Observational Evidences for Transonic Accretion Flows

Sandip K. Chakrabarti

If any black hole accretion takes place at all, then…..

All the observations from the accreting black hole are evidences of transonic flows!

This is because …..

- All black hole accretions are necessarily transonic.

So, the only things I need to show are ….

- How the transonic solutions lead to specific results which may be verified by analyzing observational data.
- However, one bugging unknown, namely, the nature of viscosity prohibits us from ‘predicting’ precisely the outcome of possible forthcoming events (e.g., when outbursts would start or end, when spectral state transition would take place, what would be the precise QPO frequency of a given black hole etc.)

Transonic solutions are not weird objects!

- Our favorite solar wind is transonic!
- All astrophysical flows (any flow for that matter) having any trace of a shock wave (Supersonic to subsonic transition) must be transonic. All the discussions about shocks, shock oscillations, in the context of neutron stars or white dwarfs (that we heard yesterday) are transonic.
- A Keplerian disk is sub-sonic. It is shock free and is NOT transonic!

One good thing that happened so far with transonic flow solution is that ….

- All the observations could be understood within the framework of theoretical results, namely, one does not have to change the basic picture from one object to another.

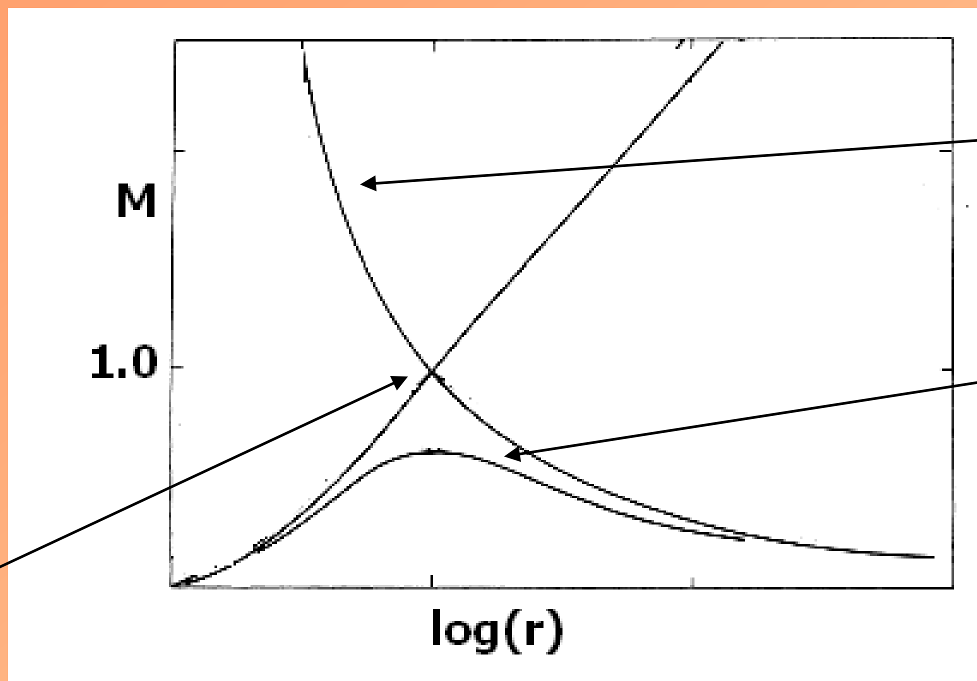
I won’t have time to prove, so please take these for granted

(these are ‘model independent’ conclusions)

- All flows onto a black hole **must be supersonic** and thus pass through at least one sonic point (M=v/a=1) if not more.
- **The inner physical sonic point is the effect of strong gravity (GR). A Newtonian accretion flow does not have two physical sonic points.**
- At the sonic points, the flow **MUST BE sub-Keplerian** (i.e., the angular momentum of the flow must deviate from a Keplerian disk). A Keplerian disk cannot enter into a black hole.
- If there are two sonic points, flows can pass through both the sonic points when **connected by a shock transition** in between.

In astrophysical situation,
the Bondi flow (spherically symmetric) is well known to be transonic

Two solutions: One for accretion and the other for the wind (Parker)



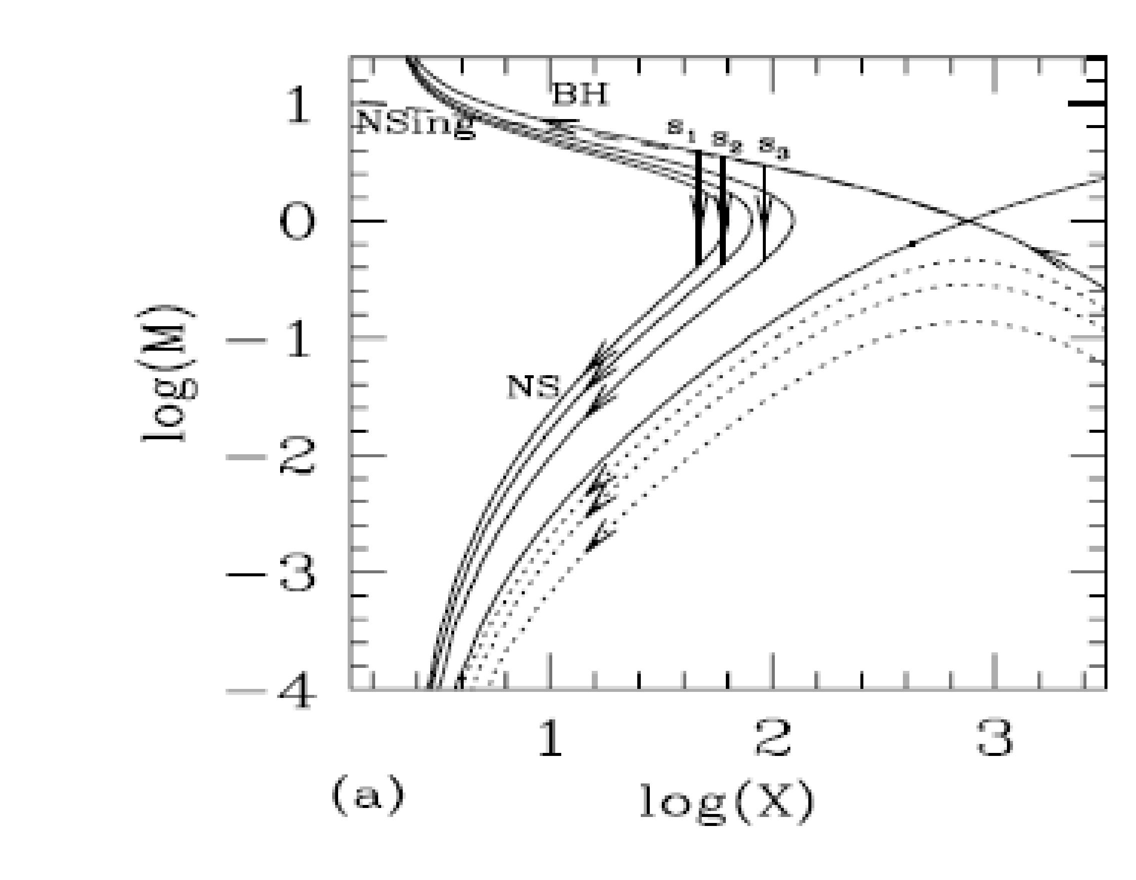
On a black hole

On a neutron star

Sonic Point

Mach number variation with radial distance

All black hole solutions are unique, but a neutron star solution depends on the boundary condition of the star



Note that there are many ways matter can accrete sub-sonically, but there is only one way, matter can enter supersonically.

Chakrabarti and Sahu 1996

Simplified version of the work can be understood using Paczynski-Wiita potential: The equations for the generalized steady flow around a compact object (Chakrabarti, 1989, 1990, 1996):

(a) The radial momentum equation:

$$\vartheta \frac{d\vartheta}{dx} + \frac{1}{\rho}\frac{dP}{d\rho} + \frac{\lambda_{Kep}^2 - \lambda^2}{x^3} = 0,$$

(b) The continuity equation:

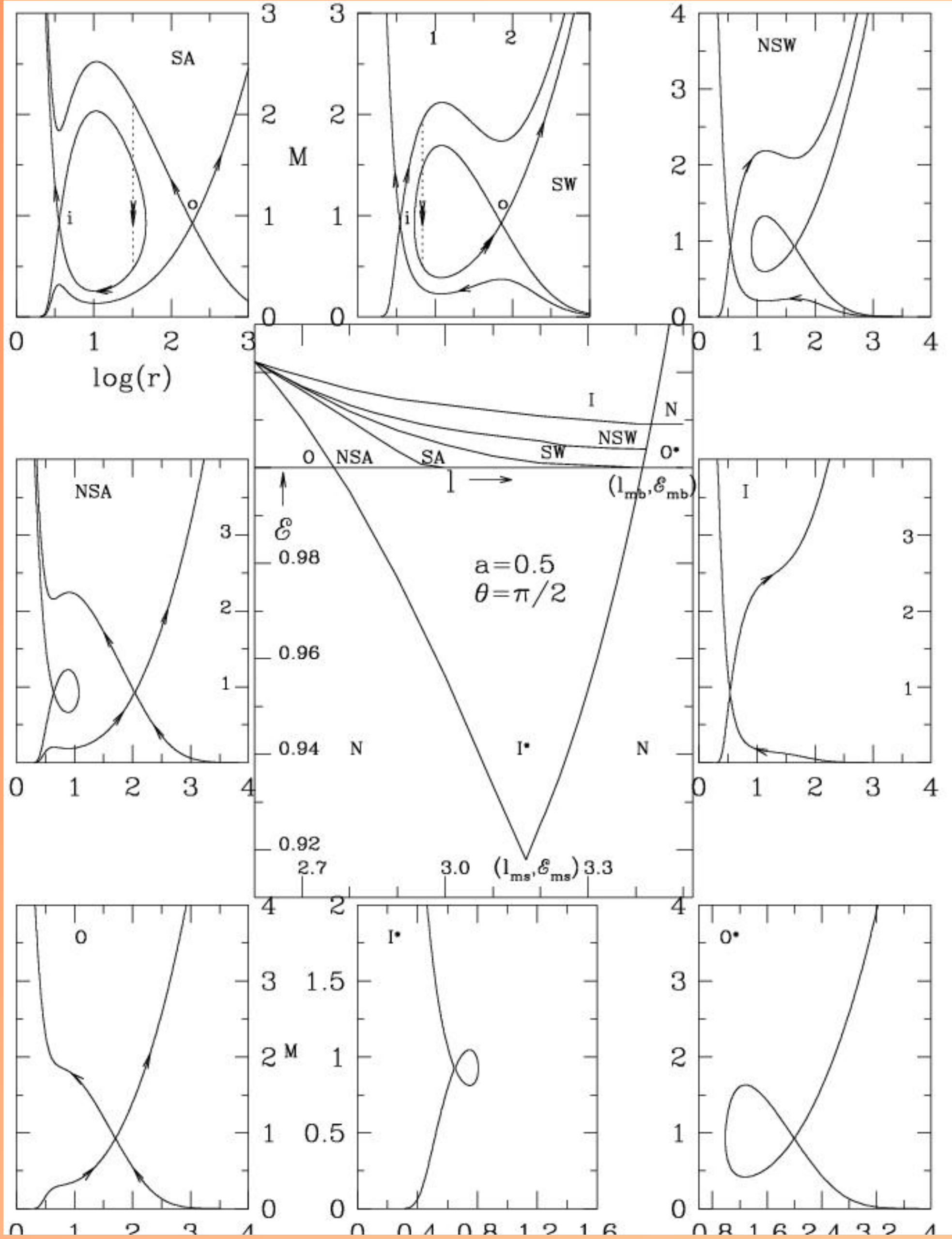
$$\frac{d}{dx}(\rho x h \vartheta) = 0,$$

(c) The azimuthal momentum equation:

$$\vartheta \frac{d\lambda(x)}{dx} - \frac{1}{\rho x h}\frac{d}{dx}\left(\frac{\alpha P x^3 h}{\Omega_{Kep}}\frac{d\Omega}{dx}\right) = 0$$

(d) The entropy equation:

$$\Sigma \vartheta T \frac{ds}{dx} = Q^+ - Q^-$$



All possible flows into a black hole in an inviscid flow. No other steady solution can exist.

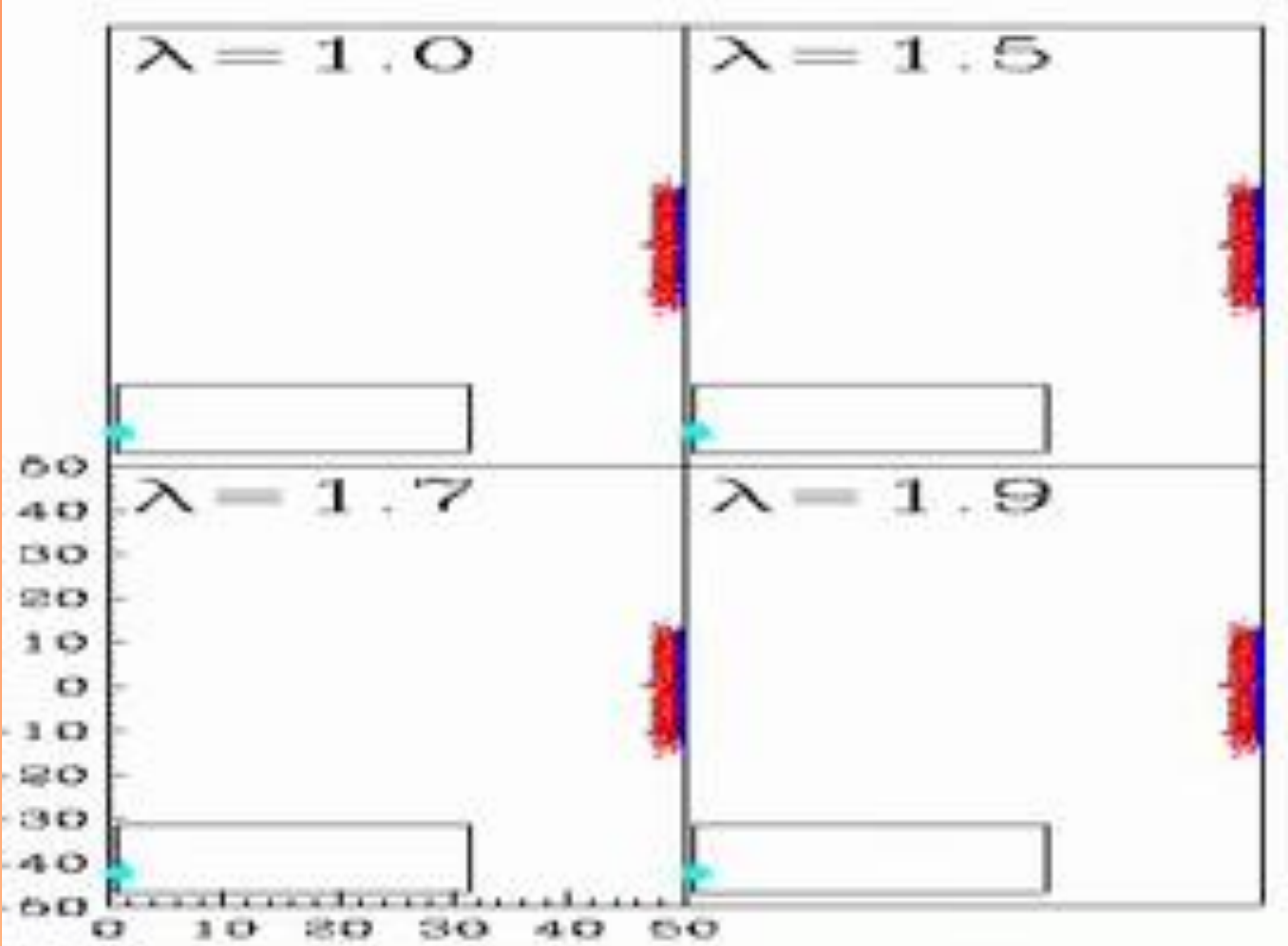
Classification of solutions for a Kerr black hole

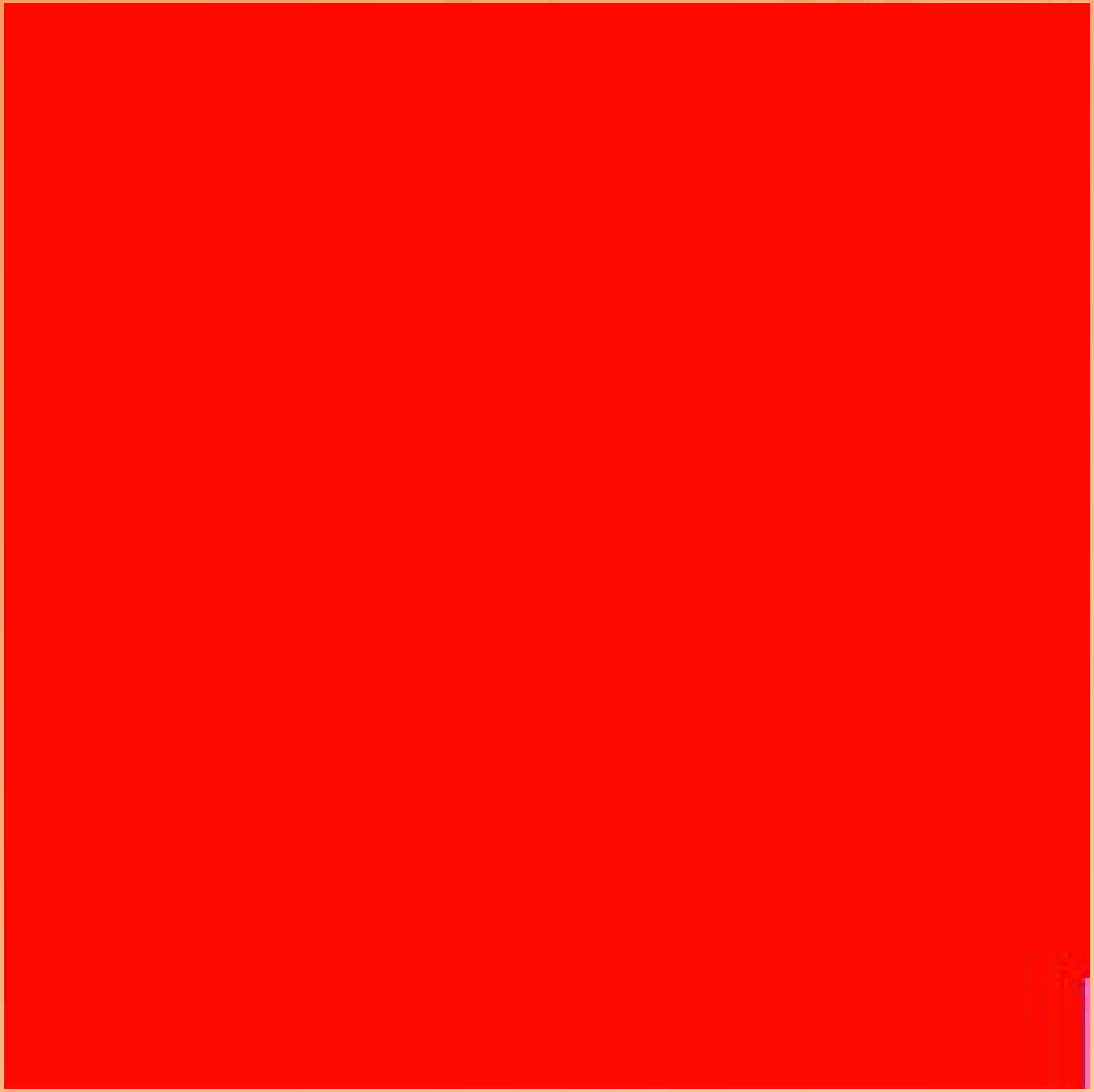
Chakrabarti 1996

Same as in Schwarzschild back hole: SKC 1989

All other independent flow solutions are just special cases

- Bondi Flow (λ=0)
- Thick disk (v=0, $\alpha>$0, post-shock region)
- Keplerian disk (v=0, $\alpha>>$0, no-shock region)
- Current version of ADAF, if done correctly, would be the supersonic branch of our solution without a shock. Original Narayan and Yi (1994) solution had constant Mach number (M=v/a=const) and thus was NOT A TRANSONIC SOLUTION. (These days any hazy cloud is called ADAF. Praise the Lord!)


λ = 1.0
λ = 1.5
λ = 1.7
λ = 1.9
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
50



Situation when the Rankine-Hugoniot conditions are not satisfied

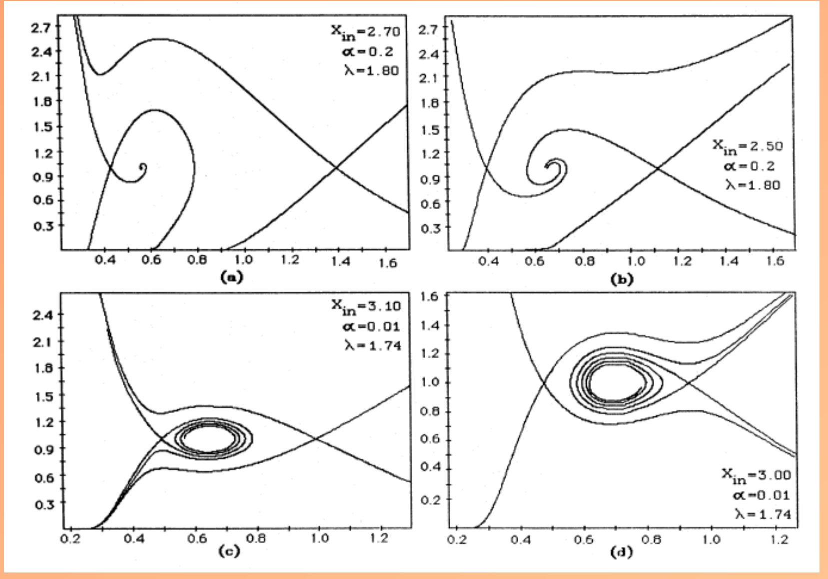
Ryu, Chakrabarti and Molteni, 1997

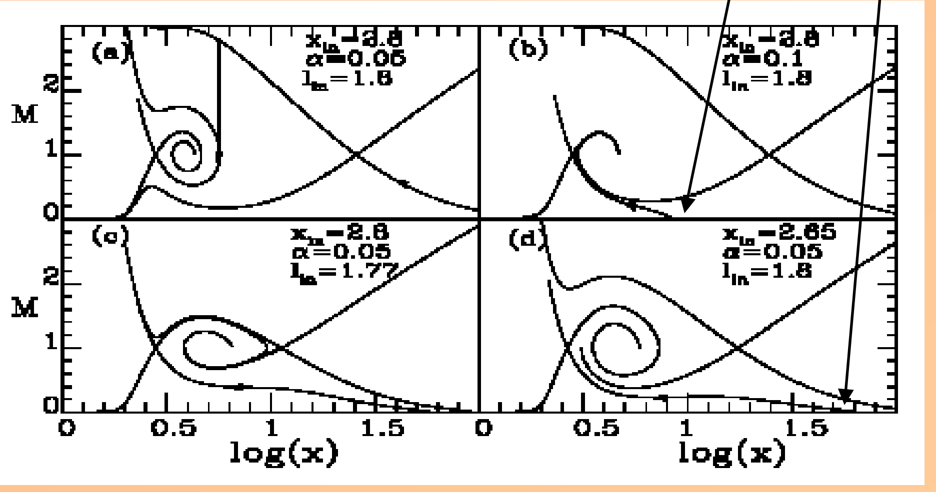
Role of viscosity (Chakrabarti 1990)

- Viscosity can re-distribute angular momentum and make Keplerian disks out of a low angular momentum flow and vice versa depending on the direction of transport.
- The topologies of the flow change and the shocks form in a lower angular momentum region of the parameter space as long as viscosity is less than a critical value.

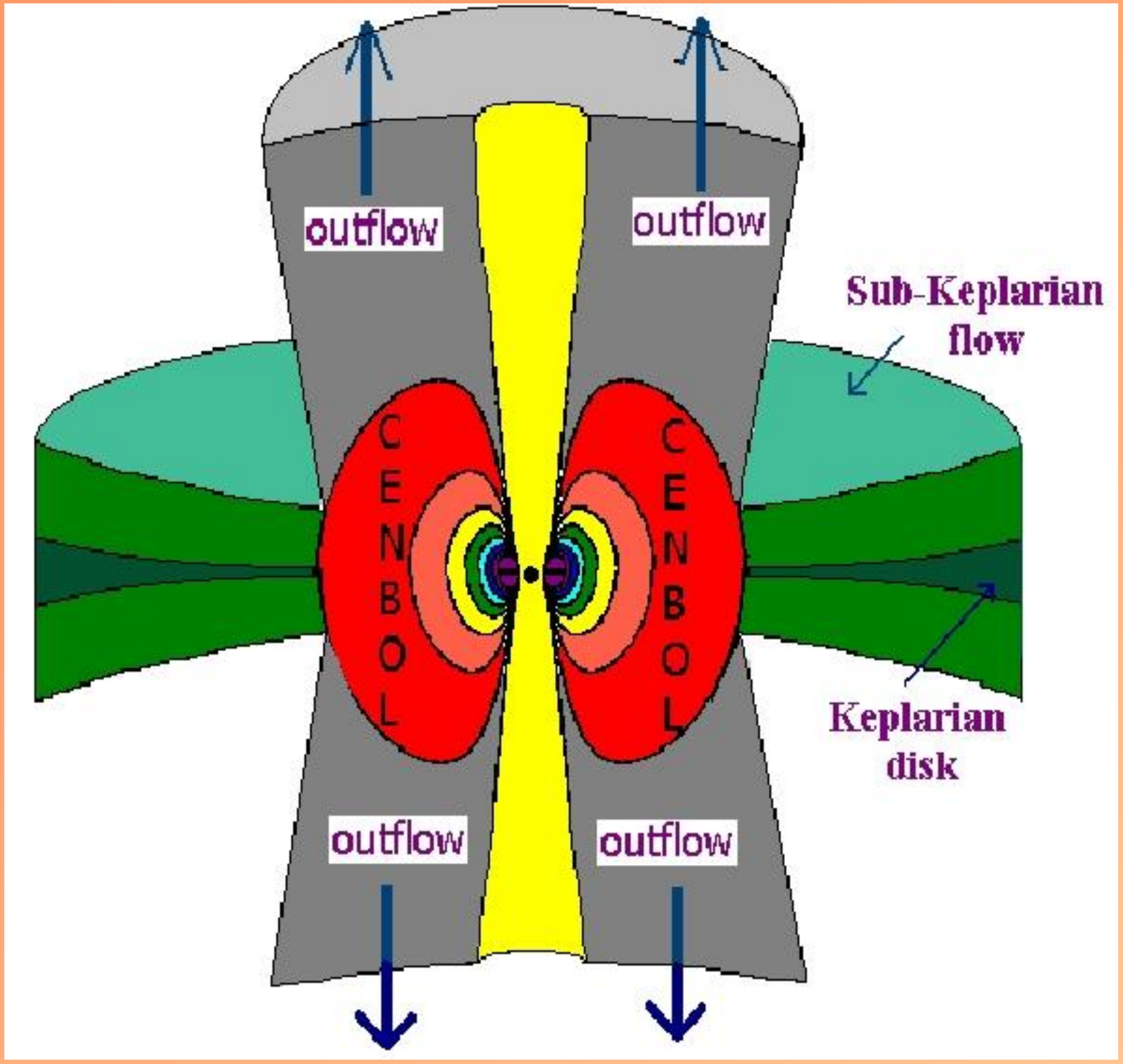
Low α

High α





The paradigm picture of accretion/outflow on a black hole is:-



The Centrifugal force and Gravity do tug-of-war and produce shocks – the post-shock region behaves as the Compton cloud and influences the spectrum. It is also responsible for the initial 'drive' of outflows and winds

We call the post-shock region as CENBOL: *the centrifugal barrier supported boundary layer*

Why is this paradigm ALL INCLUSIVE?

(rigorous theory+numerical simulations were used to solve modular problems first)

- The standard Keplerian disk (Shakura-Sunyaev 1973) is not adequate to describe the spectral and timing properties of a black hole.
- One required a 'Compton cloud' to inverse Comptonize soft photons and produce power-law photons (Sunyaev, Titarchuk, Zdziarski ….) but the origin and location of the clouds were at the most speculative (accreting corona, floating clouds, magnetic corona and many such models exist in the literature.)
- The presence of multiple sonic points produce standing (Chakrabarti, 1989, 1990); oscillatory (Molteni, Sponholz, Chakrabarti, 1996) or propagating shocks (Chakrabarti and Molteni 1995) depending on flow parameters (energy, angular momentum and viscosity).

- Two component flows with one Keplerian component and one sub-Keplerian component can describe the spectral properties very satisfactorily (Chakrabarti and Titarchuk 1995).
- The shock can oscillate and move in/out if the parameters are in the wrong region, i.e., when the Rankine-Hugoniot conditions are not satisfied. Thus for QPOs and their evolutions, we need not invoke new components (`blobs') in the flow, for example.
- The emitted radiation from oscillating shocks shows Quasi-Periodic oscillations (at least of low and intermediate frequency QPOs) as are observed (in outburst sources there is strong evidence for the Compton cloud and the QPO frequency to evolve for 10-15 days, which is impossible for a model with blobs, for example). ISCO models for QPOs are not tenable as QPO frequencies vary for a given black hole.

- Shocks oscillate when the cooling time scale roughly matches with the infall time scale (this is the only model where the accretion rate increase also increases the QPO frequency, for example). The rms in QPO is high at higher energies and low/negligible at low energies.
- Jets and outflows form when the post-shock region exists (this is the only theoretical solution which predicts that soft spectral states will have no outflows, must before they are observed, for example).
- Since the relation of outflows with states is observed, we believe the basic is as we say, only details vary (with a bit of MHD, mainly to collimate and accelerate matter, for example).

- The low angular momentum flows can change the spectral states very rapidly in a matter of seconds (free fall time is shorter compared to viscous time scale). An alternate model with an evaporated Keplerian disk forming a corona in some models cannot do, for example. An evaporated disk cannot settle back fast to change the state in few seconds.

The Black hole Astrophysics is in reality guided by the physics of this new component of the flow; namely the post-shock region (CENBOL).

ALL THE CONSIDERATIONS ARE VALID FOR MASSIVE AND SUPER MASSIVE BLACK HOLES: No NEED to write new theories (or papers) for them!

Only time scales vary and the radiation is at lower energy

Typically: Soft/Hard X-rays for Stellar mass black holes; UV/Soft X-rays for massive black holes.

QPOs: ~ 0.1-100Hz for Stellar mass black holes, and ~ micro Hz for massive black holes

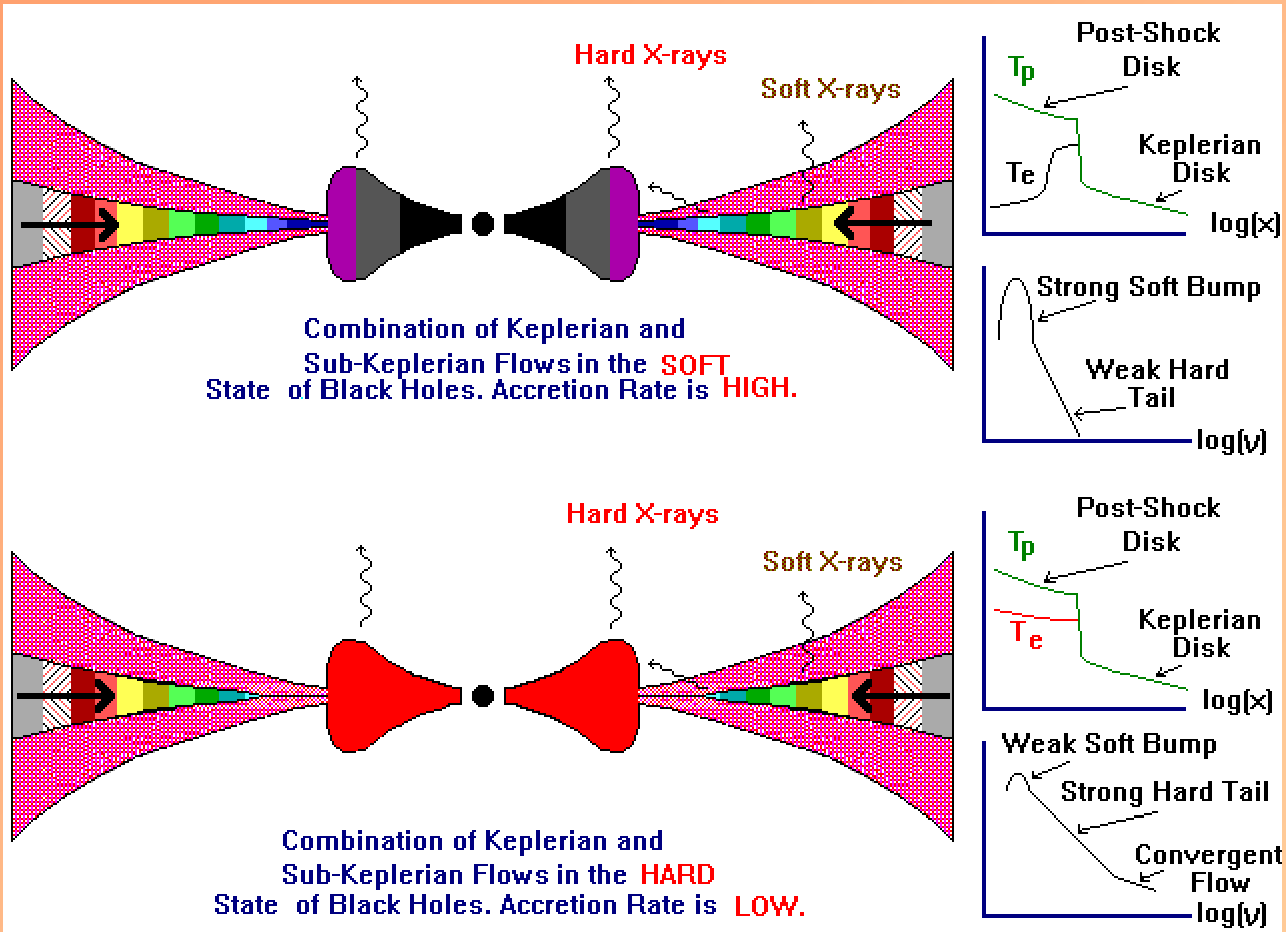
Etc.

Combined module:the basic model: The high viscosity flow stays close to the equatorial plane, while the low viscosity sub-Keplerian flow flanks it.

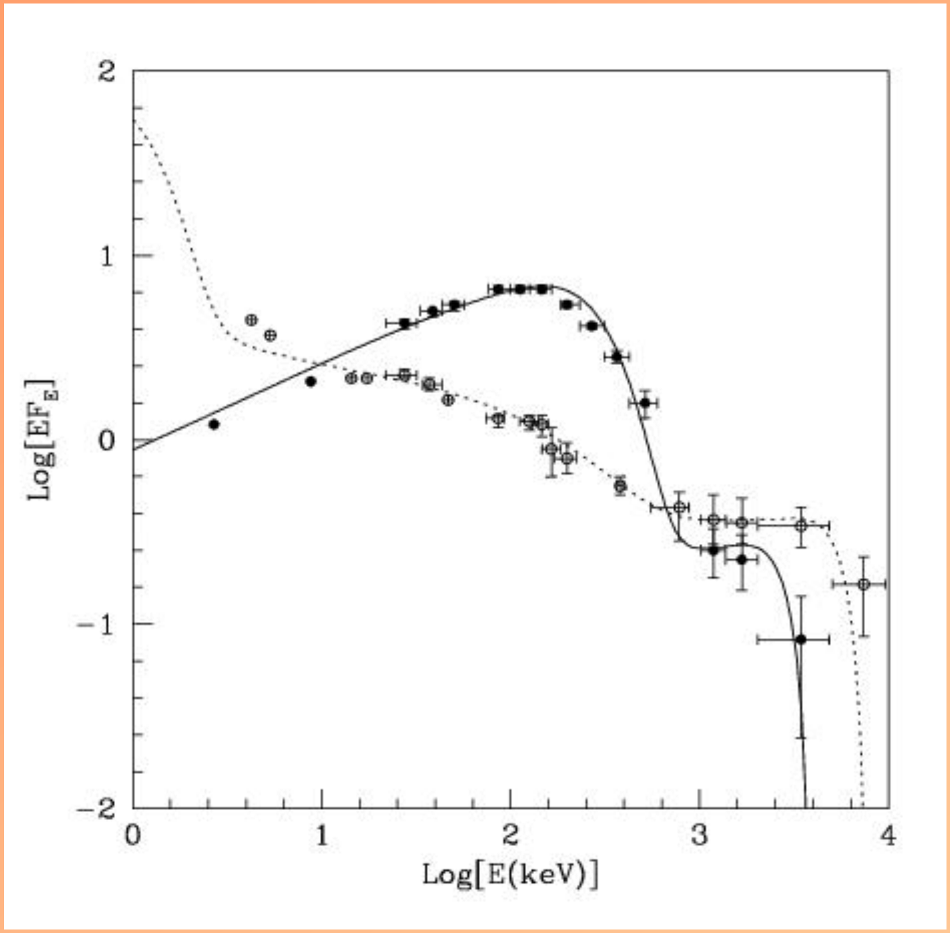
(a) In the low/hard state the sub-Keplerian rate is high and Keplerian rate is low so that the post-shock region is not cooled and produce high energy X-rays

(b) In the high/soft state: The Keplerian rate is high enough to cool the post-shock region of the sub-Keplerian flow

(c) In the intermediate state: both rates are comparable

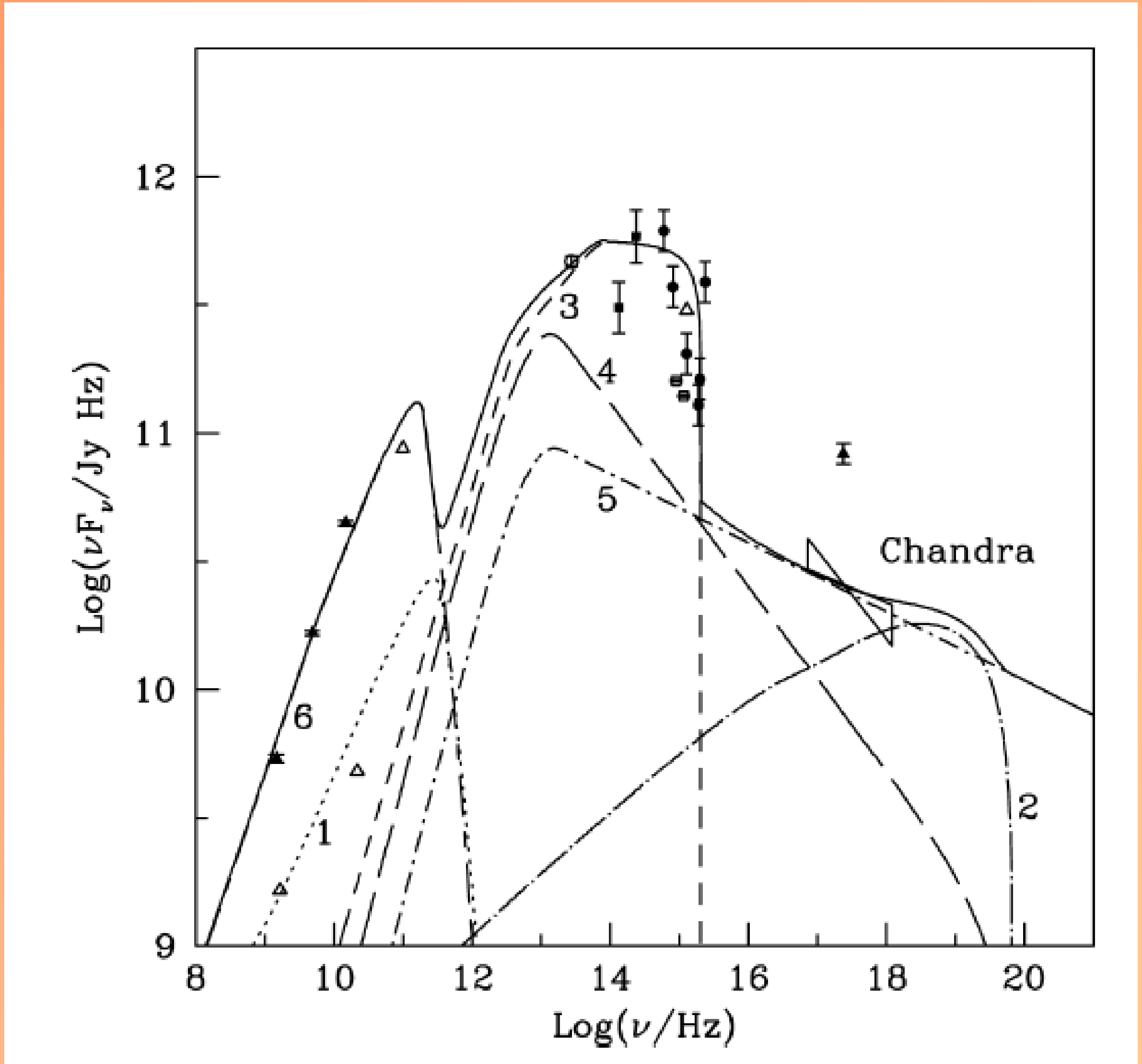


Fitting of the spectra of galactic black hole Cygnus X-1 using our solution



Chakrabarti+Mandal, ApJL, 2006

Spectral fit of the disk around the super-massive black hole in M87 (Note that it has no evidence for Keplerian disk!)

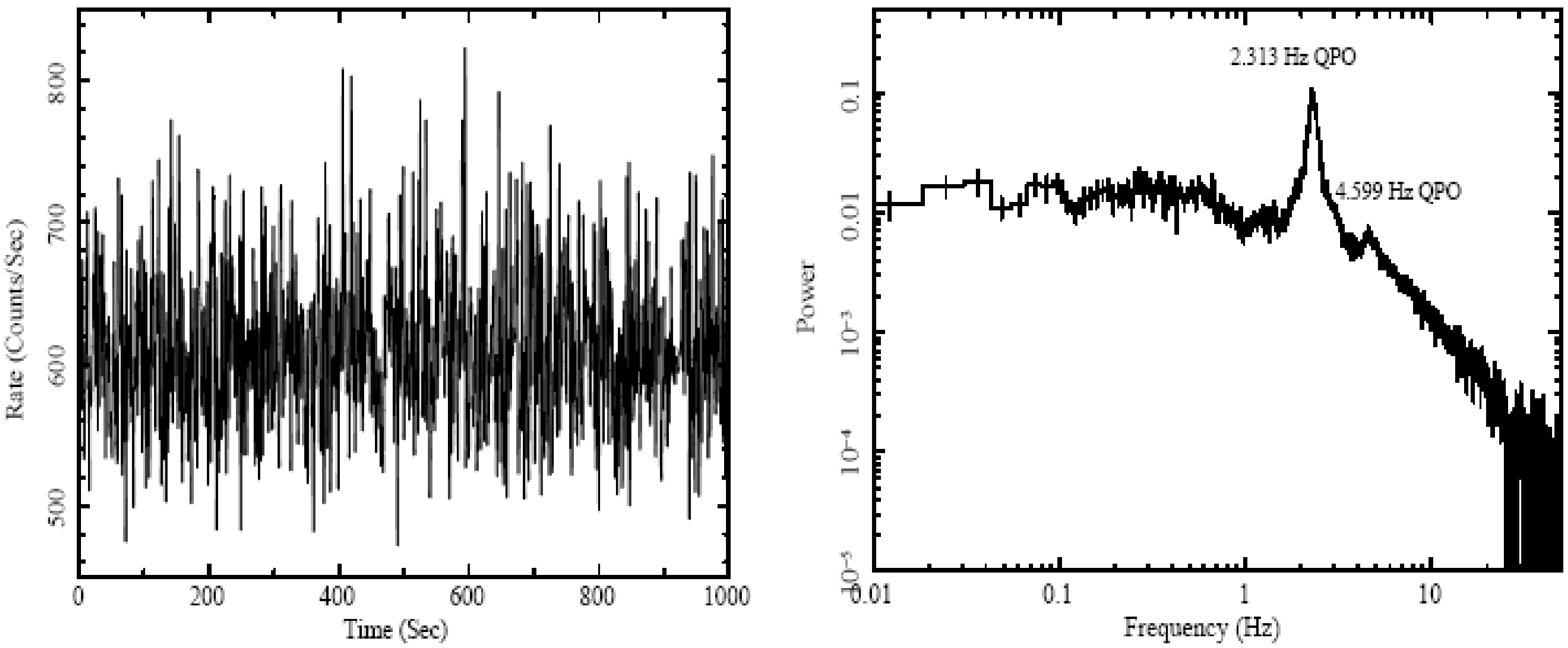


SM+SKC

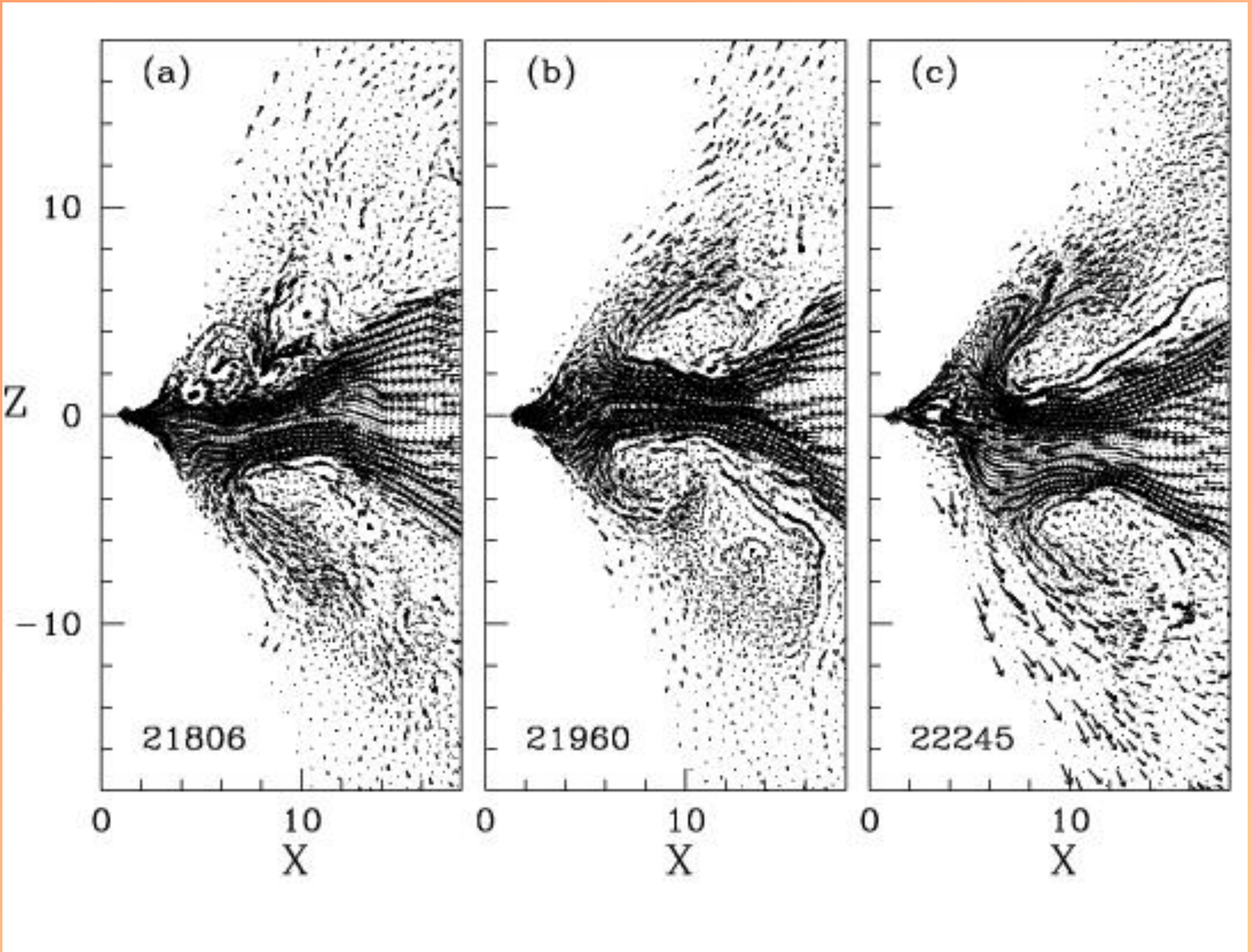
ApJL 2008

QPOs?

An example of observed QPO

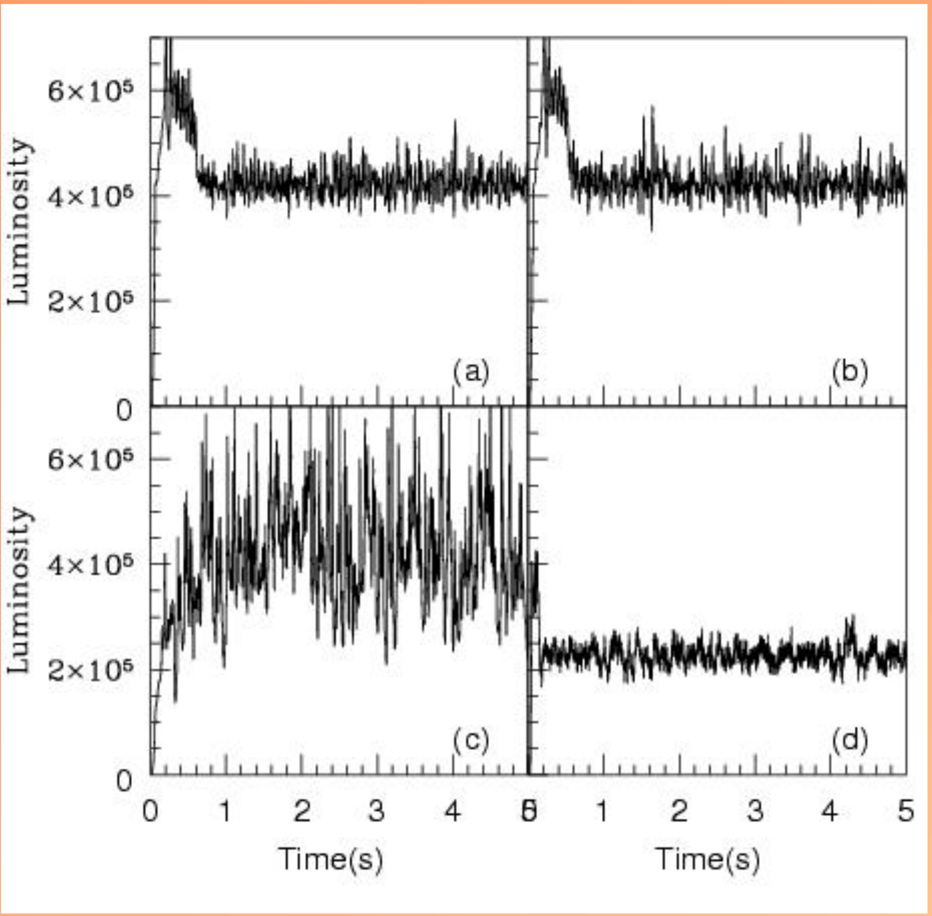


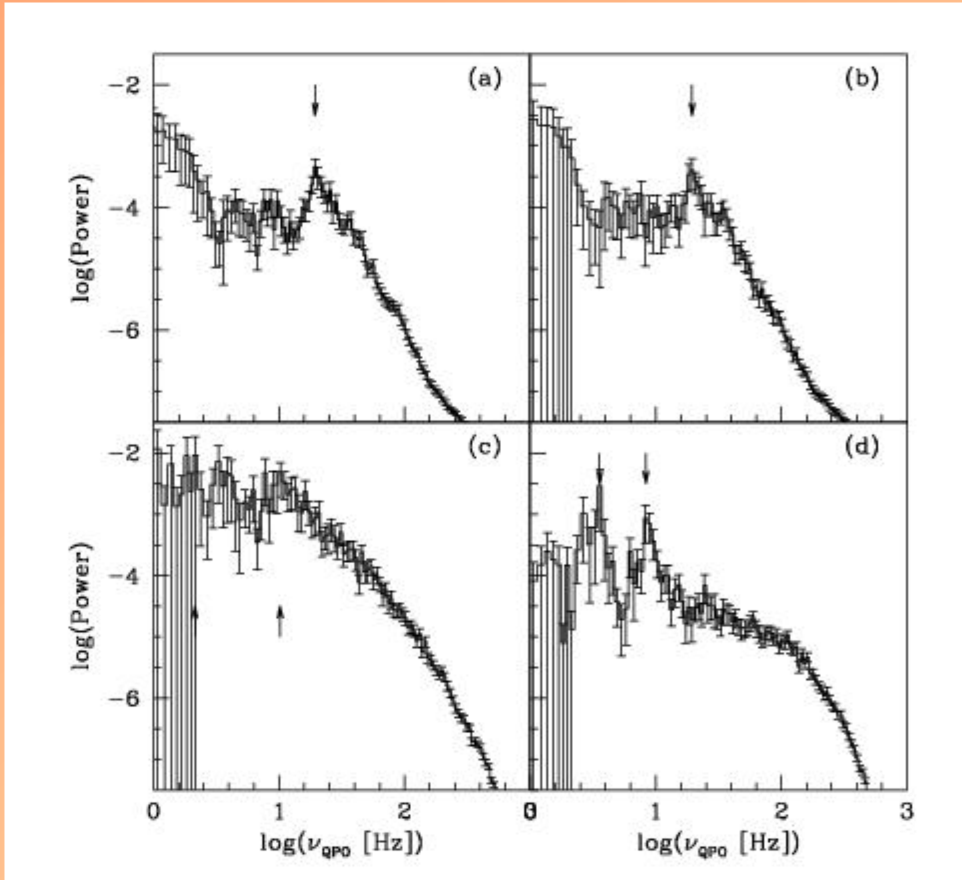
QPO module:Three snap-shots showing radial and vertical oscillations. Azimuthal oscillations are also possible at the same frequency! All of these could cause QPOs!



Chakrabarti, Acharyya and Molteni, 2004

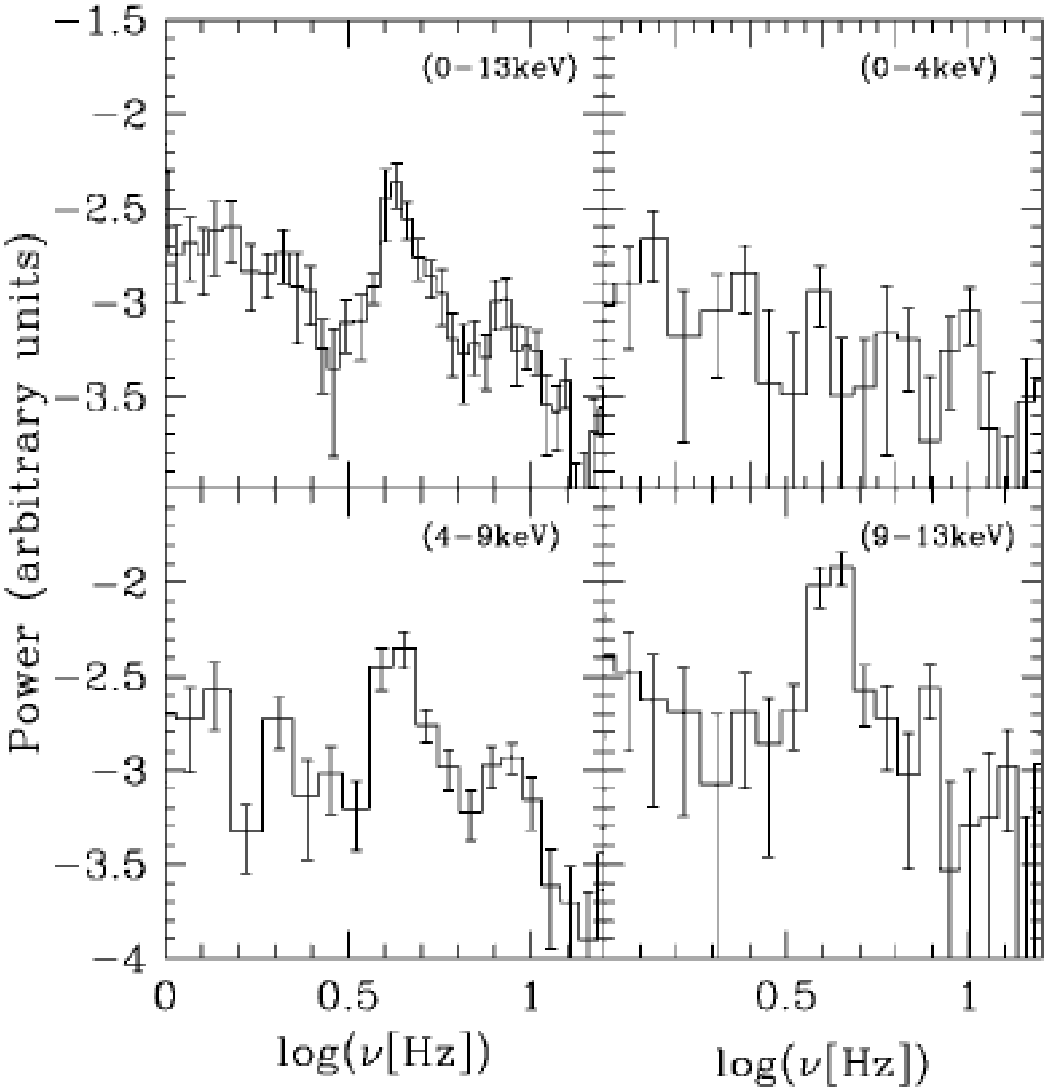
Our numerical simulations show that QPOs are formed due to shock oscillations around galactic and extra galactic black holes.





Molteni, Sponholz and Chakrabarti, 1996, ApJ;
Chakrabarti et al. 2004 A&A

Chakrabarti and Manickam 2000



Higher energy photons participate in QPOs!

This is a direct proof that only Comptonized photon intensity is oscillating due to changing intercepted soft photons as the shock moves back and forth.

What about the outburst sources?

- Outbursts are unpredictable (no periodicity for any given object)
- We understand this to be due to rise in viscosity, which converts some sub-Keplerian component to the Keplerian component.

XTE J1550-564 in 1998

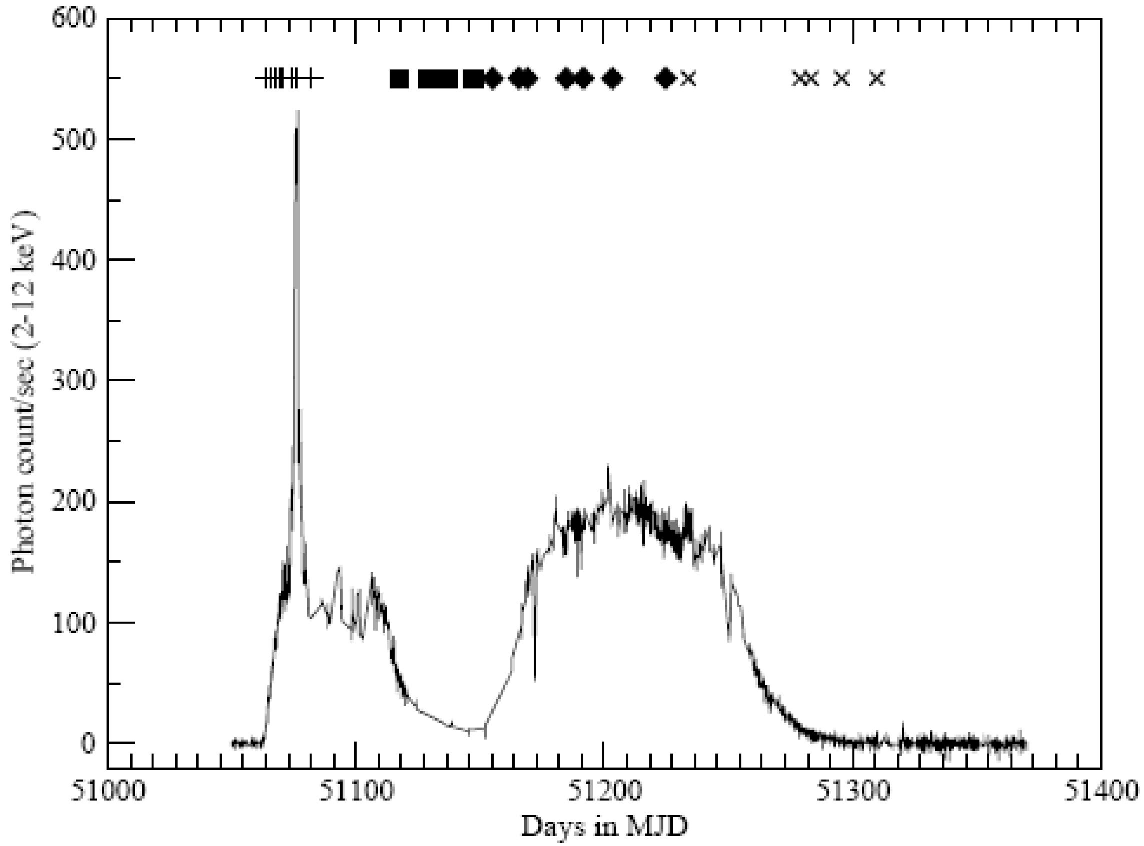
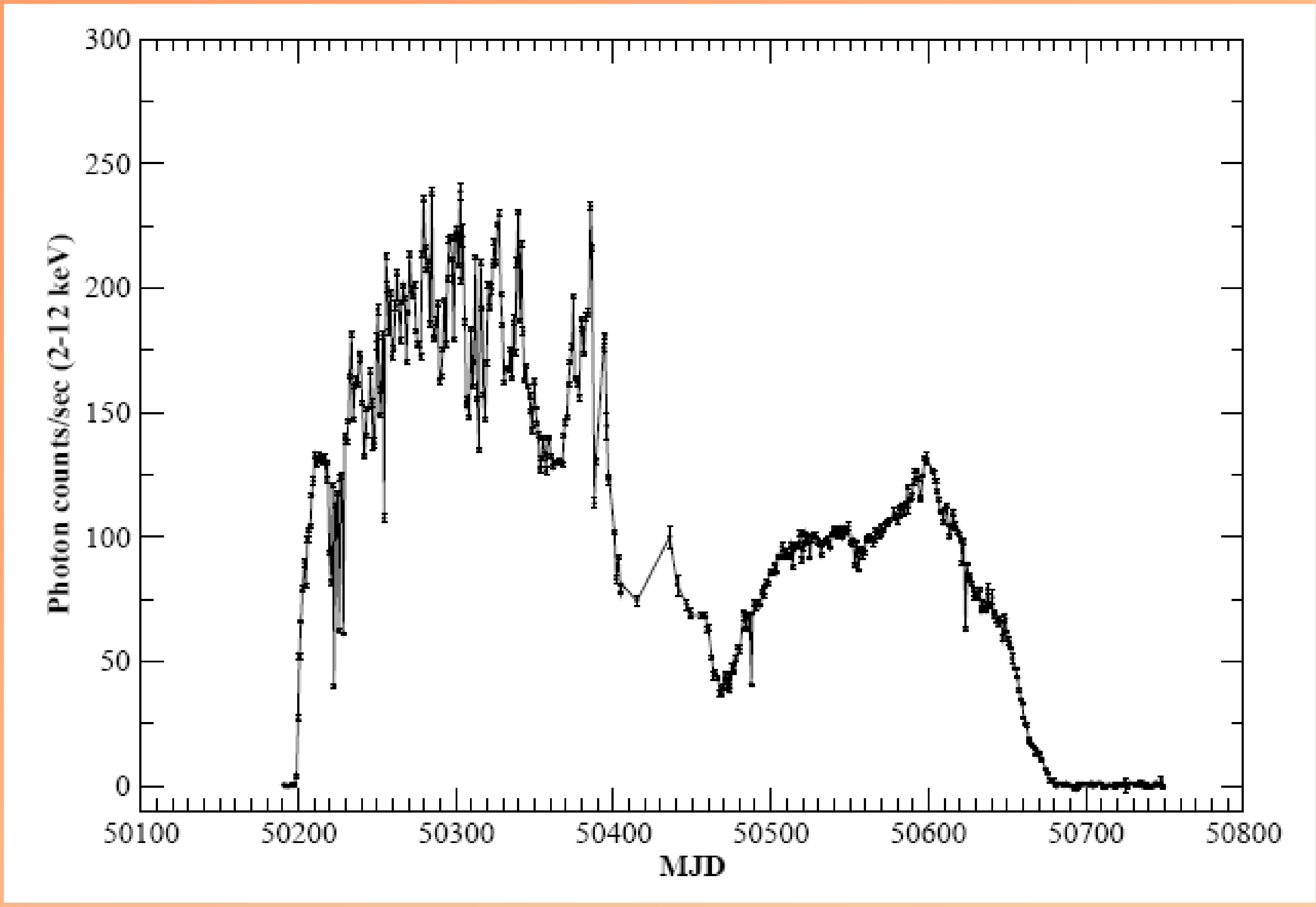
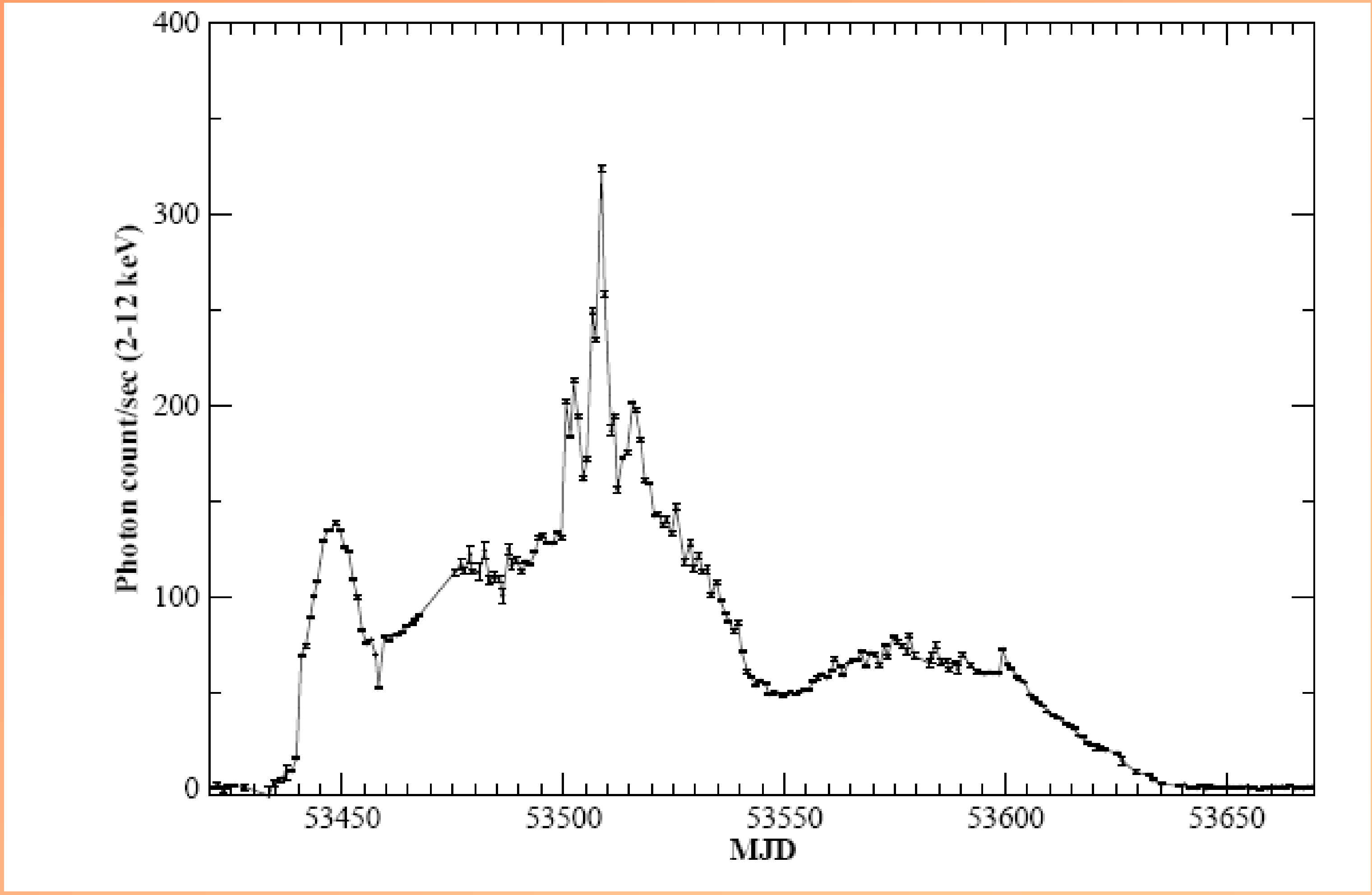


Figure 3.1: The ASM light curve (2-12 keV) of XTE J1550–564 in 1998 outburst are shown. The markers at the top indicate dates on which the spectra were examined with the two component model. Here, 'plus' sign represents the hard state, the 'rectangular' sign 'Very High/intermediate state', the 'diamond' sign represents the 'soft state', and 'cross' sign represents 'low/intermediate state' (Dutta & Chakrabarti 2010).

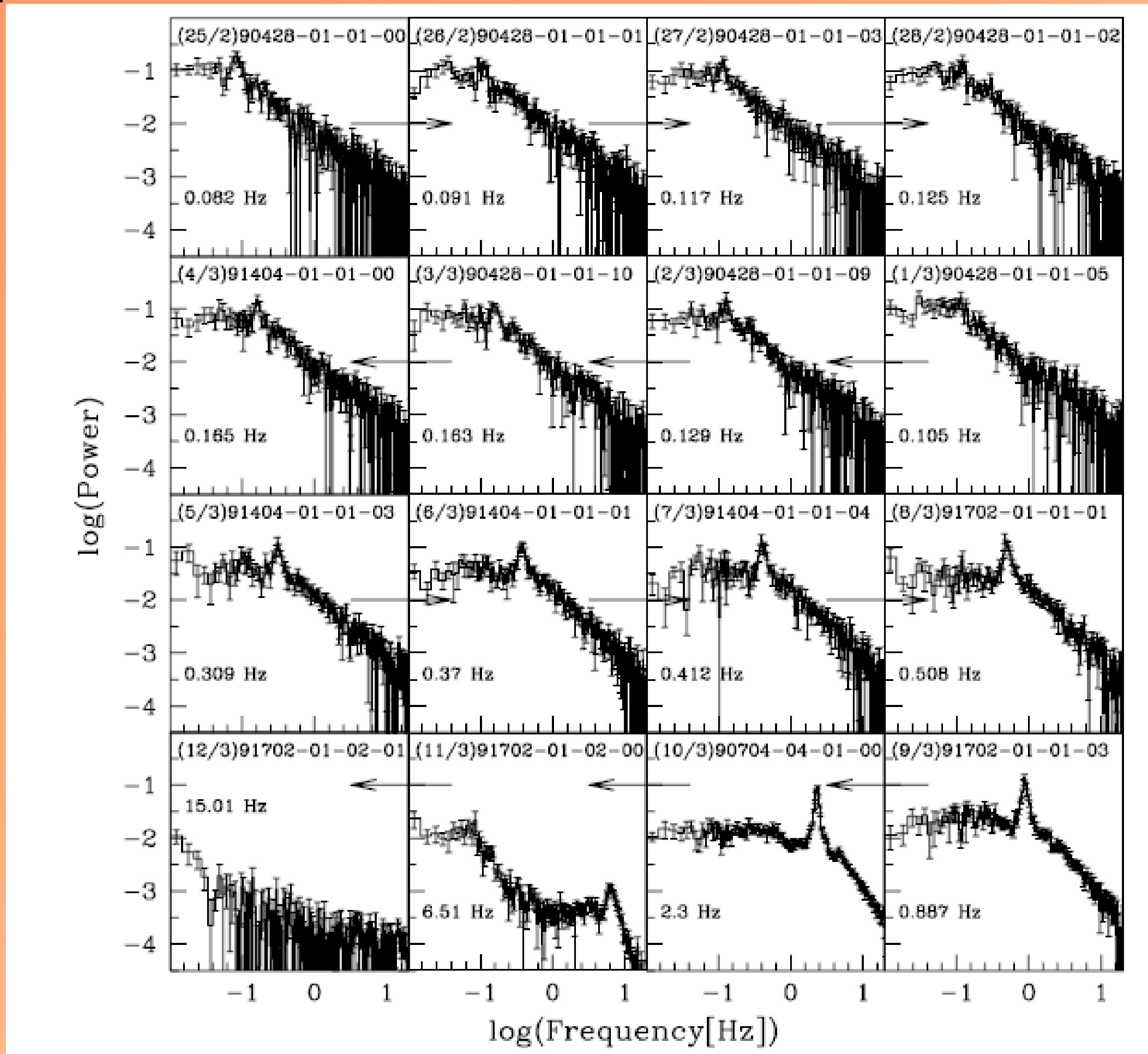
ASM of GRO J1655-40 in 1996 outburst



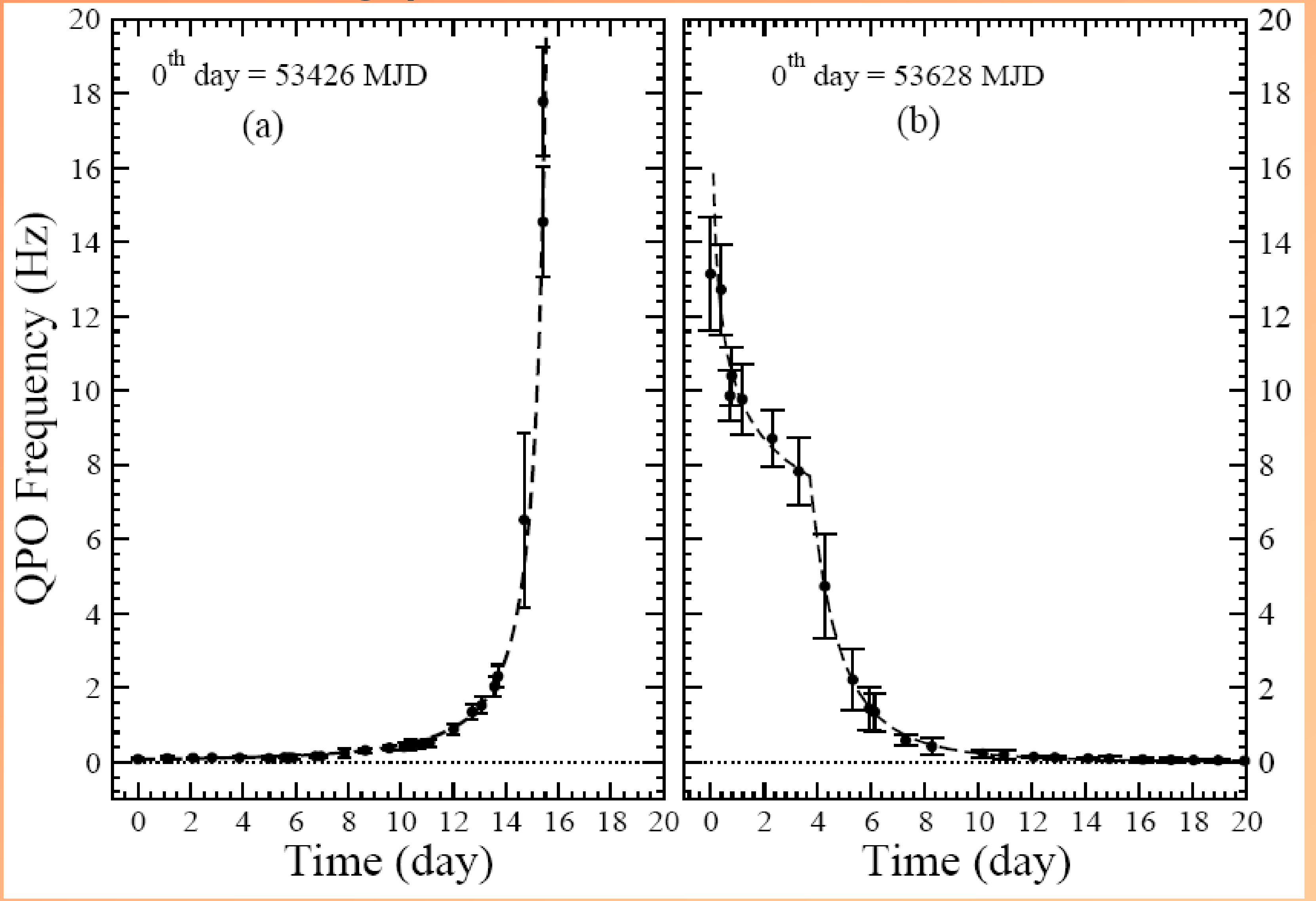
ASM of GRO J1655-40 in 2005 outburst



QPO evolution in GRO J1655-40

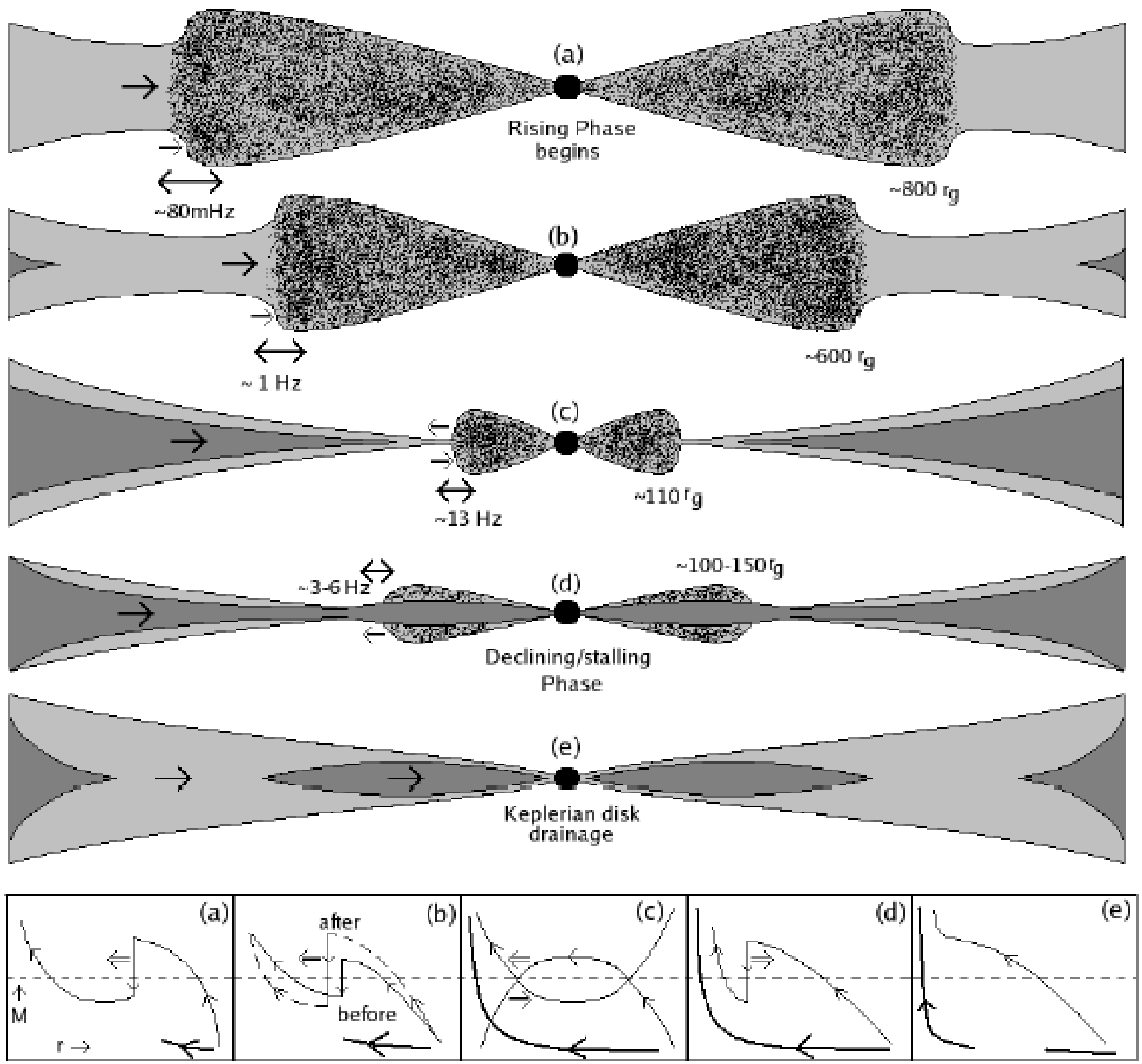


Evolution of QPOs in the rising and declining phases of GRO J1655-40

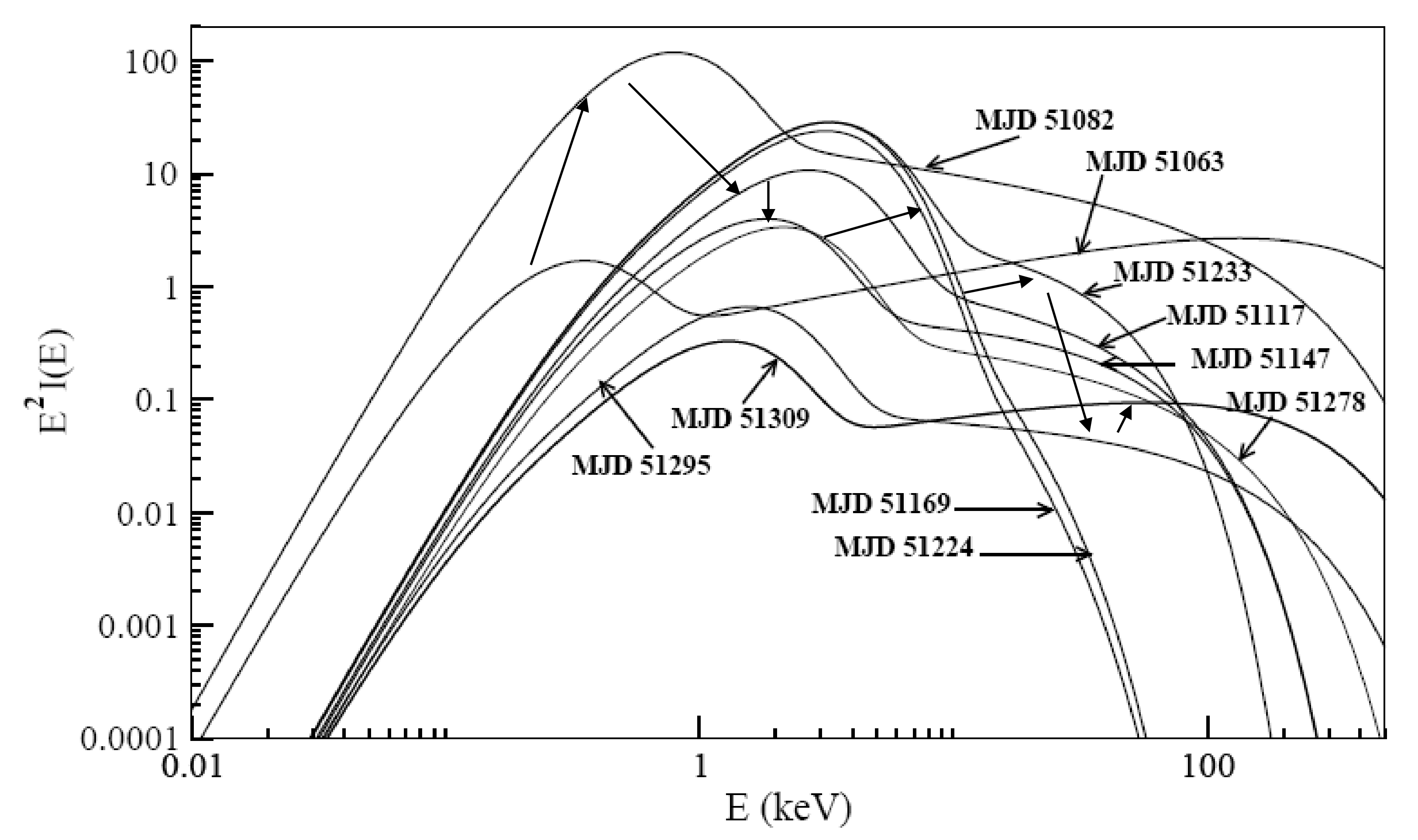


SKC+DD A&A 2008

Our picture!

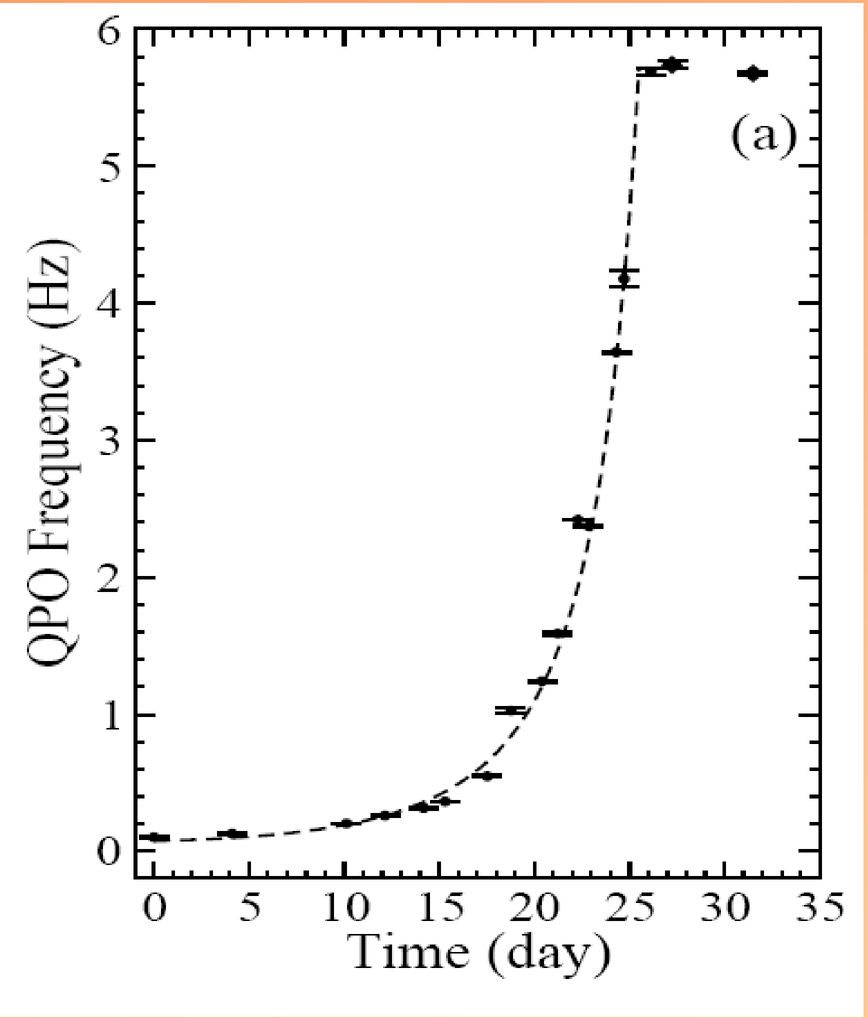

(a)
Rising Phase begins
~80mHz
~800 r_g
(b)
~ 1 Hz
~600 r_g
(c)
~110 r_g
~13 Hz
(d)
~3-6 Hz
~100-150 r_g
Declining/stalling Phase
(e)
Keplerian disk drainage
(a)
M
r
(b)
after
before
(c)
(d)
(e)

Spectral evolution over the whole outburst



Dutta and Chakrabarti, MNRAS 2010

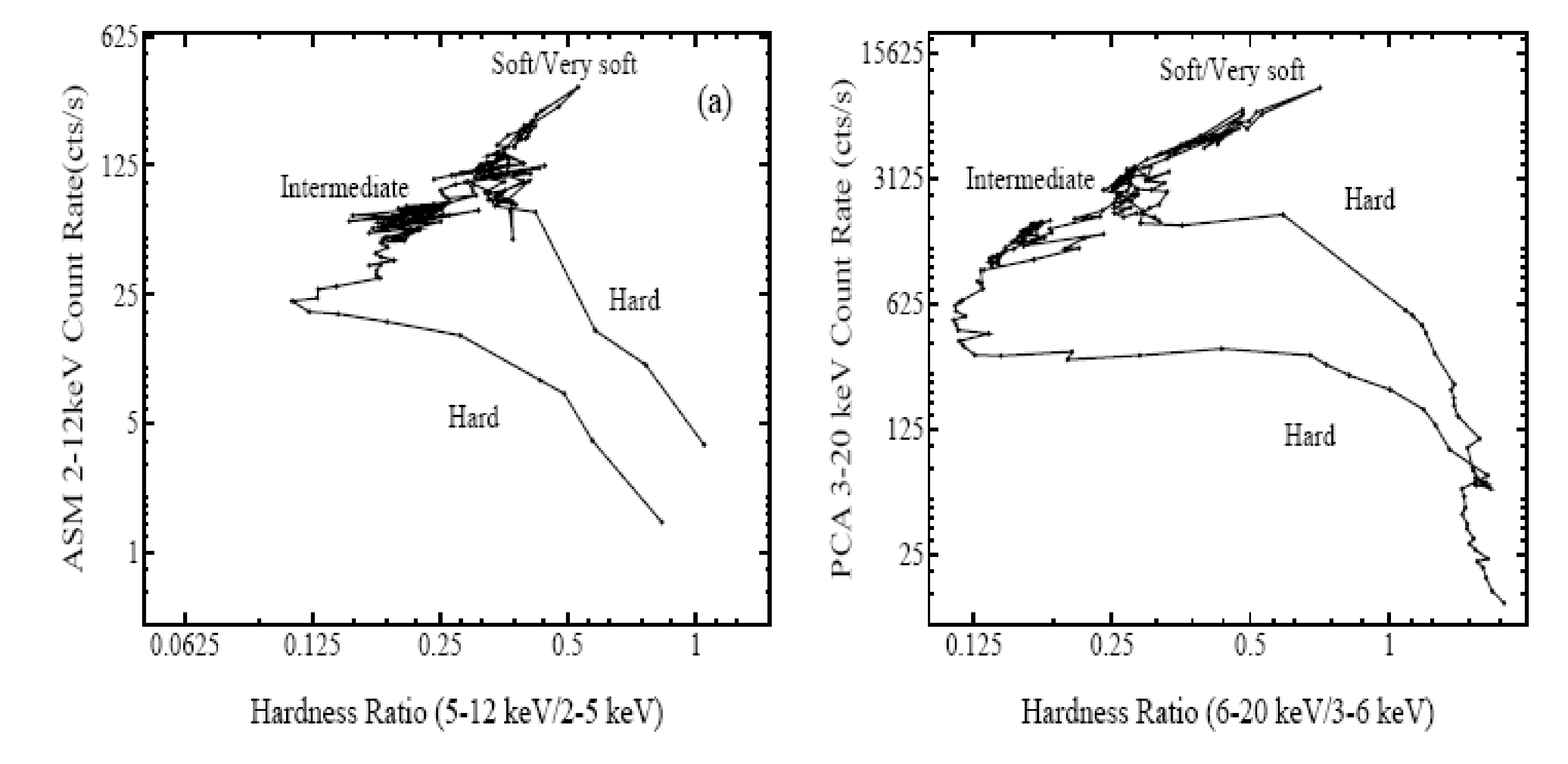
GX 339-4, recent outburst; same story of two component flow model

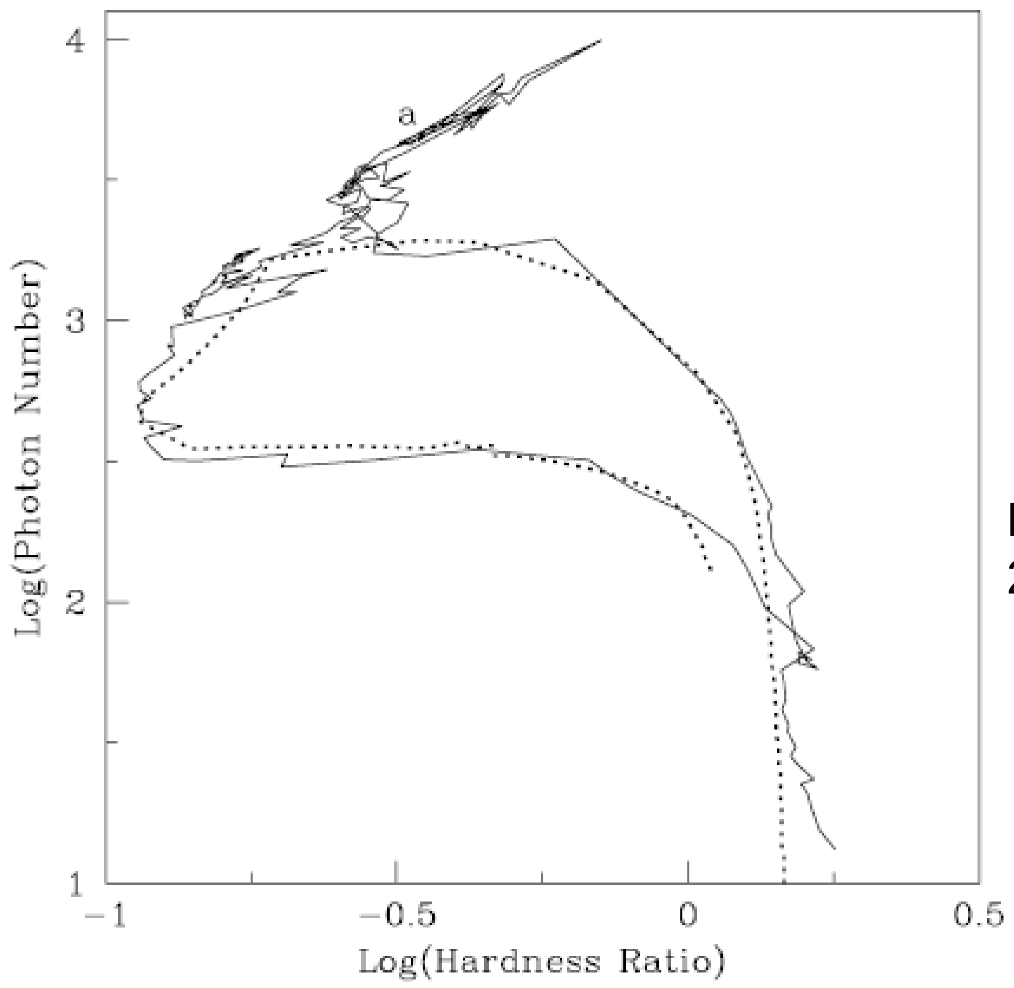


Debnath, Nandi and Chakrabarti, 2010

GRO J1655-40

Hardness intensity diagram

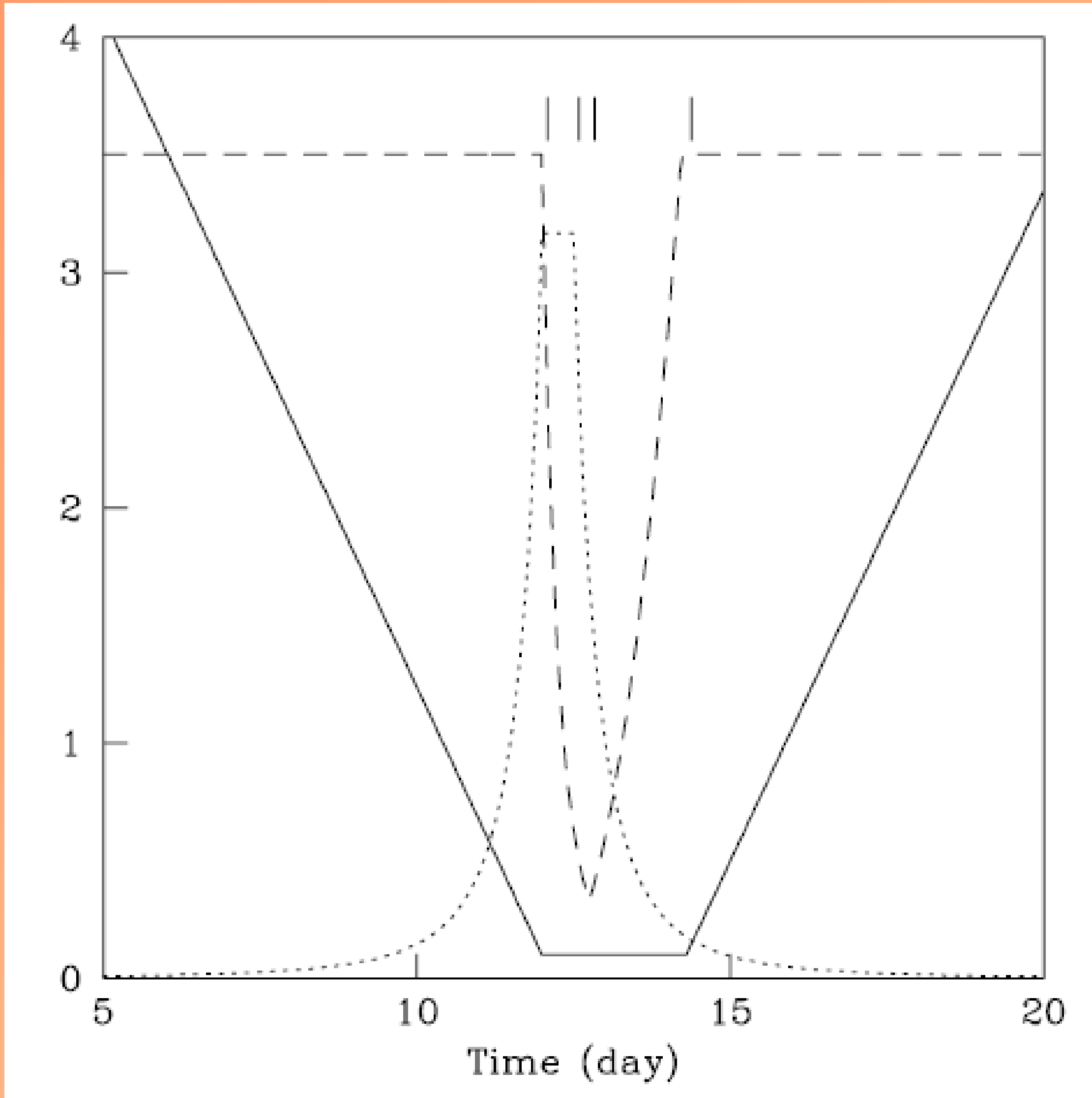




Mandal & Chakrabarti 2009

Fig. 2.— A fit of the GRO J1655-40 during its outburst (solid line) of 2005 with the model (dotted line). The parameters are given in Table 2.

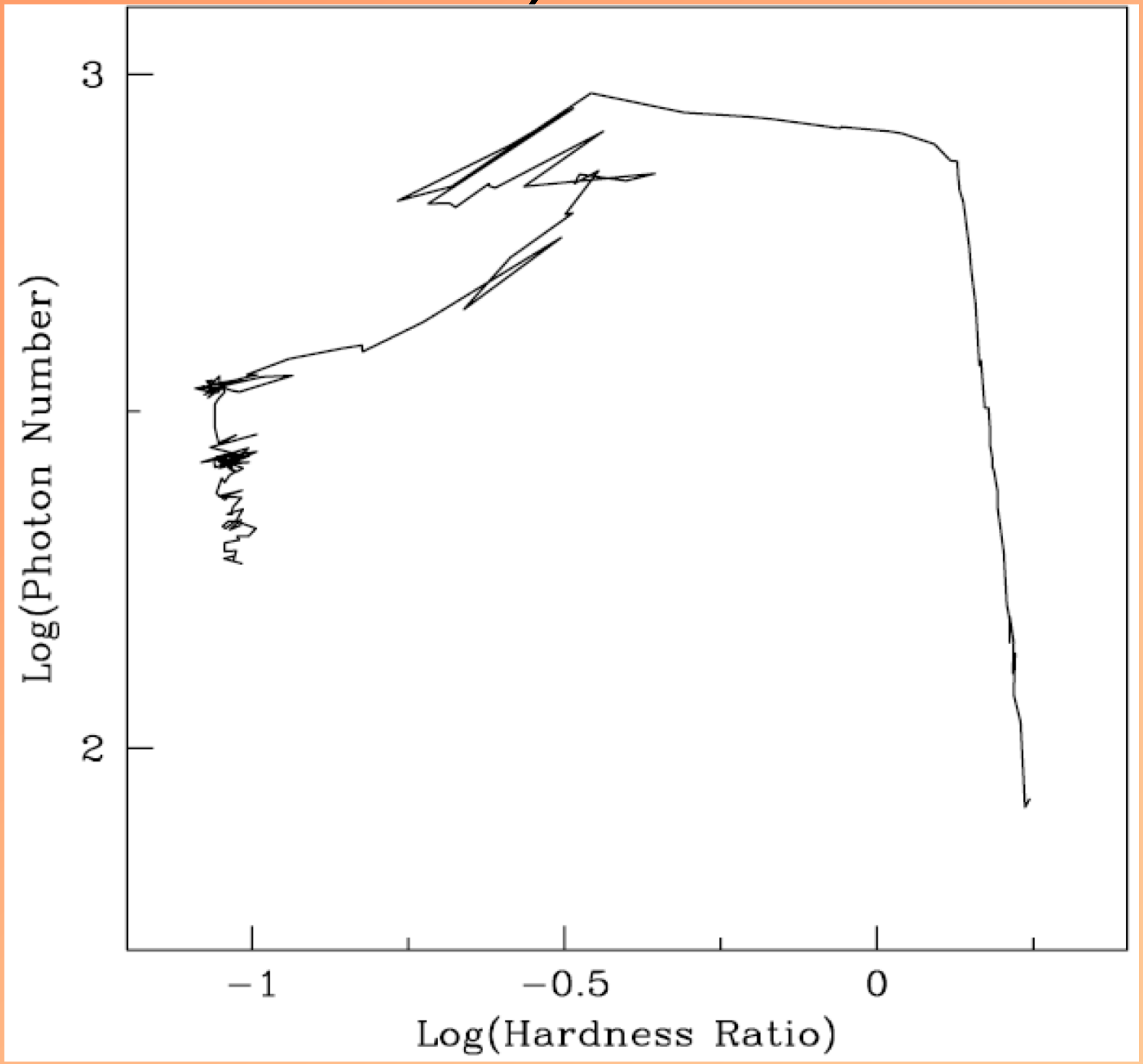
The time variation of Keplerian and sub-Keplerian rates and the variation of the shock location during an outburst



GRO J1655-40

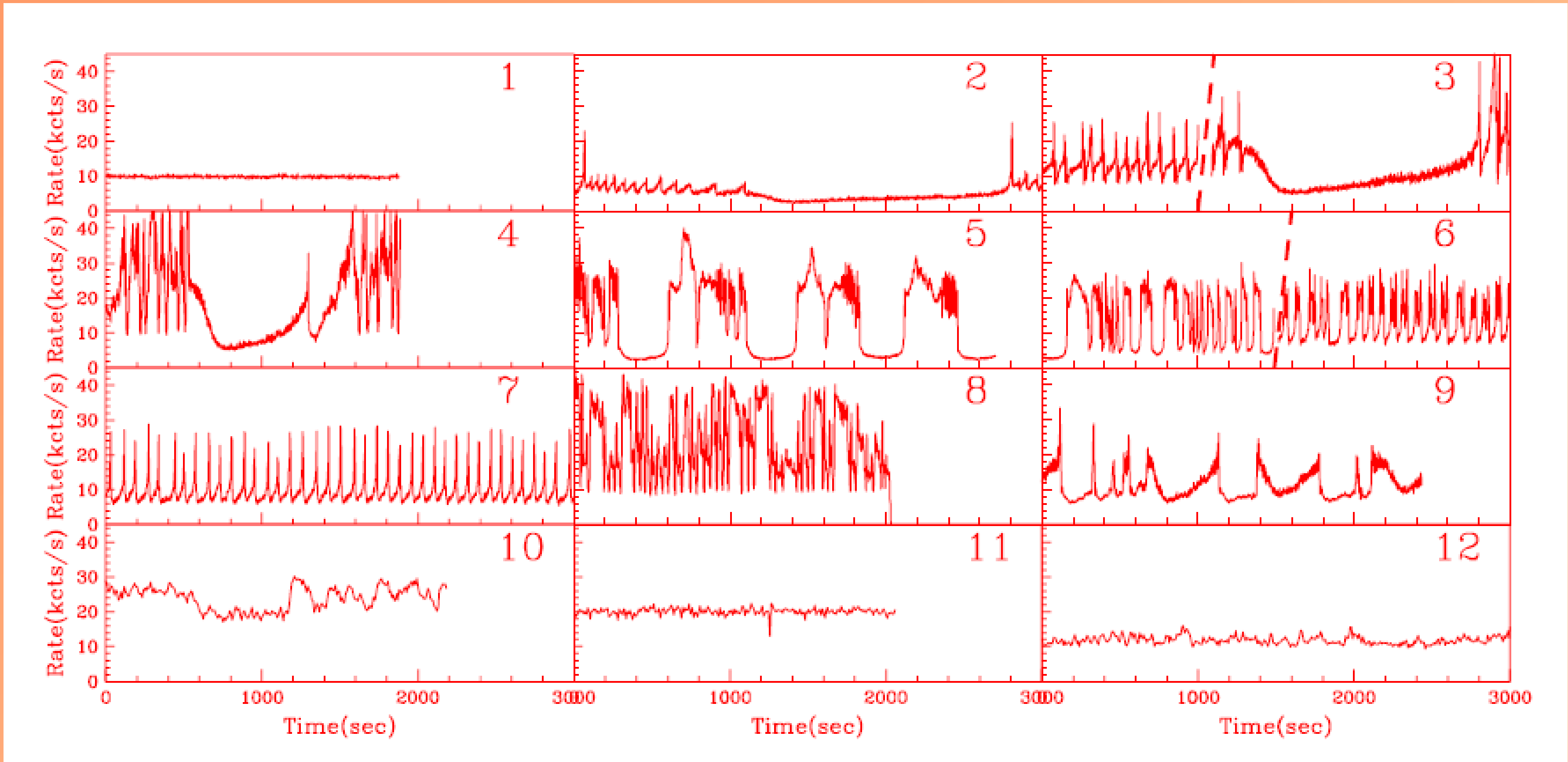
Mandal and Chakrabarti 2010 ApJL

GX339-4, no signature of coming back to hard state yet. Last six months it is in a soft state (sub-Keplerian component is gone, Keplerian component is receding; Chakrabarti 1997)



Debnath, Mandal and Chakrabarti, 2011

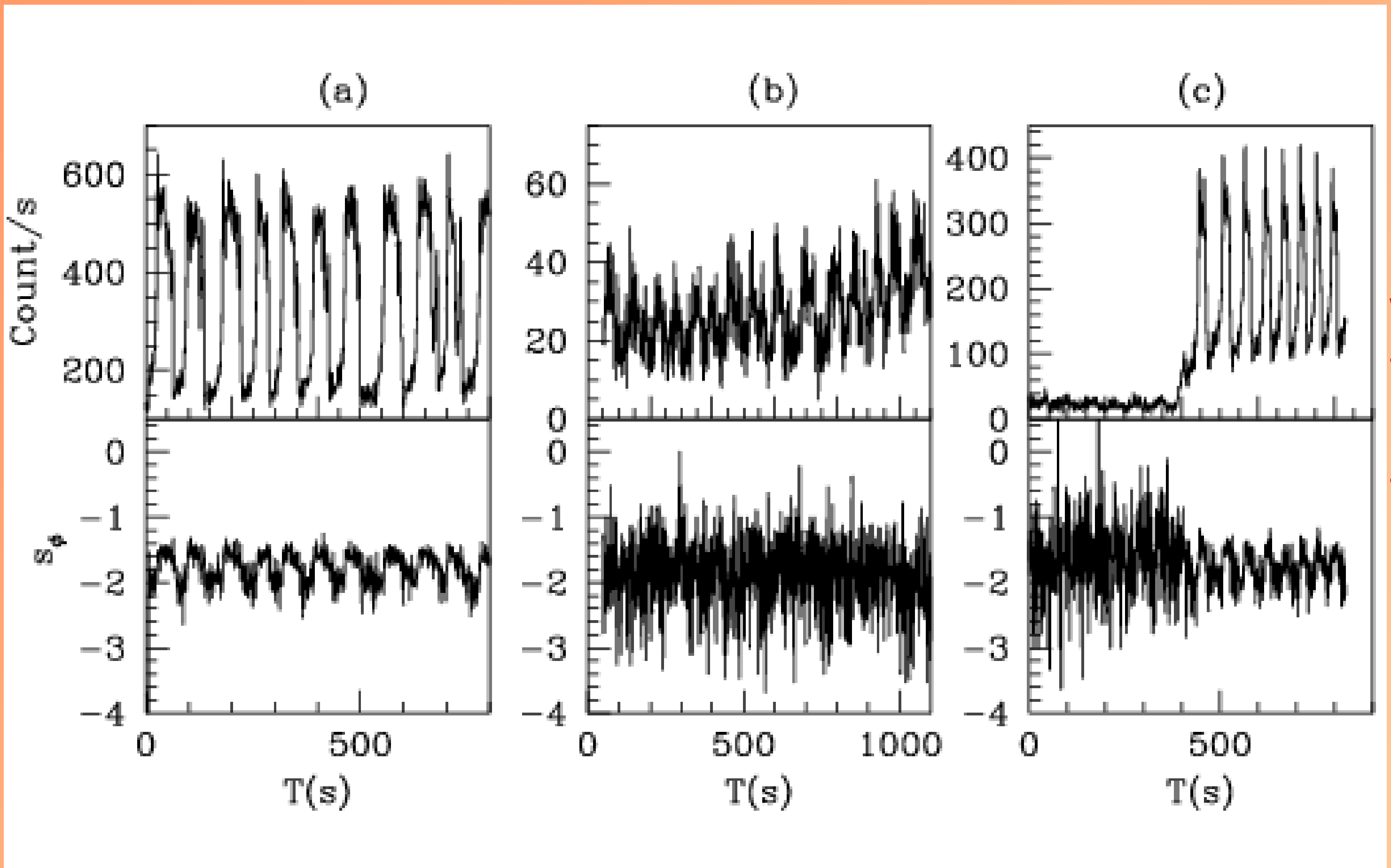
Variation of Light curves of GRS 1915+105



Belloni et al 2000 classified them in terms of hardness ratios

Chakrabarti and Nandi 2000 organized them in terms of length of the hard/burst-off state

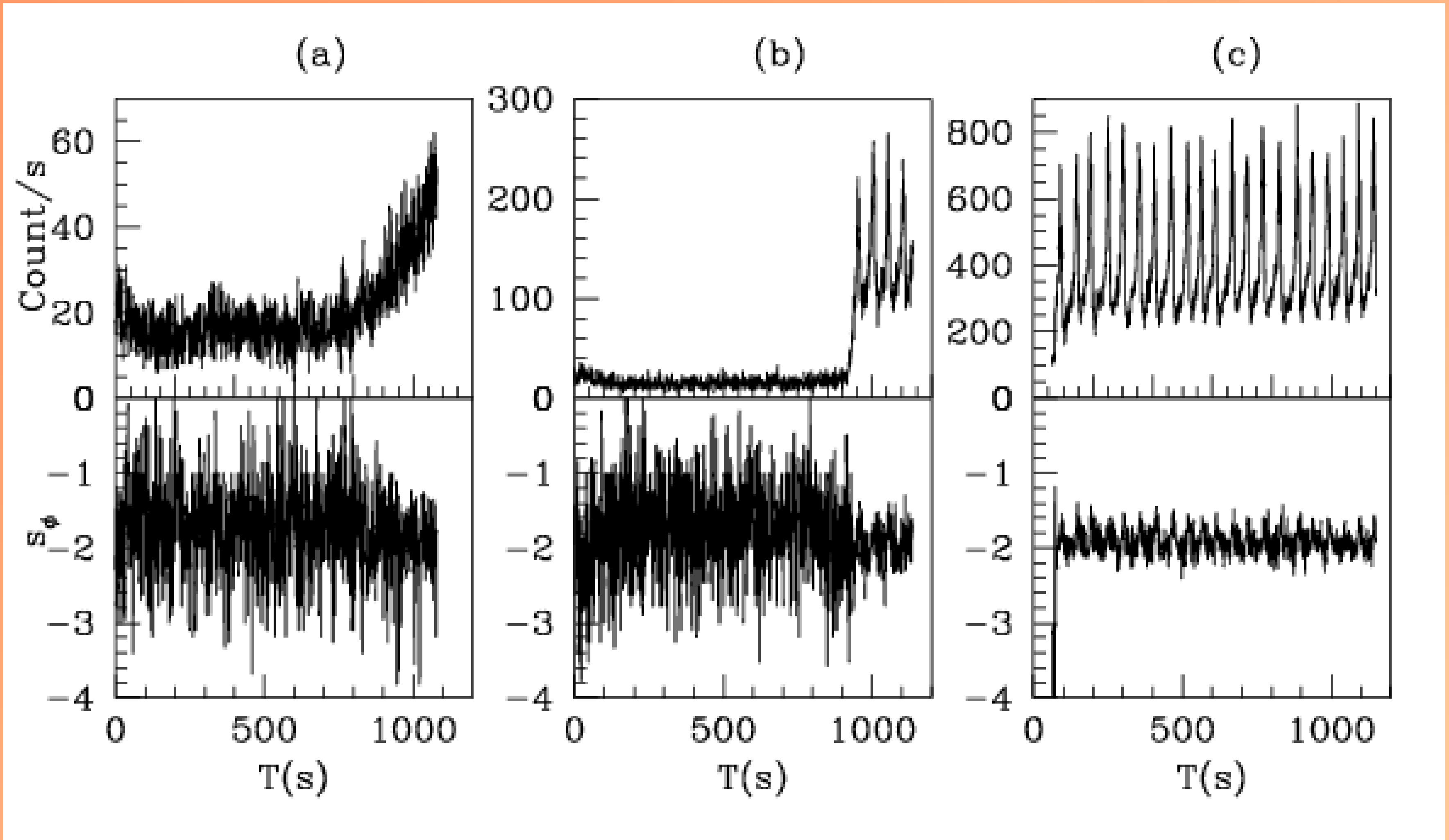
Evidence of Sub-Keplerian Flows: Time taken for variability class transition



Side remark: Evaporated disk or truncated disk model will NOT work for these fast burst-off and burst-on state transitions. That is why CENBOL become more relevant.

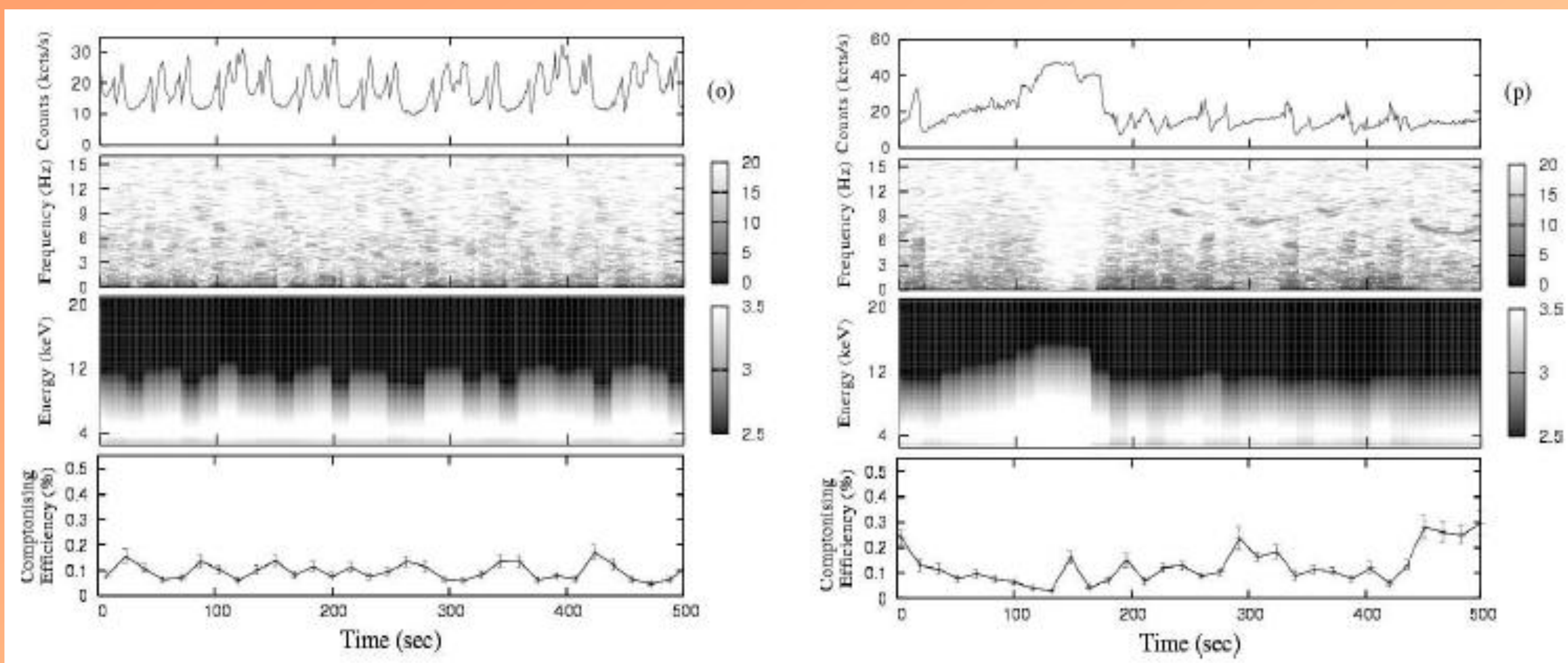
Matter of a few hours! Must be sub-Keplerian.

Chakrabarti et al. 2005

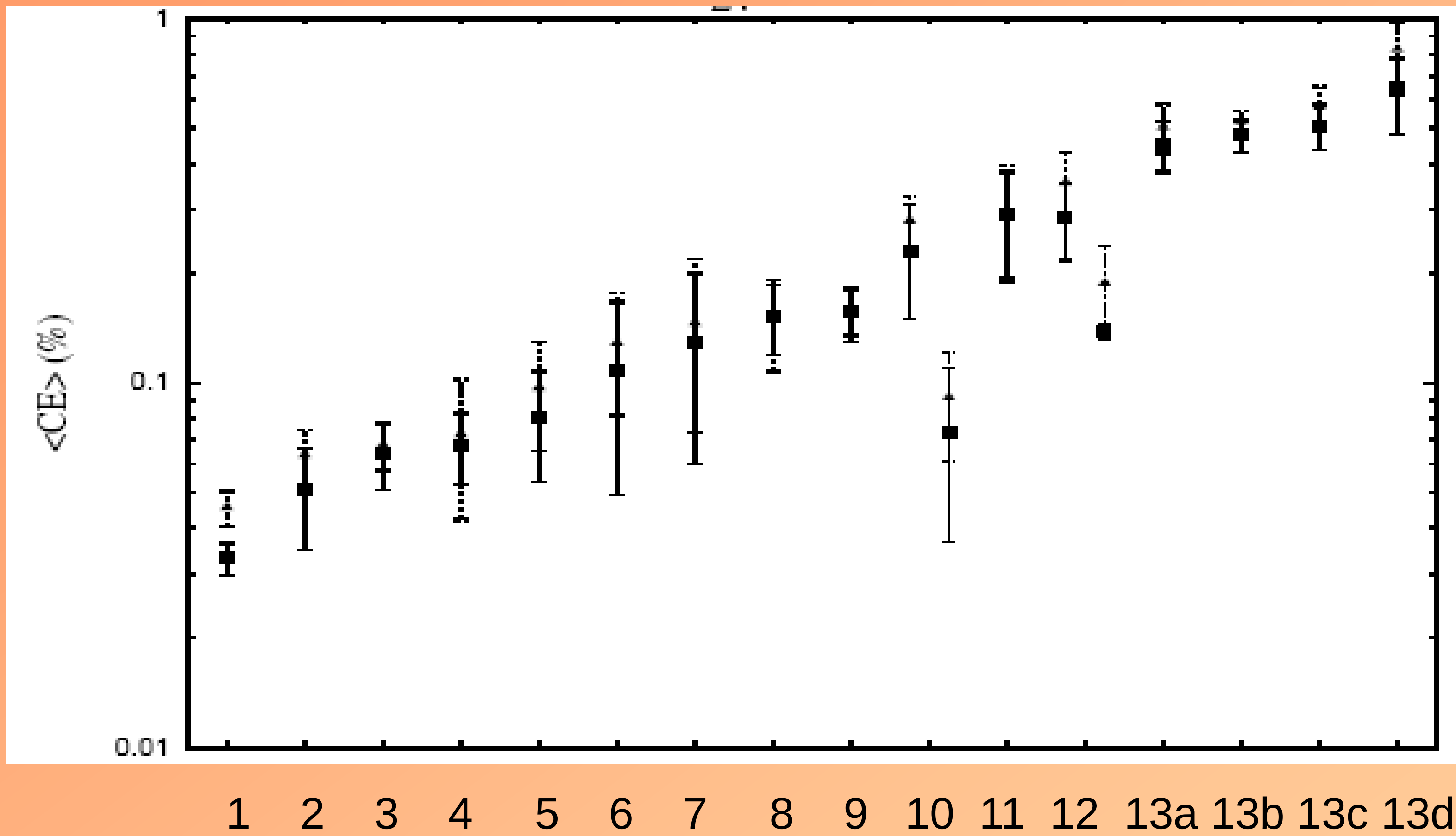


Another case of class transition in 3 hours timefor GRS 1915+105 (SKC et al. 2005)

To understand this zoo, we introduced a totally new concept: Just calculate mean Comptonizing efficiency for all these variability classes of GRS1915+105: Ratio of black body photons to power-law photons



Sequencing Variability classes



By arranging the Comptonizing Efficiency we get a sequence of the classes. Strikingly the class transitions in GRS 1915+105 actually take place in the same sequence.

What about time lag properties in HMXRB and LMXRB
(cf. B. Paul's talk this morning)?

Examples of the solutions of NASA/Berkeley group (Smith, Heindle, Markwardt and Swank, 2002, ApJ)

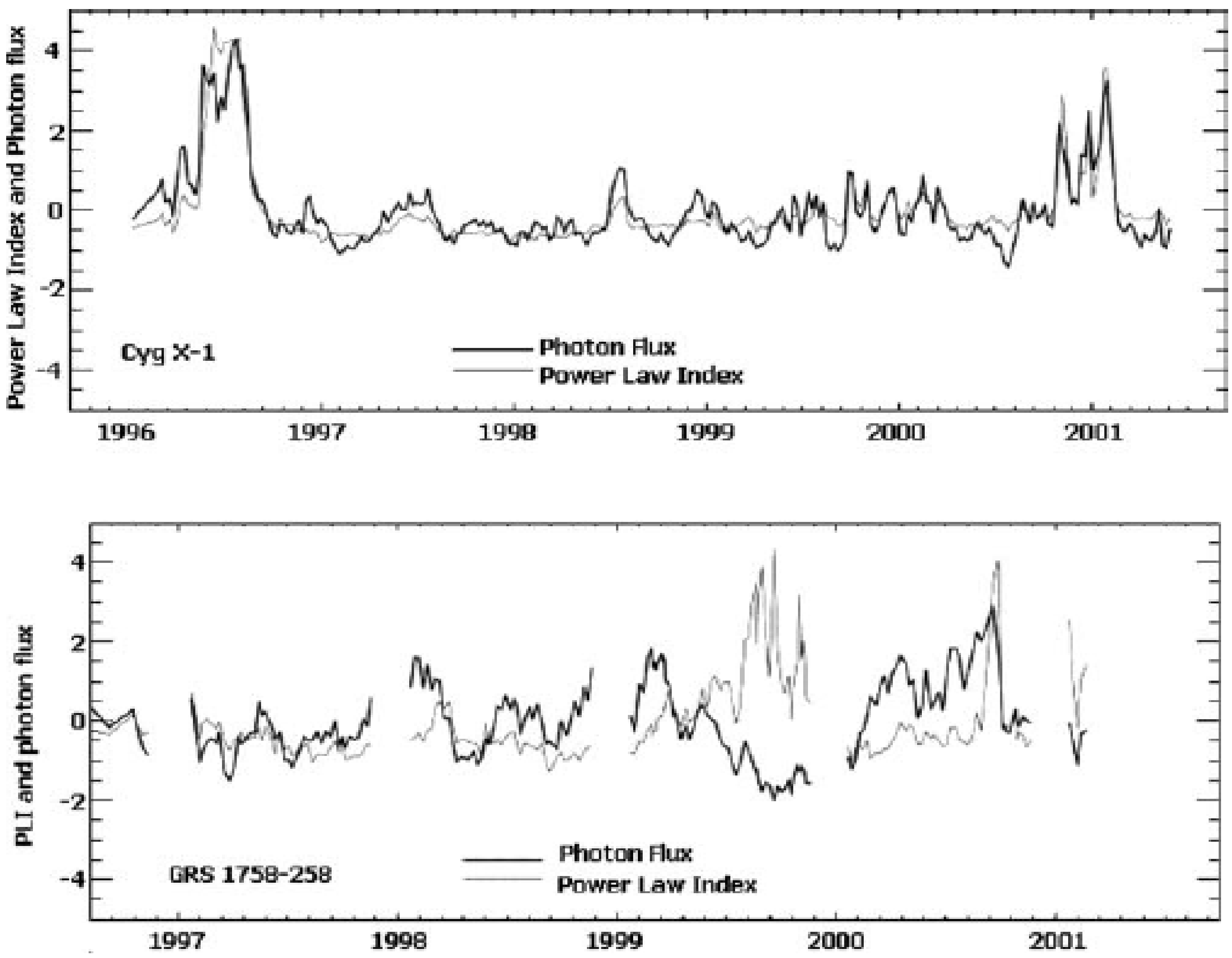
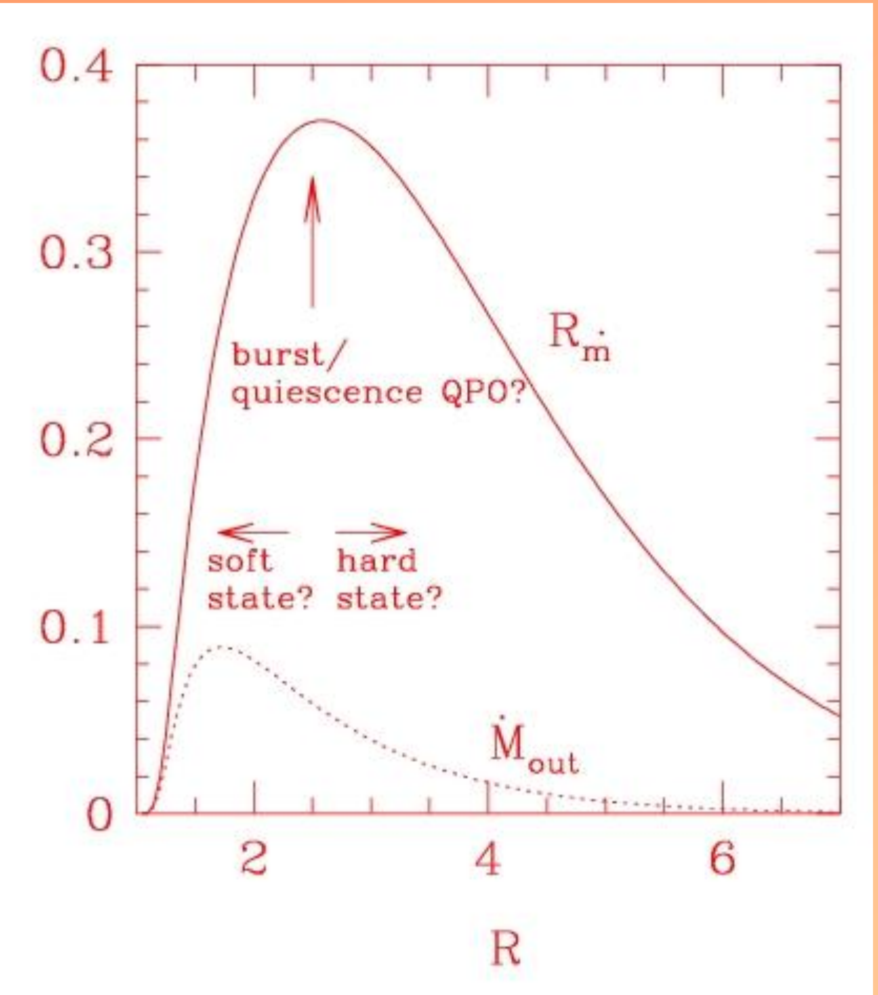
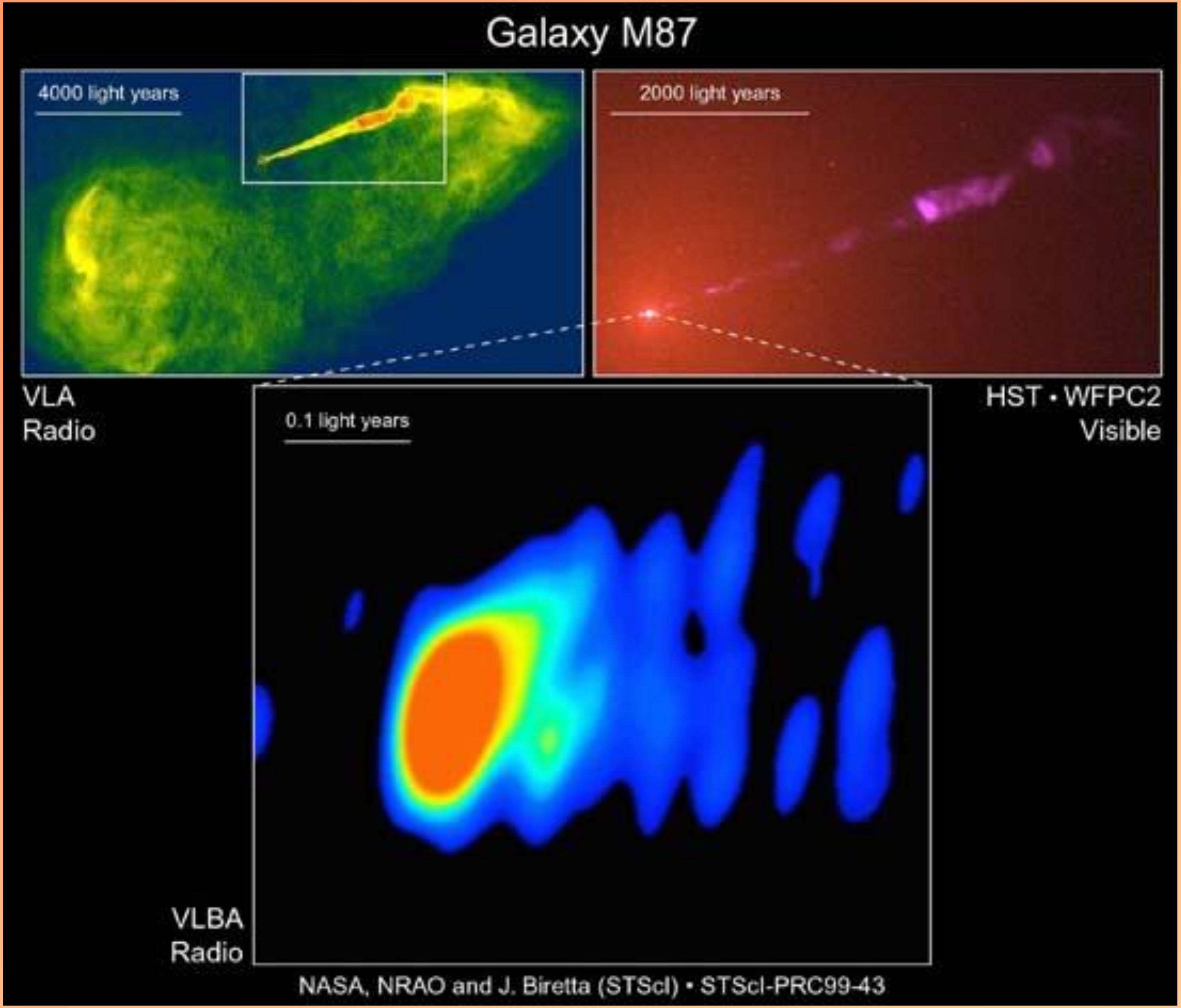


Figure 2. ASM light curves for a wind accretor (Cyg X-1) and a low-mass binary system (GRS1758-258) from RXTE data (Smith et al., 2002) showing distinctly different behaviour due to the absence and presence of a dominant Keplerian disk in these objects. Photon flux is in the units of photons/cm^2/s.

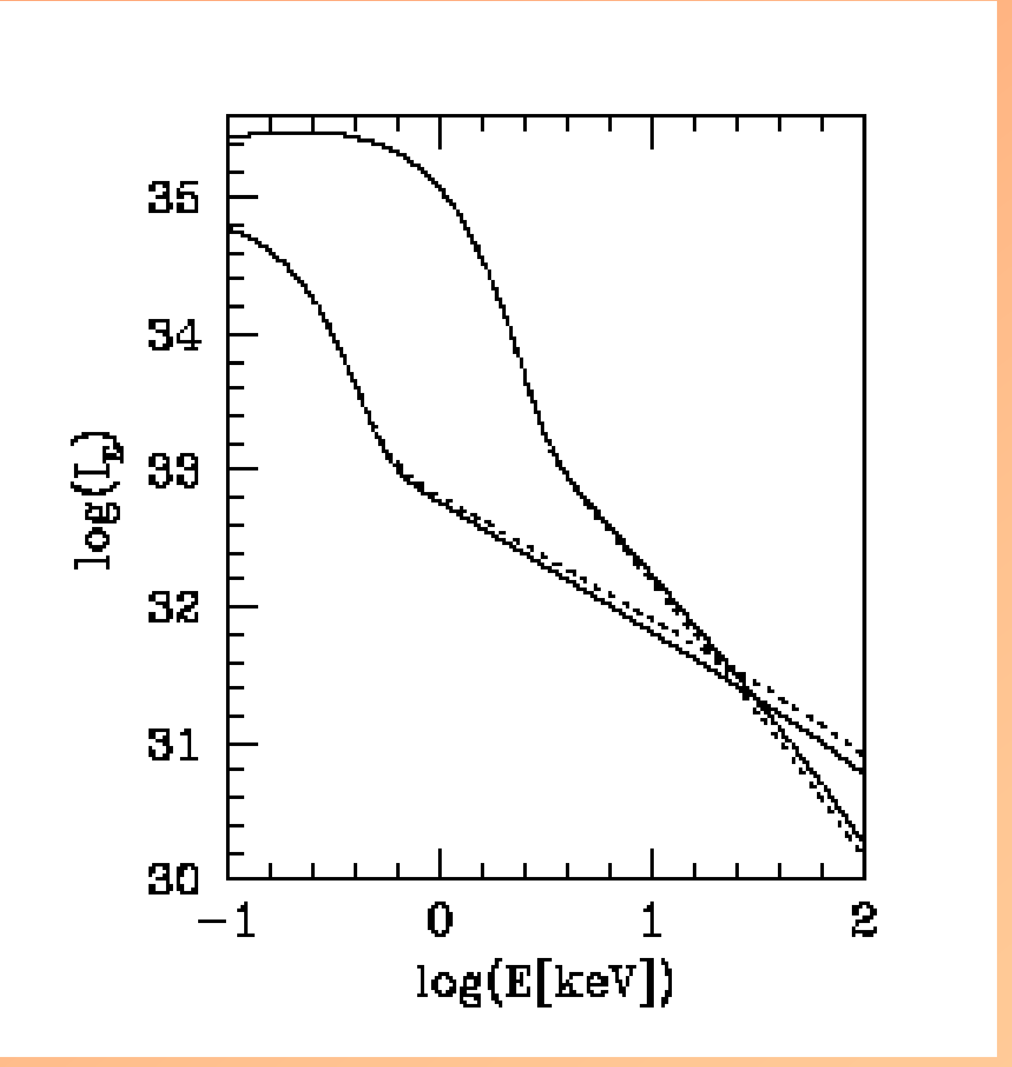


Outflow/inflow ratio as a function of the shock strength (Chakrabarti, 1998) -> No CENBOL no outflow

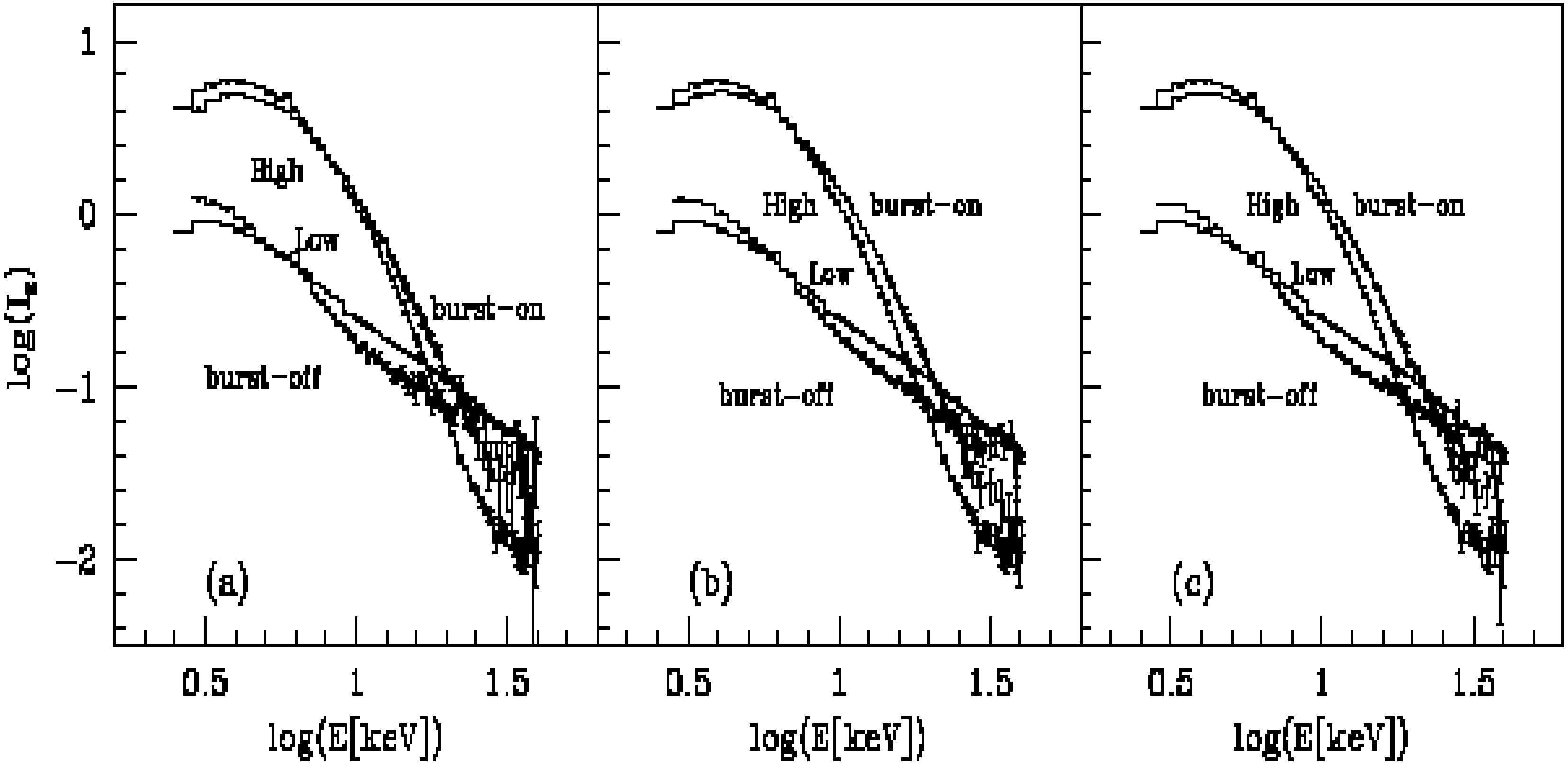
Case in Point …. M87



Effects of winds on spectra (Theory)

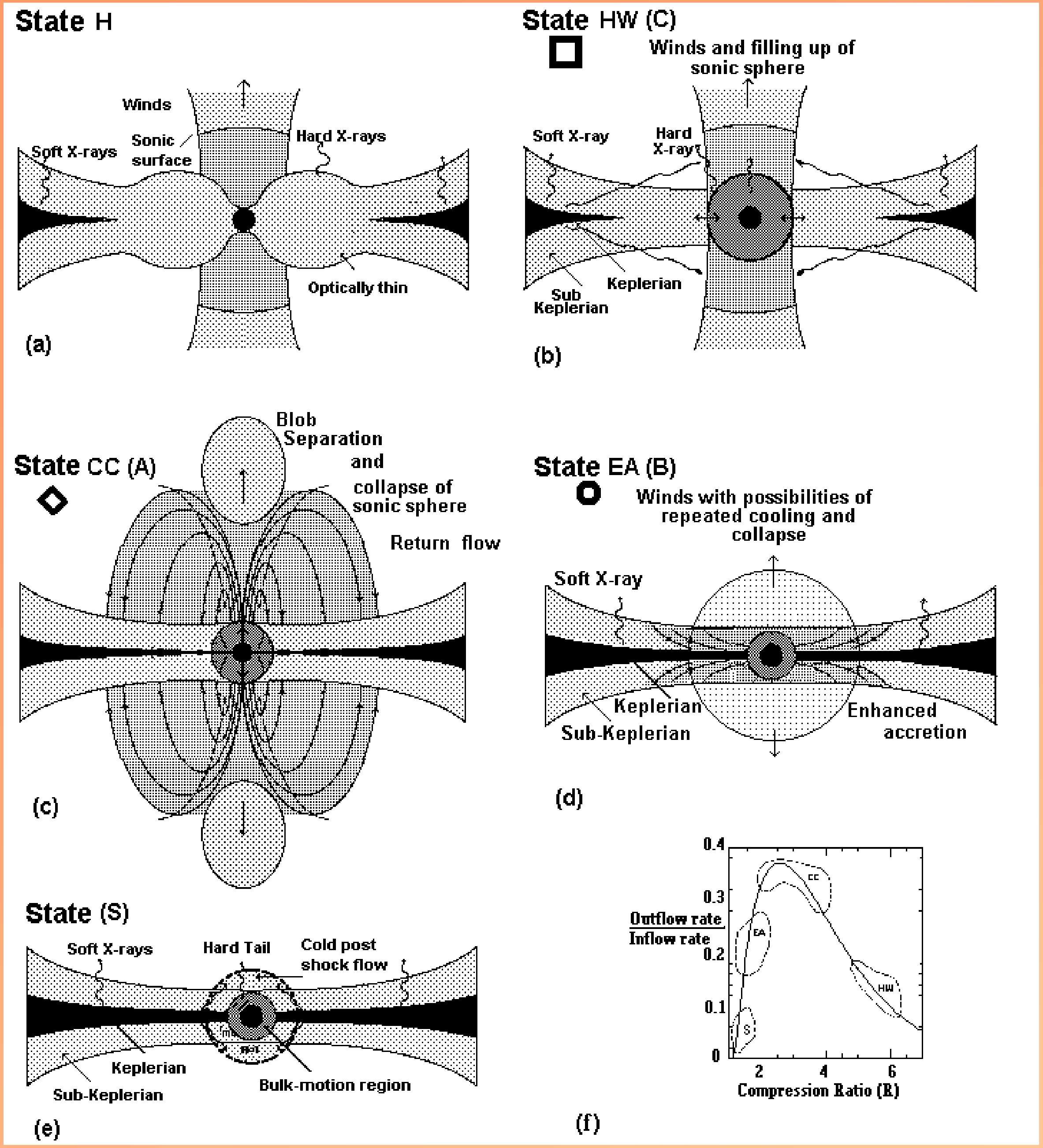


Effects of winds on spectra (Observations)



Chakrabarti et al. 2003

We talked about the Comptonization due to the jet base, i.e., CENBOL long ago!

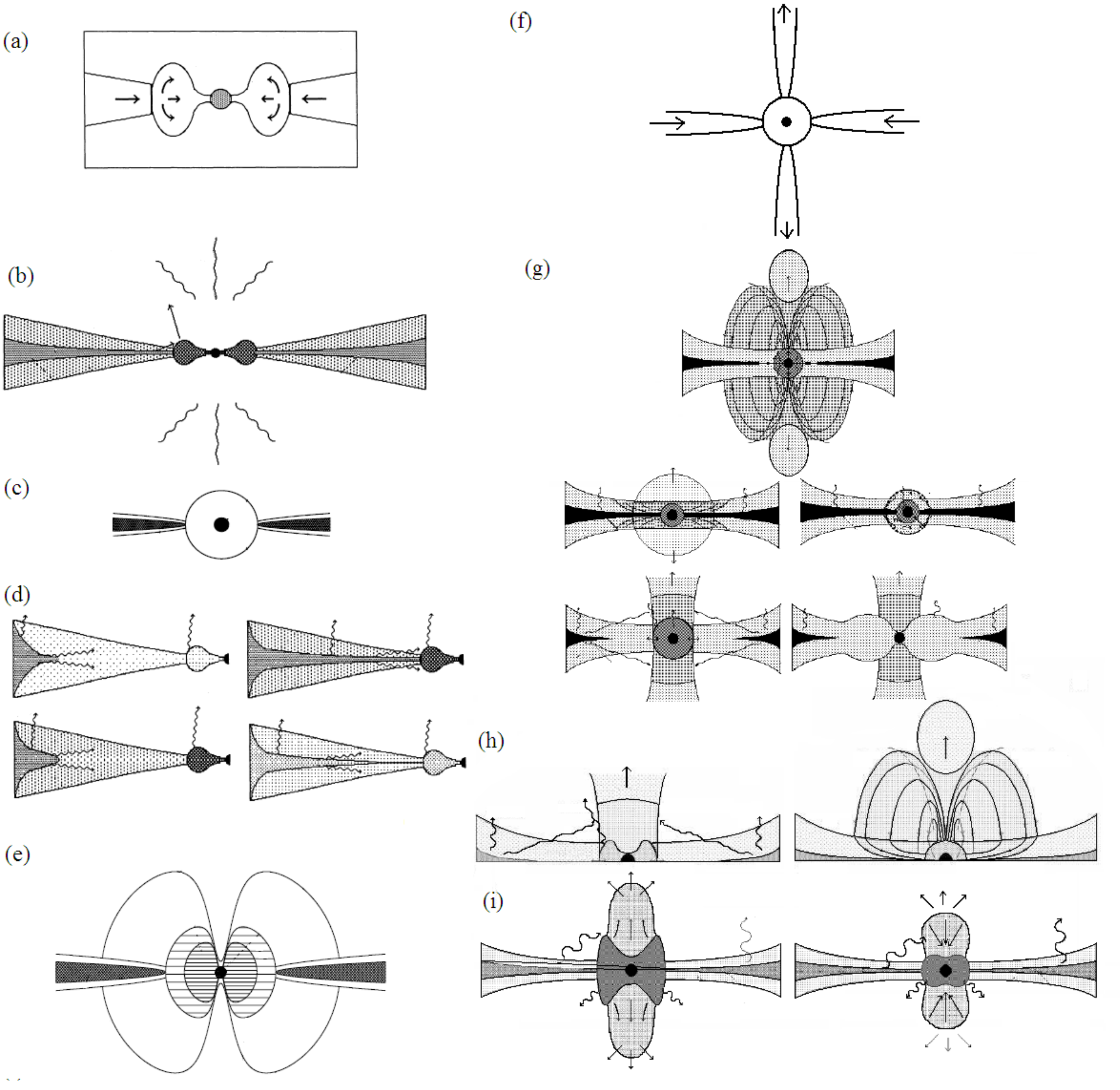


Formation of jet depends on how accretion takes place. Jets can be turned on/off depending on the relative ratios of Keplerian and sub-Keplerian matter.

Chakrabarti and Nandi, 2000

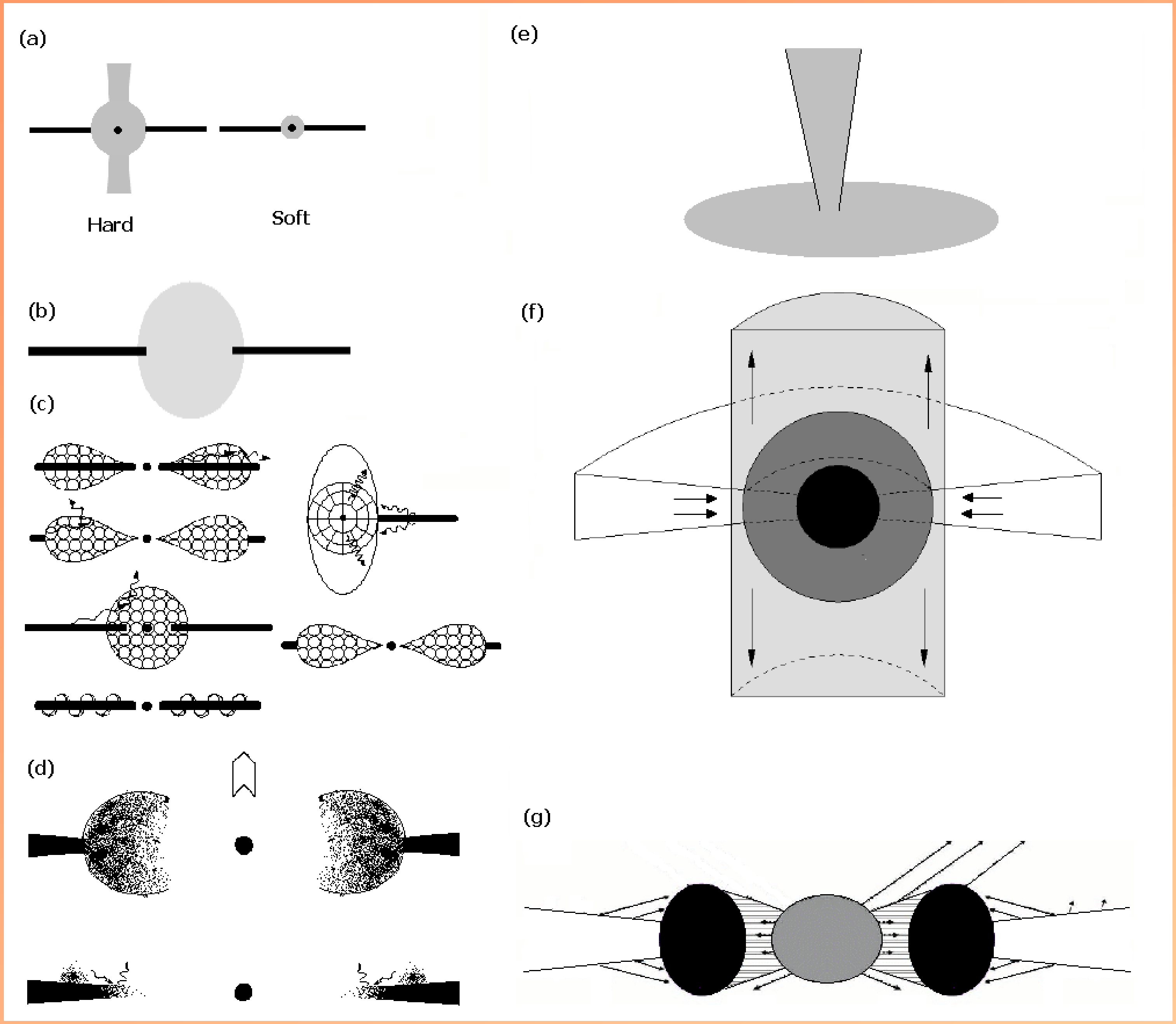
Punch line

- All the present ‘models’ with accreting corona, jet base and what nots are exactly same as our ‘solution’ which we presented two decades ago
- More and more all the models derived from observations are matching with our paradigm picture



The history of how the disk model is modified from theoretical consideration.

(a) Chakrabarti 1990a; Abramowicz & Chakrabarti (1990); (b) Chakrabarti & Titarchuk, 1995; (c) Ebisawa, Titarchuk & Chakrabarti, 1996; (d) Chakrabarti \& Sahu, 1997; (e) Chakrabarti, 1997; (f) Chakrabarti, 1998ab; (g) Chakrabarti \& Nandi 2000; (h) Nandi et al. 2001; (i)Chakrabarti et al. 2002.



The history of how the disk model is modified from observational considerations

(a) Fender et al. 1999; (b) Zdziarski, 2000; (c) Nowak, 2003;
(d) Zdziarski \& Gierlinksi 2004;
(e) Markoff \& Nowak 2004;
(f) Titarchuk \& Shaposhnikov, 2005; (g) Ferinelli, Titarchuk \& Frontera,2007.

So why the subject is not progressing beyond Shakura-Sunyaev (1973)?

In astrophysics/astronomy 2+2 is not always 4, it could be on an average 4!

Not many believe that a complicated thing such as black hole accretion could be understood by theory at all. So theorists must be bluffing.

So there is ample scope to ‘fish in muddy water’ hoping that none would notice.

THANK YOU!