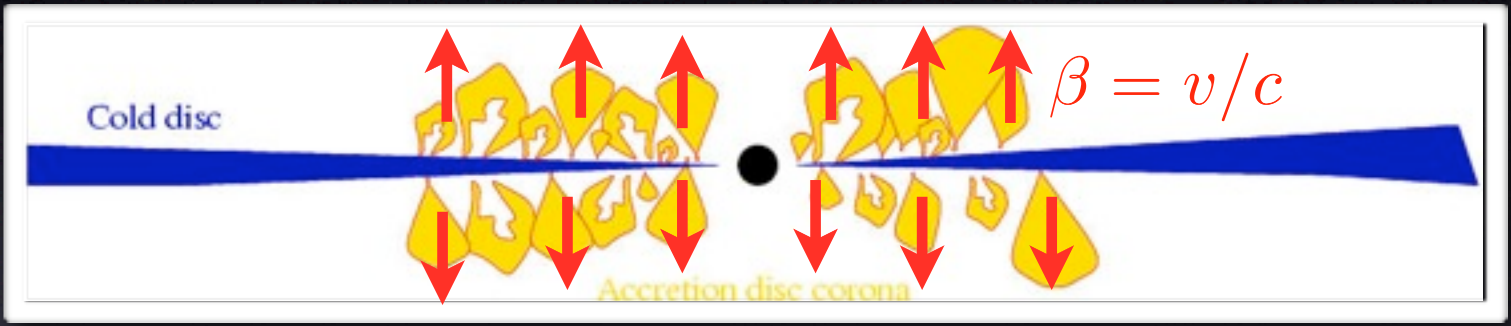
Alternative models for the hard state

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



(Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

- Hard state associated with radio jet: X-ray Jet Models

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

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)

Belmont, Malzac & Marcowith 2008

see also Vurm & Poutanen 2009 and talk by J. Poutanen

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- Continuous POWER-LAW electron acceleration in magnetised plasma
  - ➡ Cooling and thermalisation through synchrotron self-Compton + e-e Coulomb
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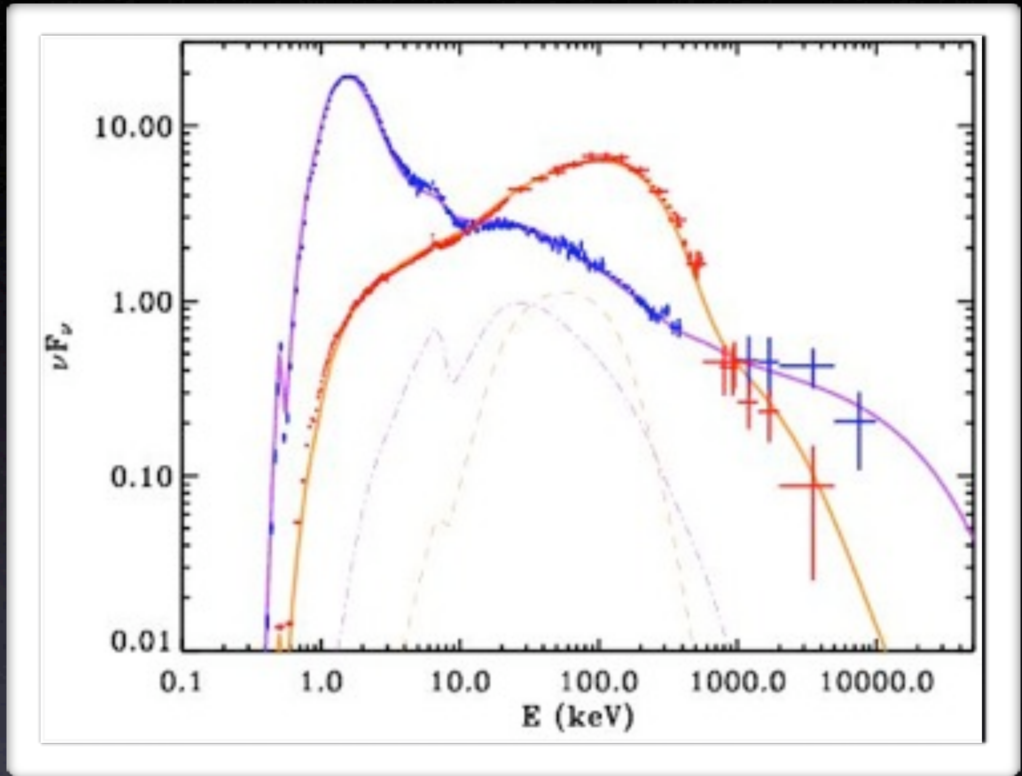
- If corona illuminated by accretion disc: additional Compton cooling on external photons

Comparisons to Cygnus X-1 spectra



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

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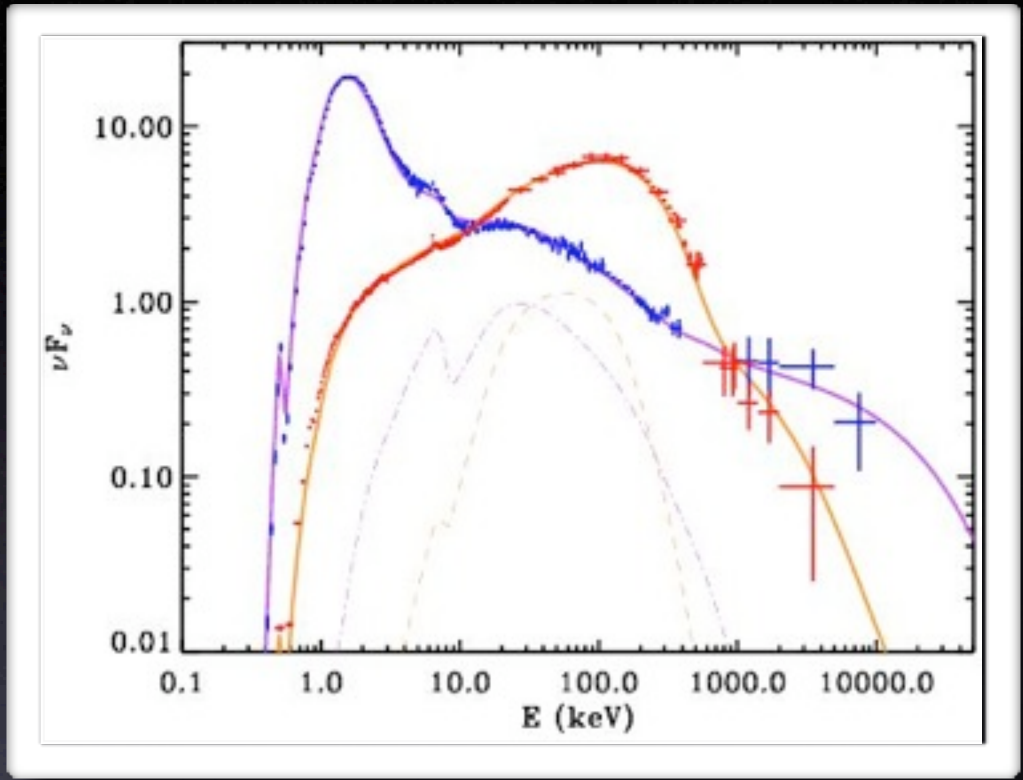
- Both states consistent with pure non-thermal acceleration models

- Different coronal temperatures due to more cooling by thermal disc photons in Soft state



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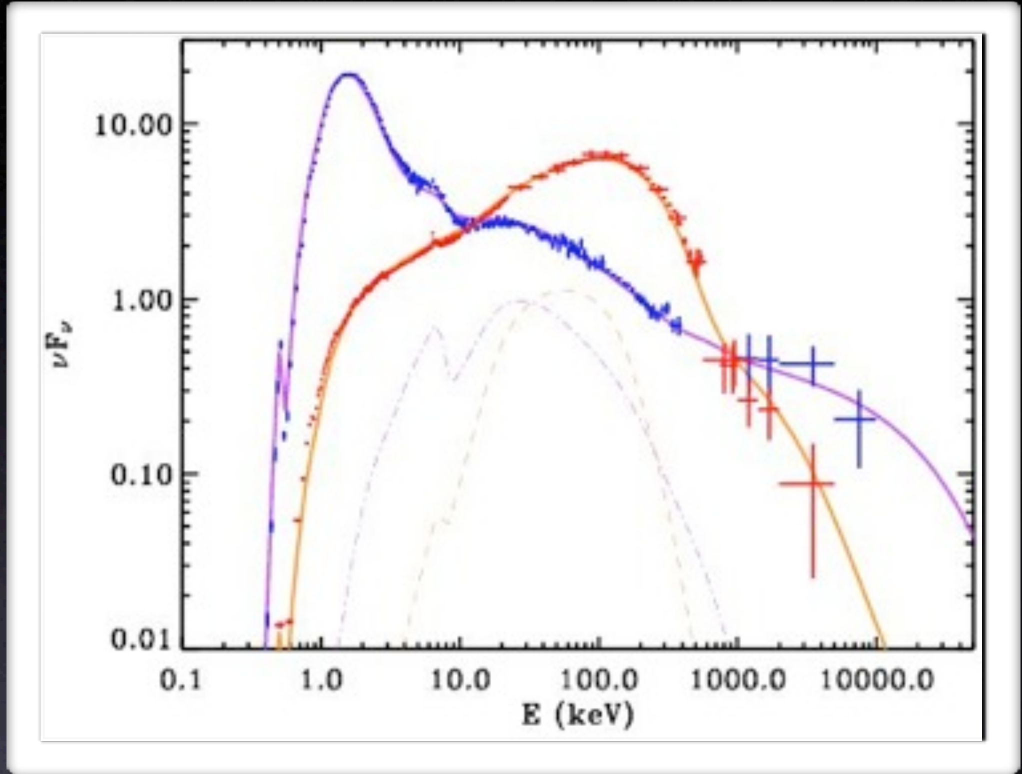


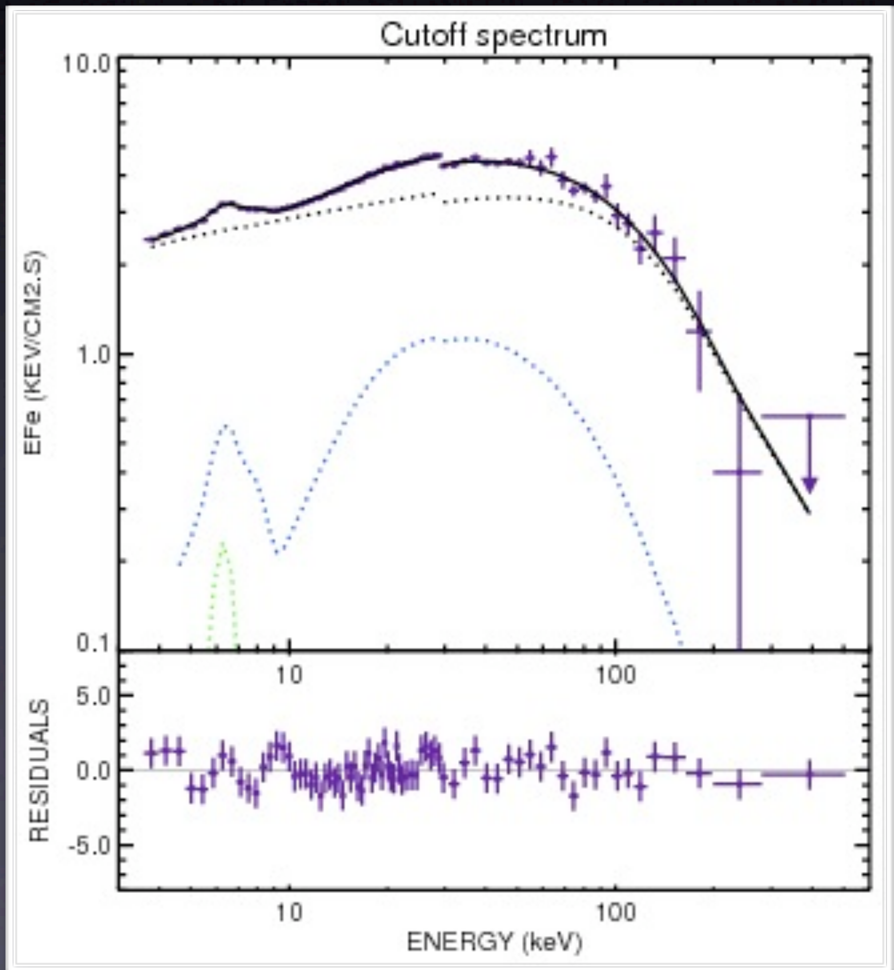
- Magnetic field in hard state: $U_B/U_R<0.3$

➡ corona unlikely to be powered by magnetic field

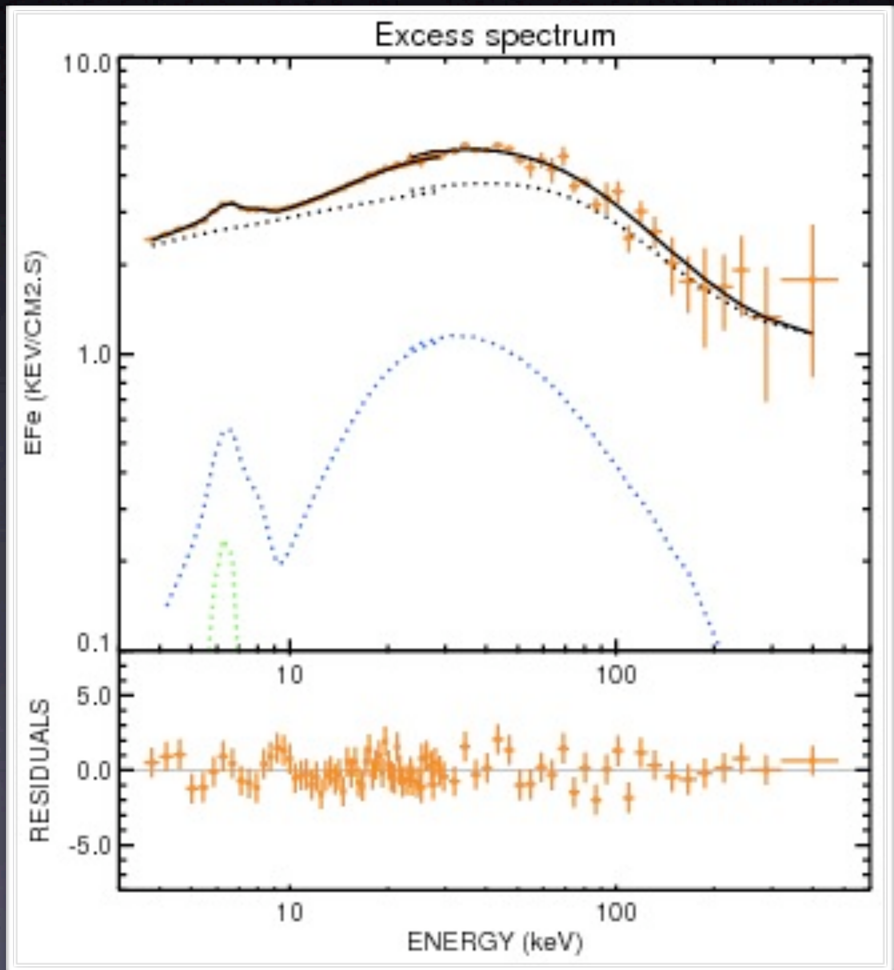
(Malzac & Belmont MNRAS 2009 ; Poutanen & Vurm 2009)

RXTE/INTEGRAL observation of GX 339-4 during a bright Low Hard State

- Spectral variability detected above 100 keV on time-scales of a few hours



lower flux: spectrum with high energy cut-off



higher fluxes: spectrum with high energy excess

Spectral fits with BELM

Spectrum	Γ_{inj}	γ_{max}	l_B	τ_{ion}	τ_T	kT_e (keV)	$\Omega/2\pi$	ξ	χ^2_ν(dof)
cutoff	$2.5f$	$15.2^{+5.5}_{-1.3}$	283^{+43}_{-36}	$2.30^{+0.17}_{-0.16}$	$2.30^{+0.17}_{-0.16}$	33.4	$0.43^{+0.04}_{-0.03}$	301^{+123}_{-100}	0.96(68)
excess	$2.5f$	187^{+111}_{-105}	$27.3^{+4.0}_{-3.4}$	$2.49^{\pm0.18}$	$2.73^{\pm0.18}$	23.9	$0.39^{+0.04}_{-0.04}$	310^{+155}_{-126}	0.92(74)

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- LHS of GX339-4 is consistent with pure non-thermal injection SSC model, B could be larger than in Cyg X-1 ($B \leq 10^7$ gauss)
- Variability of high energy tail can be interpreted in terms of fluctuation of magnetic field and $\gamma_{\max}$

➡ B changes by approximately a factor of 3

➡ The fitted dependence between $\gamma_{\max}$ and B is: $\gamma_{\max} \propto 1/B^2$

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Model with hot protons

(Malzac & Belmont MNRAS 2009)

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

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

(Malzac & Belmont MNRAS 2009)

Jet energetics of Cygnus 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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$$\Rightarrow \eta_{\rm h} \geq \eta_s/2$$

➡ accretion proceeds efficiently in the hard state

➡ cannot be strongly advection dominated

Constraints on jet terminal velocity

$$P_{\rm J} = f_{\rm j} \dot{M}_{\rm h} (\gamma_{\infty} - 1) c^2$$

(Malzac, Belmont & Fabian, MNRAS, 2009)

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➡ $\beta_\infty > 0.1$

and most likely: $0.8 \gtrsim \beta_\infty \gtrsim 0.3$

(Malzac, Belmont & Fabian, MNRAS, 2009)

Is the X-ray emission from the jet ?

- Mass flux conservation along the jet implies:

$$\dot{M}_J = \pi r_0^2 n_0 \beta_0 \gamma_0 m_{\rm p} c = \frac{P_J}{(\gamma_\infty - 1)c^2}$$

  - jet power $P_{\rm J}$ $(\simeq 2 \times 10^{37} {\rm erg/s})$
  - terminal velocity β_∞ (> 0.1)
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- If X-ray emission is Comptonisation in the jet:

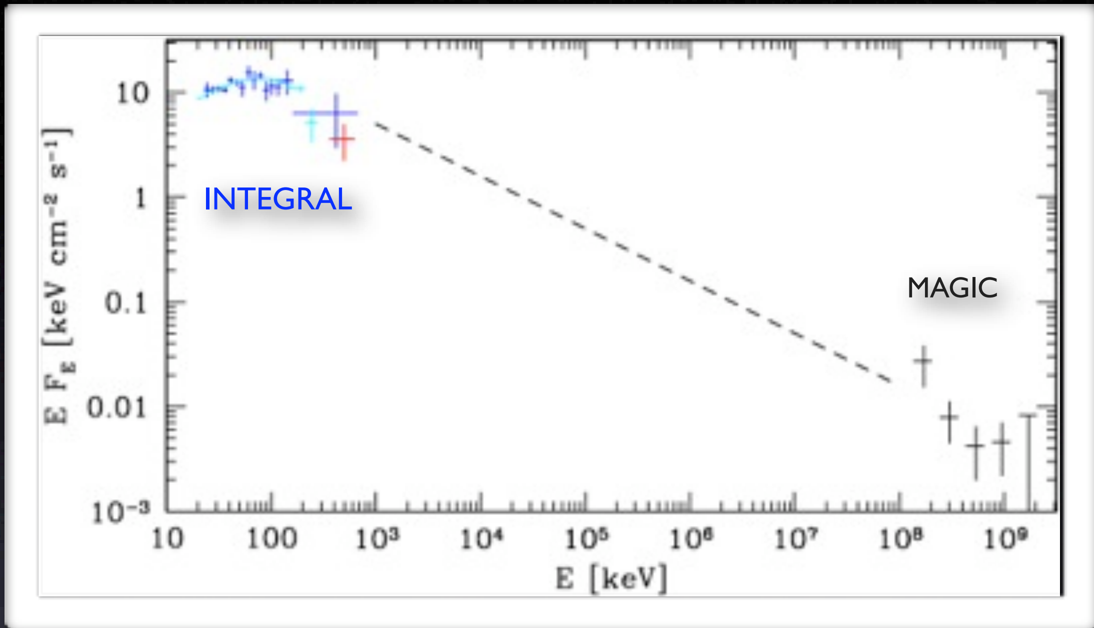
$$\tau_T = n_0 \sigma_{\rm T} r_0 > 1$$

$$\Rightarrow \beta_0 < 0.1$$

➡ velocity of X-ray emitting region much slower than in any X-ray jet model

(Malzac, Belmont & Fabian, MNRAS, 2009)

TeV detection of Cyg X-1 by MAGIC (Albert et al., 2007)



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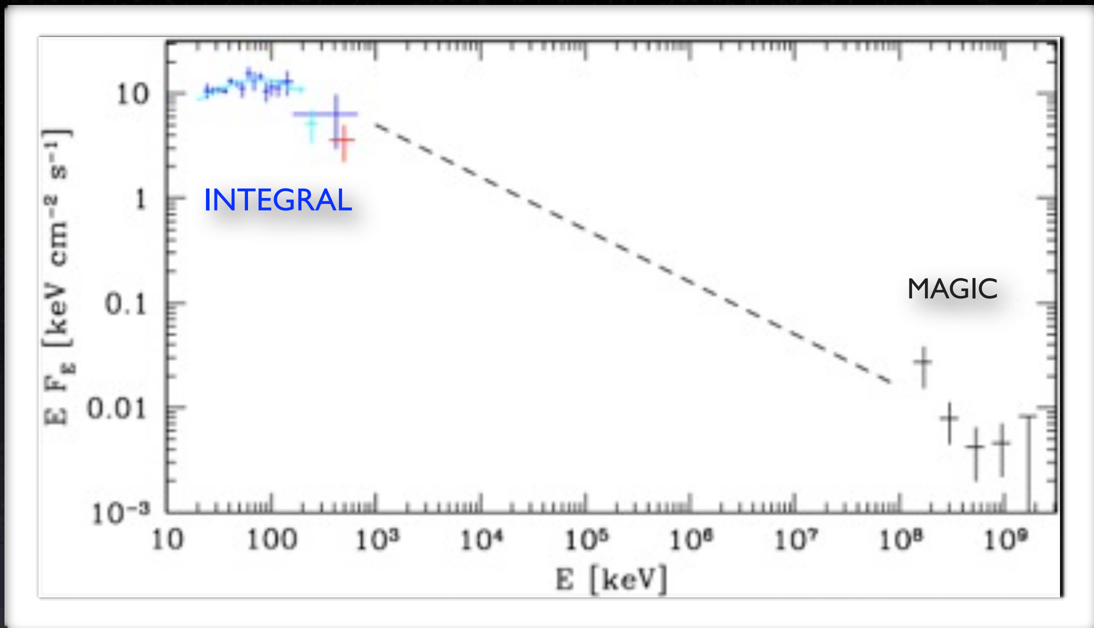

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Origin of TeV emission ?

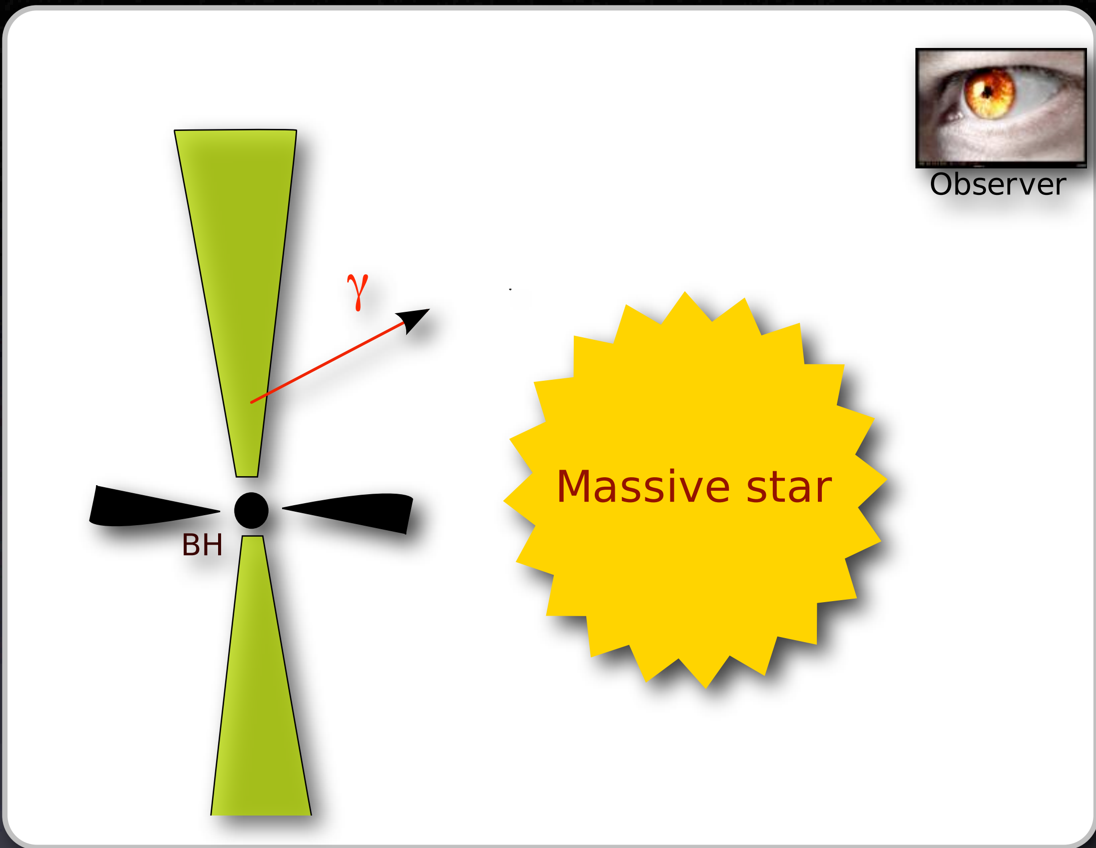
➡ in the X-ray corona radiative cooling is too strong to accelerate particles up to TeV energies

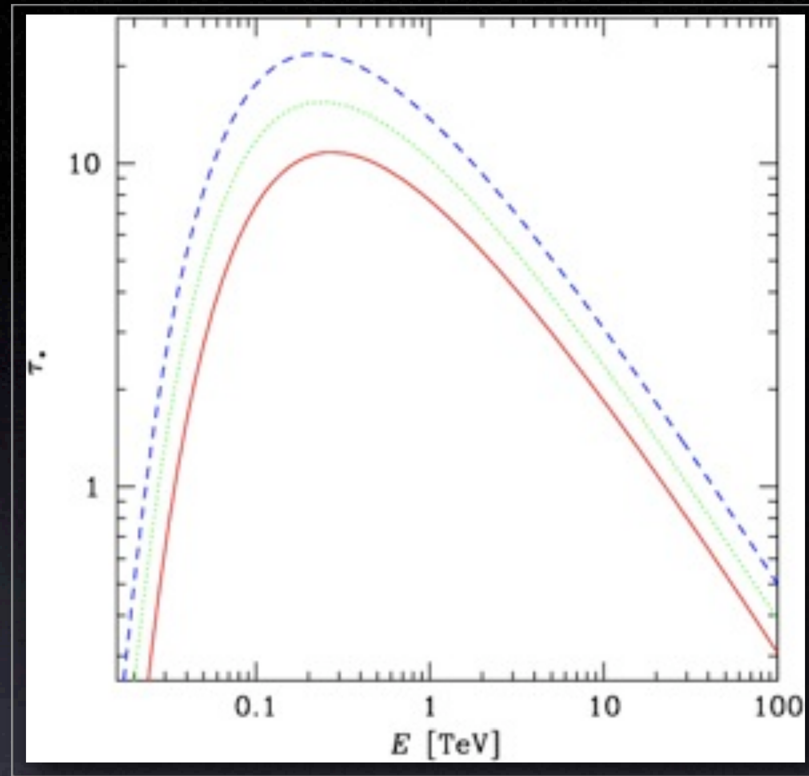
➡ shocks in jet, or interaction of outflow with wind of companion star

➡ relatively close to the black hole

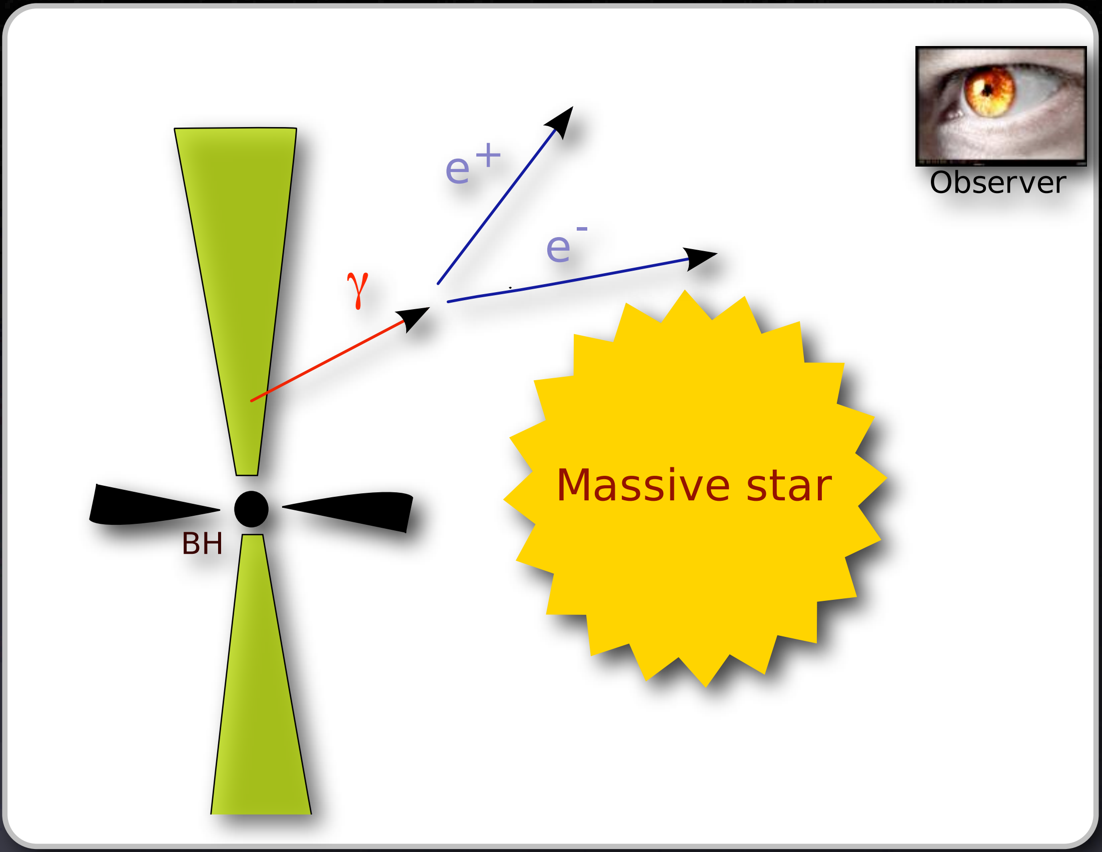
➡ main constraint: pair absorption in the field of companion star

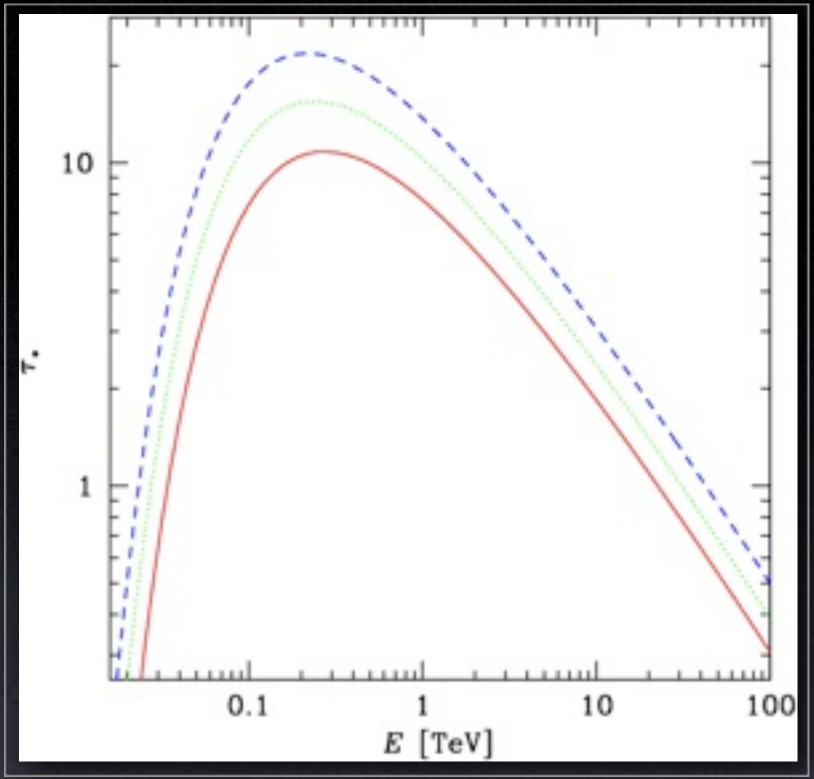
➡ BH behind companion: pair absorption in radiation field of star





➡ BH behind companion: pair absorption in radiation field of star





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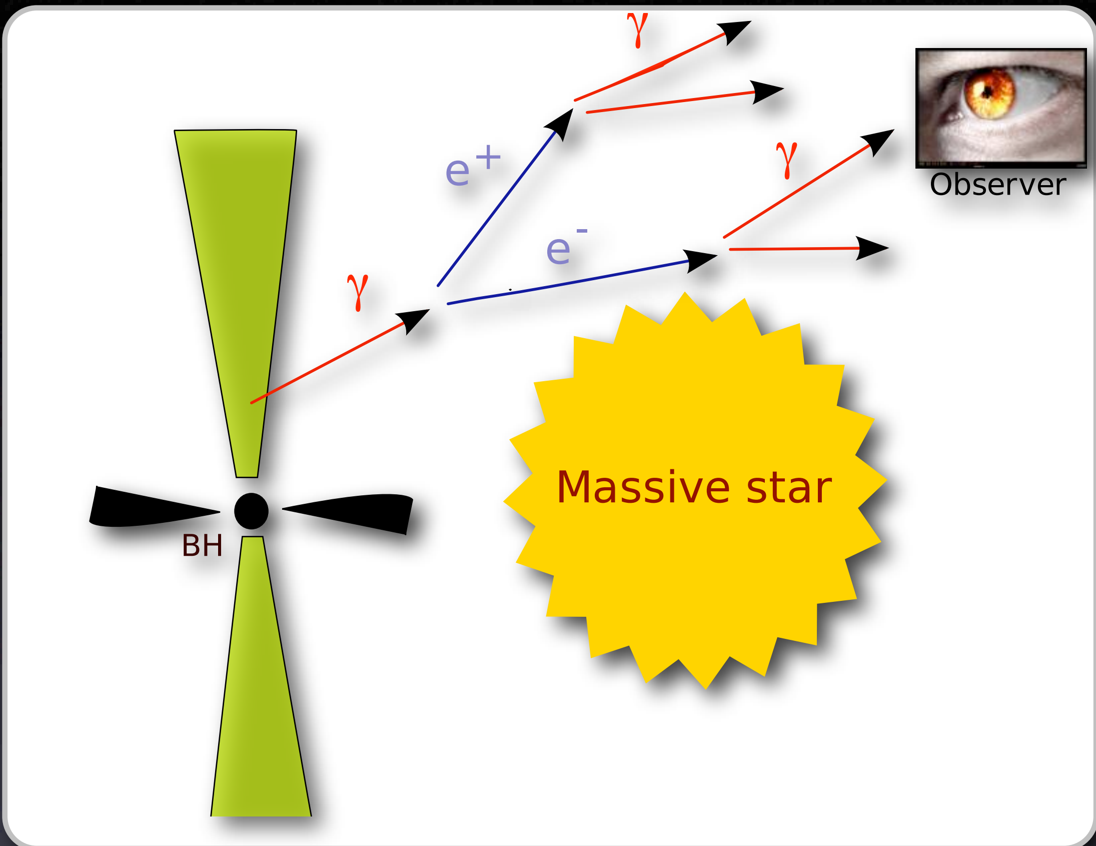

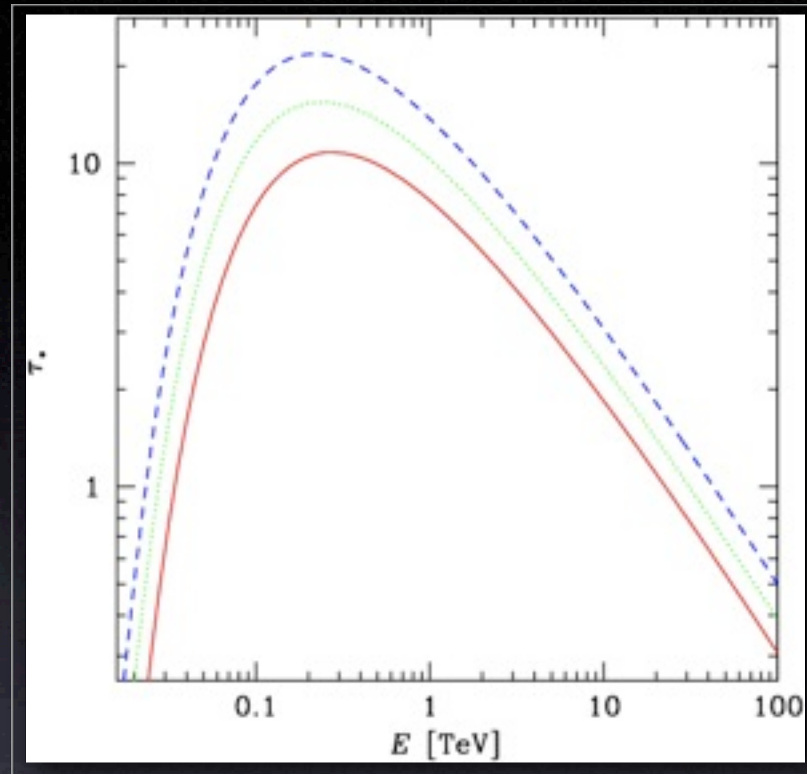

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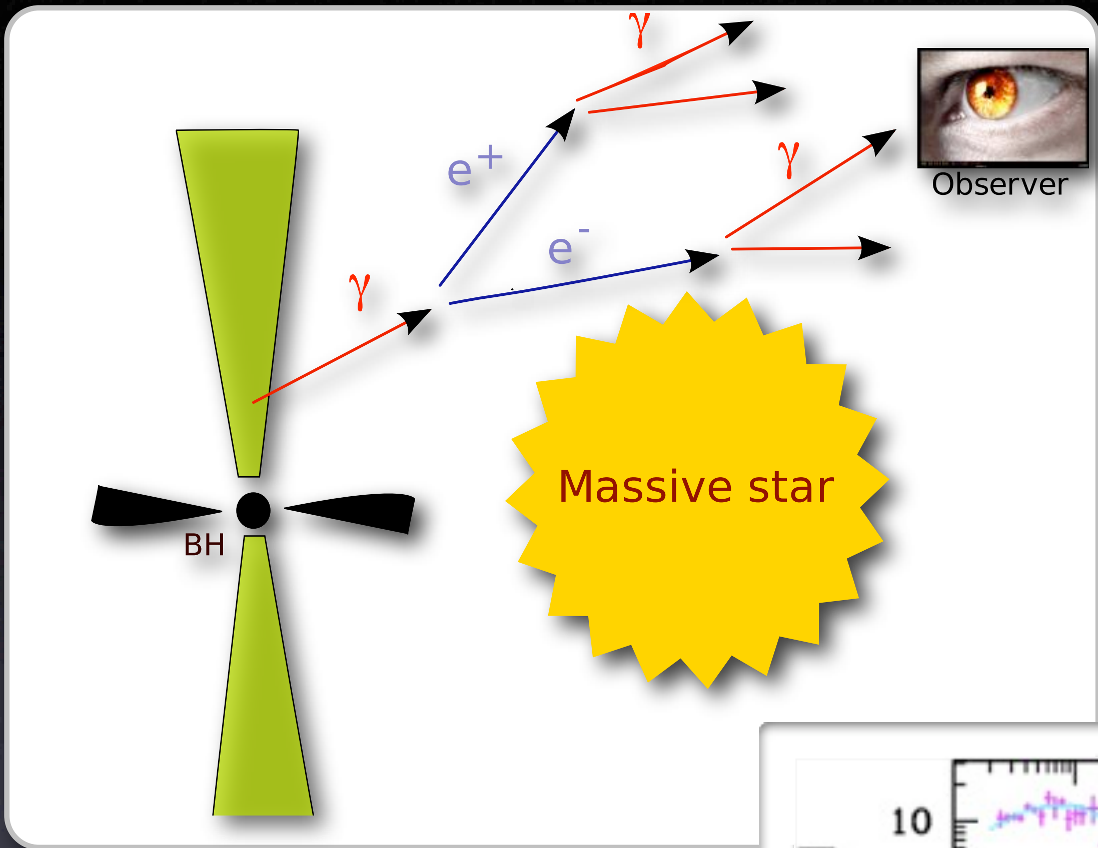

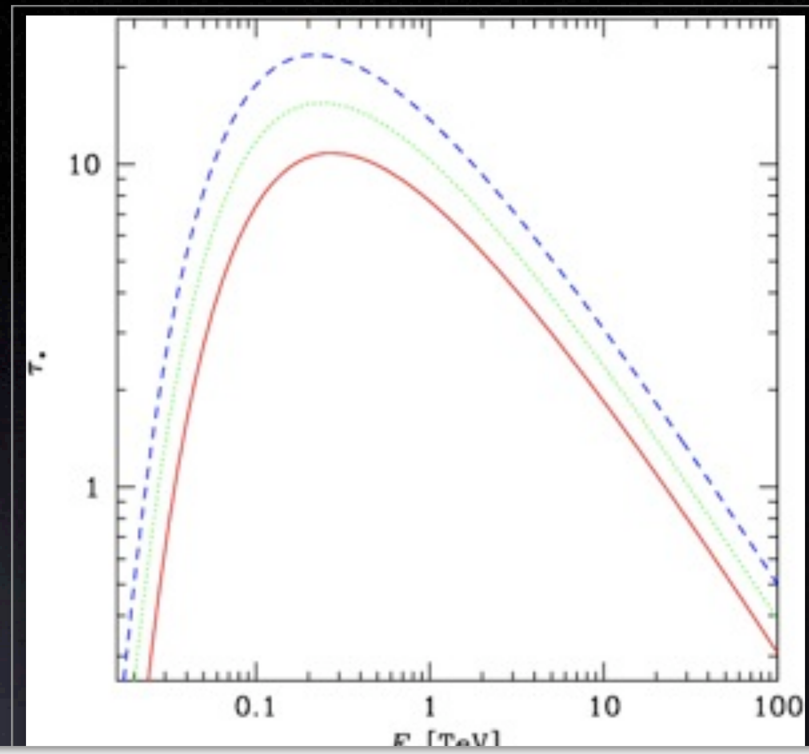

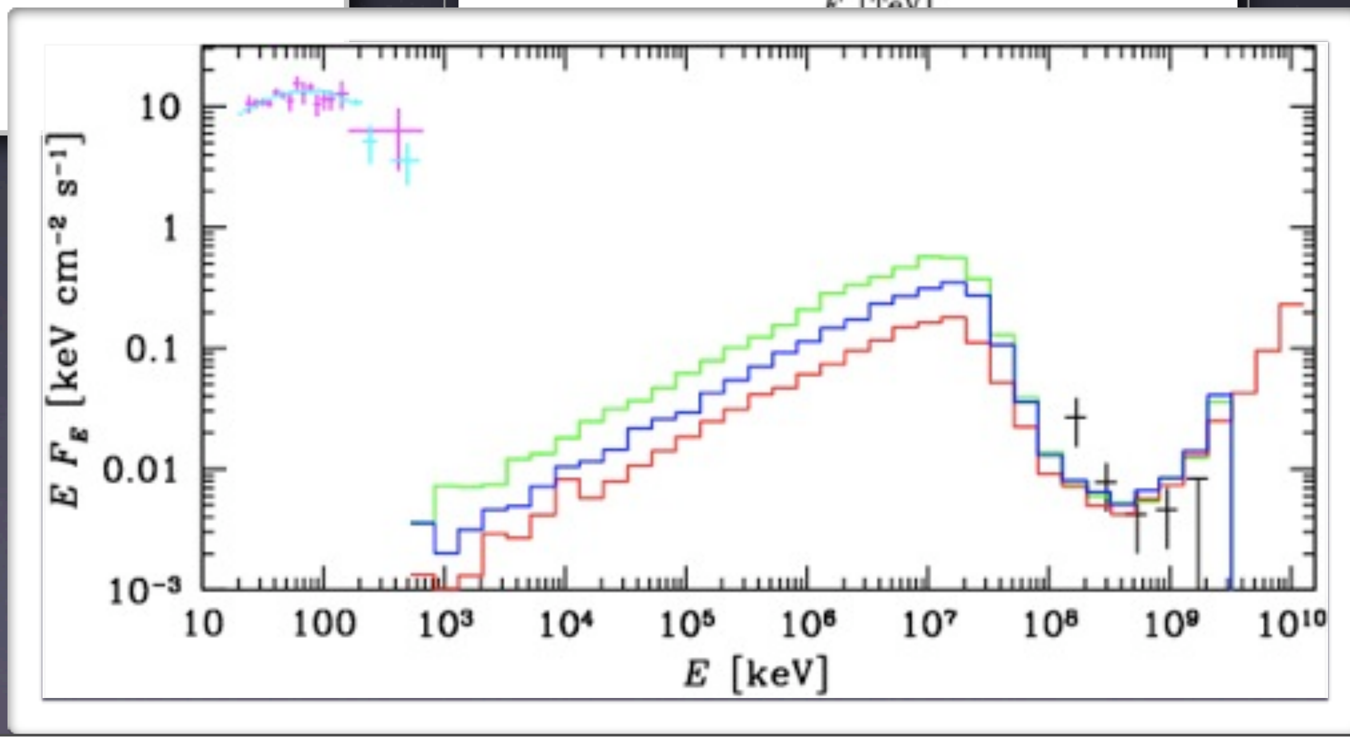

➡ spatially extended pair cascascades

(Zdziarski, Malzac, Bednarek, MNRAS, 2009)

Conclusions:

- Radio jet velocity appears to be mildly relativistic
- X-ray Jet models: appear to be ruled out

  (although jet may contribute to gamma-ray emission)
- Outflowing accretion disc corona:
  - corona not powered through magnetic dissipation
  - small mass loading on the jet
- Hot accretion flows models:
  - appear quite efficient
  - temperature of electrons and protons are comparable