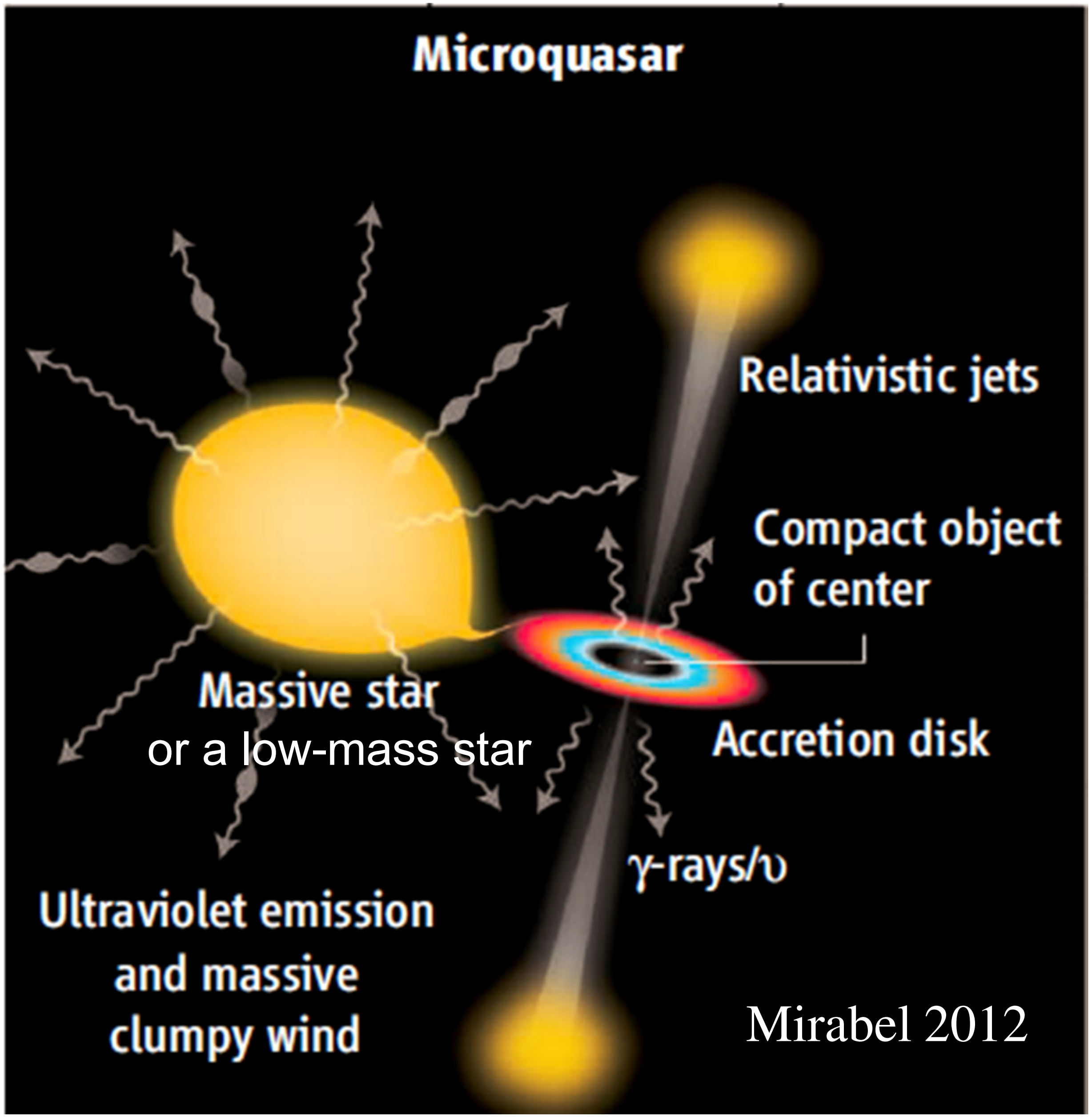
Global evolution of XrBs in outburst: theory

Andrzej A. Zdziarski
Centrum Astronomiczne im. M. Kopernika
Warszawa, Poland

Accreting stellar binary systems with a compact object (black hole or neutron star)



Mirabel 2012

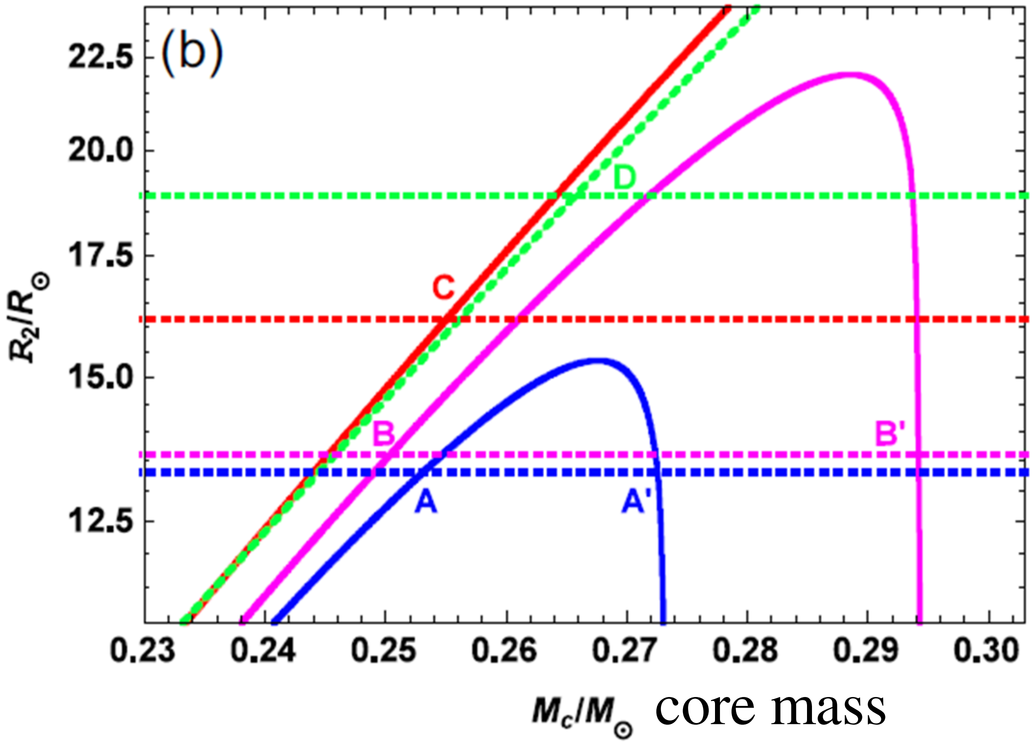
A sketch of an accreting binary. The donor can be either a high-mass or a low-mass star. Systems containing a black hole and a massive donor are persistent, and those with a low-mass donor are mostly transient. Those transient systems are called SXTs.

Donors and mass transfer

Accreting binaries containing a low-mass star accreting onto a black hole

- The donors are either stars of the luminosity class III (giants), IV (subgiants) or V (main sequence, dwarfs).
- Mass transfer driven by expansion of the donor, which fills its Roche lobe.
- A dwarf starts to expand at some stage, while still on the main sequence, which will drive the mass transfer.
- Subgiants and giants are stars which exhausted hydrogen in their cores while still burning it in a shell on the He core surface.
- The giant radius depends primarily on the core mass (only weakly dependent on the total mass). The radius increases with the core mass, which drives the mass transfer.

An example of an evolutionary solution for a giant:



- A, B, C, D correspond to the total mass of M_2=0.26, 0.28, 0.3 and 0.5M$_\odot$, respectively. The horizontal lines correspond to the Roche lobe radii. The luminosity also increases with M_2.
- The mass transfer rate can be expressed as $\dot{M}_2 = \left(\frac{\mathrm{d}R_2}{\mathrm{d}M_2}\right)^{-1} \frac{\mathrm{d}R_2}{\mathrm{d}M_\mathrm{c}} \dot{M}_\mathrm{c}$, where the 3 terms are the Roche radius vs. M_2, the above $R_2(M_\mathrm{c})$, and $\dot{M}_\mathrm{c}(L)$, respectively. Thus, we can calculate $\dot{M}_2$.

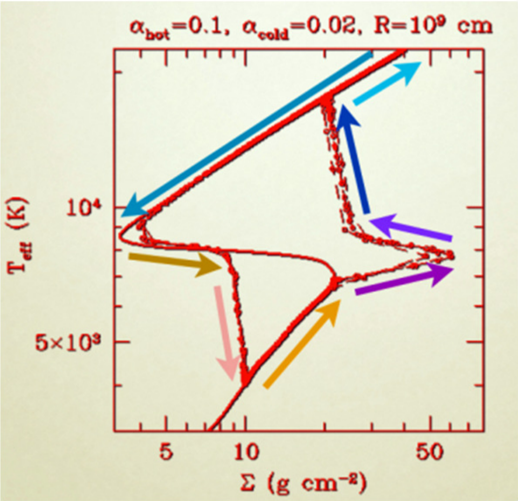
Some examples of $\dot{M}_2$ estimates

- GRS 1915+105: at the best estimate of $M_2 = 0.5 \mathrm{M}_\odot$, $\dot{M}_2 \approx 6 \times 10^{-9} \mathrm{M}_\odot/\mathrm{yr}$, and the duty cycle (the fraction of the time spent in outbursts) ≈ 5% (Ziółkowski+AAZ 2017a).
- V404 Cyg: $\dot{M}_2 \approx 10^{-9} \mathrm{M}_\odot/\mathrm{yr}$ from the model, while $\dot{M}_2 \approx 10^{-10} \mathrm{M}_\odot/\mathrm{yr}$ from L during outbursts and the interval between outbursts (Ziółkowski+AAZ 2017b). A possible solution: most of the mass is not accreted but lost in disc winds (as observed by Muñoz-Darias+2016).
- GX 339–4: $\dot{M}_2 < 10^{-9} \mathrm{M}_\odot/\mathrm{yr}$ from the model (Muñoz-Darias+ 2008), while $\dot{M}_2 > 10^{-8} \mathrm{M}_\odot/\mathrm{yr}$ from L during outbursts and outburst interval. Possible solution: outbursts in GX 339–4 are so frequent that the irradiation of the donor leads to an additional increase of its radius.

The disc instability model (DIM)

The disc instability model (DIM)

- During quiescence, $\dot{M}_2$ from the donor forms a non-steady disc, with $\dot{M}$ ($< \dot{M}_2$) decreasing towards the compact object. Thus, mass accumulates in the outer disc. The disc is cold, $T < 3\times10^3$ K or so, and H is neutral. The viscosity parameter is $\alpha_{\rm cold} \approx 0.02$ (but its nature unknown, not MRI).
- At some point in the disc, T increases above that for H ionization, which triggers a viscous/thermal instability, and an outburst starts. The instability leads to an increase of T to $> 3\times10^4$ K, and two heating waves start to propagate through the disc, one up and one down. The viscosity parameter becomes $\alpha_{\rm hot} \approx 0.1$.



- When the heating wave reaches the inner disc edge, $\dot{M}_{\rm in}$ increases by several orders of magnitude, which drains the disc, the system goes through a sequence of luminous states, and finally returns to quiescence.

The disc instability model (DIM)

The above model fails for SXTs on several grounds.

- It predicts all LMXBs to be transient, while many NS ones are persistent.
- The timescales for outbursts and recurrence are too short.
- The decay is too fast and dominated by reflares (not observed).
- The observed outburst fluences and the quiescent accretion rates are much too low if the quiescent disc extends down to the ISCO. Also, a disc extending down to the ISCO cannot explain the observed quiescent X-ray luminosities.

The disc instability model (DIM)

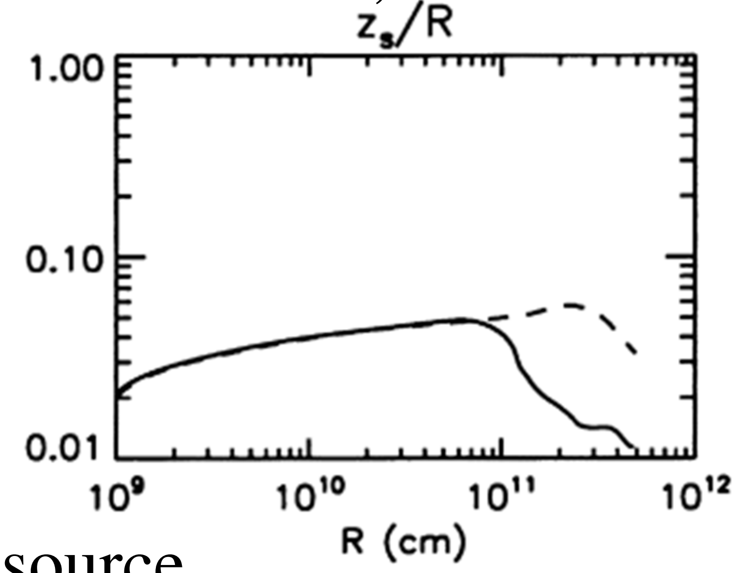
This DIM for SXTs has to be thus modified:

1. Since BHs and NSs have much deeper gravitational potentials than WDs in CVs, the emission from the central region is much brighter, and thus the irradiation of outer regions can be much stronger. Including irradiation stabilizes discs during outbursts and makes the outbursts longer.
2. The disc in quiescence has to be truncated at a radius $\gg r_{\rm ISCO} \sim 10^4\, r_{\rm g}$. This allows for much larger quiescent accretion rates. The region below the disc inner radius can be an ADAF, which explains the X-ray emission.

The disc instability model (DIM)

Both modifications have their problems. Irradiation:

- As shown by Dubus+1999, the shape of the disc in self-consistent solutions is concave (rather than convex, as in the Shakura-Sunyav model):



- Thus, the disc self-shields the central source.
- However, observations ***require*** irradiation.
- Solutions: scattering in an outer corona or disc warping.

The disc instability model (DIM)

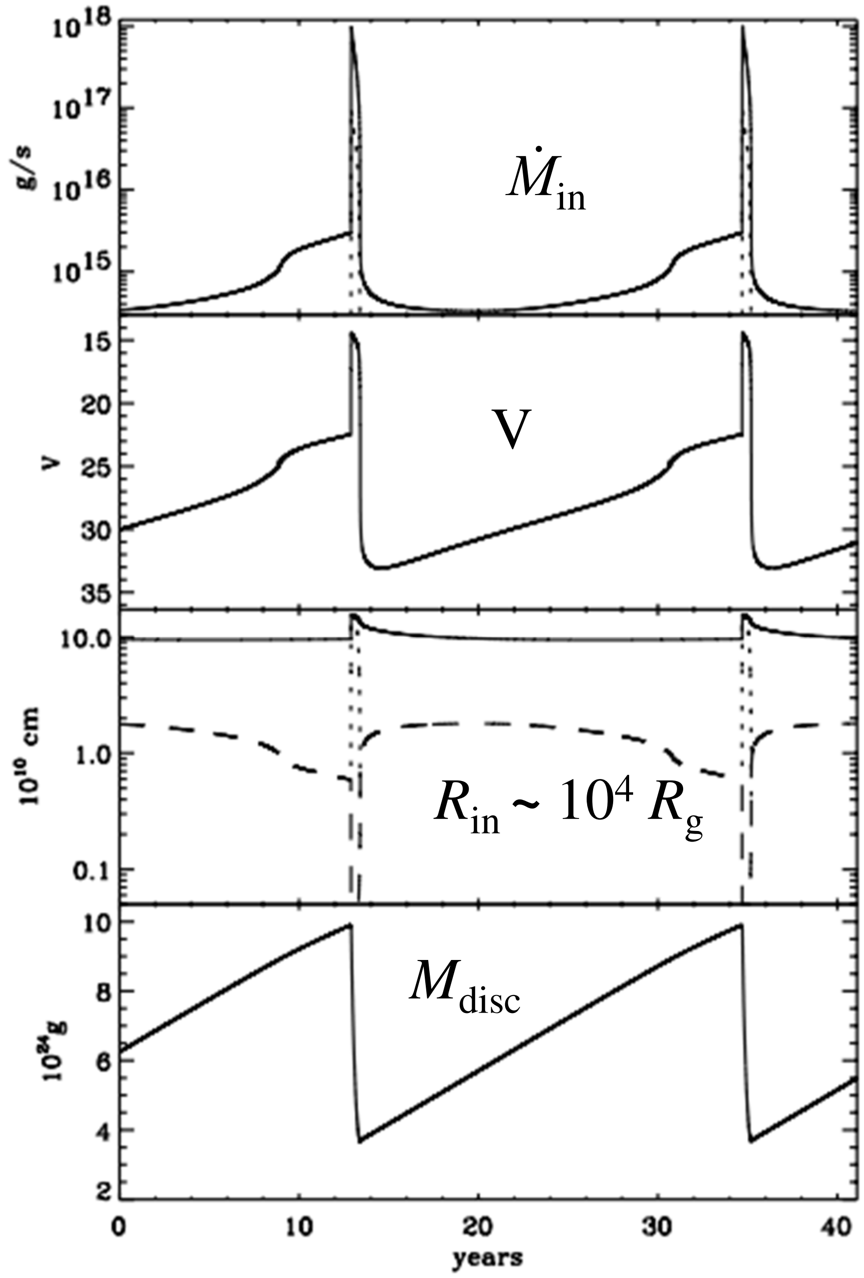
Disc truncation:

- The formula for the truncation usually assumed (Menou+2000) in SXT DIM models is ad hoc:

$$\dot{M}_{\mathrm{ev}}(R) = 0.08\dot{M}_{\mathrm{Edd}}\left[\left(\frac{R}{R_{\mathrm{s}}}\right)^{1/4} + \mathcal{E}\left(\frac{R}{800R_{\mathrm{s}}}\right)^{2}\right]^{-1}$$

- The usual explanation for the truncation is disc evaporation due to, e.g., electron conduction between disc and corona (Meyer & Meyer-Hofmeister 1994; Liu+ 1999; Różańska & Czerny 2000).
- However, the evaporation rates depend on a number of parameters that are not easily measured.

The disc instability model (DIM)

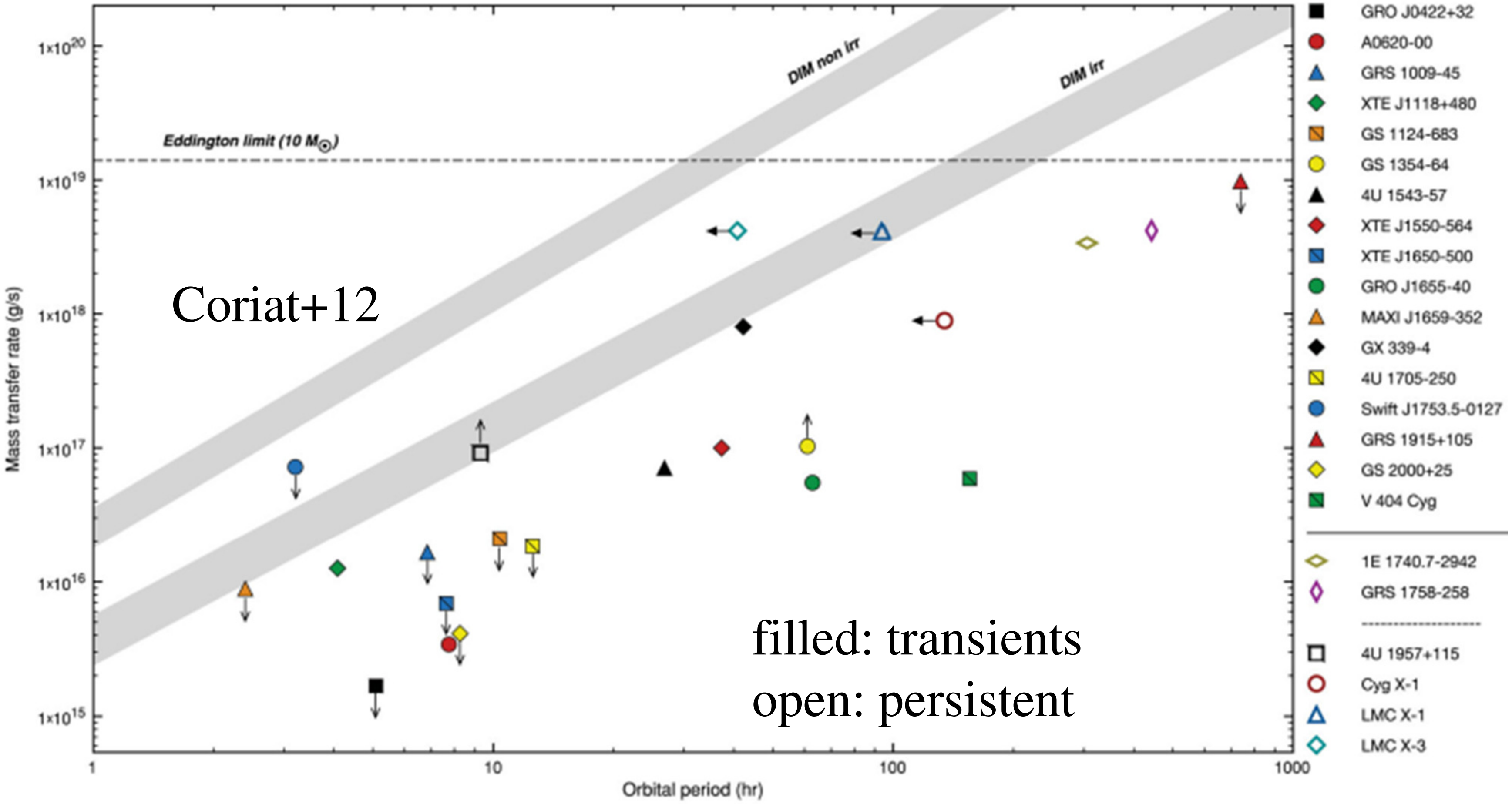


Dubus+2001

$R_{\rm out}$ (solid)

Unfortunately, this particular model assumes the minimum disc radius of 10^9 cm, so the disc evolution down to the ISCO was not followed.

A test of DIM: the critical $\dot{M}_2$ dependent on the disc size:



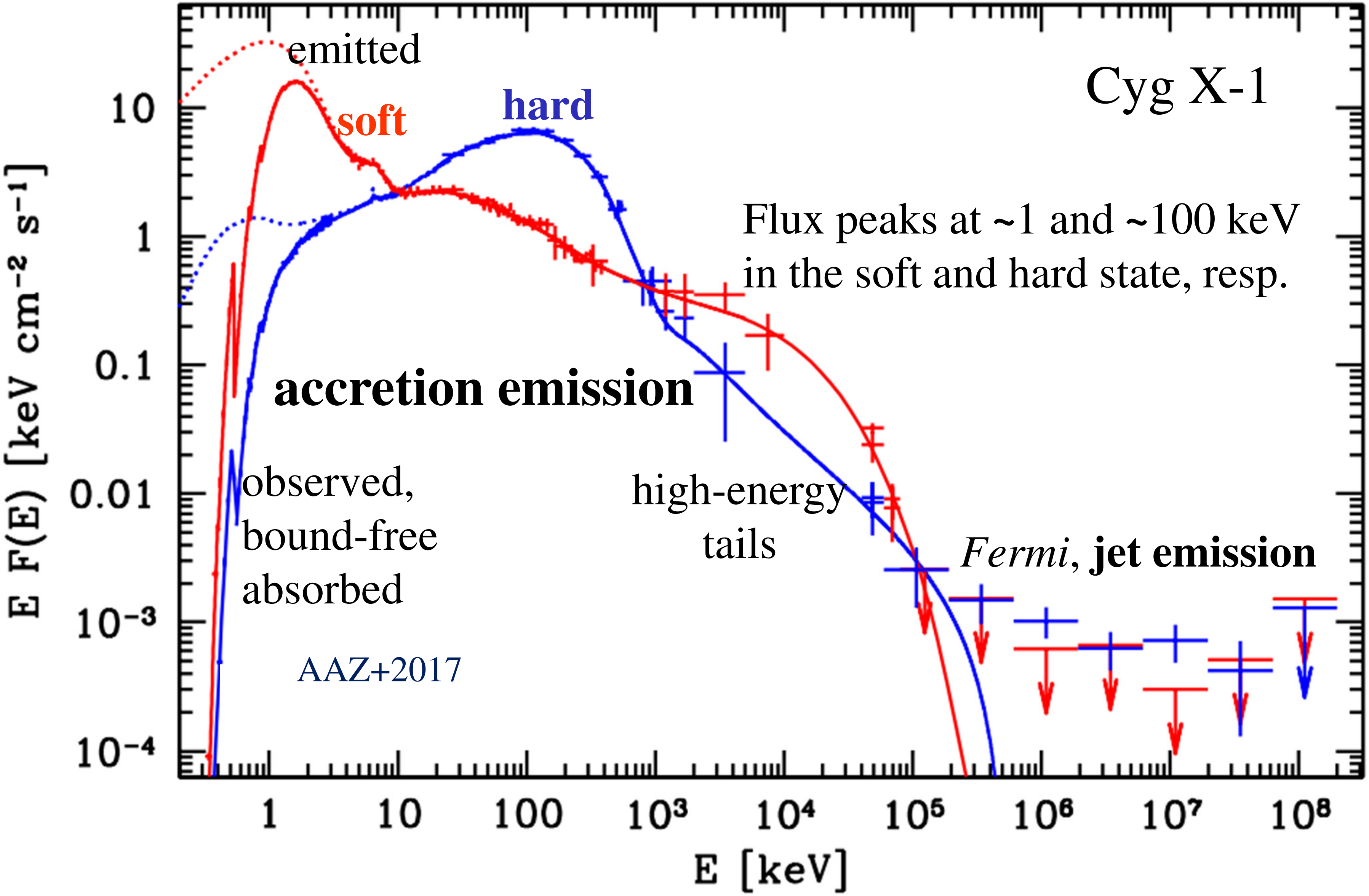
Coriat+12

filled: transients
open: persistent

The core prediction of the irradiated DIM is mostly satisfied. Cyg X-1 is here predicted to be transient, but its disc size is ≪ that in LMXBs (wind accretion). The only problems: 1E 1740.7 and GRS 1758, which may be transient in long outbursts (similar to GRS 1915).

Spectral states and hysteresis

Both transient and persistent black-hole binaries show two main luminous states, hard and soft



An example of the outburst light curve: two main spectral states and hysteresis.

Hard-to-soft transitions can occur at much higher L than soft-to-hard ones. The soft-to-hard transition occurs at similar L in different sources/outbursts.

L_{hard} up to **≈2–30% L_{Edd}**.
L_{soft} down to ≈1–2% L_{Edd}.

GX 339–4

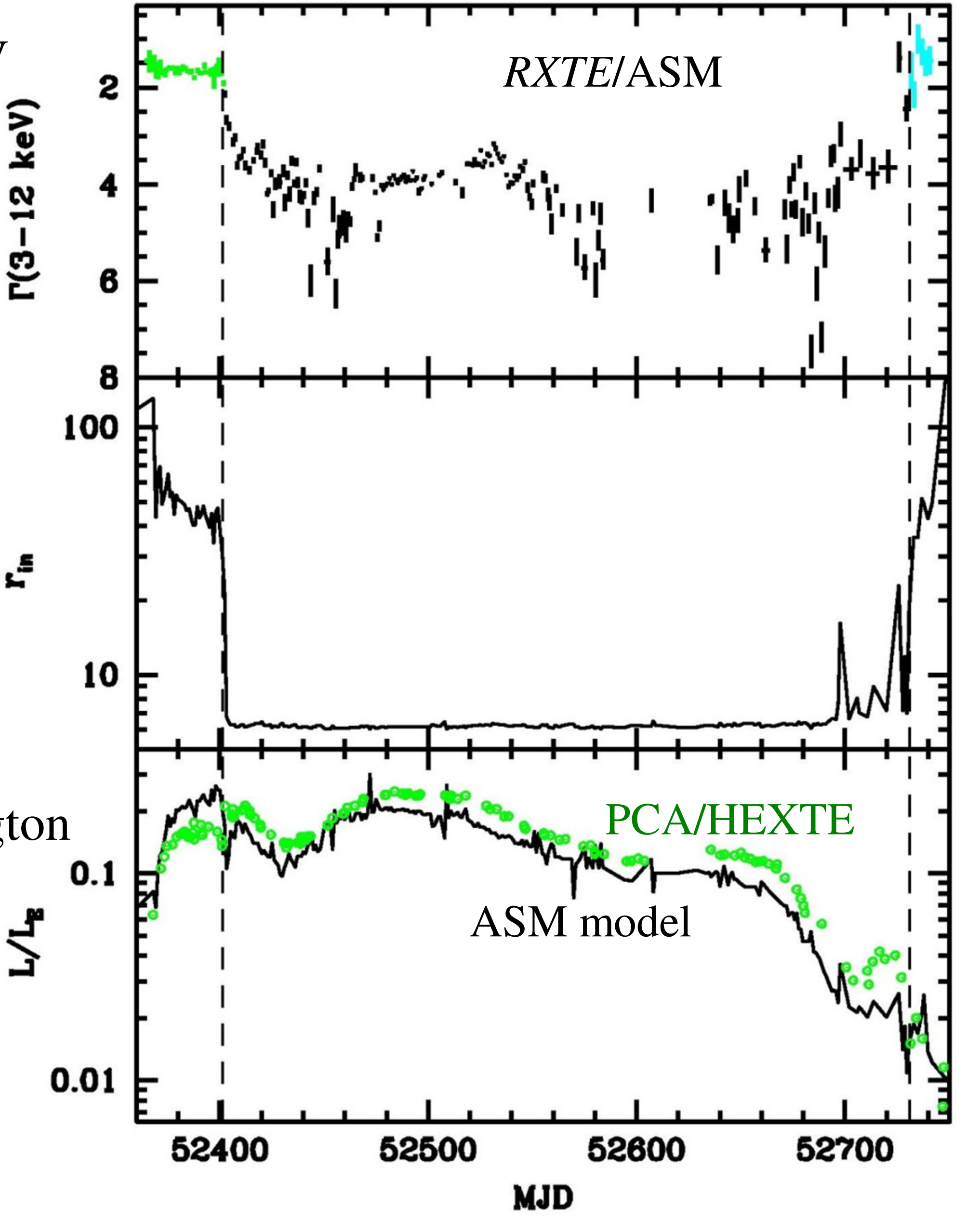
hard-to-soft

soft-to-hard

3–12 keV index

inner disk radius GM/c^2

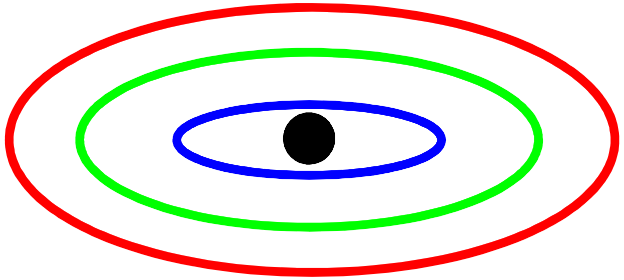
Eddington ratio

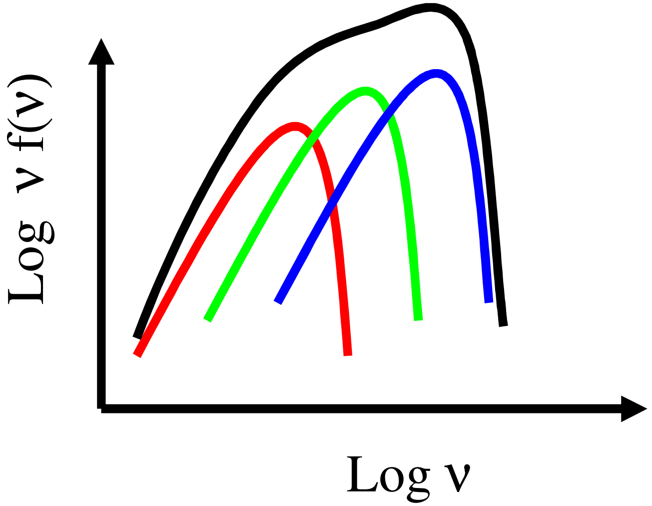


AAZ+ 2004

Soft state: standard disc accretion

- Keplerian orbits, differential velocity, inner edge faster than outer edge.
- Frictional viscosity (MHD dynamo) transports angular momentum out so that material can fall inwards.
- Gravitational energy radiated as blackbody (Shakura & Sunyaev 1973).
- Robust optically-thick spectra; kT_e ~1 keV, 10 eV (BHB, AGN) at $L/L_{\rm Edd} \sim 1$.





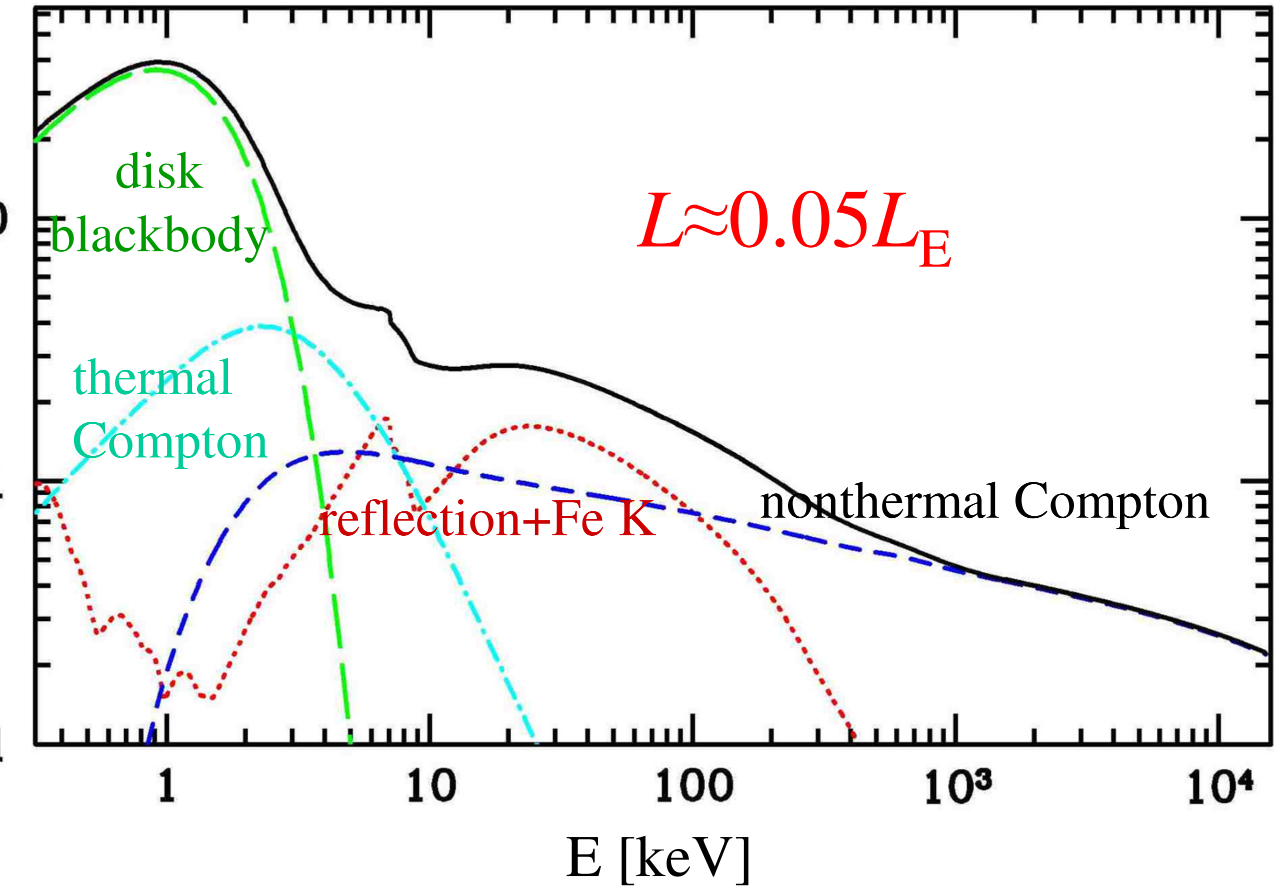
The soft state

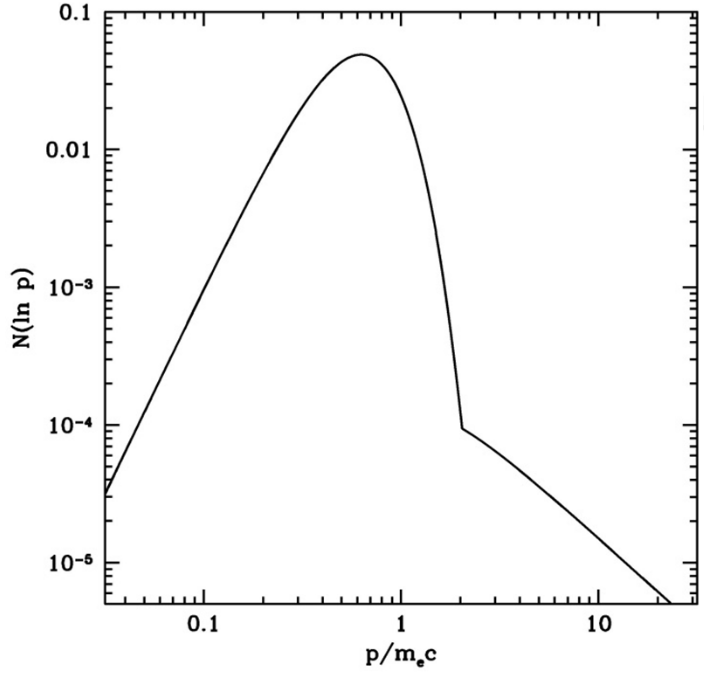
- Blackbody (with a colour correction) emission of an optically thick disc extending to the innermost stable circular orbit, ISCO (stability of r_{in}); $L \propto T^4$ in most cases.
- The blackbody emission is stable, almost no variability. This disagrees with the SS73 accretion disc model, but it agrees with some simulations.
- The blackbody is often followed by a variable high-energy tail from Compton upscattering of the blackbody photons by relativistic electrons with a non-thermal distribution, with the spectrum measured up to ~10 MeV.

Cyg X-1: a soft-state spectrum

$\frac{L_{\mathrm{hot}}}{L_{\mathrm{disk}}} \ll 1$

Disk blackbody + hybrid Comptonization

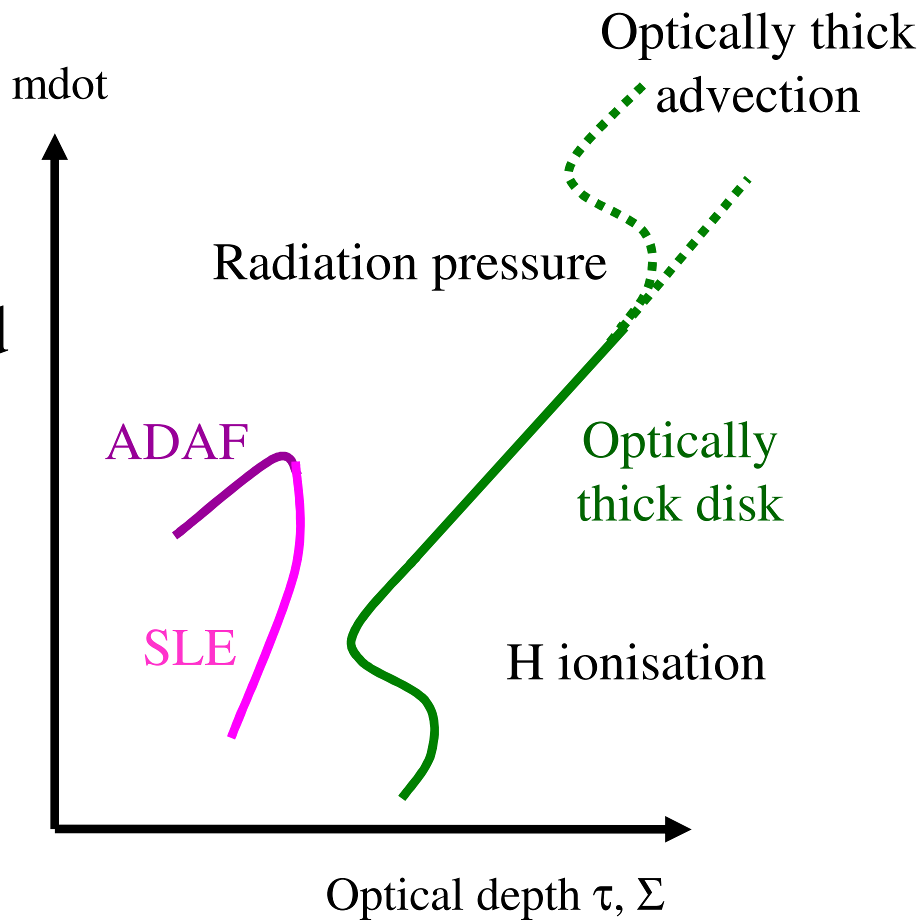




An electron distribution consisting of a Maxwellian and a high-energy (power-law like) tail.

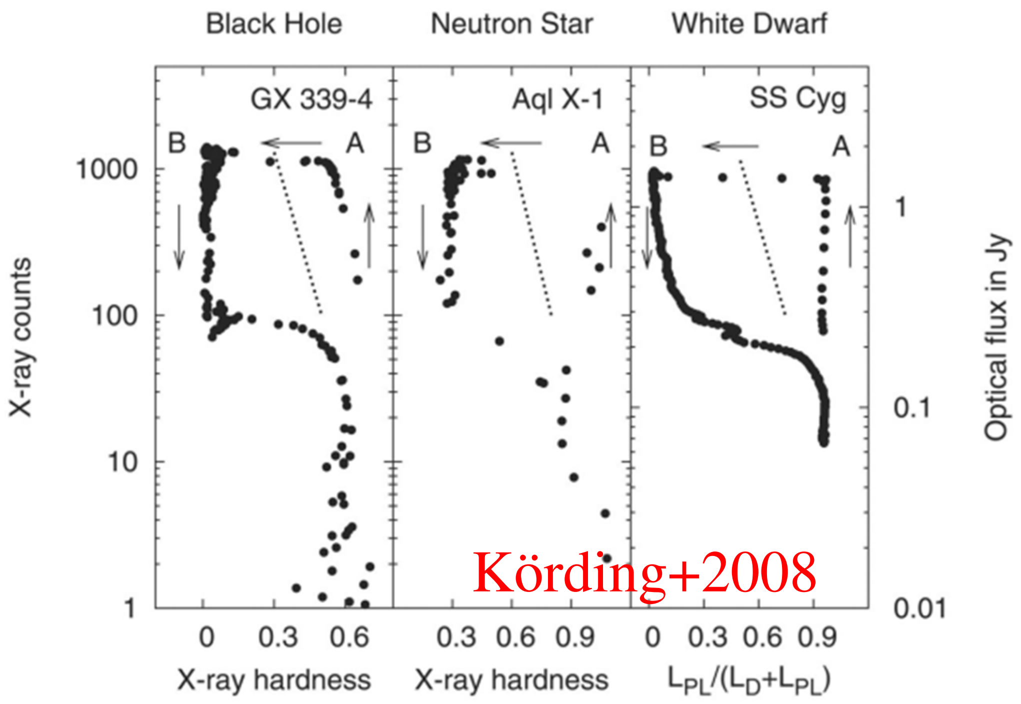
Hard state: possibly a hot disc

- Standard disc solutions assume protons & electrons have the same *T*. Not valid at low densities; protons heated by gravity, electrons by Coulomb collisions – 2-*T* plasma .
- Cooled by Compton scattering and advection. Protons get heated to virial temperature, electrons limited to ~100 keV.

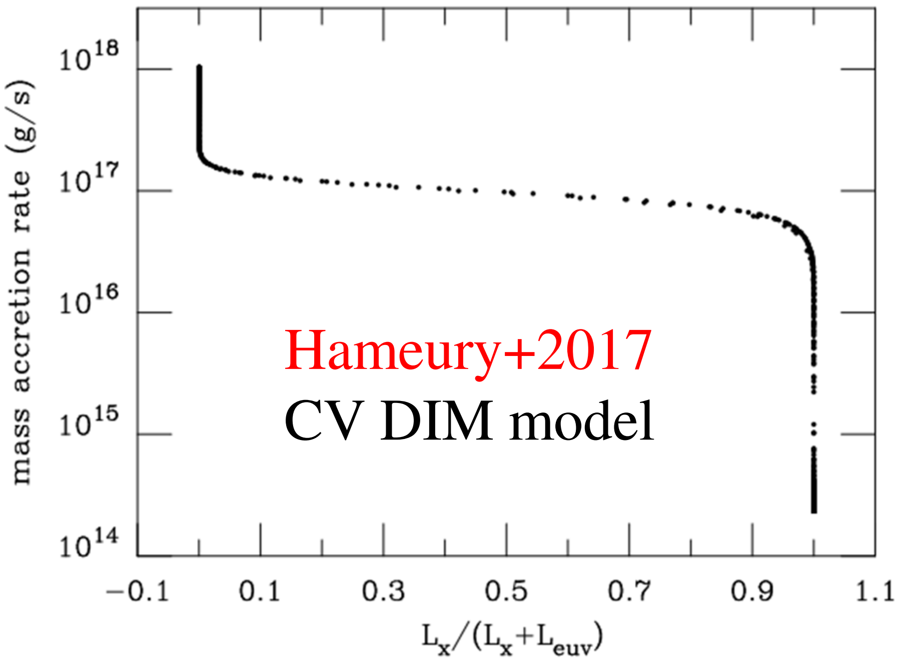


Hysteresis

- The DIM model by itself does not explain the SXT hysteresis.



Körding+2008



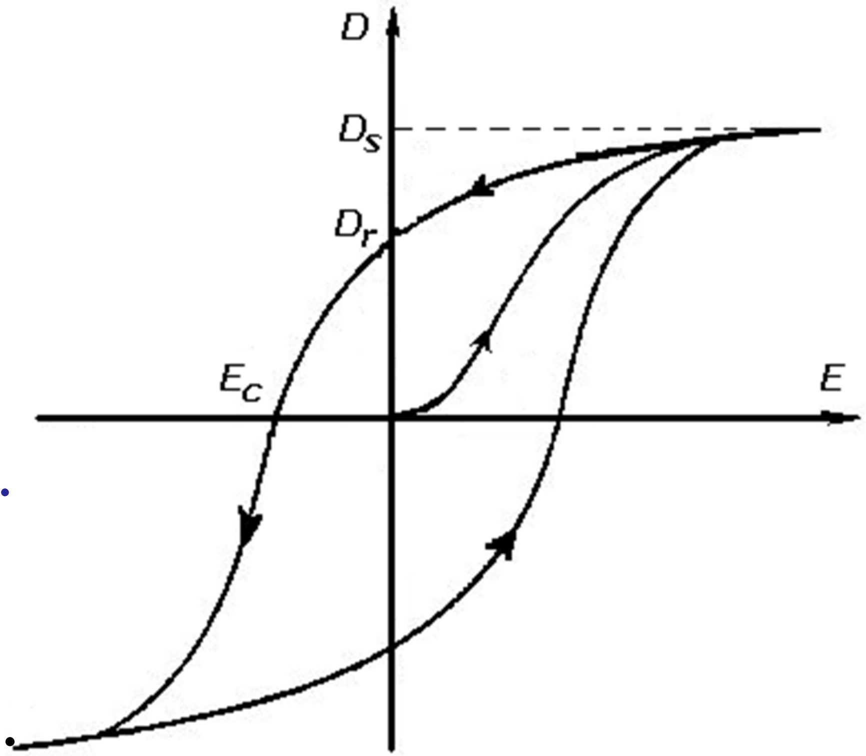
Hameury+2017
CV DIM model

- The CV hysteresis occurs because it takes a viscous time for the mass transfer rate to vary at the inner disc edge whereas the optical luminosity varies on the much shorter thermal time. This is a ***time lag effect***.
- The SXT hysteresis relates soft and hard X-rays that are both emitted in the innermost parts of the disc.

Hysteresis

- Definition: Hysteresis is the dependence of the state of a system on its history, in the presence of two states possible for the same parameter.
- An example:

The electric displacement field *D* of a ferroelectric material as the electric field *E* is first increased, then decreased. The curves form a ***hysteresis loop*** (due to two spin states).

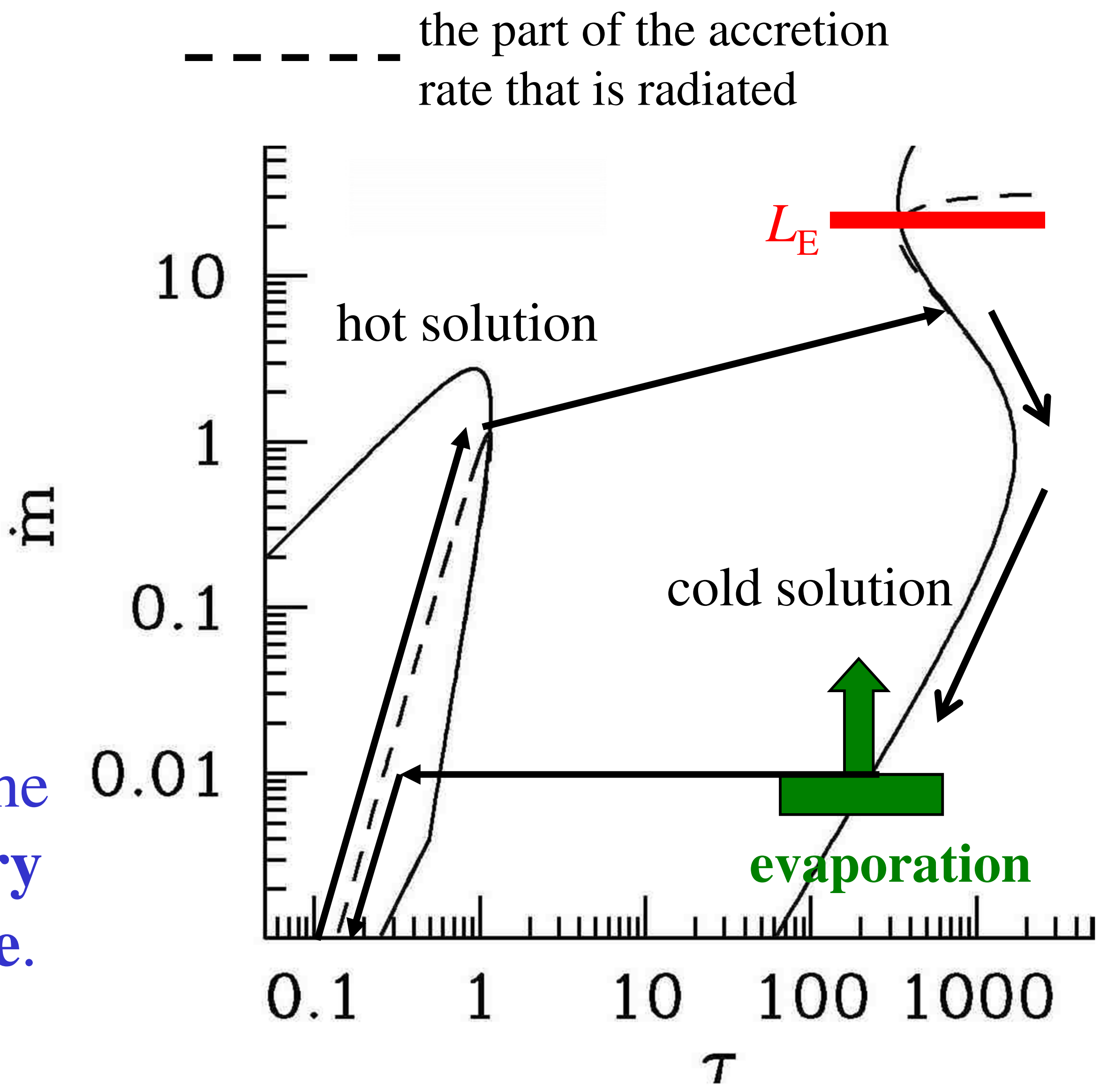


- There is no hidden parameter, and this is not a time-lag effect.

Accretion solutions

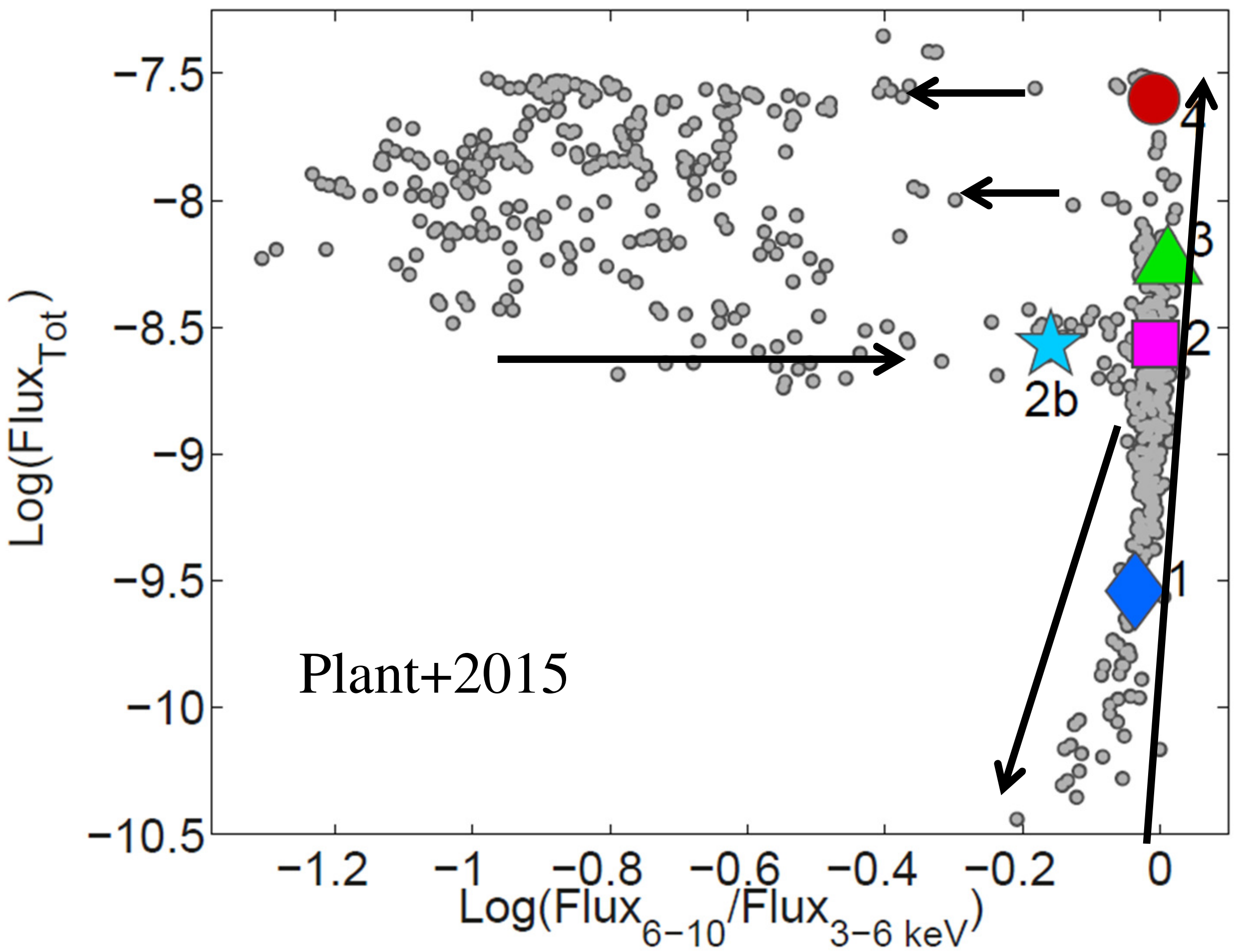
A limit cycle in the presence of a variable accretion rate, first increasing and then decreasing.

Two accretion solutions in the same range of *L*. **The history determines the actual state**.



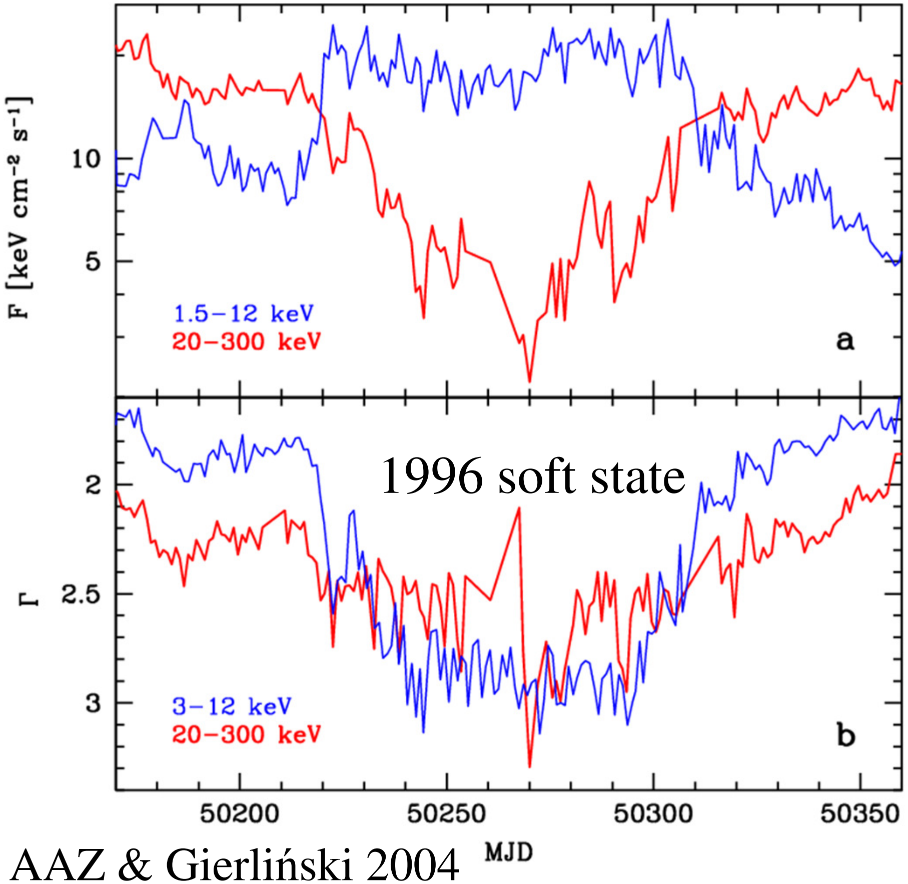
Thus, the existence of the SXT hysteresis can be entirely explained by the existence of two allowed states for the same accretion rate. We only need to explain $L_{\mathrm{max,hot}}$, $L_{\mathrm{min,cold}}$.

Hysteresis in GX 339−4



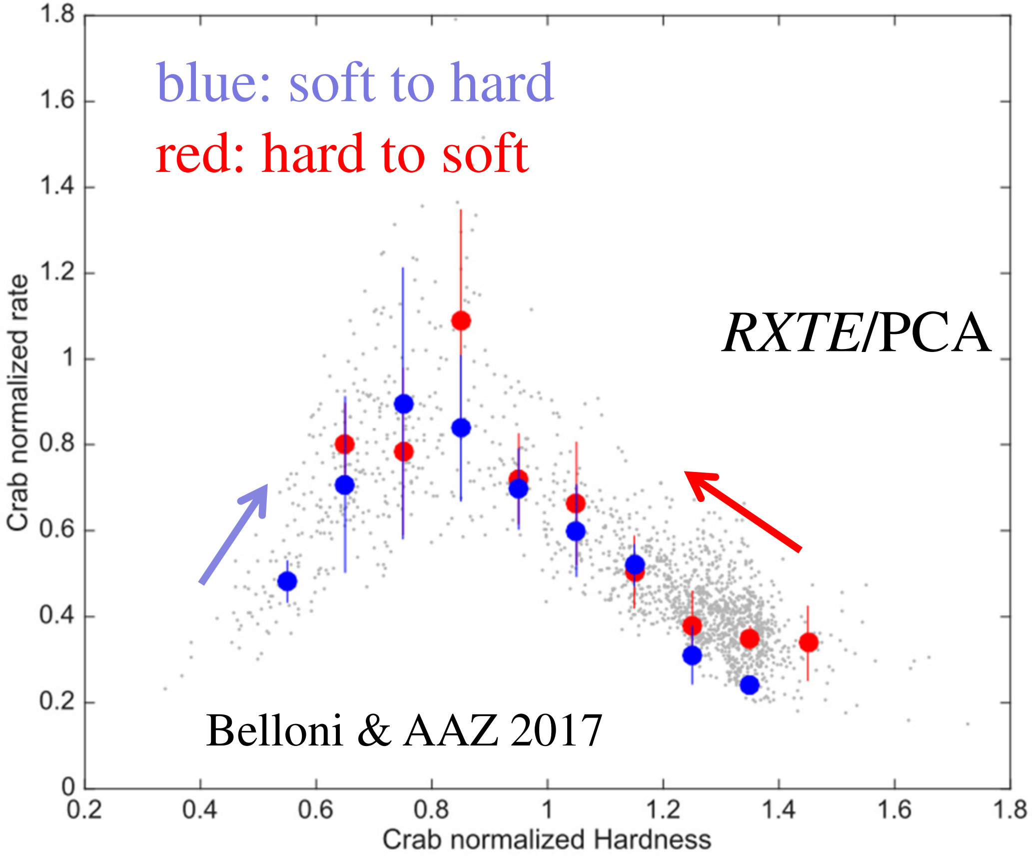
- However, what also does require an explanation are different maximum values of the luminosity in the hard state, different for different sources or even for different outbursts of the same source.
- What parameter does control that?

No hysteresis in Cyg X-1



1996 soft state

AAZ & Gierliński 2004



blue: soft to hard

red: hard to soft

RXTE/PCA

Belloni & AAZ 2017

Symmetric transitions at $\approx 2\%\ L_{\rm Edd}$

Hysteresis models

- Meyer-Hofmeister+2005: Different irradiating spectra in the hard and soft states. The hard spectrum keeps the plasma hot and allows a condensation to a cold disc to occur at a high L. The soft spectrum cools the evaporating plasma and allows an evaporation to occur at a low L.

- Then a number of models invoke magnetic field.

- Petruccci+2008: A vertical field, B_z, treading the disc, and assumed constant in time. A change of the disc magnetization, $\mu \equiv P_B/(P_{gas}+P_{rad})$. $\mu \approx 1$ in weak hard states, decreasing to 0.1 at $L_{max,hard}$, and associated jet emission, a constant cold disc inner radius, r_{in}. Then a further increase of $\dot{M}$ leads to a decrease of r_{in} down to ISCO (soft state), no jet. Then a decrease of $\dot{M}$ leads an increase of μ back to 1 at ISCO. This triggers the appearance of a hot, jet-emitting disc and an increase of r_{in} (hard state).
- A problem: no hysteresis in Cyg X-1. The authors mention this issue but do not provide convincing explanations.

What controls $L_{\mathrm{hard,max}}$?

- Begelman & Armitage 2015: different values of α; $L_{\mathrm{hard,max}} \approx \alpha^2 L_{\mathrm{Edd}}$ and α increases with *B*. During quiescence, magnetic field loops are generated by the magnetorotational instability at the interface between the inner hot flow and outer thin disc. Close to the interface, field loops are created with one footpoint trapped in the inner hot zone and the other escaping into the thin disc. As the loop opens up and the footpoints lose causal contact, the inner hot flow is left with an element of net magnetic flux. This flux is then advected during the outburst rise (hard). The initially magnetized thin disc expels its net field during the soft state on the diffusion time associated with the turbulent diffusivity.
- A problem: why doesn’t it happen in Cyg X-1? Not discussed in the paper.

Hysteresis models

- Kylafis & Belloni 2015: similar changes of B to those of Begelman & Armitage 2014. However, they rely on the Poynting-Robertson cosmic battery (PRCB), which efficiency is $\propto L$, and which provides locally a poloidal magnetic field. The field forces the ADAF solution to remain up to a high $\dot{M}$. Then, a thin disc cannot sustain a strong poloidal B, and it remains thin down to a low $\dot{M}$ until it evaporates. They stress the importance of the history of the system in determing the actual state.
- Cao 2016: a similar model to that of Begelman & Armitage, but instead of changing α the model relies on a magnetic wind, which removes the angular momentum from the disc and thus allows a faster radial inflow, allowing in turn reaching a higher L in the hard state.

- A problem: no hysteresis in Cyg X-1. The authors do not mention this issue.

Hysteresis models

- A key property which can lead us to understand the nature of the hysteresis may be its presence in transient, Roche overflow, sources but its absence in persistent, wind accretion, sources.
- The hard states in Cyg X-1 and GX 339−4 have very similar properties, but GX 339−4 has quiescence, during which the cold disc retracts back to $>10^3\ r_{\rm g}$. Consequently, at ~4% $L_{\rm Edd}$, it still appears to have the disc inner radius at $>10^2\ r_{\rm g}$ (De Marco+2015; Basak & AAZ 2016).
- On the other hand, Cyg X-1 at ~1% $L_{\rm Edd}$ appears to have the disc inner radius of ~15 $r_{\rm g}$ (Basak+2017). Also, the disc outer radius is $\ll$ that in GX 339−4.
- Thus, the large truncation radius during quiescence may prevent the disc reaching the ISCO at a low L.

The nature of the hard state

Controversies regarding the hard state

- Disputed geometry and components, either:
  1. X-ray emission from accretion.
  2. X-ray emission from a jet.
- Different possible accretion geometries, either:
  1. a hot inner flow overlapping with a truncated outer disc;
  2. a hot inner flow containing blobs or a residual inner disc;
  3. a standard disc extending to ISCO with a corona;
  4. a standard disc extending to ISCO with a ‚lamppost';
- The dominant physical process is Compton upscattering by thermal electrons (with a possible weak non-thermal tail).
- The main seed photons for Compton scattering are either disc blackbody photons or synchrotron photons.

The issues to be discussed now in red

Different possible disc-corona geometries and energy balance

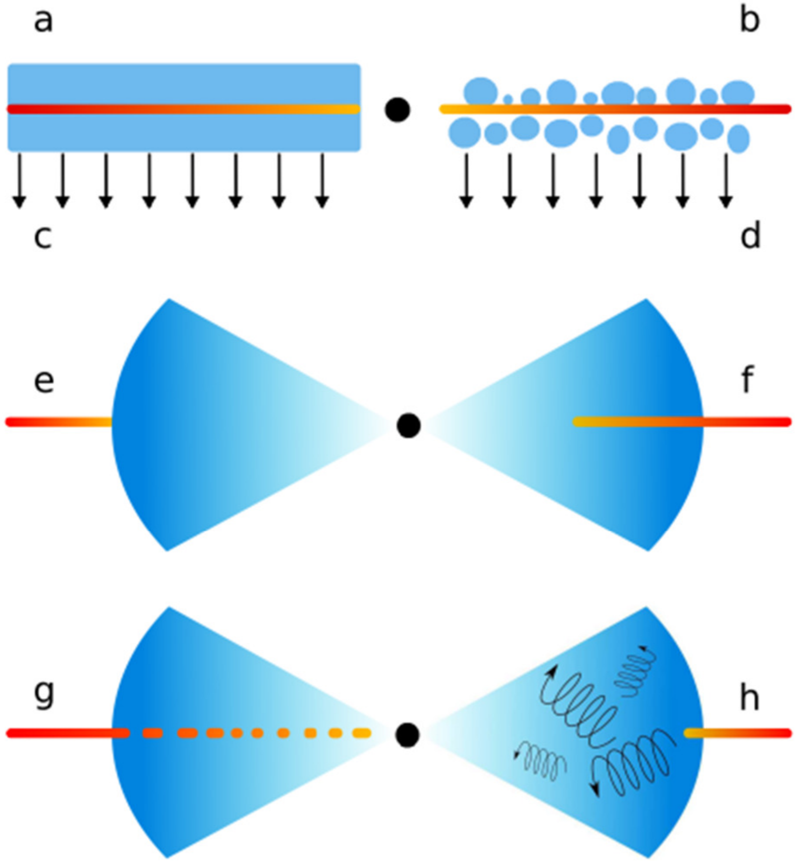


Fig. 1. Geometries of the central parts of the accretion flow proposed over time. (a) Static sandwiching corona, (b) static patchy corona, (c) outflowing sandwiching corona, (d) outflowing patchy corona, (e) cold accretion disc detached form the hot flow and (f) intersecting with it, (g) hot flow with cold condensed regions, (h) truncated disc and hot flow with substantial cyclo-synchrotron radiation.

- **We study energy balance in those systems.**
- The cold medium is irradiated by the emission of the hot plasma. It partly back-scatters the irradiating photons (Compton reflection), and partly absorbs them and re-emits, mostly in the soft X-ray range (reprocessing).
- The reprocessed radiation cools the plasma, in addition to the blackbody emission from the intrinsic, viscous, dissipation.
- We neglect the intrinsic emision, to get the most conservative results (the hardest possible spectra).
- We use the current best reflection/reprocessing code, xillverCp (by J. García).
- We calculate the self-consistent X-ray spectra, taking into account, in particular, Compton scattering of the reflected photons.
- **We find only the cases f, g, h to be compatible with the observational data.**

Poutanen, Veledina & AAZ 2017

• A homogeneous corona above a disc

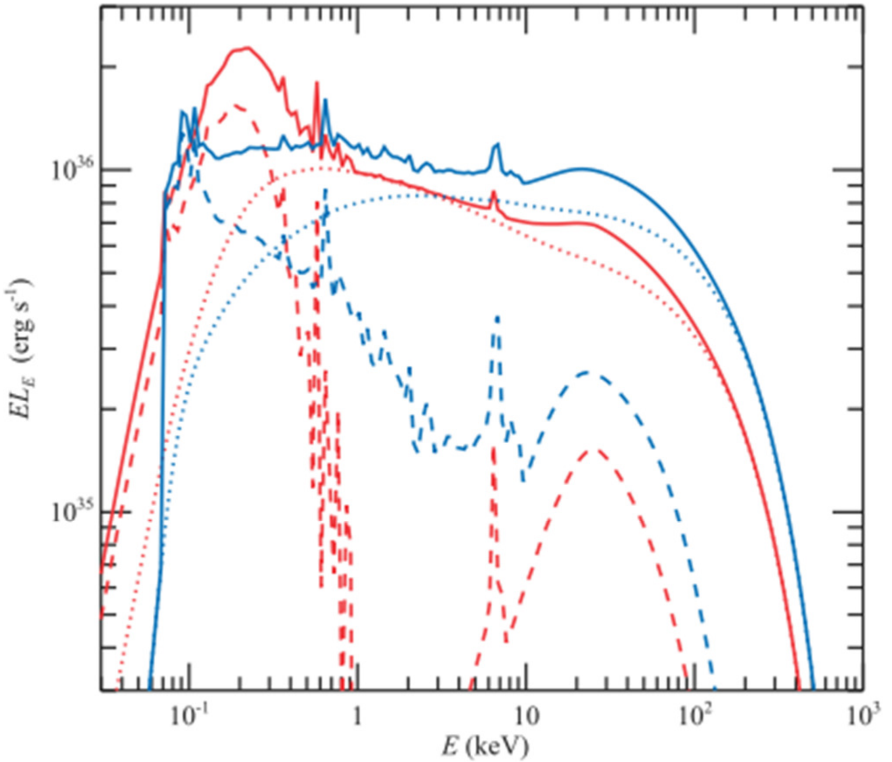


Fig. 2. Self-consistent spectra from a homogeneous slab-corona above a disc of $\tau_T = 0.4$ as observed at inclination $i = 60°$. The red and blue curves correspond to $\log\xi = 1$ and 3, respectively. The dotted lines show the Comptonization continuum, the dashed lines show the reflection XILLVERCP spectrum together with reprocessed blackbody emission, and the solid lines give the total spectrum. The reflection spectra have been re-binned at a resolution $\Delta \lg E = 0.025$.

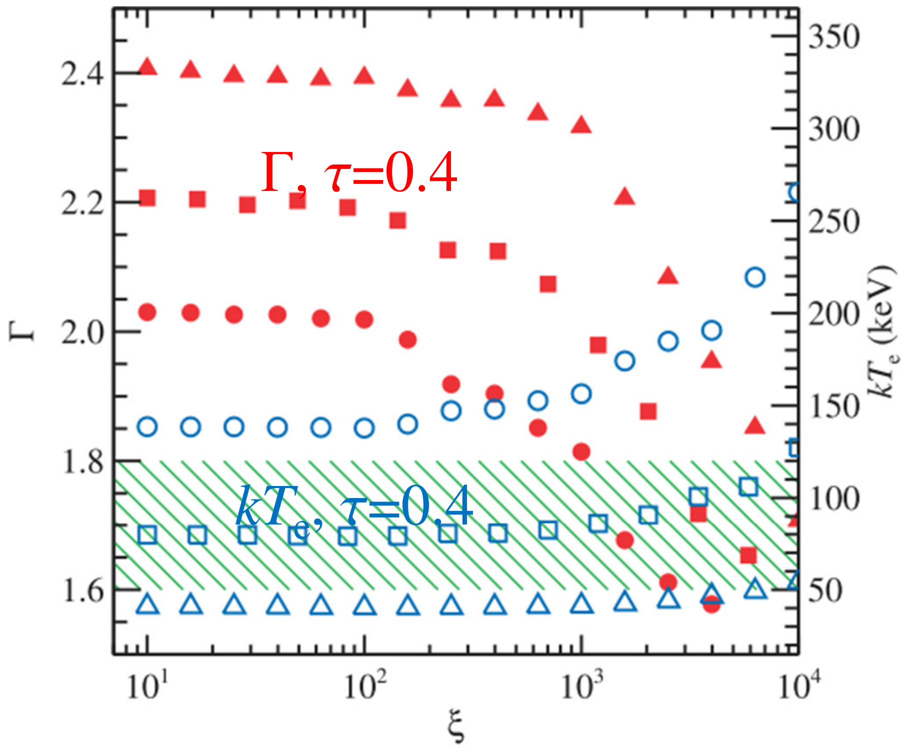
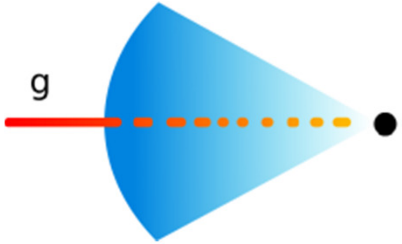


Fig. 3. Dependence of the 2–10 keV photon spectral index Γ of the Comptonized spectra from sandwich-corona (red filled symbols and left axis) and of the coronal temperature kT_e (blue open symbols and rights axis) on the ionization parameter for various coronal optical depths. Circles, squares, and triangles correspond to $\tau_T = 0.2$, 0.4 and 0.8, respectively. Shaded area represents the typical observed range for Γ (1.6–1.8) and kT_e (50–120 keV).

Spectra in this geometry are generally too soft, as found before (Haard & Marachi 91,93). In order to match the observations, $\Gamma \approx 1.6–1.9$, $kT_e \approx 50–100$ keV, very high ionization parameters, $\xi \equiv 4\pi F_X/n_e \gtrsim 3000$ are required, which are not observed. Thus, this geometry is ***not*** compatible with the hard-state data.



Cold clumps within the hot flow

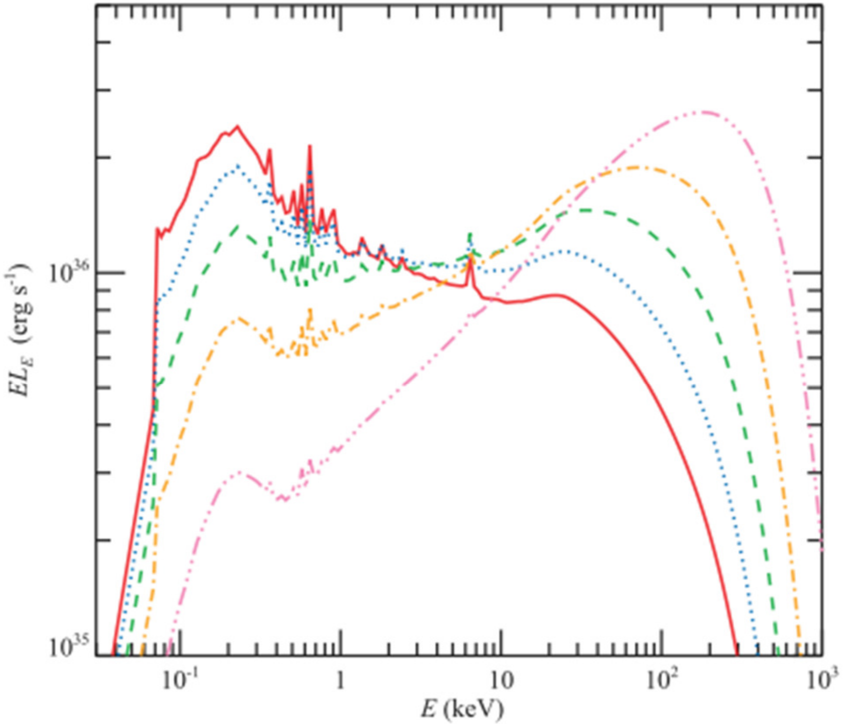


Fig. 4. Self-consistent spectra from hot thermal plasmas mutually interacting with cold media without internal dissipation (see fig. 5 in Zdziarski et al. 1998). The Thomson optical of the hot flow down to the central plane is $\tau_\mathrm{T} = 0.4$ and the spectra are observed at inclination of $i = 60°$. Red solid, blue dotted, green dashed, brown dot-dashed and pink triple-dot-dashed lines correspond to the covering fraction of the cold clumps of $f_\mathrm{cl} = 1.0, 0.8, 0.6, 0.4$ and 0.2, respectively. The ionization parameter here is $\log \xi = 1$.

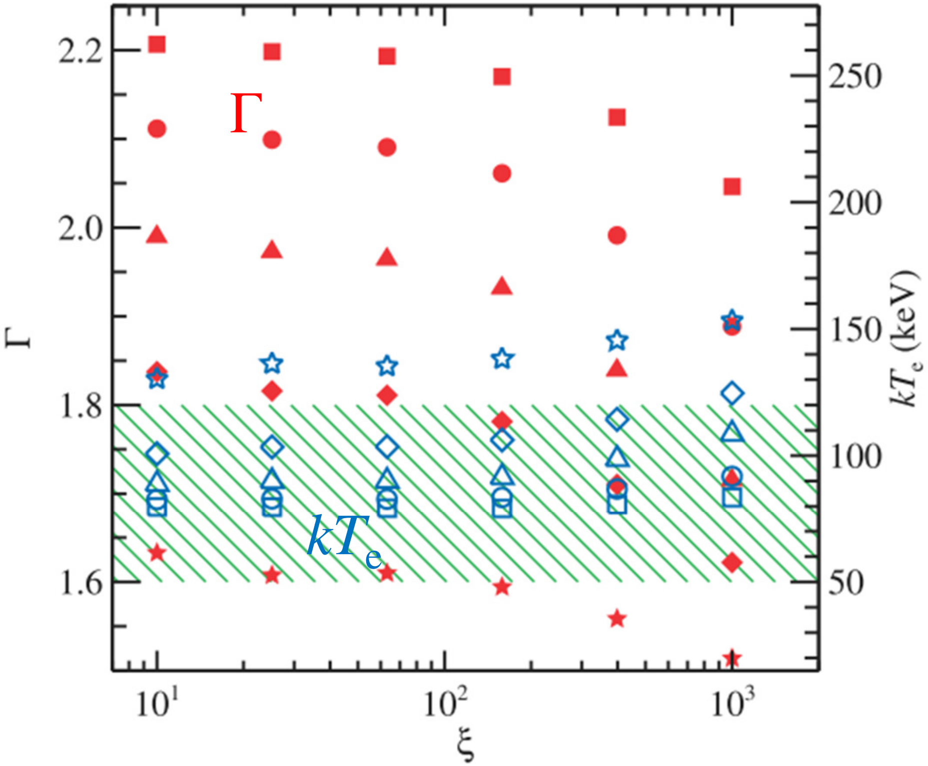


Fig. 5. Dependence of the 2–10 keV photon spectral index, Γ (red filled symbols and left axis), of the Comptonized spectra from the hot flow with cold clumps and of the coronal temperature, kT_e (blue open symbols and rights axis), on the ionization parameter for various covering factors f_cl. Squares, circles, triangles, diamonds and stars correspond to $f_\mathrm{cl} = 1.0, 0.8, 0.6, 0.4$ and 0.2, respectively.

Spectra in this geometry can be compatible with the observations ($\Gamma \approx 1.6$–1.9, $kT_\mathrm{e} \approx 100$ keV, $\xi \sim 10^2$). The cold clouds cover a fraction, f_cl, of the plane of the flow, and $f_\mathrm{cl}=0.4$ seems to fit the data best.

A recent claim based on the energy balance that the accretion disc in the hard state has to extend to the ISCO, Steiner et al. 2017

- A detailed disc/corona model, with Compton reflection, scattering of a fraction of the reflected photons in the corona, and GR effects.
- The only seed photons: are those from viscous dissipation within the accretion disc (with or without truncation). The energy balance → if the disc were truncated, $\dot{M}$ would have to be very high in order for the disc blackbody emission to supply enough seed photons for the observed Comptonized spectra. They present it as a strong evidence for the disc extending to the ISCO.
- However, the assumption above is incorrect. The disc in the coronal geometry is strongly irradiated by the hard radiation and the reprocessing gives rise to a flux that can be $\gg$that from the viscous dissipation. This leads to strong softening of the spectra and rules out the disc/corona geometry for the hard state.
- This was first found by Haardt & Maraschi (1991) and confirmed by us by using the state-of-the-art reprocessing code, xillverCp.

Conclusions

- DIM: truncation and irradiation required.
- Hysteresis: two states existing for the same parameters; differences between transients and Cyg X-1 remain unexplained.
- The geometries in the hard state allowed by energy balance and the observational data are:
  - an truncated outer cold disc overlapping with an inner hot flow;
  - a truncated disc and an inner hot flow with embedded cold clouds or a residual inner disc.