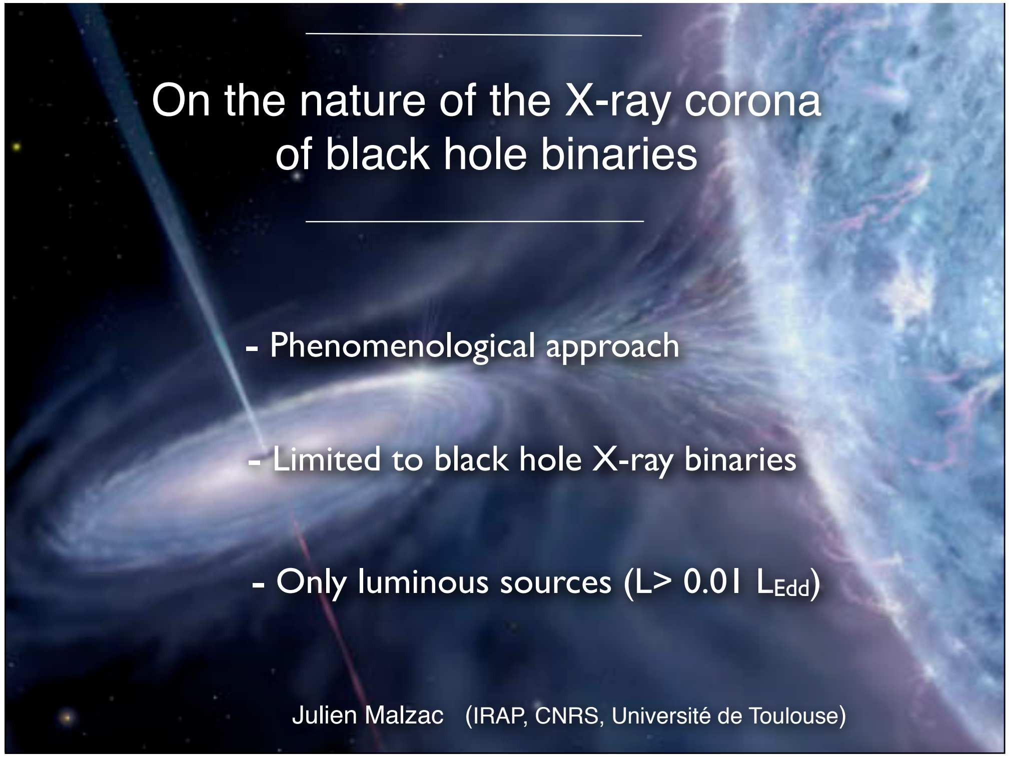
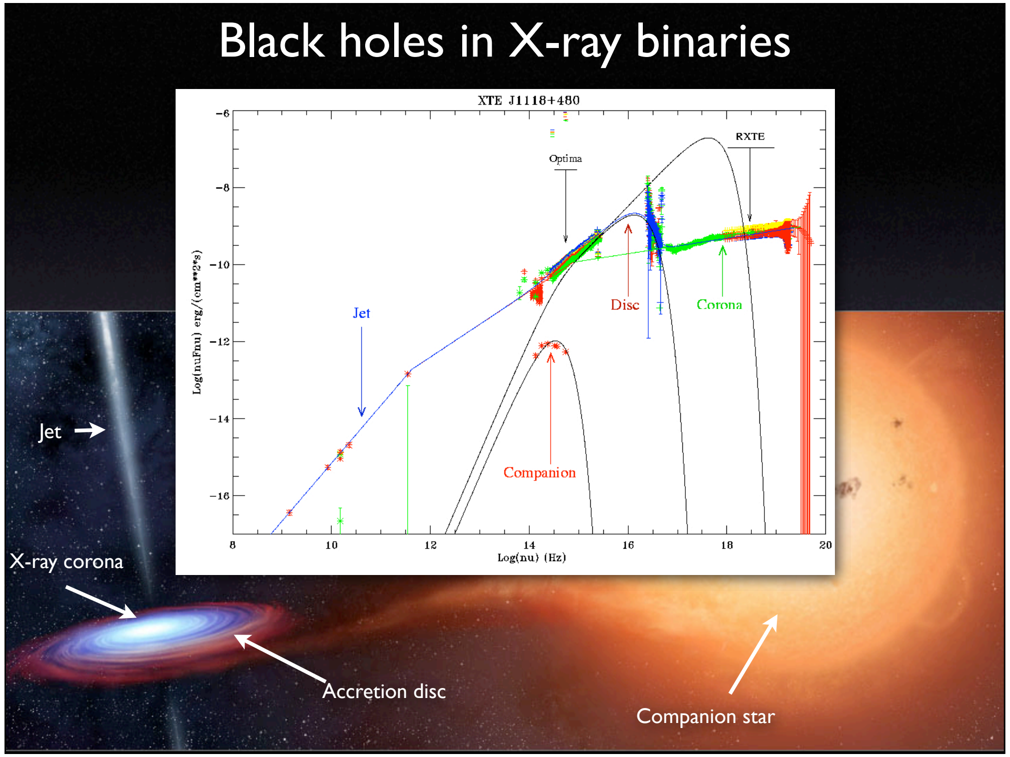


Cygnus X-1 is a famous black hole in a high mass X-ray binary system. It is one of the brigtes X-ray sources observable from earth which was was discovered in 1964 during a rocket flight.   It was the first dynamically proven black hole. In other words. By measuring the orbital velocity of the companion star it was infered that the mass of the compact object was about 10 solar masses, larger than the 3 solar mass upper limit for neutron star stability. And therefore this can only be a black hole. Since then it was observed by all the X-ray instruments sent into space but also at other wavelength. In particular Cygnus X-1 is associated with a rvariable adio source which shows interesting correlations with the X-ray activity. This radio source was more recently resolved annd shown to form a compact jet launched by the black hole. There are also claims of detection in the gamma-rays at GeV, TeV energies. So Cygnus X-1 is probably the most studied black hole. And the aim of this talk to illustrate how some of the very accurate data that are avaialble can help to contrain the physics of the accretion and ejection around a black hole.
And in fact I am going to show that none of the the current accretion model can fully explain the data.



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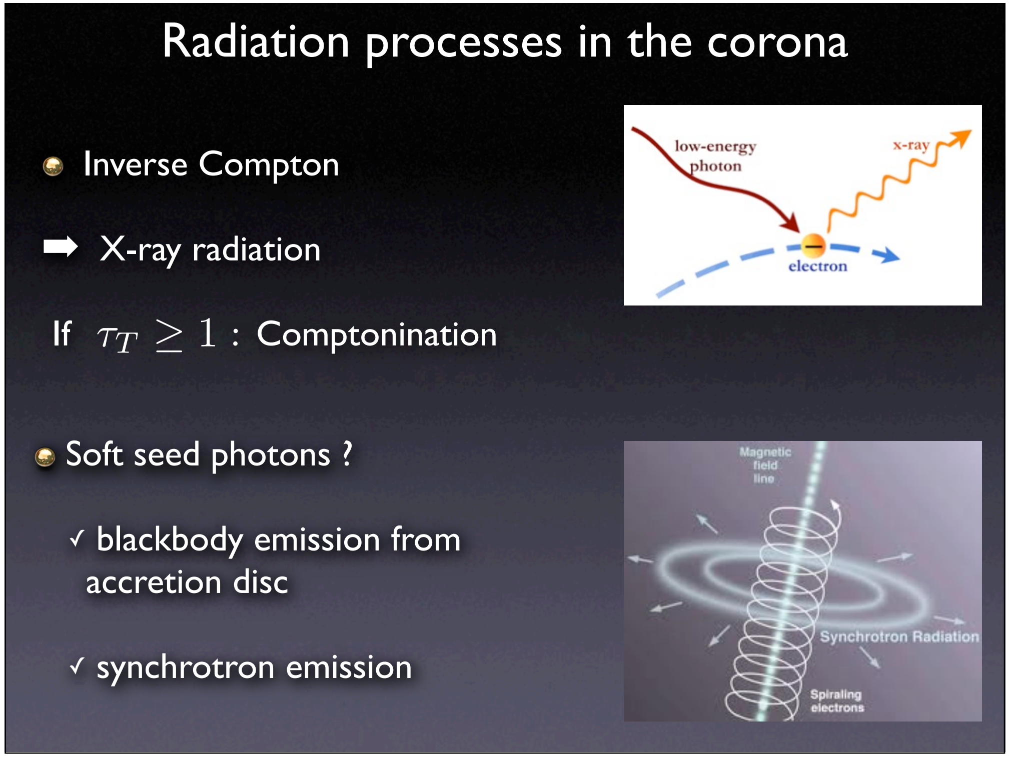

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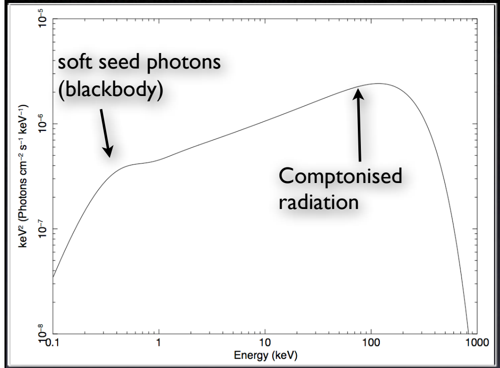
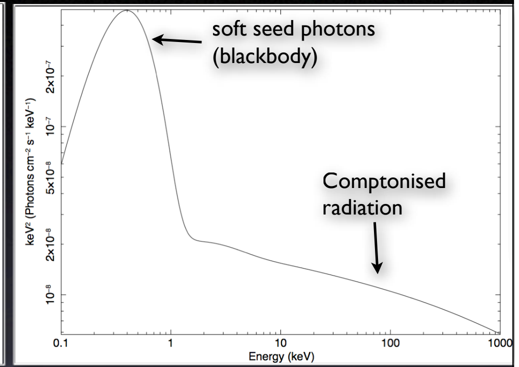
Comptonisation models

- Hard X-ray spectrum depends on electron energy distribution

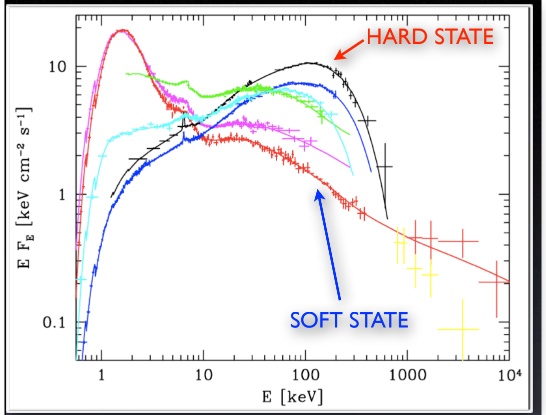




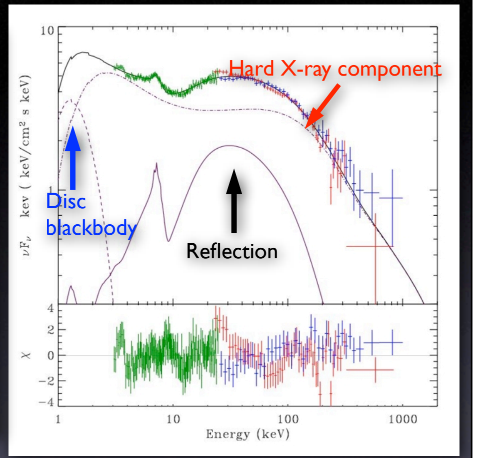
Thermal electron distribution (Maxwellian)

Powerlaw electron distribution

High energy emission of Cygnus X-1



Zdziarski et al 2003



Malzac et al. 2006

HARD STATE: (compact radio jet)
disc blackbody and reflection: weak / Corona: THERMAL Comptonisation

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

The main piece of information that we have are the high energy spectra. And you have here various nuFnu spectra observed in Cygnus X-1. You that the spectral shape is very variable although the luminosity of the bolometric luminosity of the source is rather stable around a few percent of the Eddington luminosity. There are 2 main spectral states. In the so call high soft state the spectrum peaks around 1 keV and is dominated by the thermal emission of the accretion disc at high energy there is a non-thermal quasipower law tail extenging up to at least a few MeVs. In the so called low hard state the sepctrum is formed by a hard power law peaking at around 100 keV with a sharp cut off above that.

These changes in spectral shape are believed to be caused by changes in the geometry of the accretion flow. In the hard state the accretion disc is not seen because it is truncated at large istances from the black hole and the emission
is dominated by thermal Comptonisation in a hot geometrically thick optically thin accretion flow. That is to say that ypou have hot plasma close to the black hole and the electron of thi hot plasma have a temperature tht can reach 10^9 K. In this plasma you alo have soft UV or soft X-ray photons coming from the external accretion disc or generated internally by synchrotron process. These soft photons are gradually upscaterred into the hard X-ray band due multiple Compton interaction with the electrons of this hot plasma. This produce this kind of hard state spectra.

In the soft state on the contrary the accretion disc goes very close to the black hole and dominates the hard X-ray spectrum. The non-thermal component is believed to be produced by Inverse compton of the soft disc photons on a poulation of non-thermal electrons in compact active regions located above and below the accretion disc. THe states transition would be triggered by changes in the mass accretion rate the soft states has a higher luminosity (by a factor 4)

Beside hard and soft state we also observe intermediate state when the source is about to switch from one to the other spectral state.

And in fact if we now consider in more details the modelling of these spectra we can see that all these spectra can be understood in terms of three main spectral components.
You have The disc black body and reflection component which is due to the illumination of the disc by the X-ray source and forms this bumps peaking around 30 keV and also the iron line peaking around 6.4 keV. And the hard X-ray component. The disk bb componnet and reflection are weak in the hard state and stronger in soft states.

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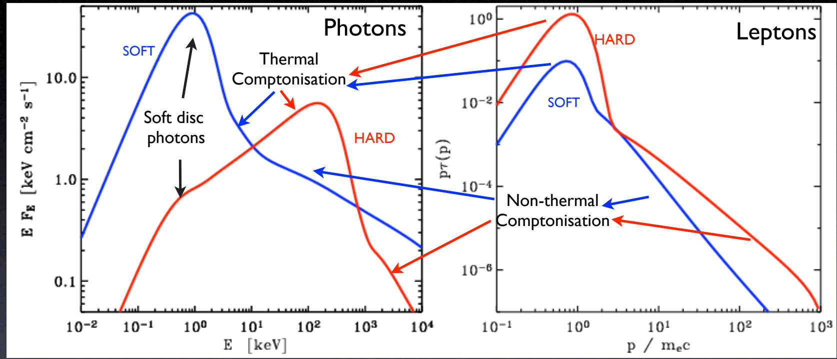
So all of these spectra are very well modeled by an hybrid thermal -non -thermla comptonisation.

Hybrid thermal/non-thermal comptonisation models



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

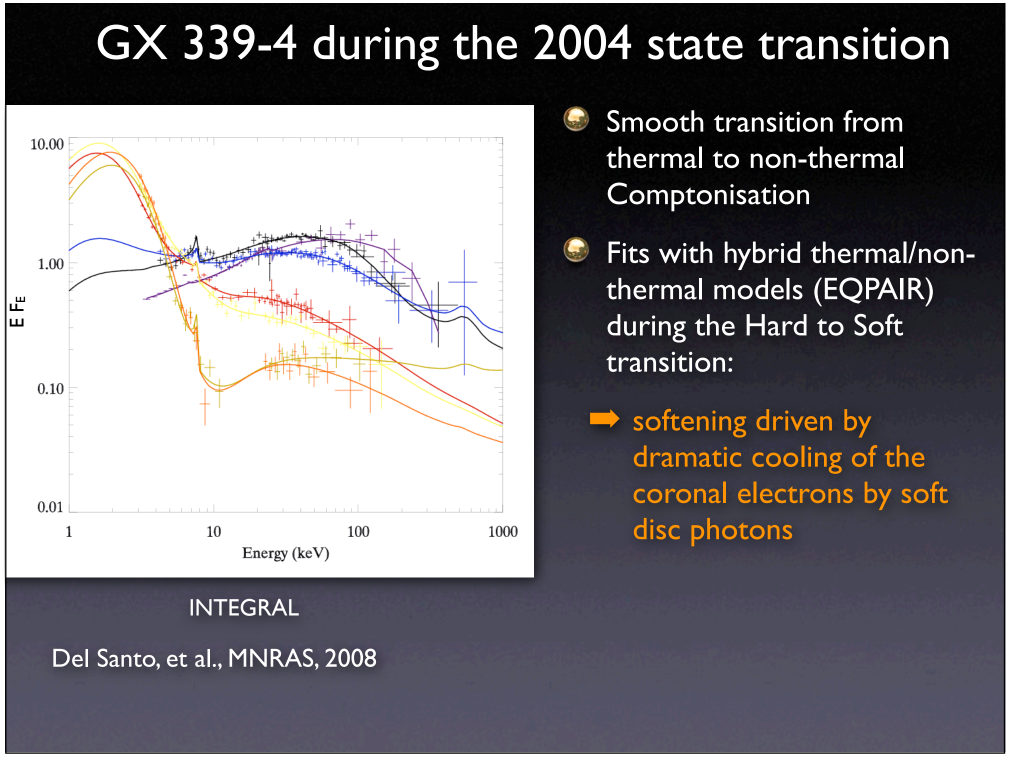
HARD STATE: kT~50-100keV, τ_T~1-3: Thermal comptonisation dominates
SOFT STATE: kT~10-50 keV, τ_T~0.1-0.3: Inverse Compton by non-thermal electrons dominates

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

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

These are the best fit models in the hard state and soft state. On the left this is the distibution of the Comptonising electrons. You see that the despite the very different
photon spectra, the distribution of comptonising leptons are quite similar in both states, formed by a quasi maxwellian at low energy and powerlaw tail at higher energy.

The main difference is that the electron temperature and optical depth are higher in the hard state making the emissivity of the thermal electrons much larger, so that the X-ray emission is dominated by the thermal electron. While in the soft state this thermal emission is barely detectable. And the high energy spectrum is dominated by the non-thermal comptonisation.



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Similar results are obtained in other sources like GX 339-4 which was monitored by INTEGRAL durng its 2004 state transition.
HEre you see the smooth transition from an essentially thermal to non-thermal comptonisation spectrum which occurs at the same time as the disc thermal luminosity increases.

Spectral fits with hybrid thermal comptonisation model suggest that the softening could be associated with the cooling of the corona by the soft disc photons (while the coranal luminosity remains rough ly constant. During the hard to soft transition the temperature of the comptonising electrons decreases due to the enhanced soft photon flux from the disc. As a consequence, the peak of the thermal Comptonisation spectrum deacreases both in luminosity and energies, leaving a non-thermal power emission.

power law in all states (detected when statistics is good enough)
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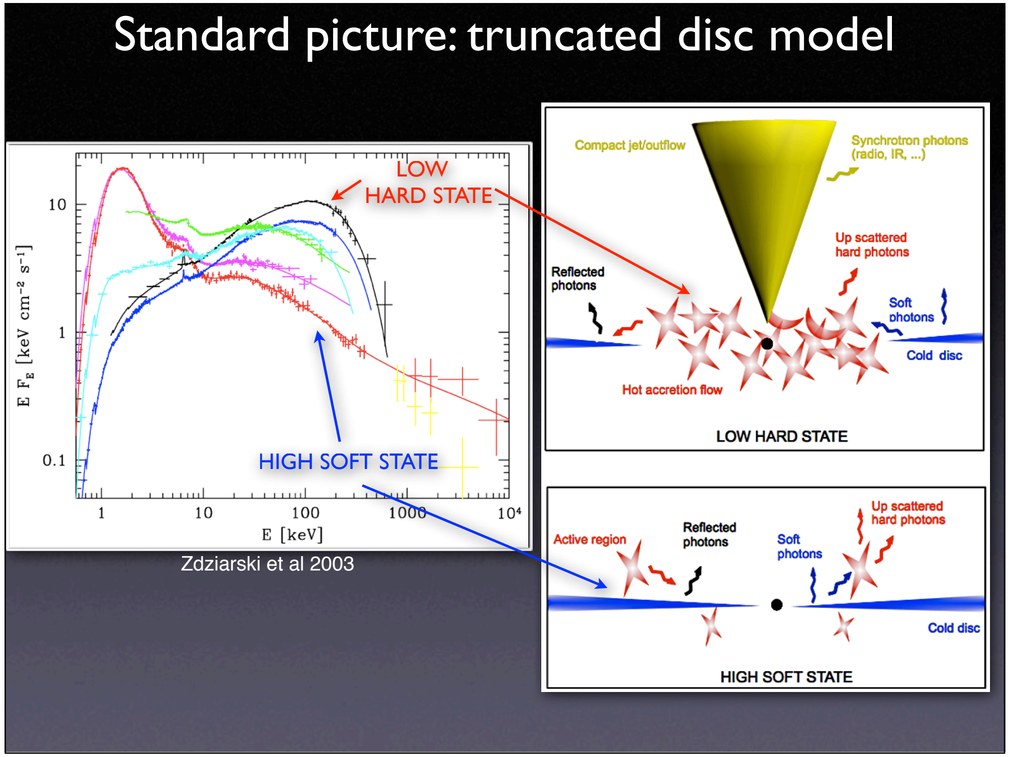

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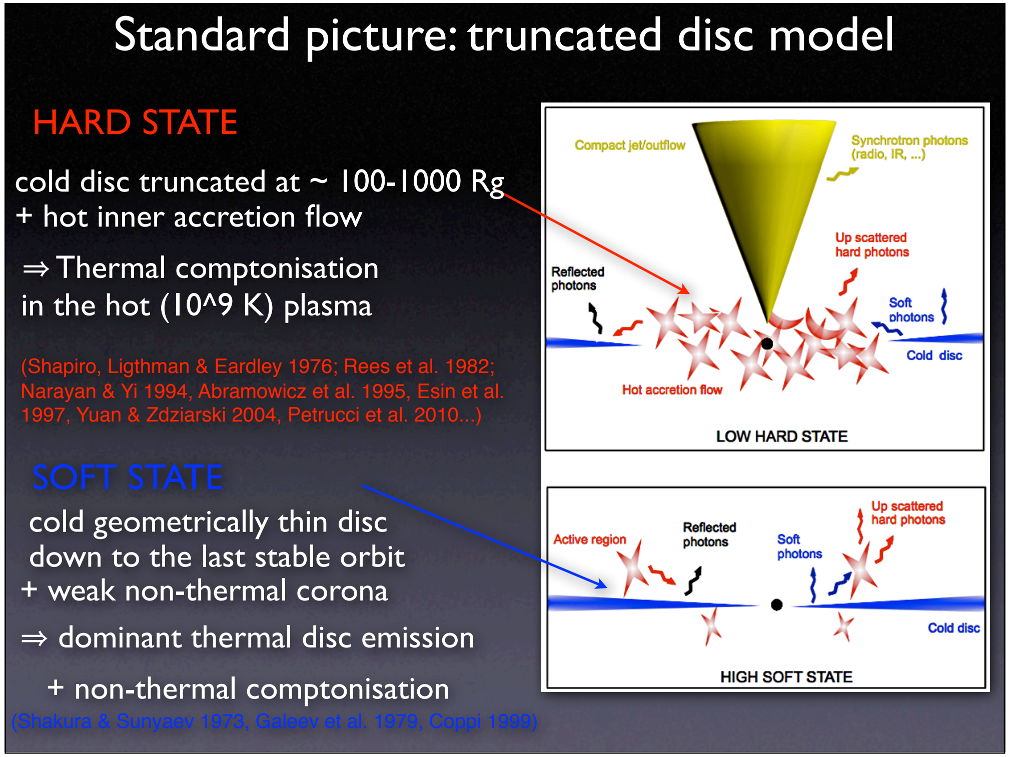

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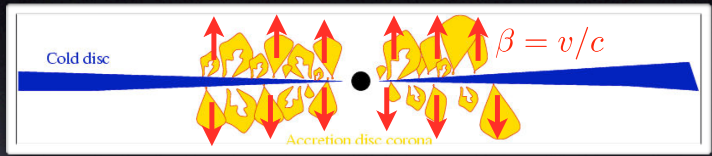
Alternative models for the hard state

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

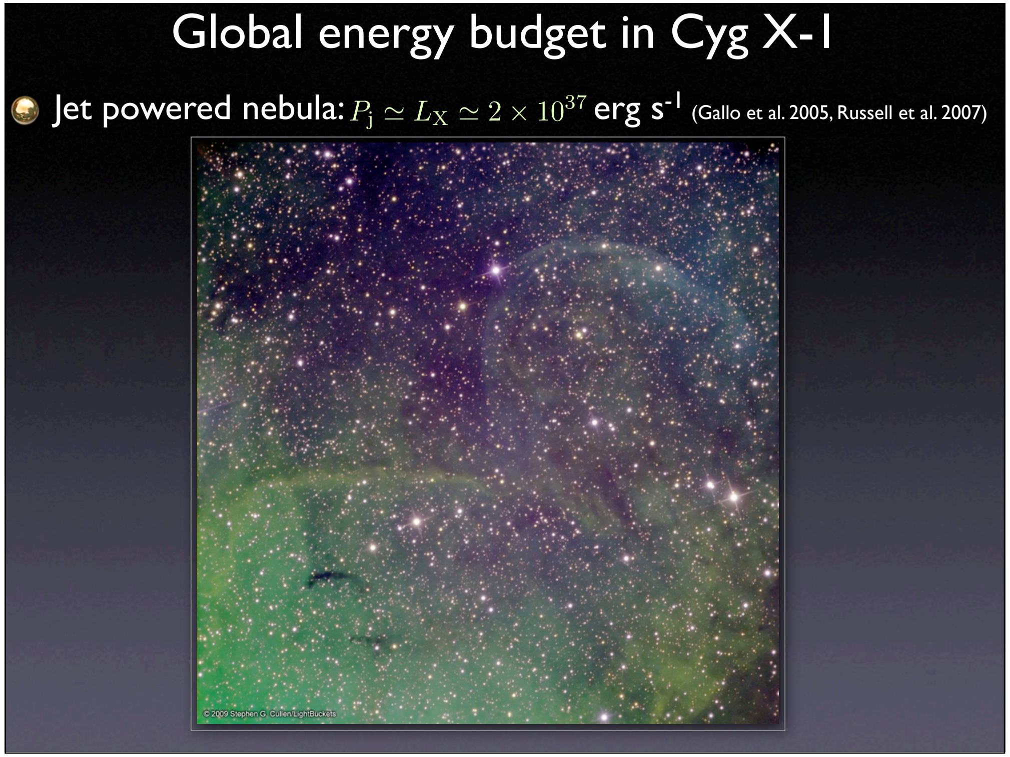


(Beloborodov 1999; Malzac Beloborodov & Poutanen 2001)

- X-ray Jet Models

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

There are however indication that the disc may not be truncated in the Low hard state t(his will be disccussed later on by R Reis) . If so the hard emission of the hard state could be produced in an accretion disc corona similar to that of the soft sate.
Beloborodov pointed out that due to the anisotropy of the energy dissipâtion process and due to radiation pressure from the disc this corona is likely to be outflowing away from the disc with mildly relativistic velocities. In this framework the hard state spectrum of Cygnus X-1 could be produced in compact active regions of scaleheight of order unity moving away from the disc with a velocity of about 30 percent of the speed of light.



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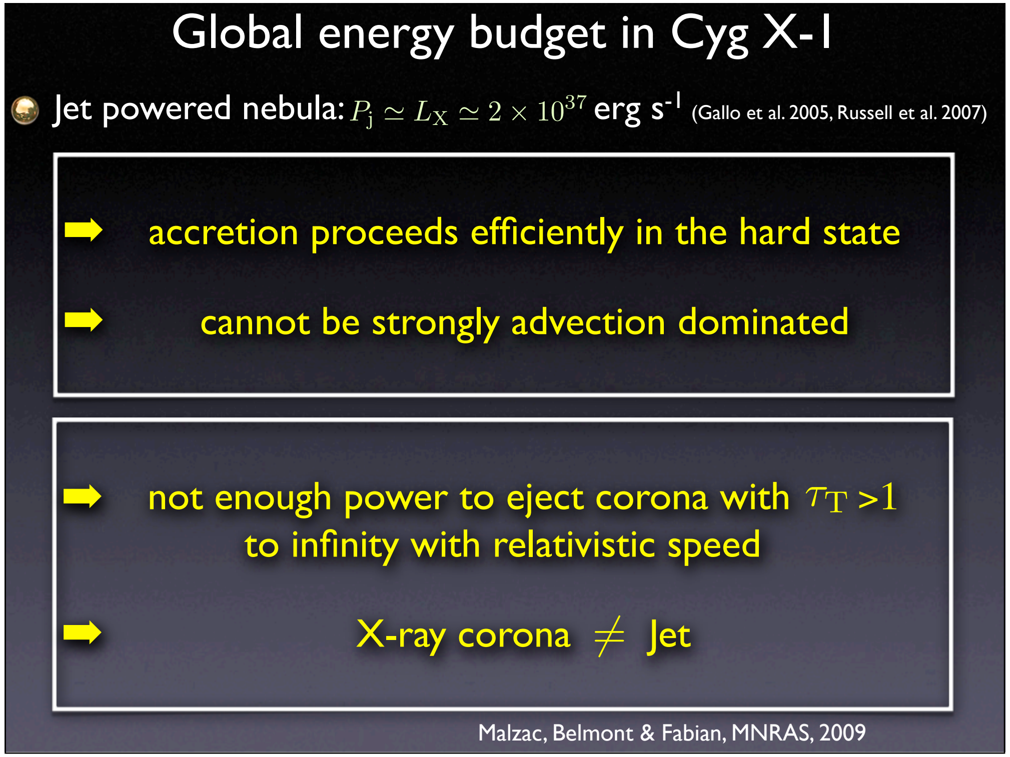
Global energy budget in Cyg X-1

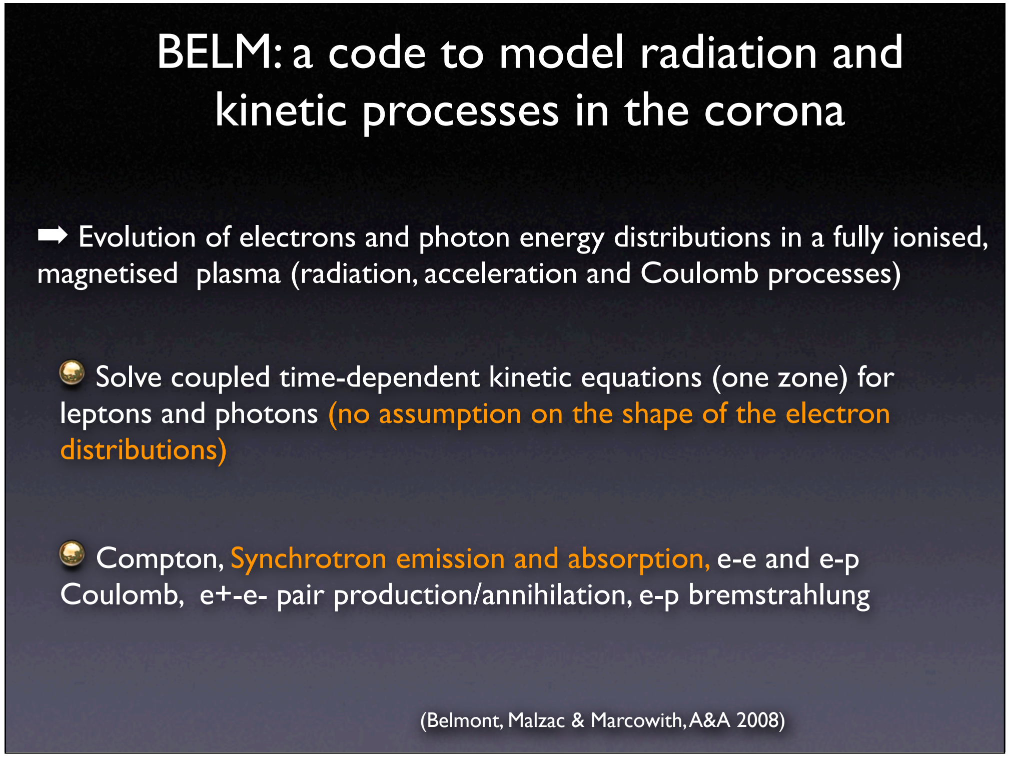
- Jet powered nebula: $P_{\mathrm{j}} \simeq L_{\mathrm{X}} \simeq 2 \times 10^{37}$ erg s^{-1} (Gallo et al. 2005, Russell et al. 2007)



I would like to point out briefly that the jet power estimated by Elena Gallo and her collaborators, obtained from the jet powered optical nebulas surrounding the source has interesting consequence for accretion and ejection model.
Indeed, based on rather simple energetic arguments and for a few reasonable assumption that I have no time to explain now. This estimate it implies that the jet velocity is at least mildly relativistic most likely in the range 0.3 0.8c.
Moreover it implies that accretion porceeds efficiently in the hard state and therefore the accretion flow cannot be strongly advection dominated.

Finally it also implies, for eneretics reasons that the X-ray emission cannot be produced in the jet.

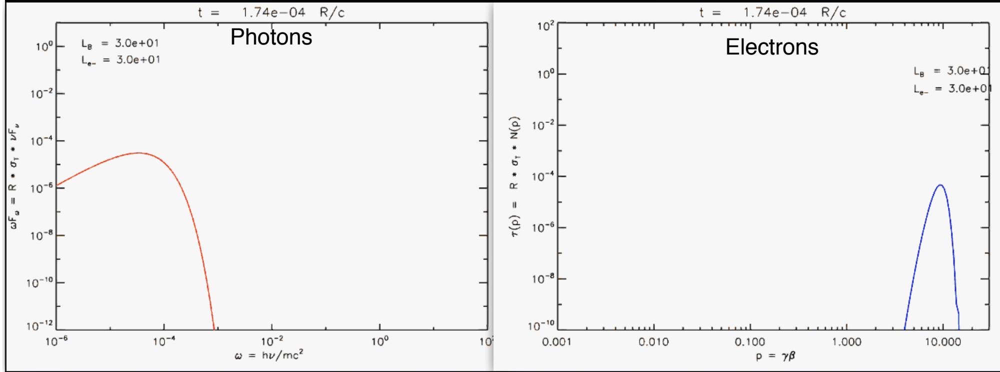
You can find all the detail in this paper that is on the astro-ph



In order to constrain and aybe discriminate among these model we have developped in Toulouse a new code to study radiation and kinetic processes in the X-ray corona

The Synchrotron boiler

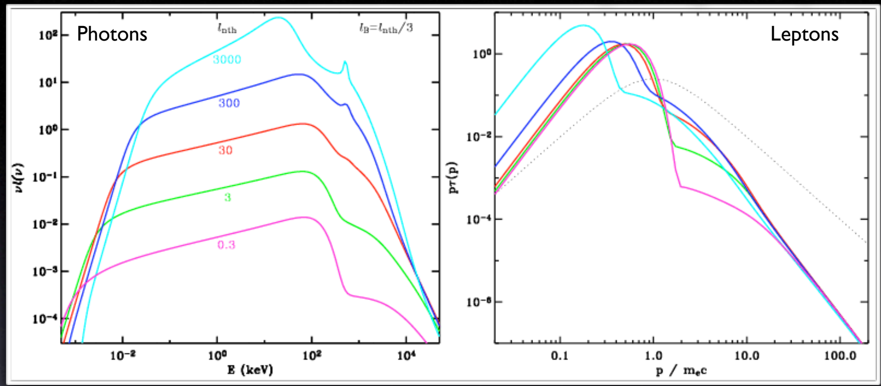
(Ghisellini, Guilbert and Svensson 1988)



- 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)

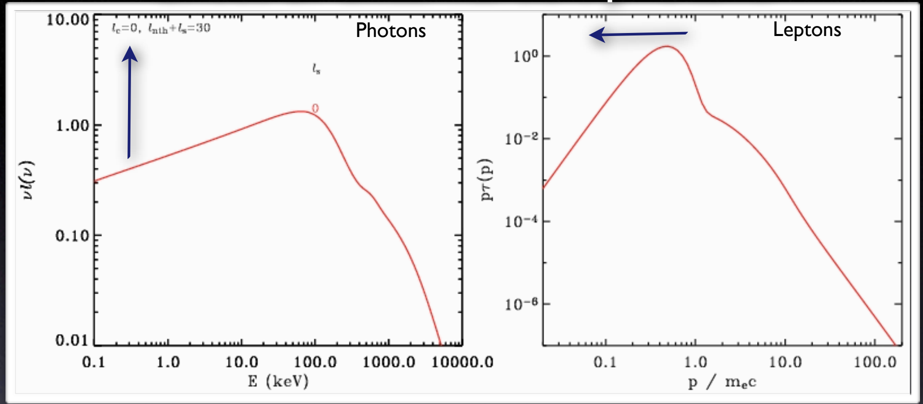


- Magnetic field B at ~equipartition with radiation, $l_B=(\sigma_T/m_ec^2)$ R B^2/(8π)
- Continuous POWER-LAW electron injection $\Gamma_{inj=3}$, $l_{nth}= (\sigma_T/m_ec^3)$ L/R
- ➡ Cooling and thermalisation through synchrotron self-Compton + e-e Coulomb
- ➡ Equilibrium distribution: Maxwellian+ non-thermal tail
- ➡ spectra look like hard state !

(Malzac & Belmont MNRAS 2009)

The equilibrium temperature is the consequence of the balance between synchrotron anc Compton losses and heating by coulomb interaction with non-thermal electrons and synchrotron absorption of soft radiation

Effect of external soft photons



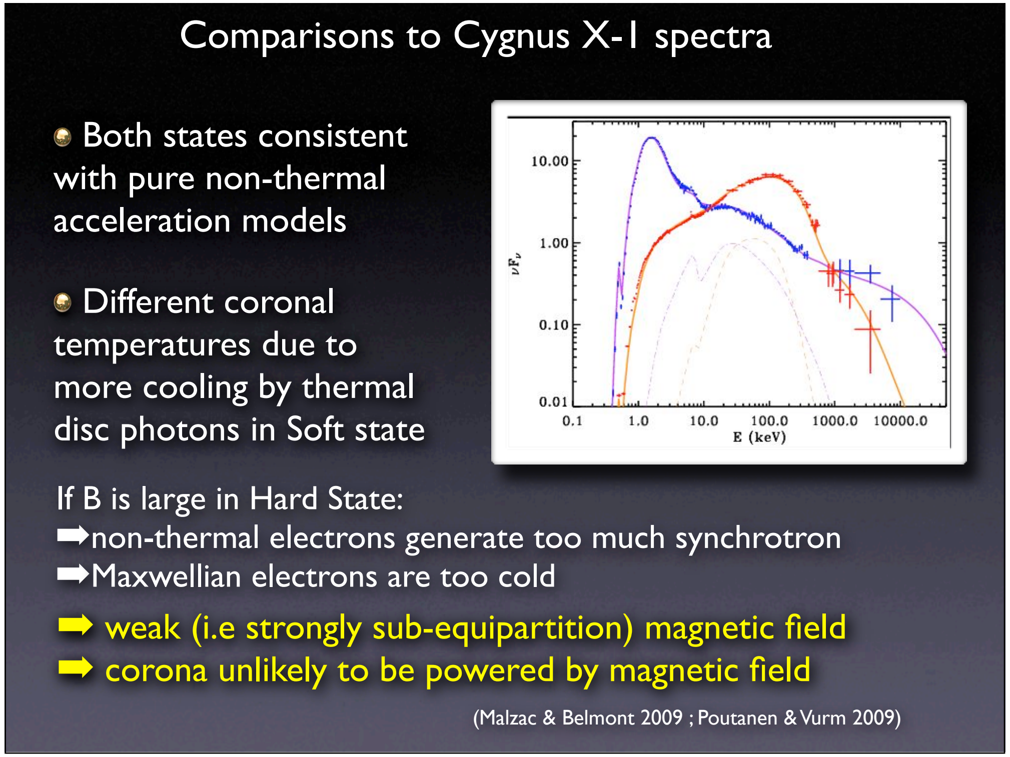
- Add soft thermal photons:

➡ temperature of Maxwellian electrons decreases

➡ Compton emission increasingly dominated by non-thermal electrons

➡ looks like a state transition!

(Malzac & Belmont MNRAS 2009)



We compared the result of our simulation directly with observed spectra of Cyg X-1 and found that indeed
both spectral states are consistent with a similar non-thermal acceleration process
and that the differences that we observe are essentially due to a change in the cooling by the disc soft photons.

You do not have to assume that there is a thermal distribution in the hard state. The particles thermalize y themselve at the right temperature.

This also alowed us to put some constraints on the paramameters in the hard state like the magnetic field which must be low.
We find that the ratio of magnetic to radiation energy density in the source is lower than 0.3 which immediately implies that the X-ray emitting region cannot be powered by magnetic field. Which question accretion disc corona model based on magnetic reconnection.

We also tried to fit the spectra with models in which electrons and protons have a different temperature
as in two temperature accretion flow models like ADAFs. But we found that the temperature of the protons must be much lower than what is predicted in these model and the ratio of ion electroncannot exceed a factor of 10.

In the soft state magnetic field and proton temperature are much less constrained.
These results were obtained from a rough comparison of the model with CGRO data.

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):

- 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:

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

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

- 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)

WE can gt also some constraints on

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

➡ strong magnetic field

but...

- Non-thermal high energy excess ➡ weak magnetic field

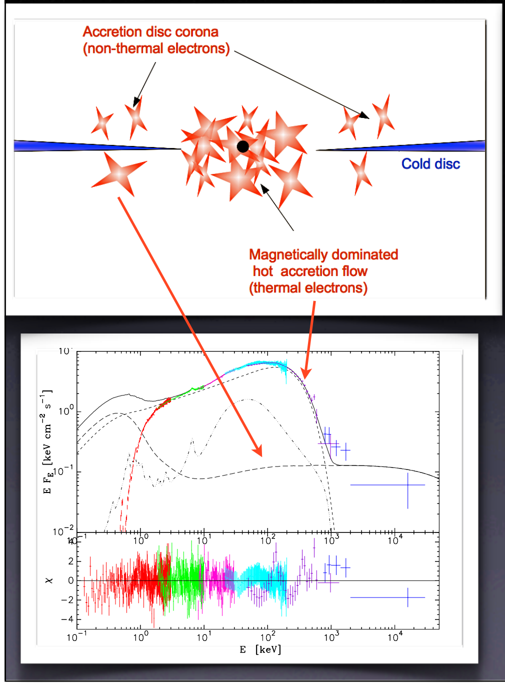
If B is large:
➡non-thermal electrons generate too much synchrotron
➡Maxwellian electrons are too cold

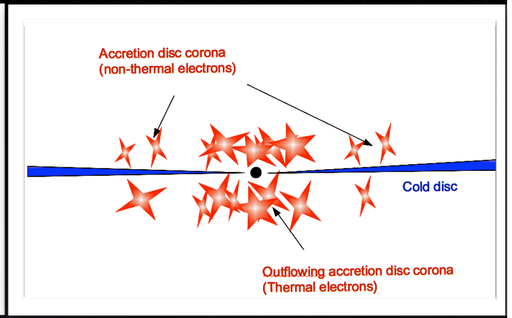
????

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

➡ multi-zone corona ?

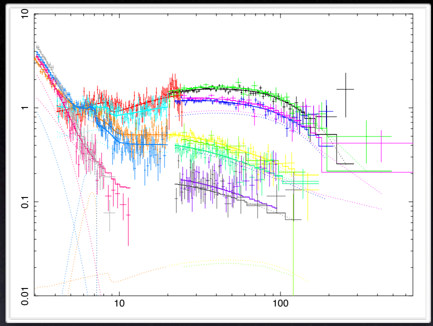
A two-component model for the LHS

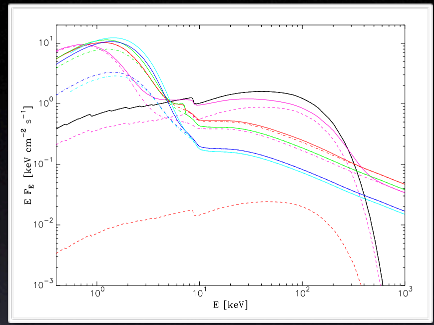




- Thermal comptonisation component dominates hard X-ray emission
- Non-thermal component reproduces soft X-ray excess and MeV emission

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
- 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

I let you read the conclusion.