Short term aperiodic variability of X-ray binaries: its origin and implications

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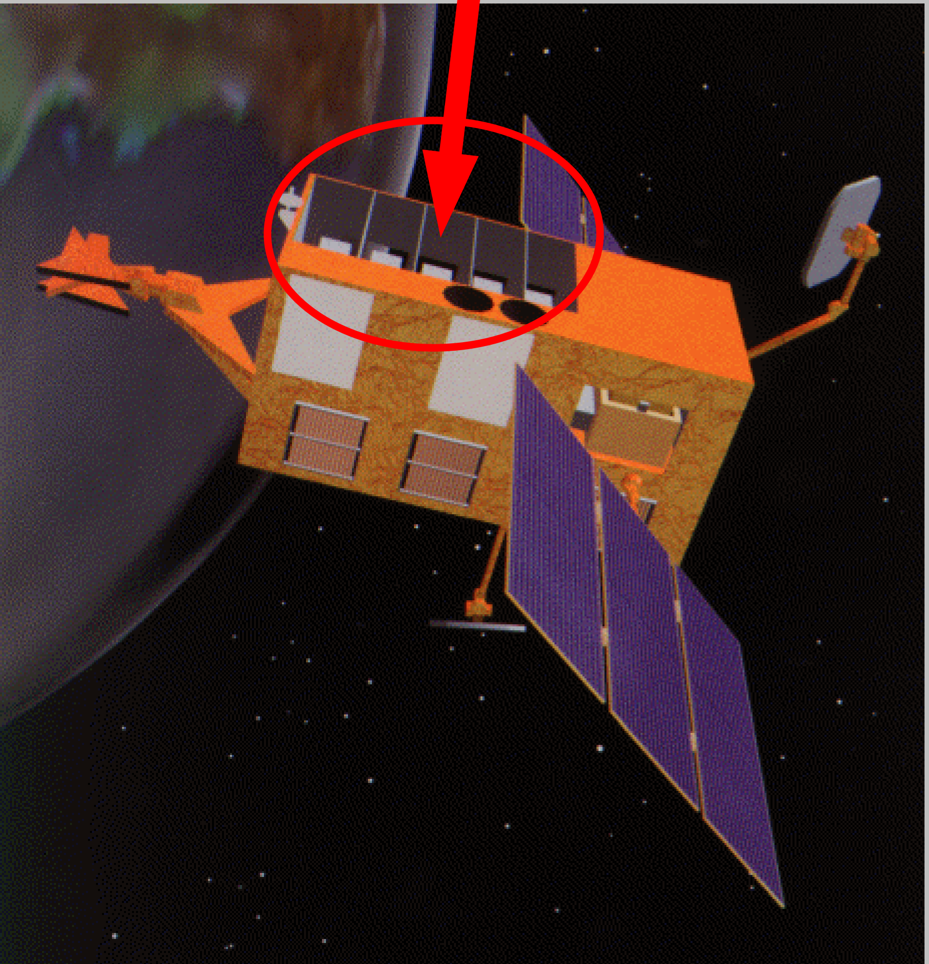
Why we study variability of X-ray sources?

Something like: *why we like to listen sound, speach?*

Additional information about astrophysical phenomena, which <u>does not duplicate</u> any other type of astronomical information

Instruments collecting sound information

X-ray



Why we study variability of X-ray sources? *(why listening sound?)*

1. Rapid variability (<1 sec) should originate close to the compact object. Strong gravity.

2. Innermost regions of the accretion flow are radiation pressure dominated.
How the plasma behaves in this case?

3. In NS binaries the fastest varibility should originate close to NS. Equation of state?

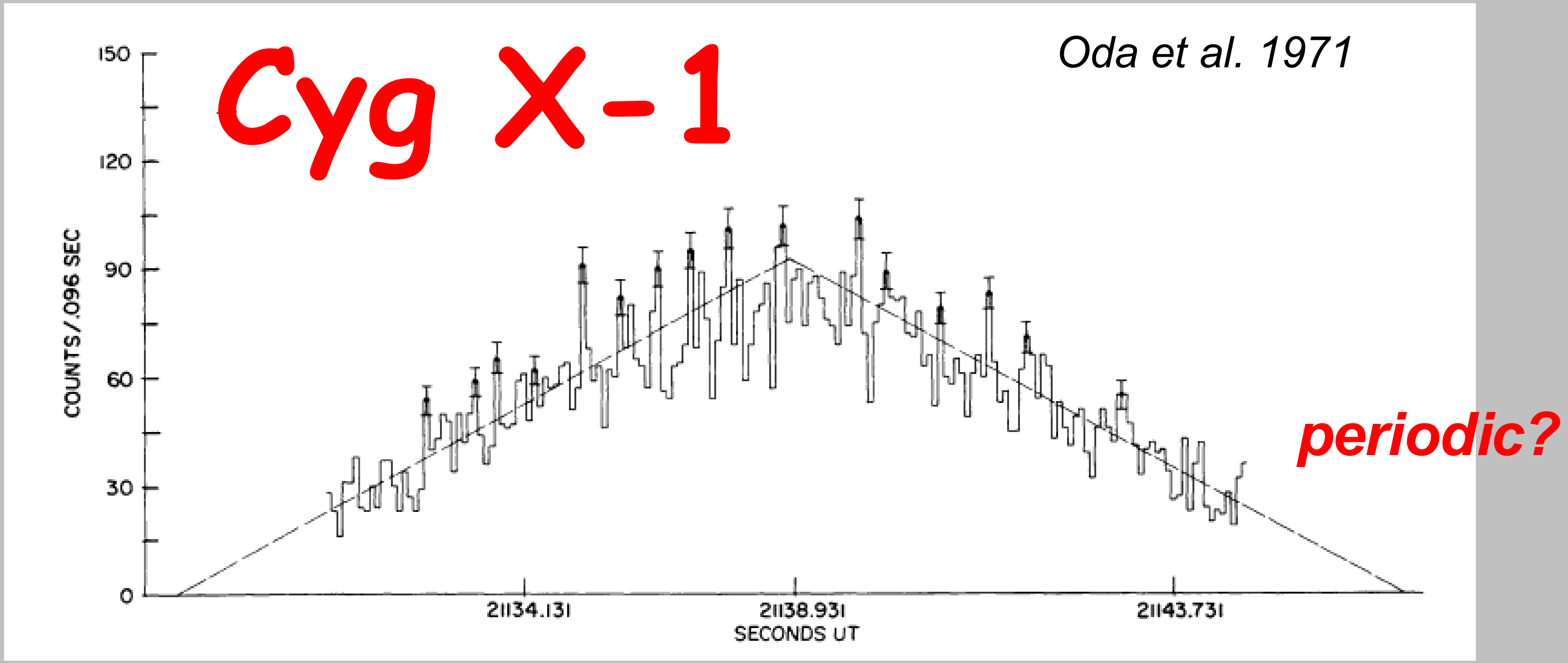
4....5.....6....

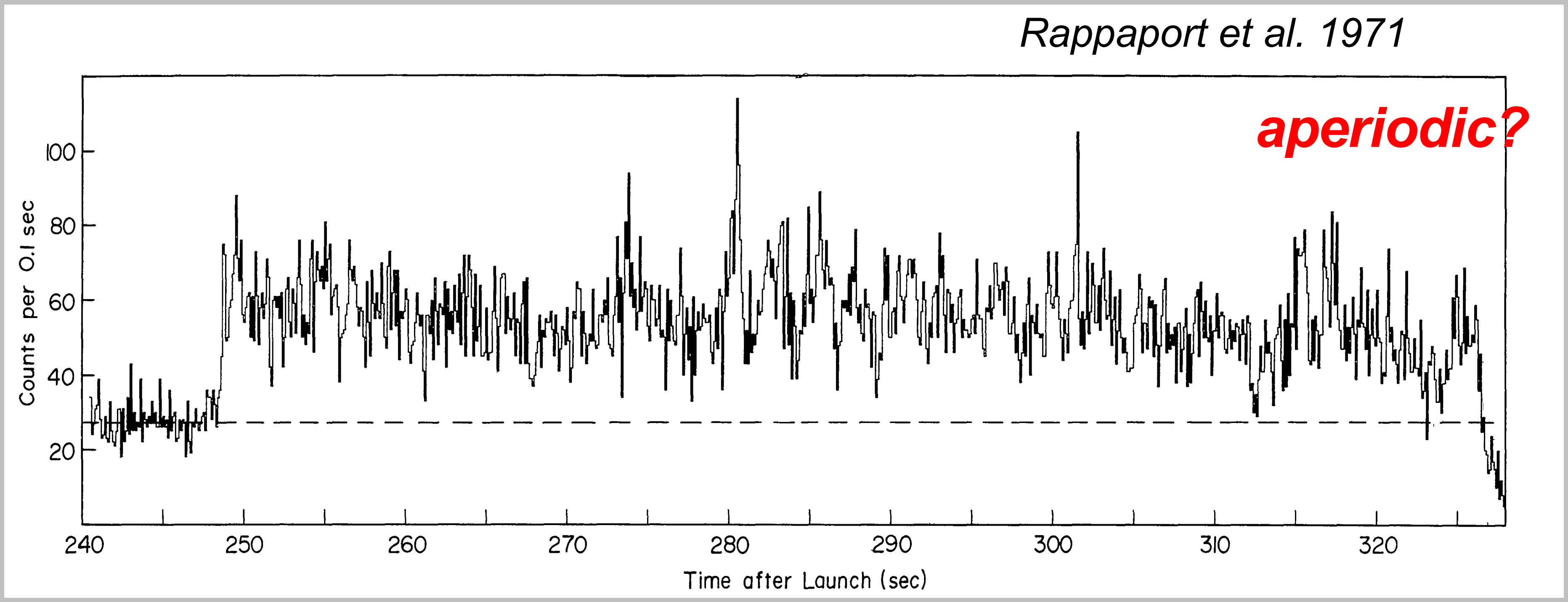
Questions to the nature of the variability:

1. Where the flux variability emerges? What creates the modulation of X-ray luminosity?

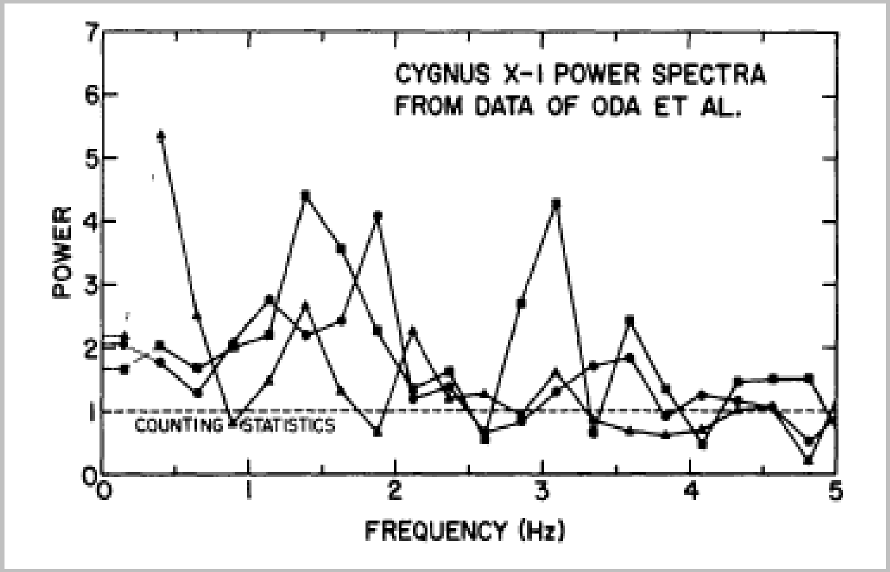
2. What inserts the modulation? Time scales of what processes modulations contain?

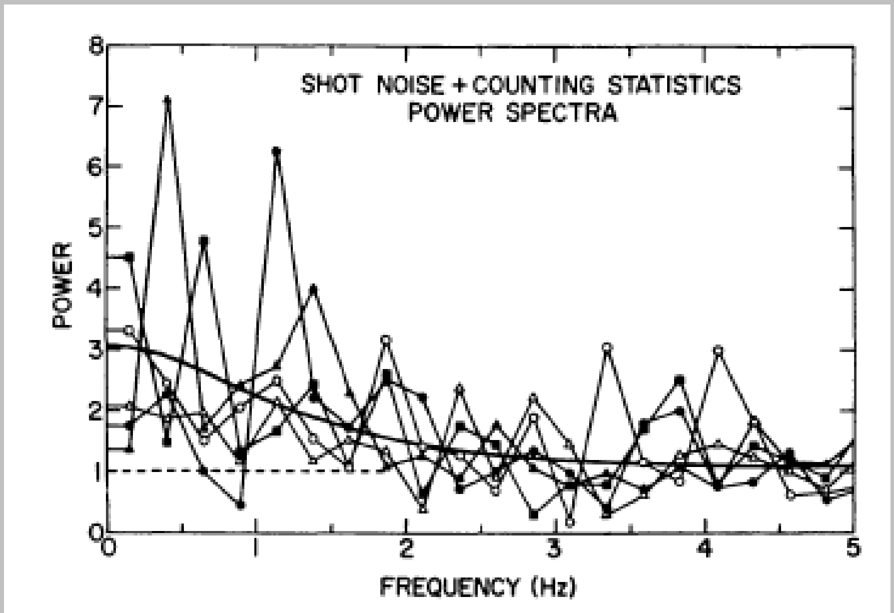
3. How information about variability can be used to constrain physical parameters of the system/object?


Cyg X-1
Oda et al. 1971
periodic?
COUNTS/.096 SEC
150
120
90
60
30
0
21134.131
21138.931
21143.731
SECONDS UT


Rappaport et al. 1971
aperiodic?
Counts per 0.1 sec
100
80
60
40
20
240
250
260
270
280
290
300
310
320
Time after Launch (sec)

Shot noise paradigm. Terrell 1972





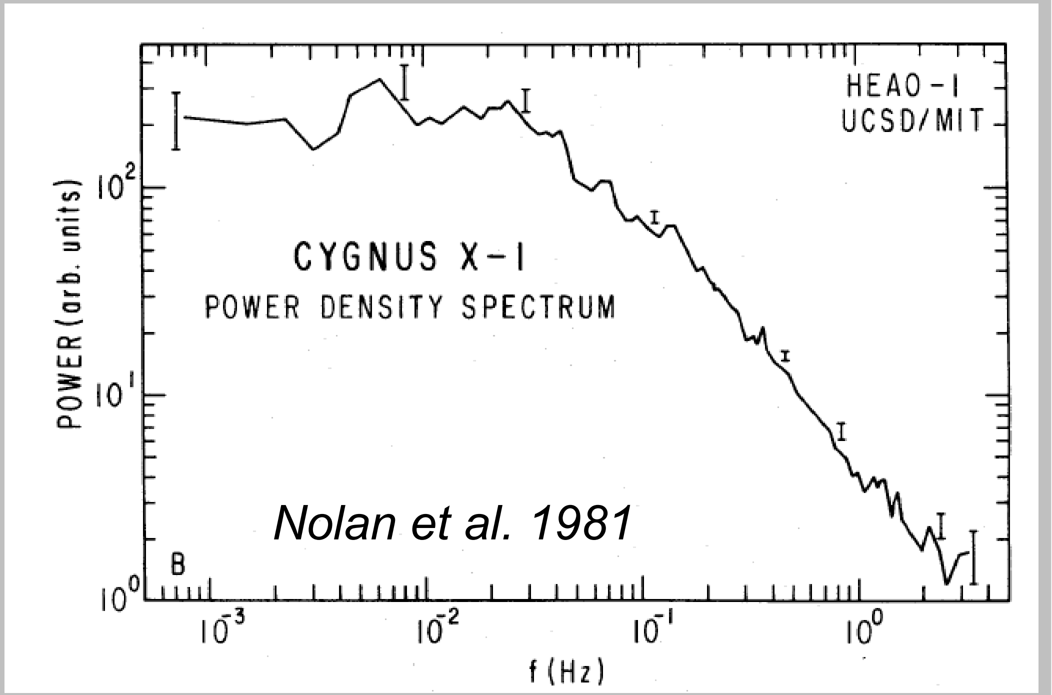
Shot noise model for Cyg X-1(1972):

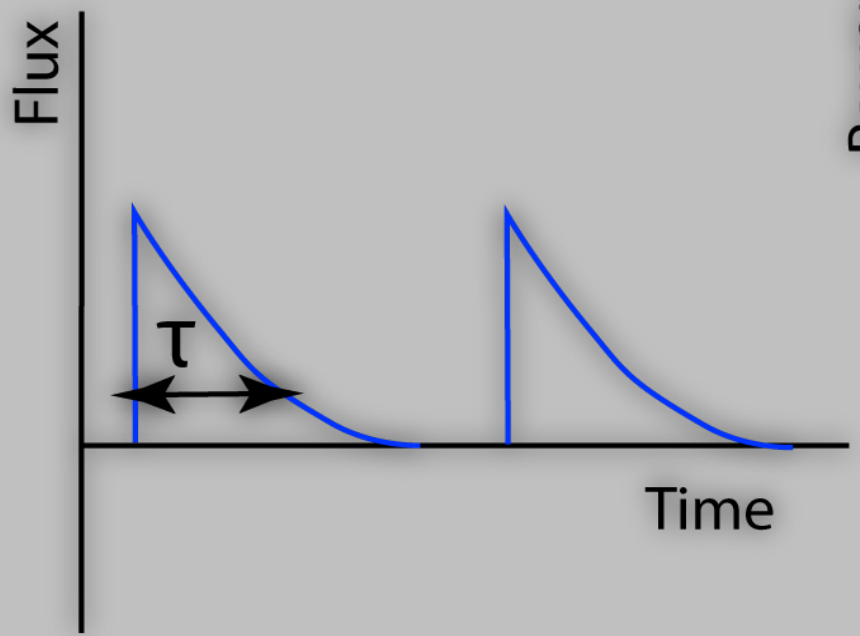
Variability is aperiodic.

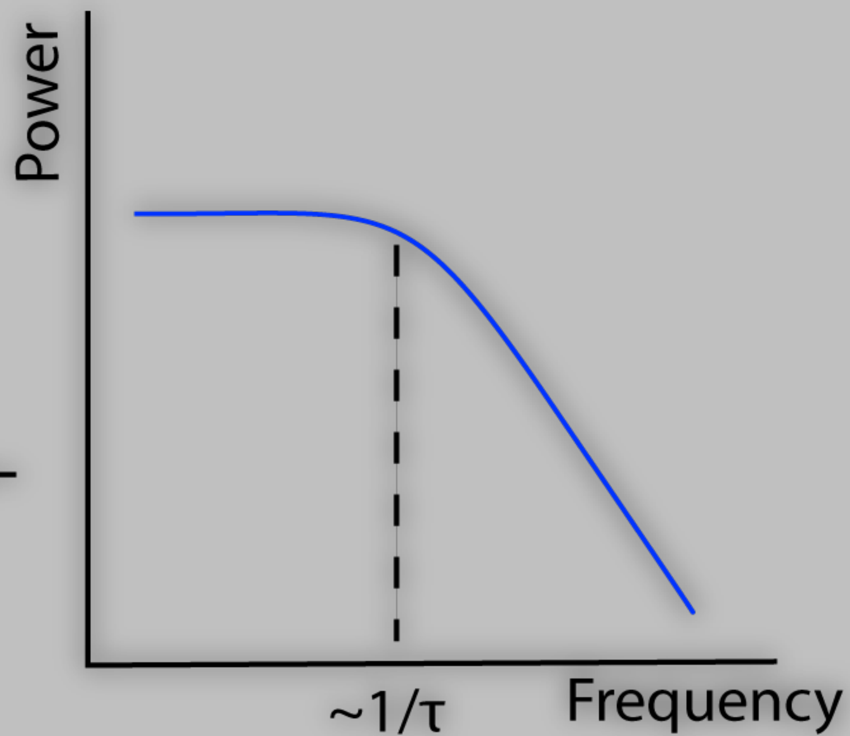
Variations come as a result of randomly occuring «shots»

Effective length of shots ~1 sec

Shot noise model





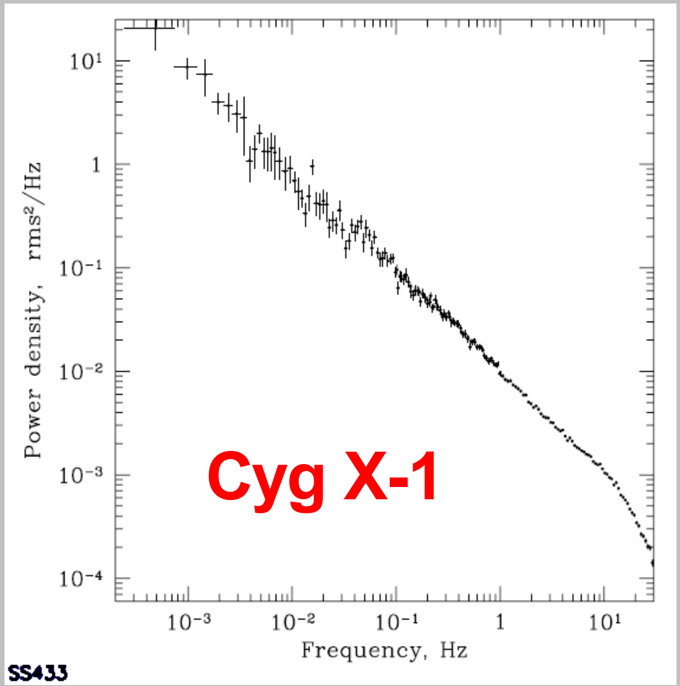


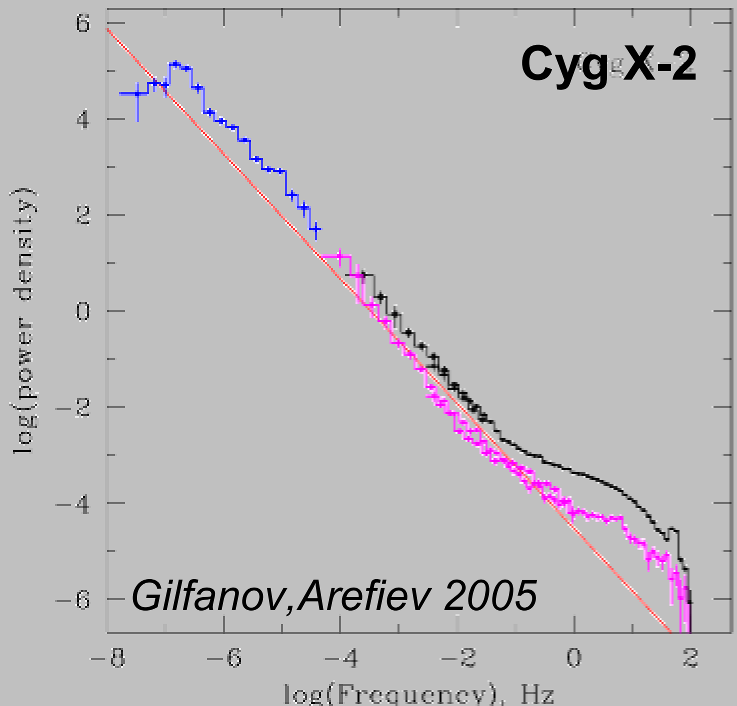
Thirty years after...

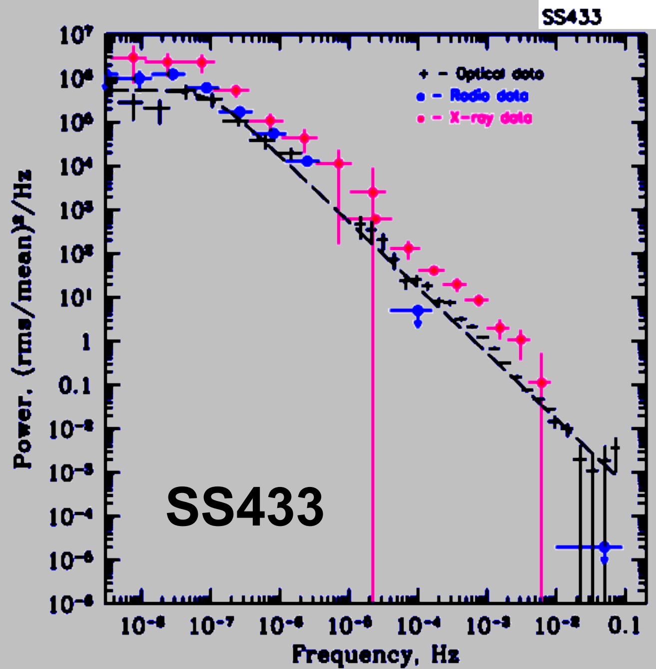
Problems of original shot noise model.
Hints on the origin of variability

1. Variability of accreting systems are self-similar on enormous range of time scales (>5 orders of mag). How it is possible in small region of main energy release?

Churazov et al. 2001





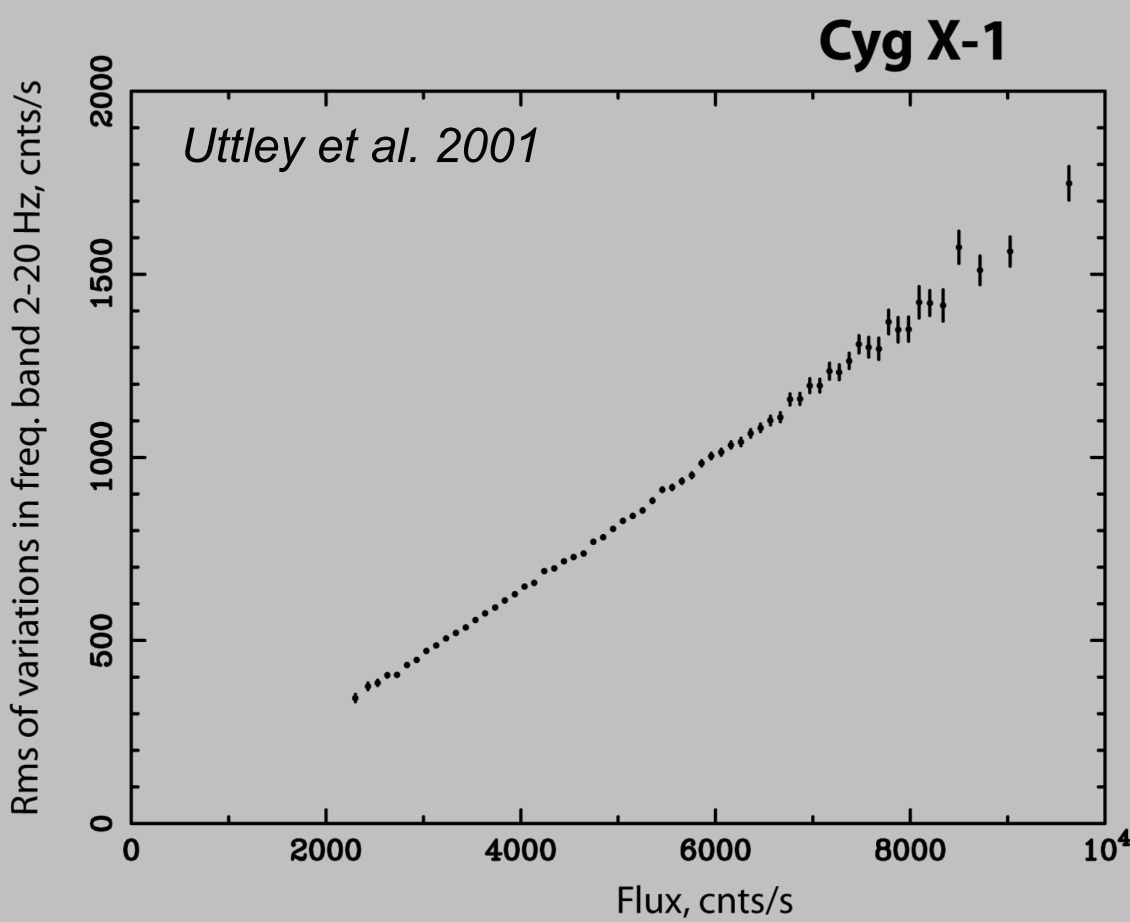


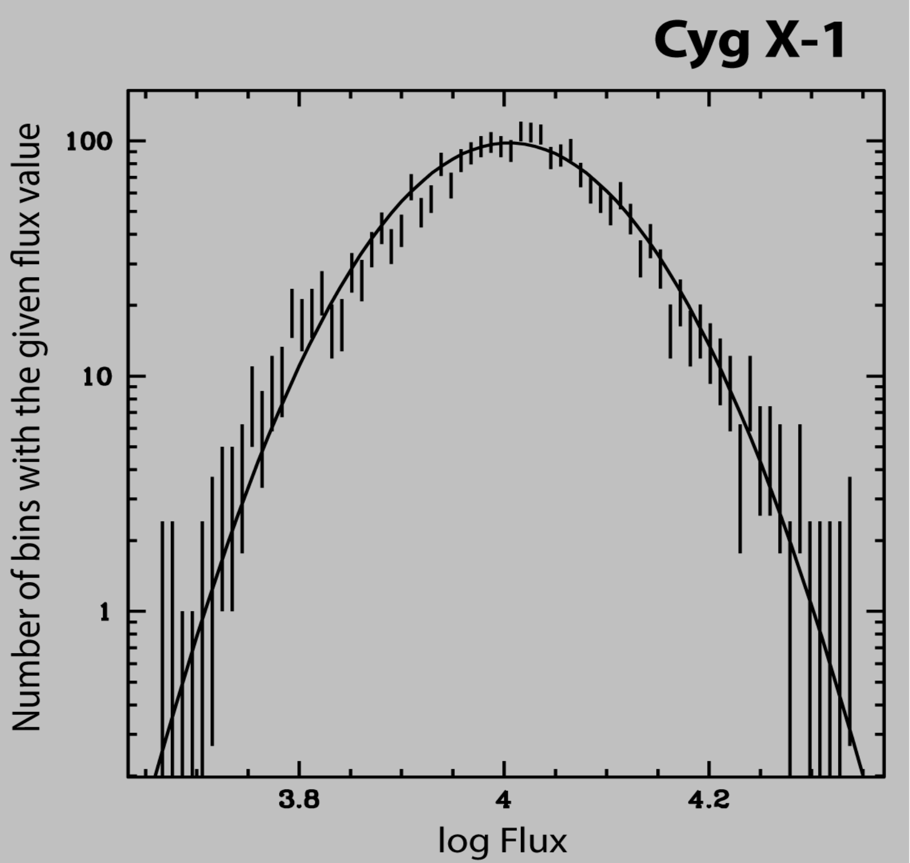
Revnivtsev et al. 2006

Thirty years after...

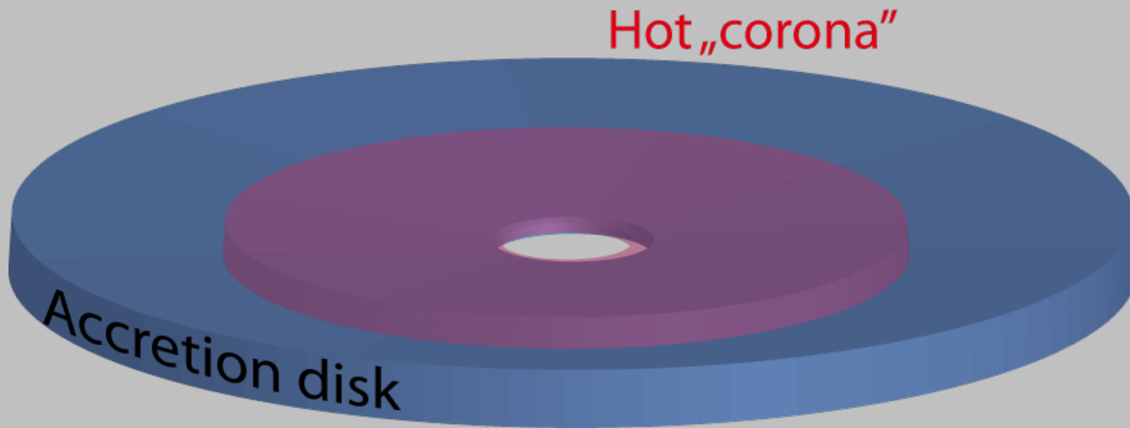
Problems of original shot noise model.
Hints on the origin of variability

2. Amplitude of variations of X-ray flux is proporional
to the average flux level («rms-flux» relation)
Model of additive shots does not produce it!

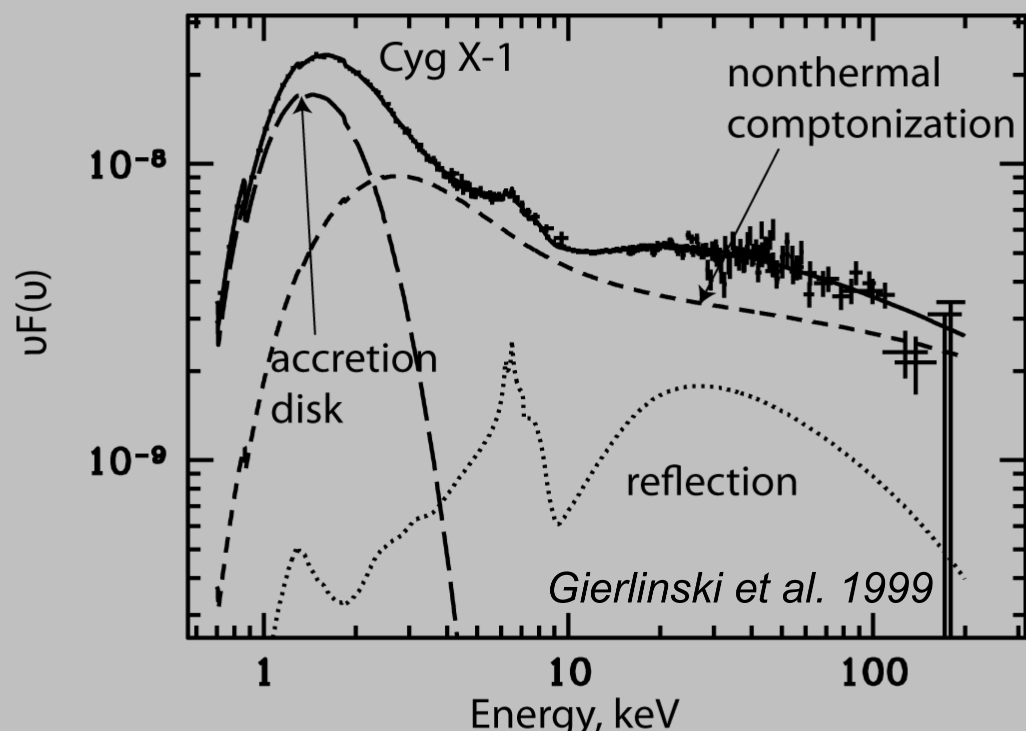




1) What actually modulates the flux. Photons of what component variates?



Cyg X-1. Soft/high state.



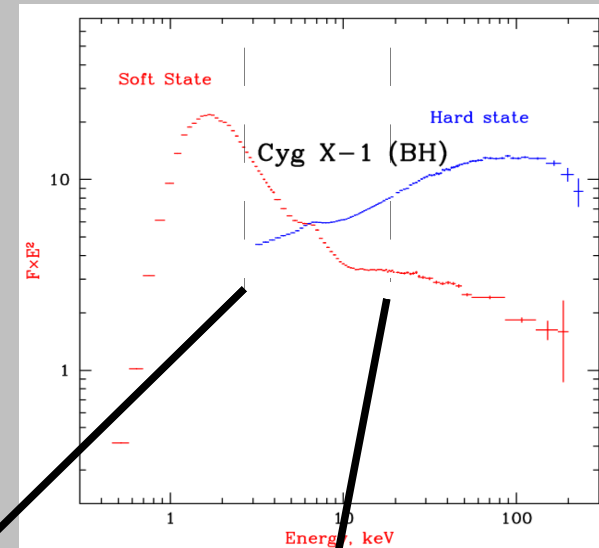
Let's check energy dependent variability

Two distinct spectral components:

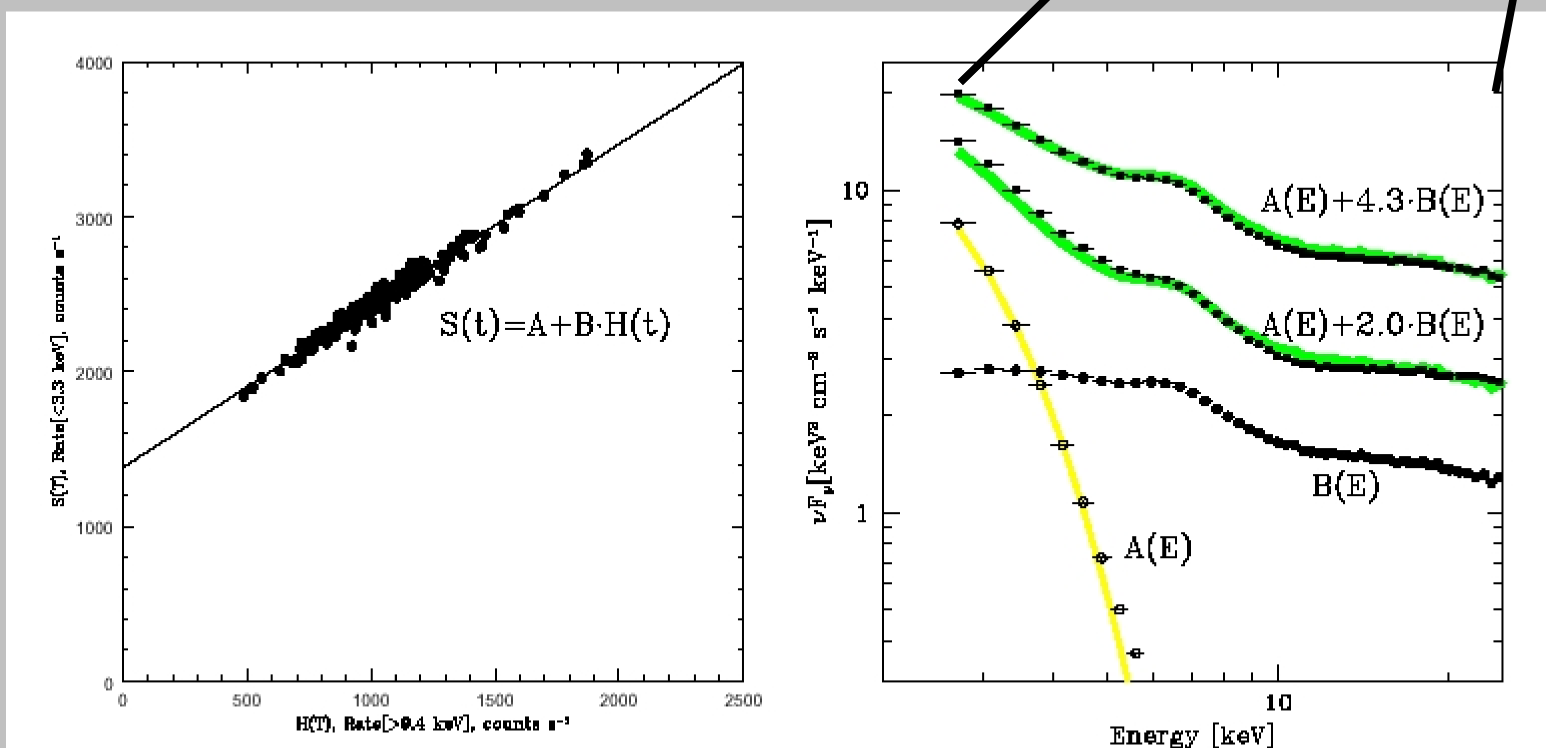
a)Accretion disk(kT~1 keV)

b) «Corona»: Non-thermal/hybrid?

Soft state of Cyg X-1

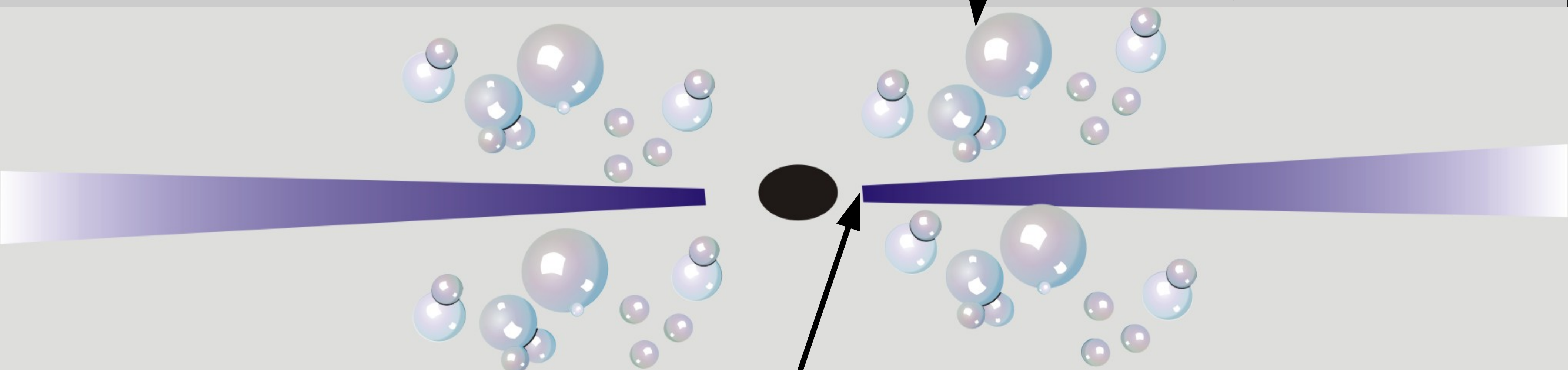


- Accretion disk is stable
- Only the coronal flow variates its X-ray flux



Churazov et al. 2001

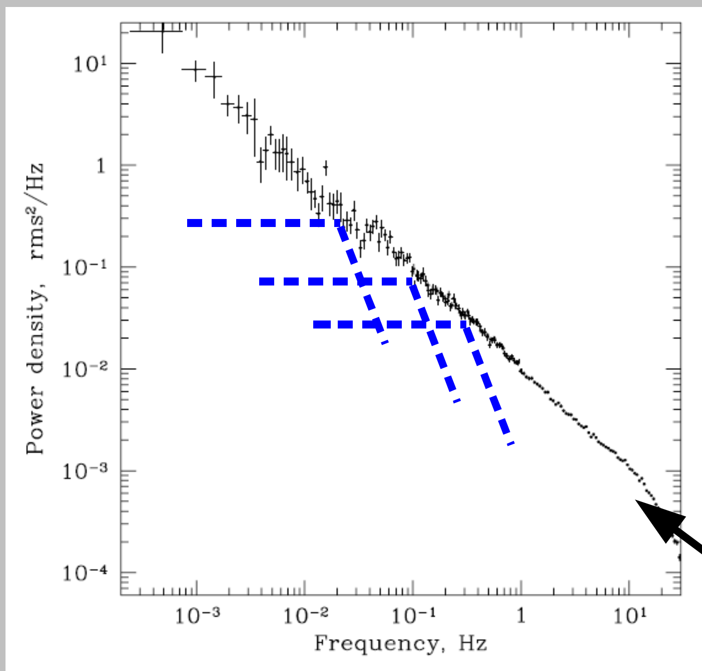
Only photons
from coronal flow
creates X-ray flux
variations



Accretion disk flux
is stable

Even being rad.pressure dominated!
(regards to numerical simulators)

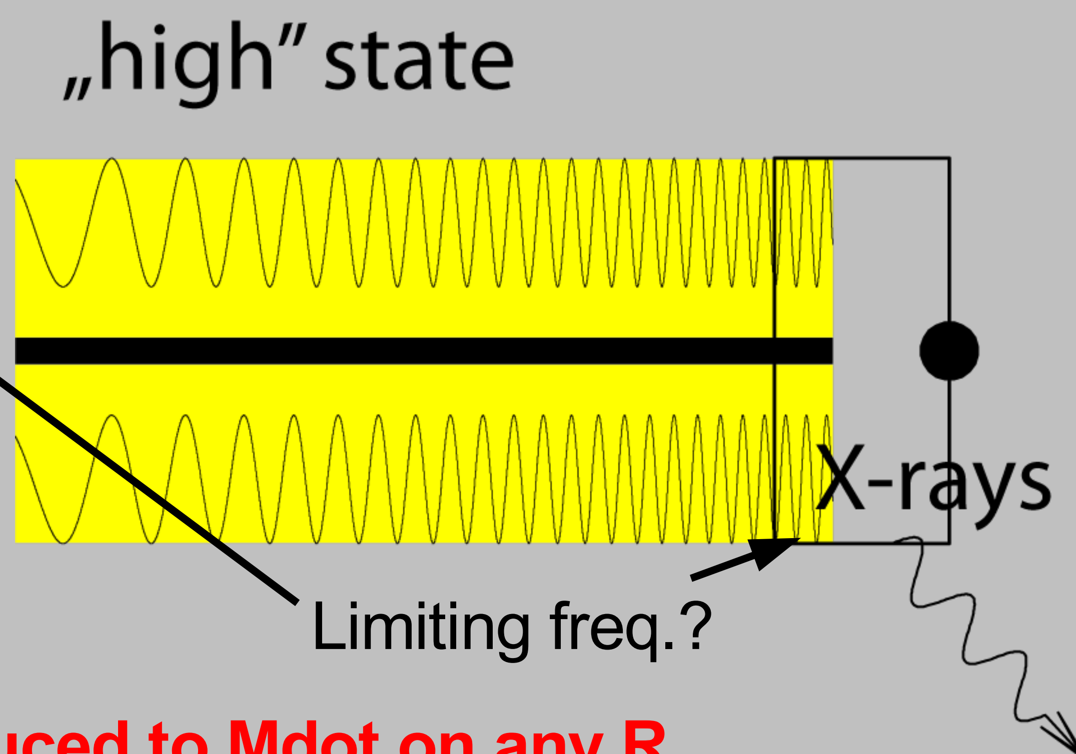
2) What creates wide-range variability?



Self-similar variability of Mdot in large accretion disk – flicker noise

Lyubarskii 1997

some ideas already in Miyamoto et al. 1988

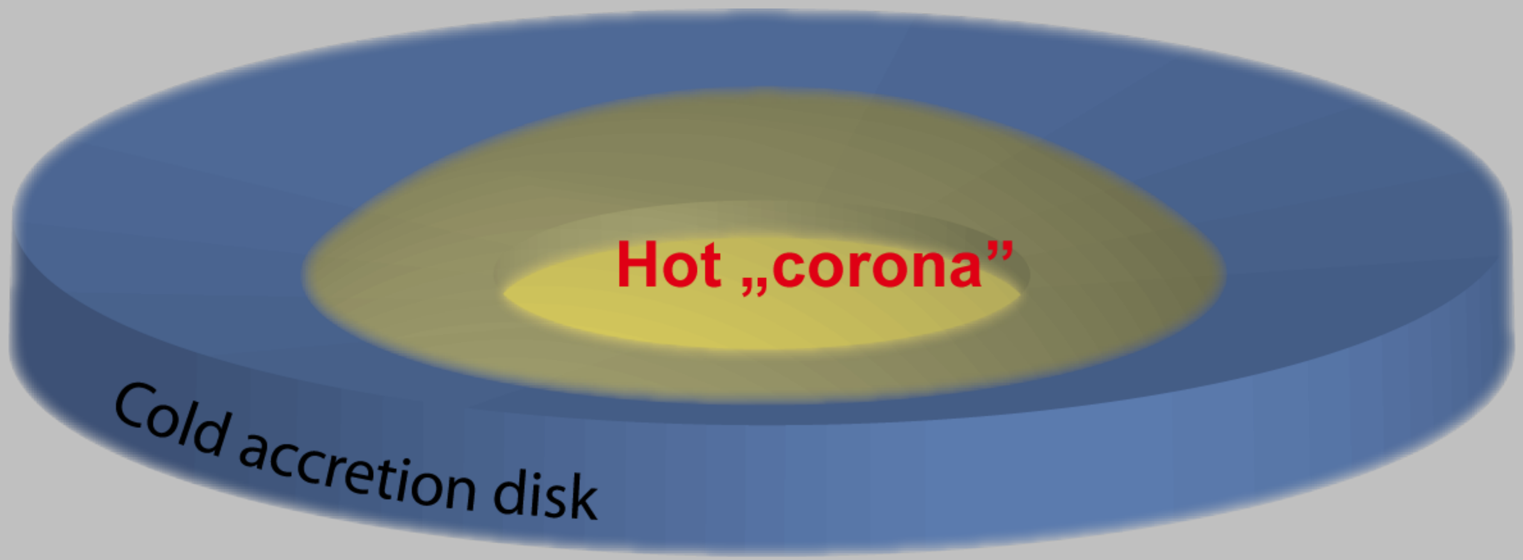


Variations are introduced to Mdot on any R.

All emission leaves the AD at the innermost region

Churazov et al. 2001

What can be predicted in the framework of this model for Cyg X-1 in hard state?



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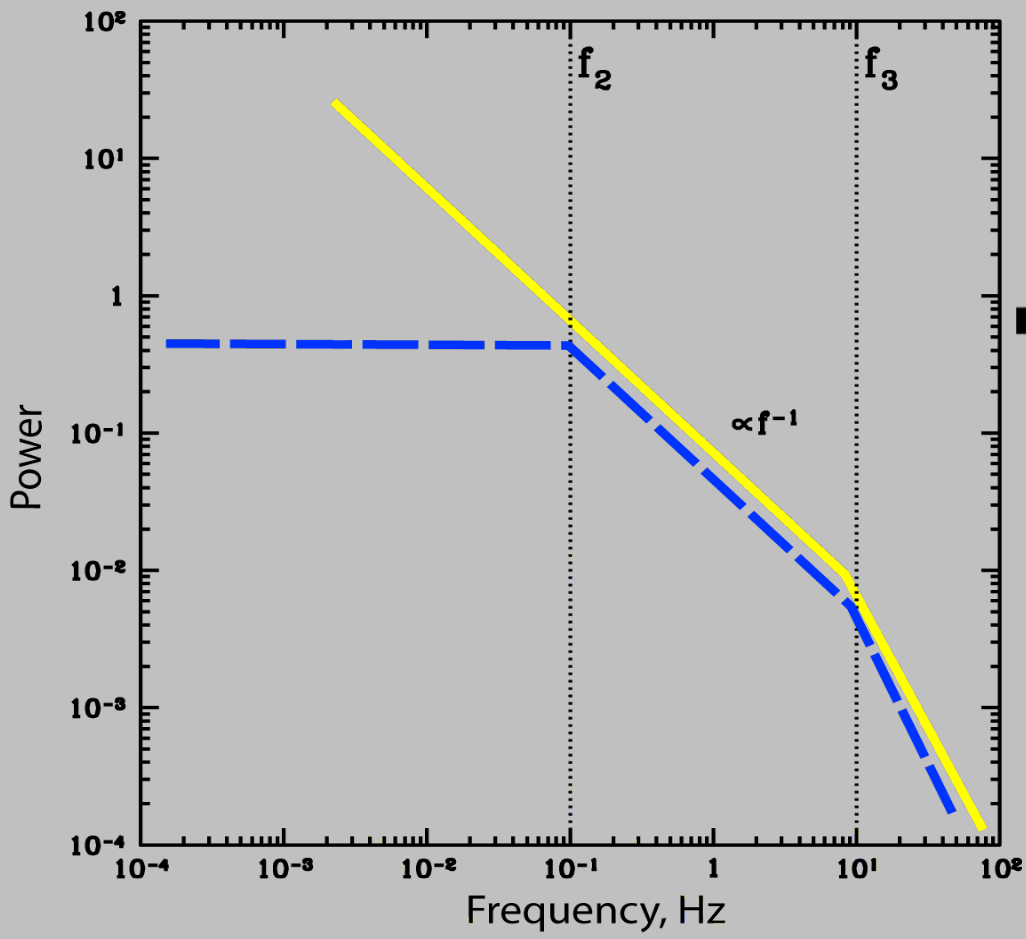

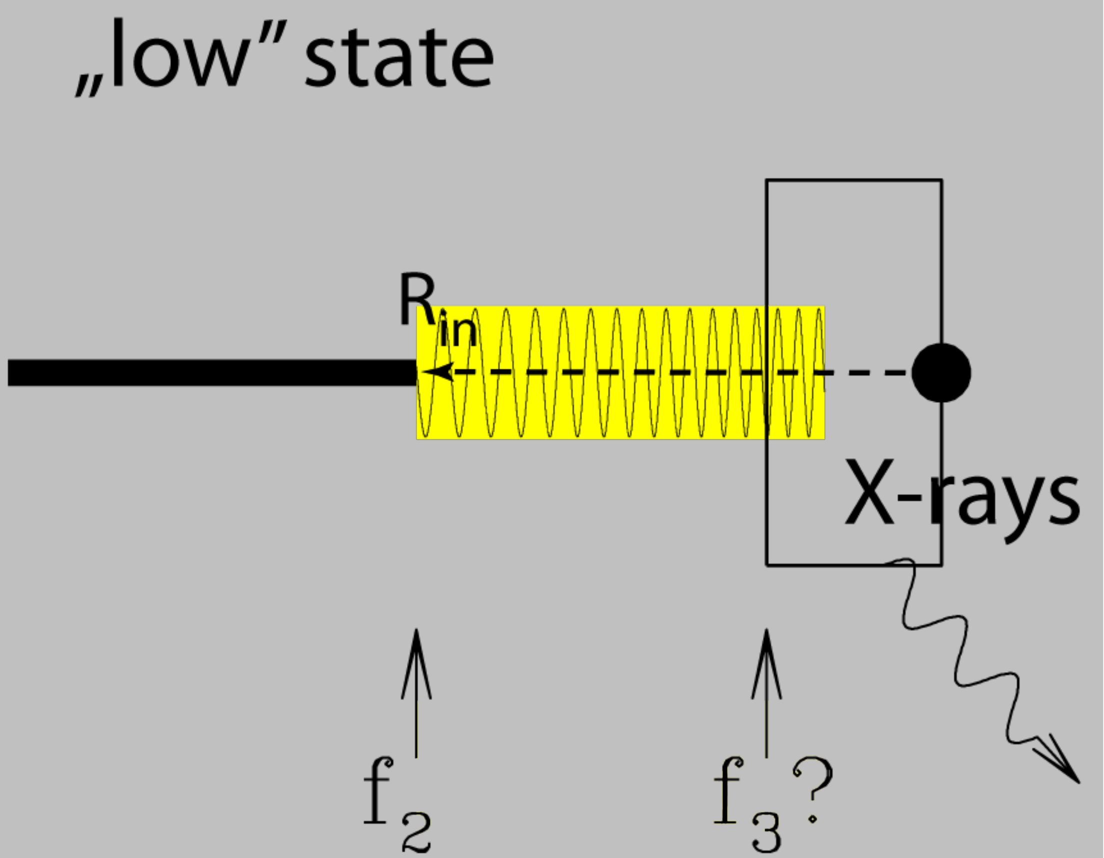

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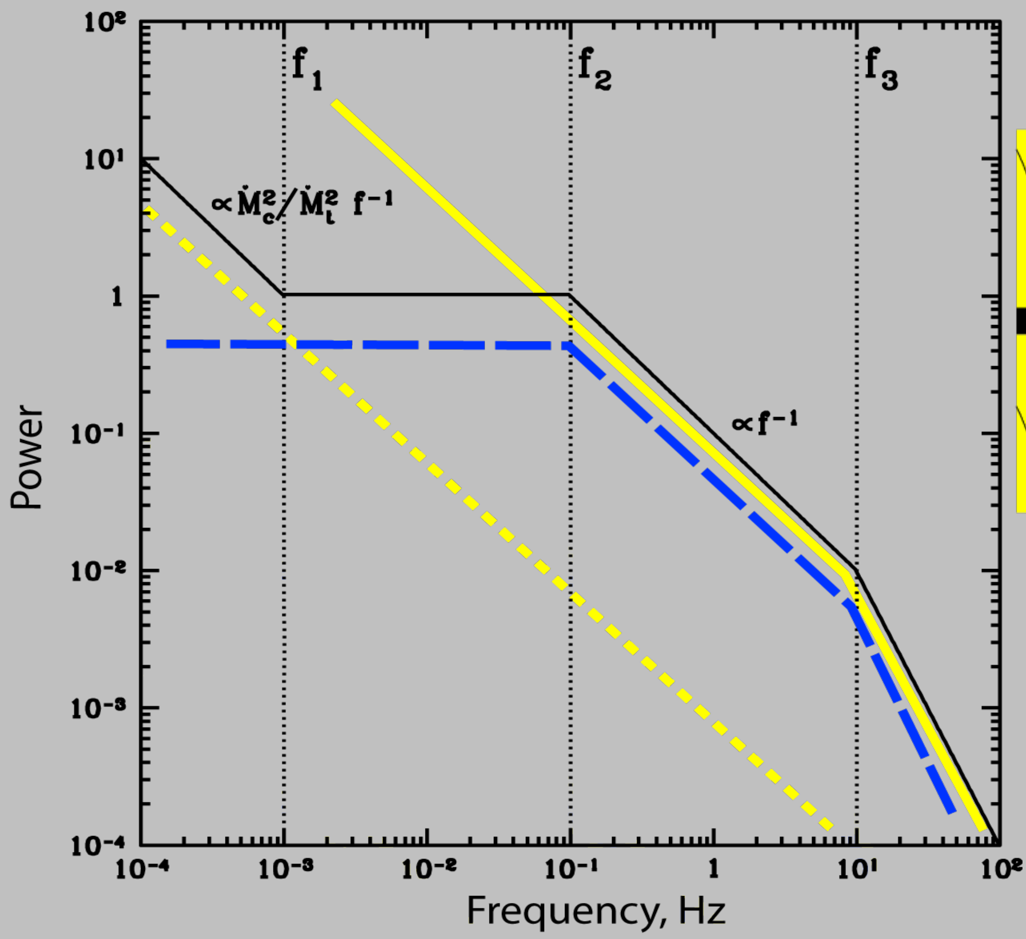
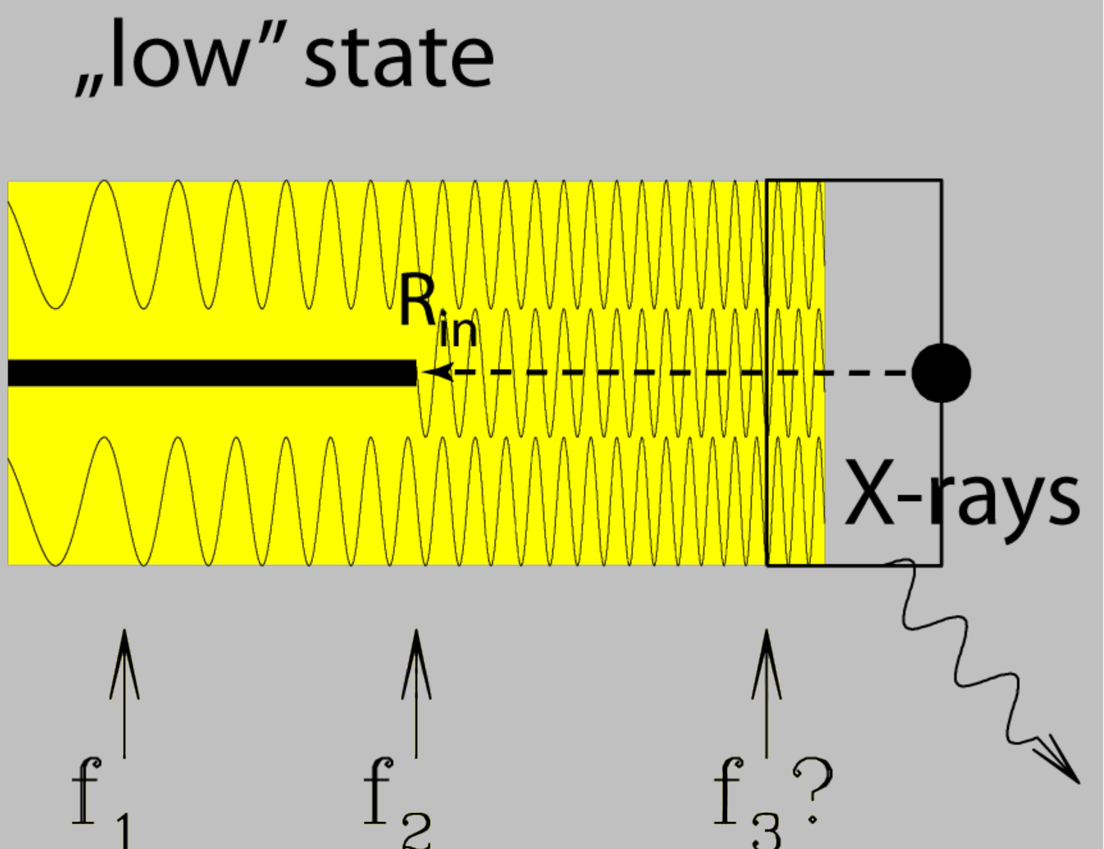
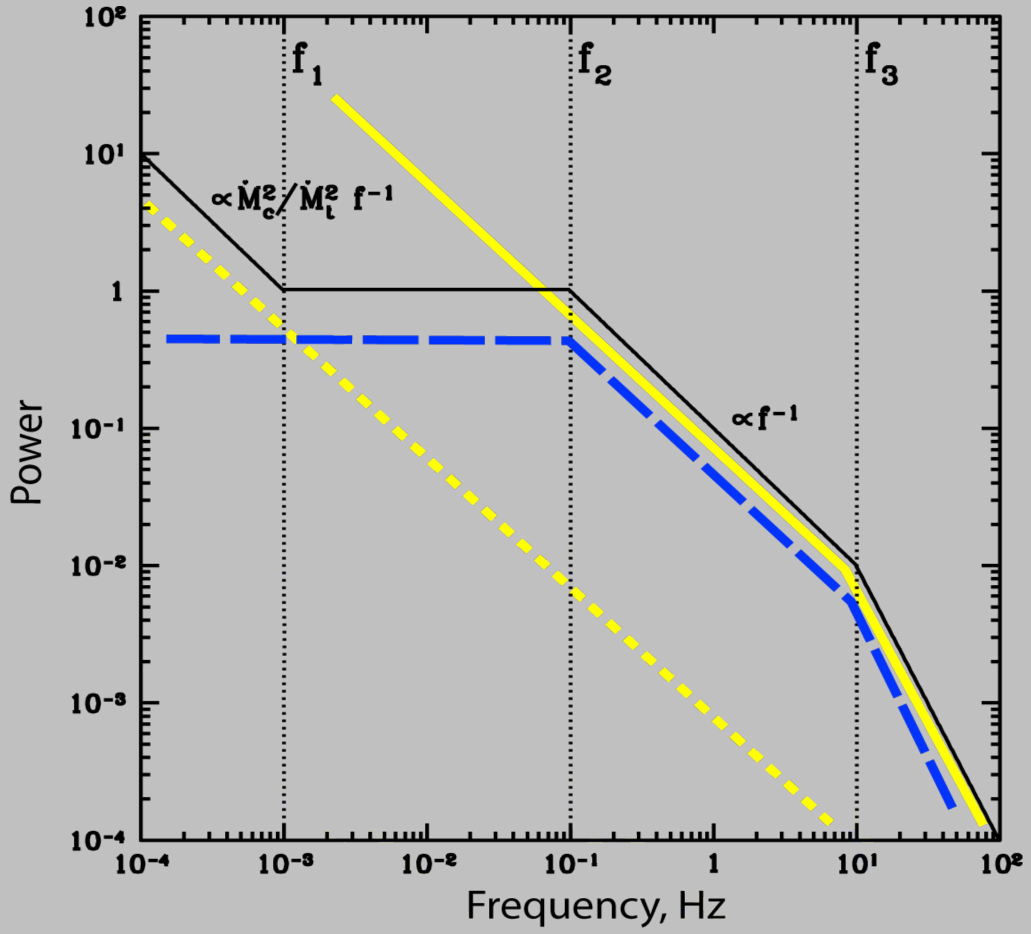
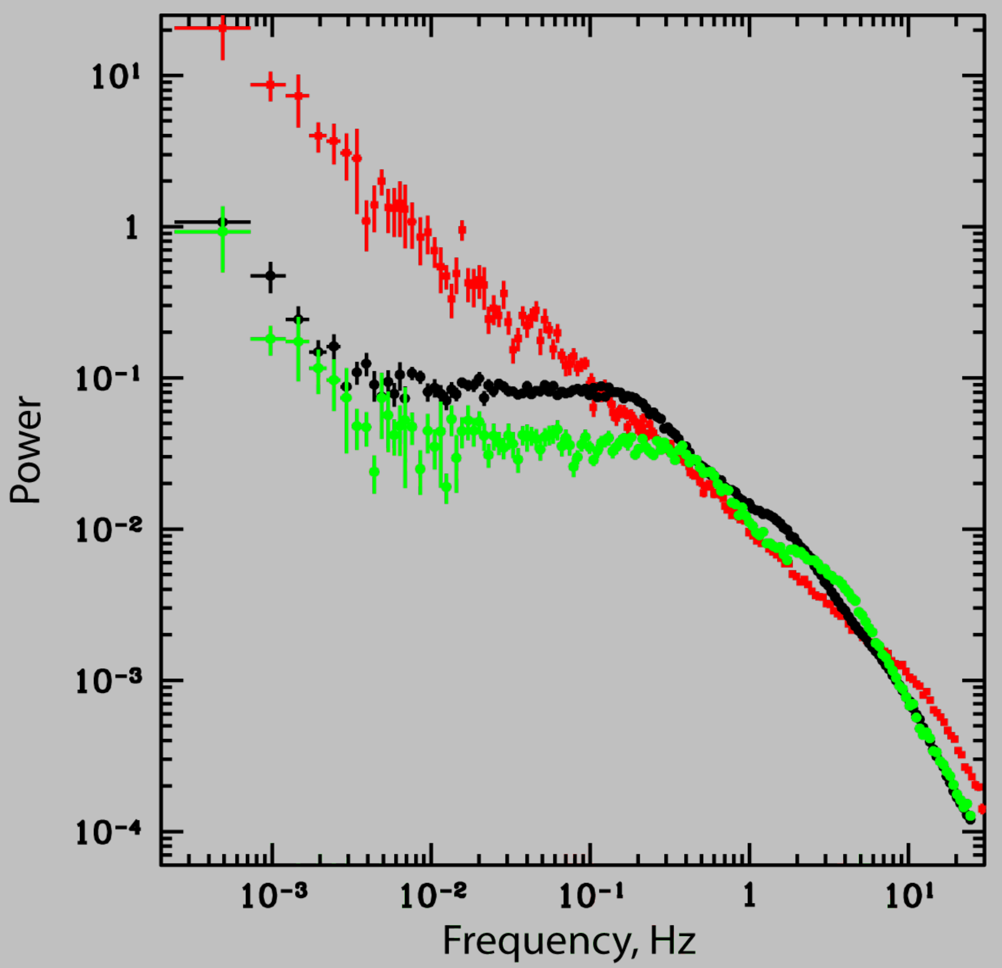


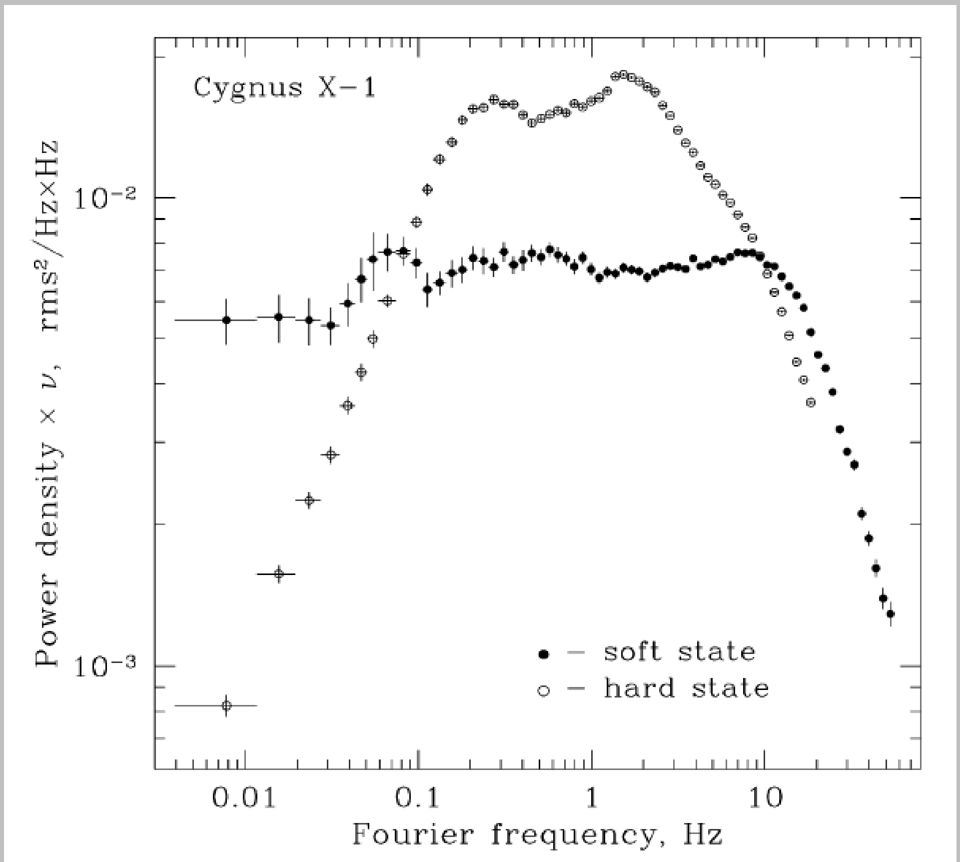


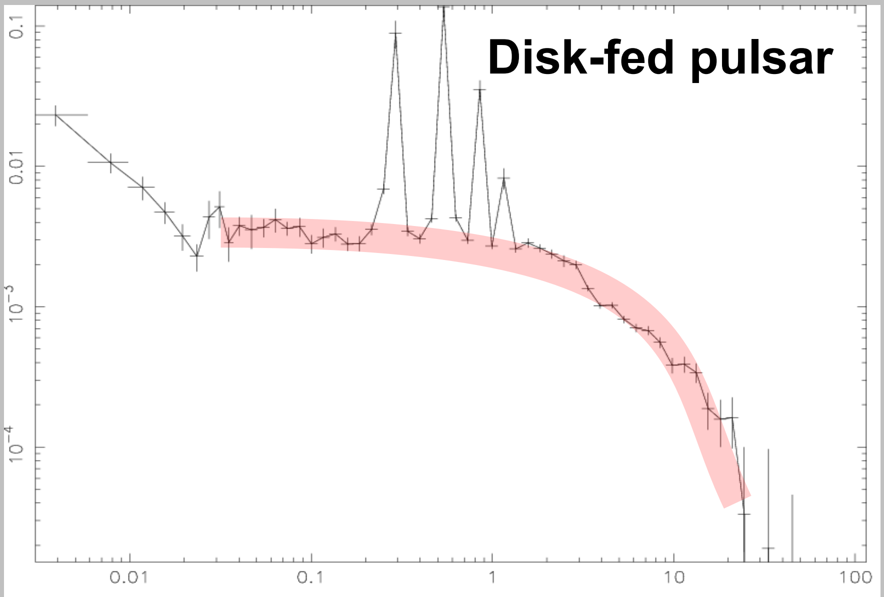
Power spectra of Cyg X-1 in high and low states

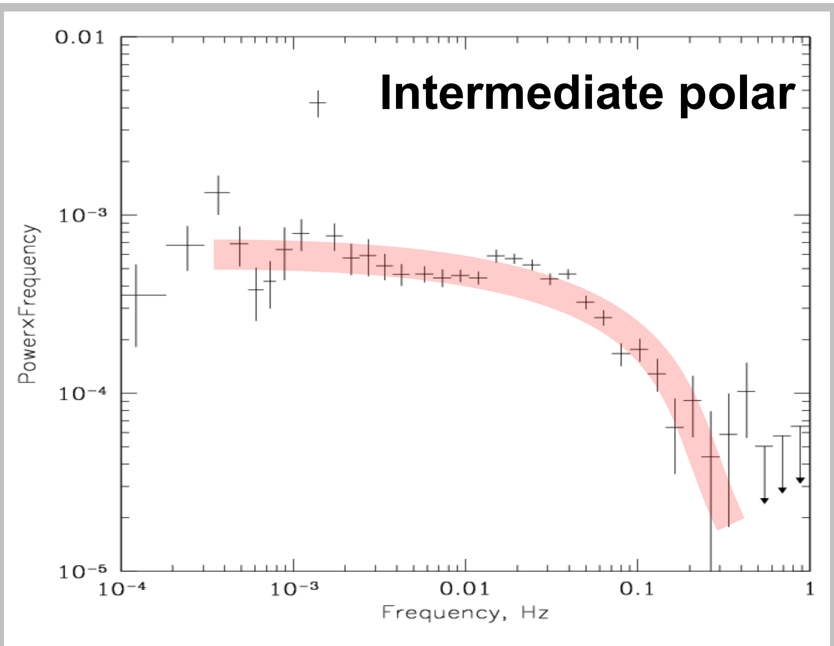




In what accreting systems we do expect to see the truncated accretion disks?







Cutoff in power spectra
of these systems- direct support
of our model

Freq. dependent time/phase lags

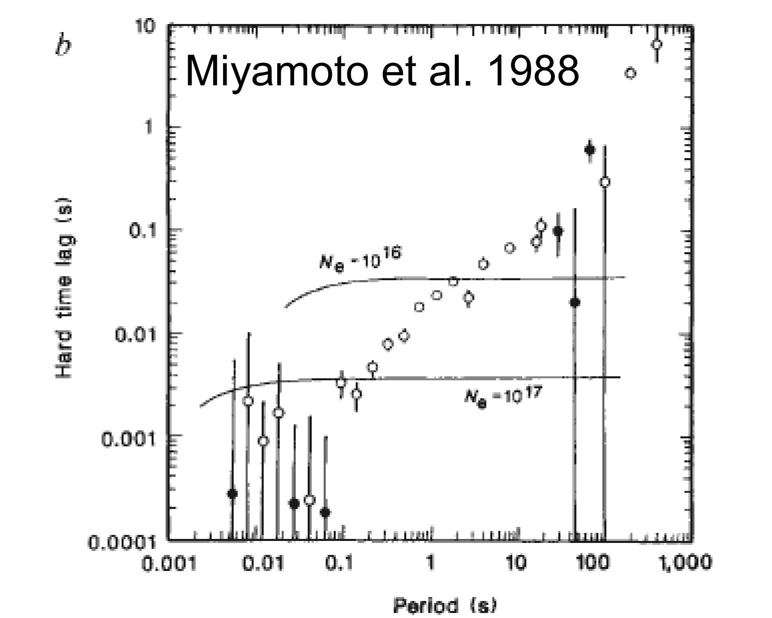
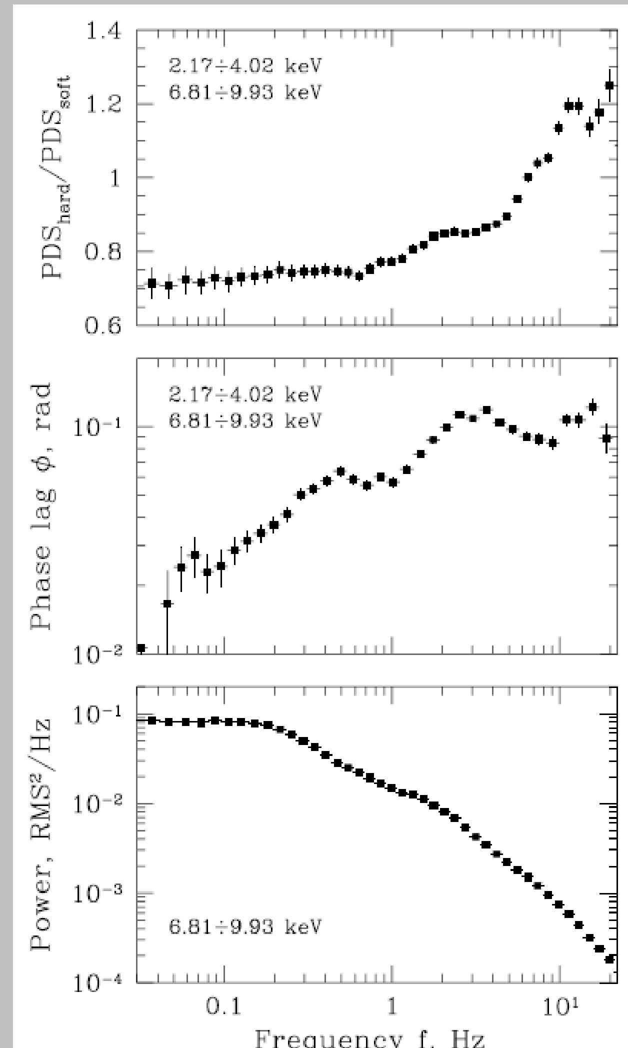


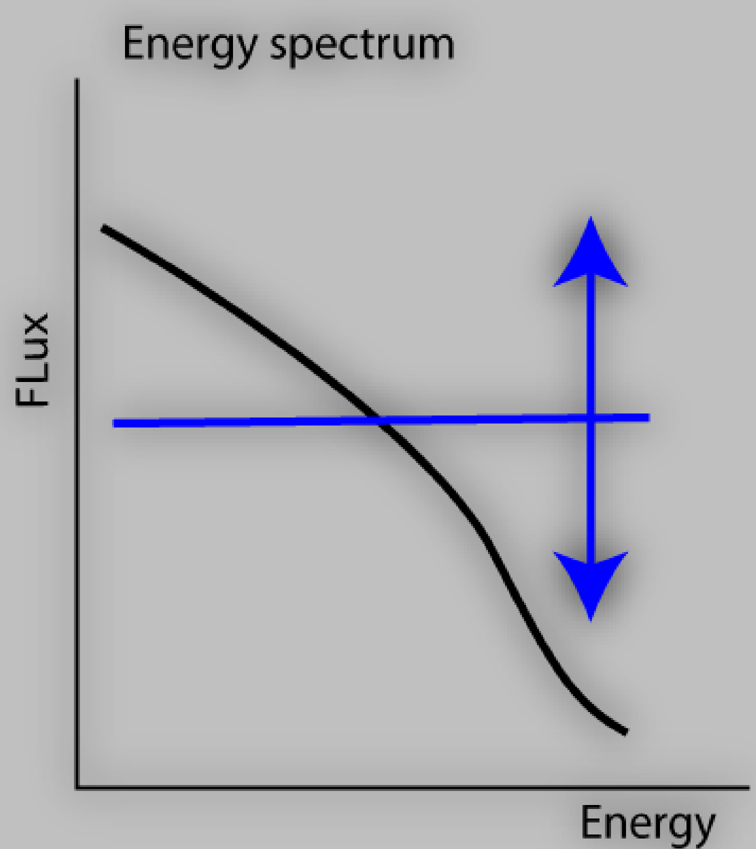
Fig. 1 The phase lag (*a*) and the time lag (*b*) between the hard X-rays (15.8–24.4 keV) and the soft X-rays (1.2–5.7 keV) (5 August data). Open circles denote positive values and filled circles correspond to negative values (soft-X-ray lag). Similar results are obtained between other X-ray energy ranges and from the data of other observations. Also shown in *b* are the simulated time delays between X-rays of energies 3.5 keV and 20 keV, where we have assumed that $\tau_{es} = 5$, $kT = 27$ keV, $N_e = 10^{16}$ and 10^{17} cm^{-3}, and the initial photon energy is 100 eV. Except for N_e, the parameters are those proposed by Sunyaev and Trumper[4].

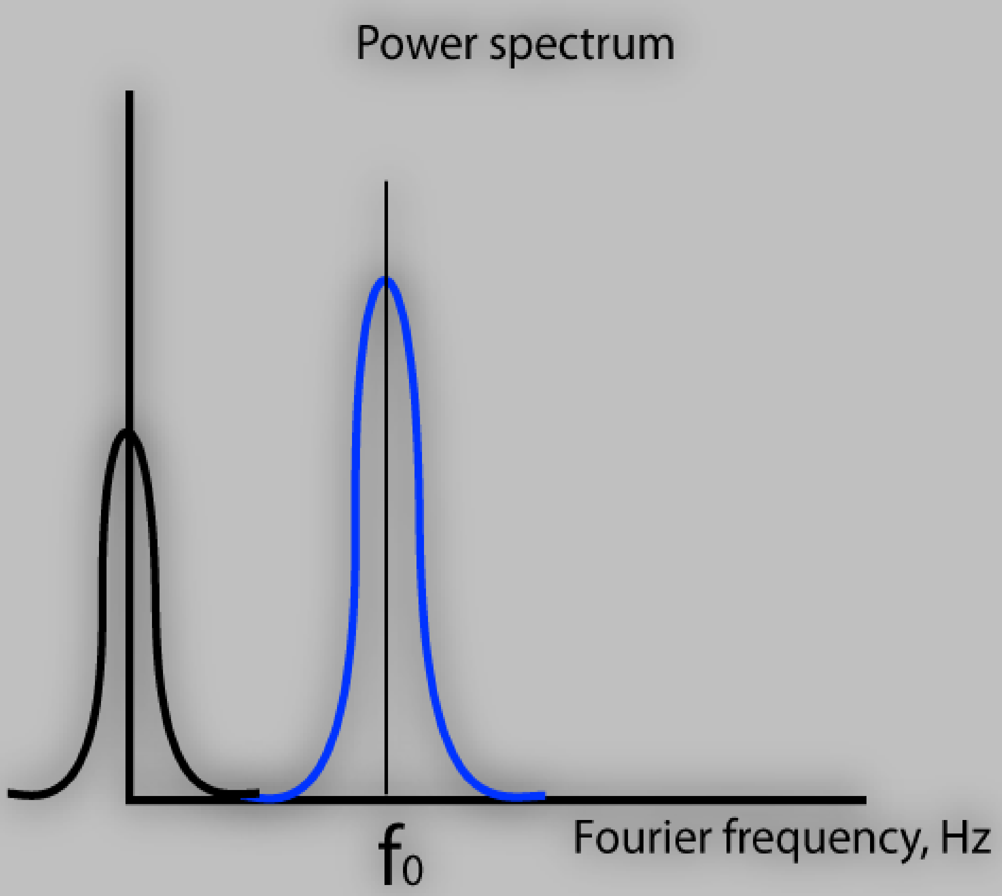
Hard photons have frequency dependent «lags»

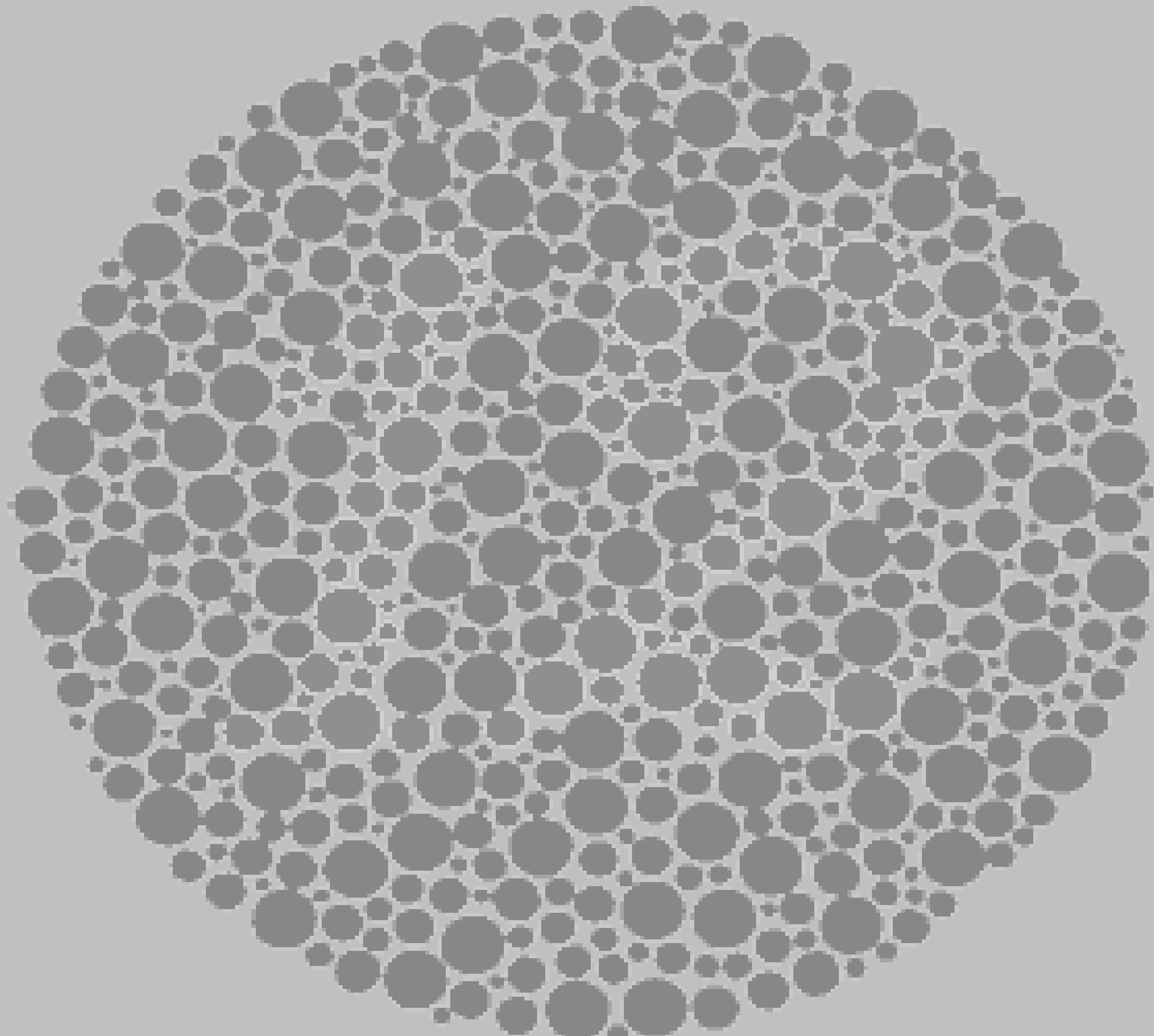


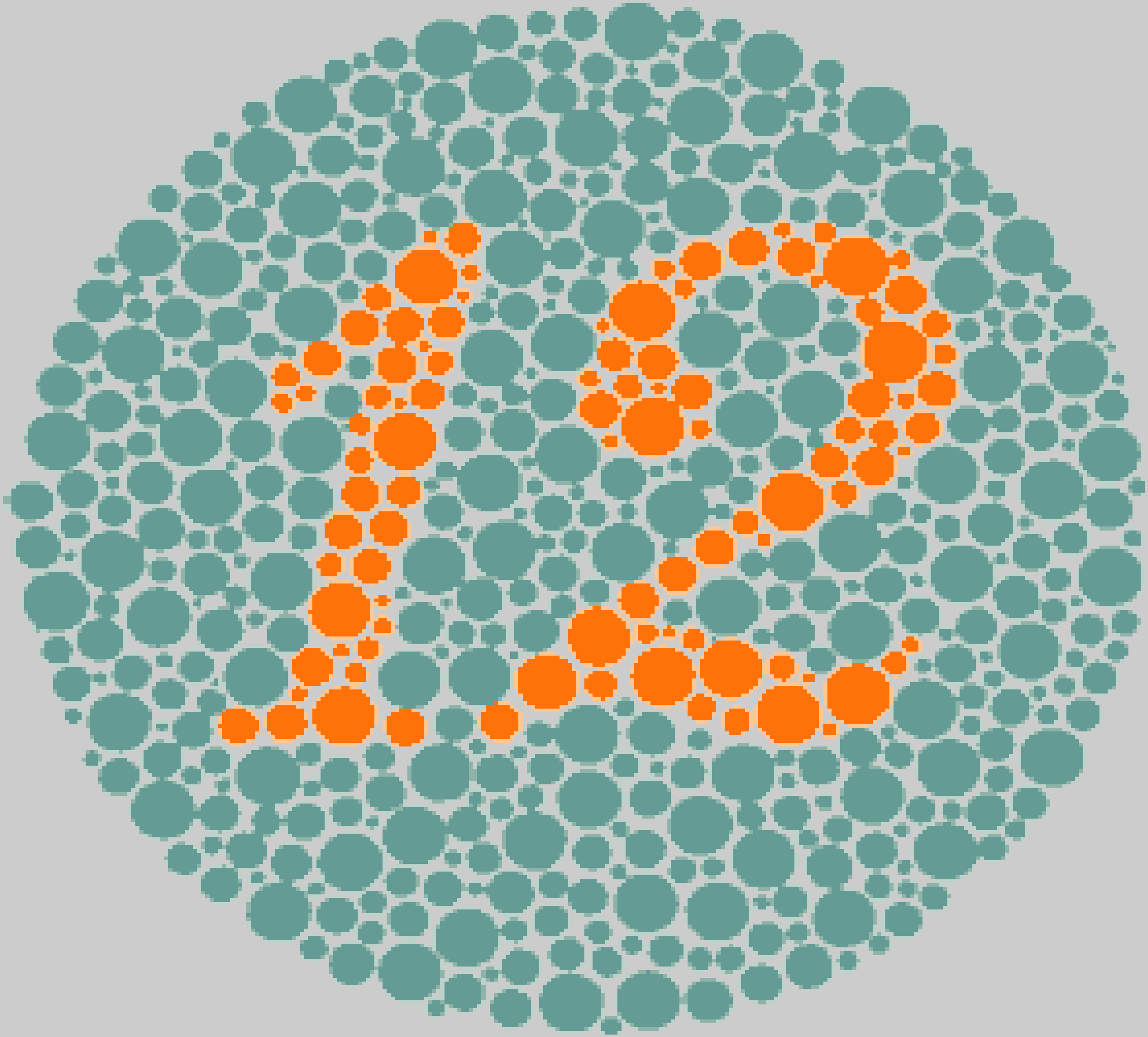
Kotov et al. 2001

Approach from different direction:
Fourier frequency resolved spectroscopy

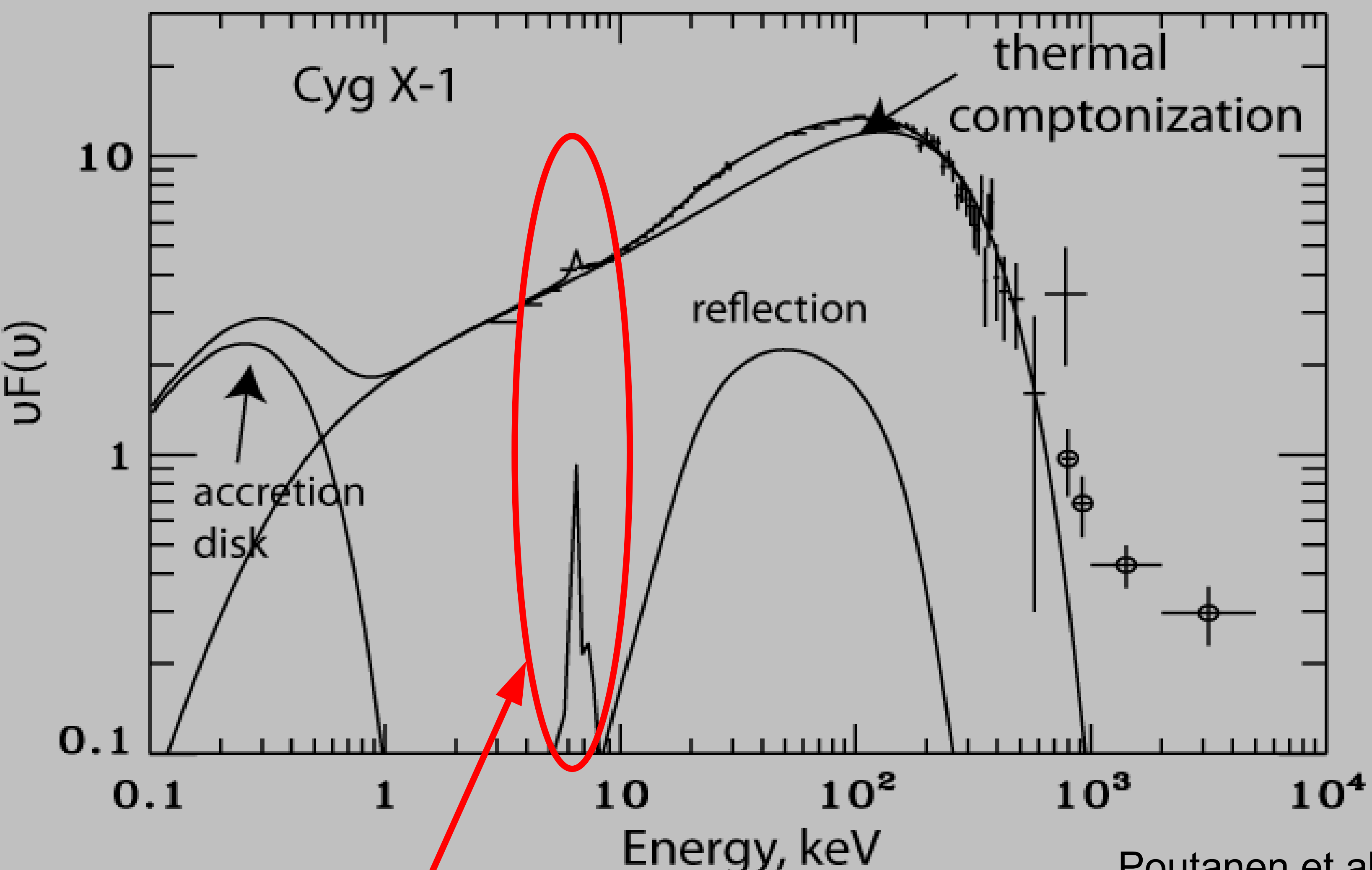







12

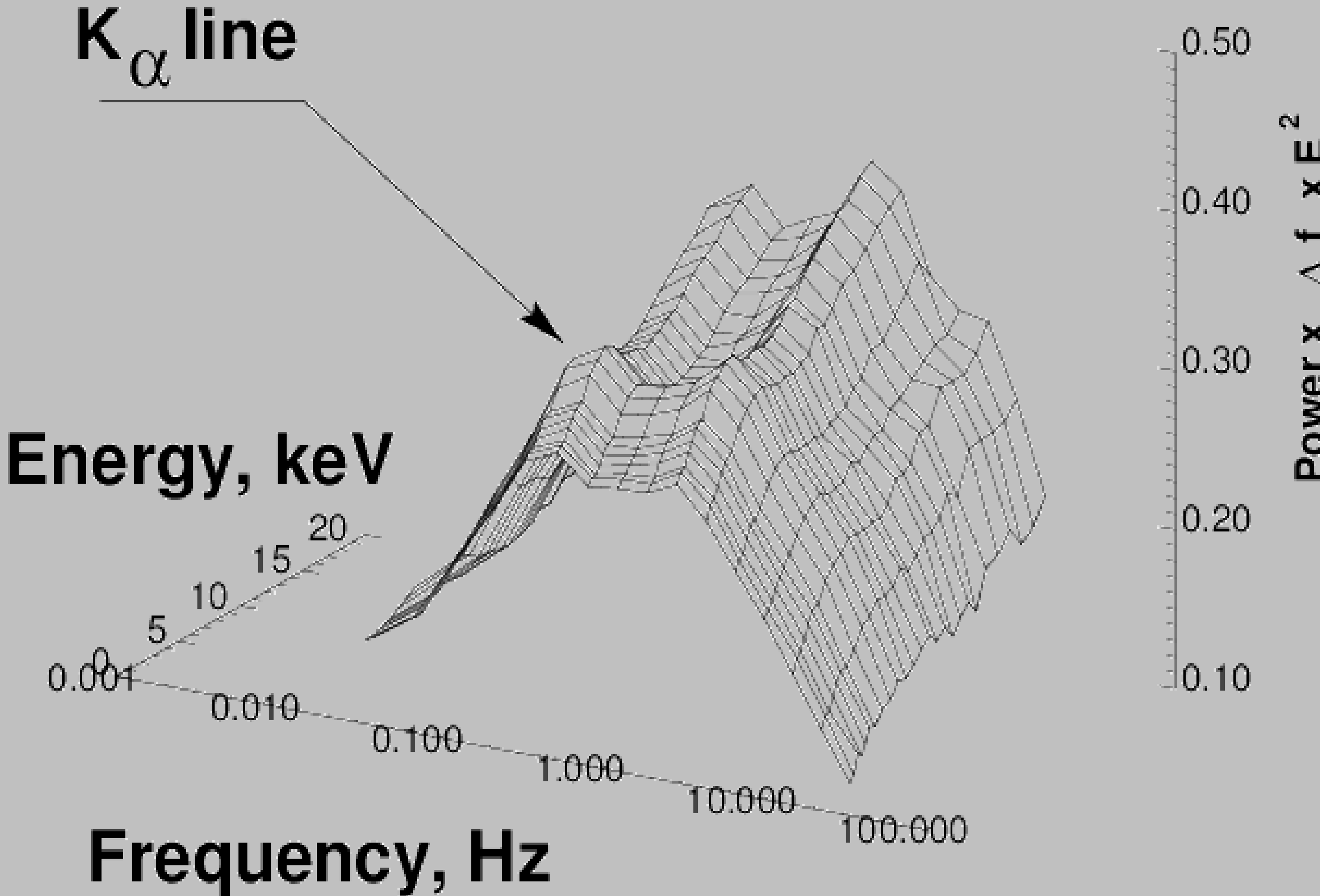
Application of the method



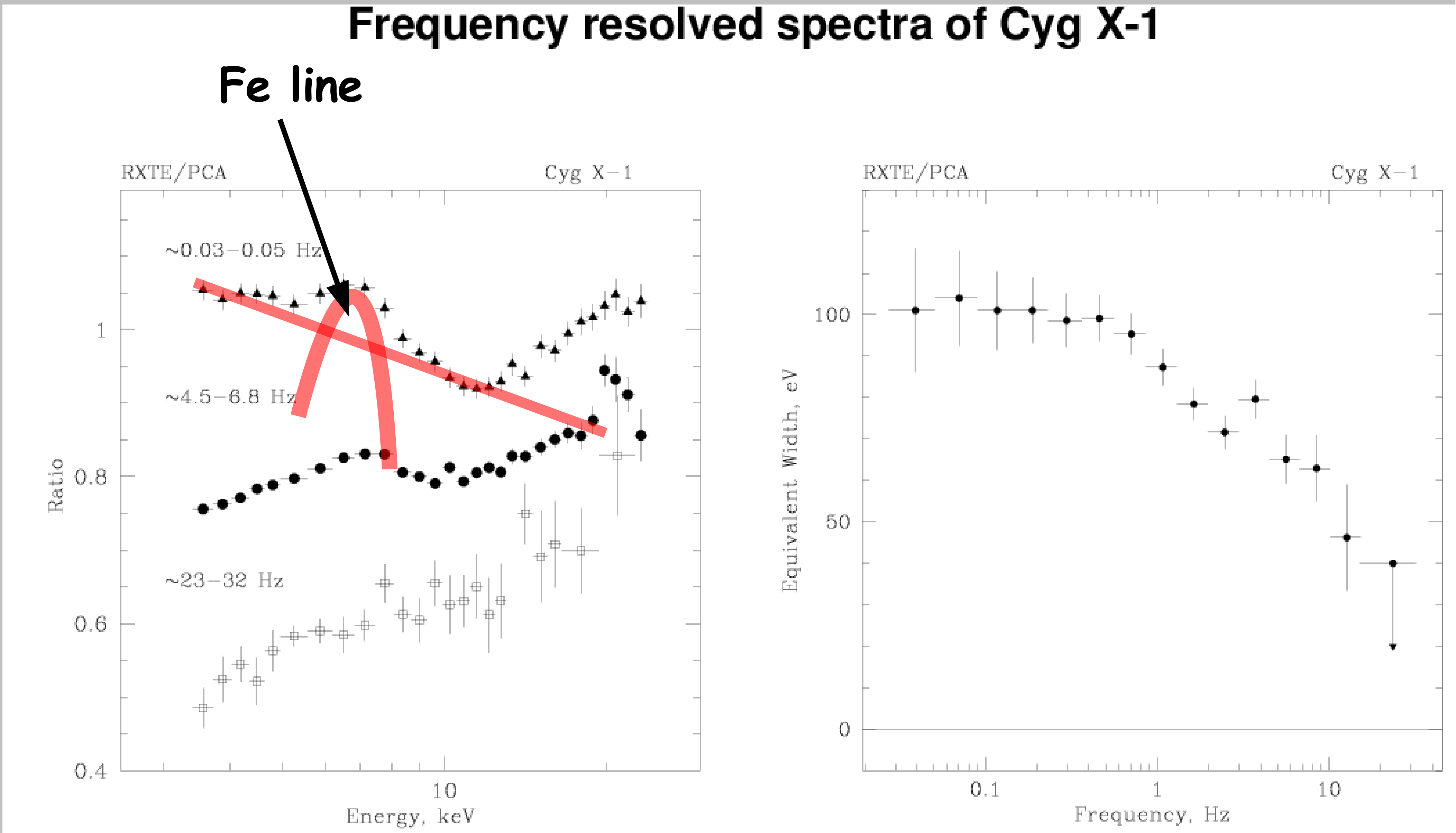
Poutanen et al. 1998

Easy visible component

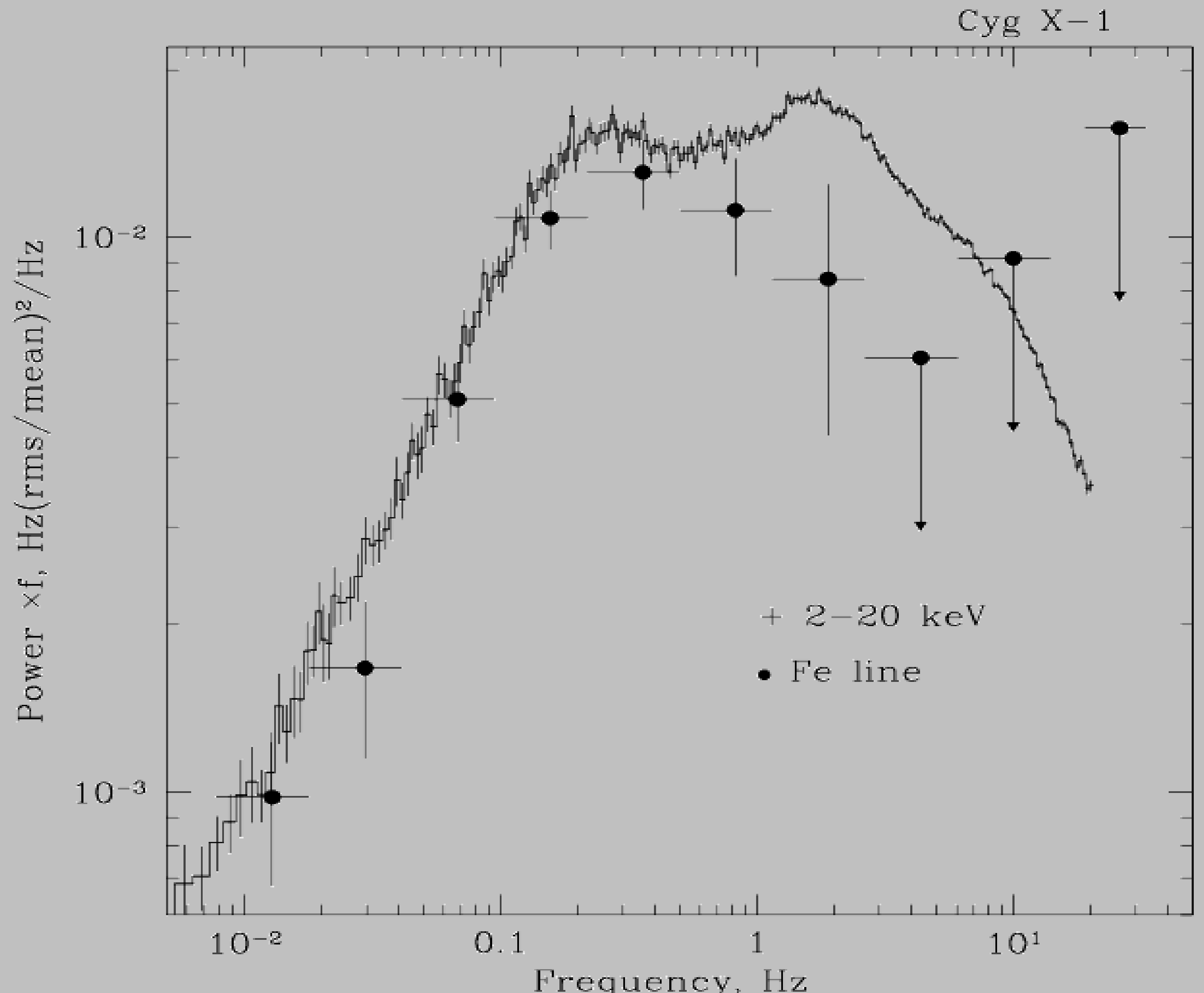
Approach from different direction:
Fourier frequency resolved spectroscopy



Variability information!

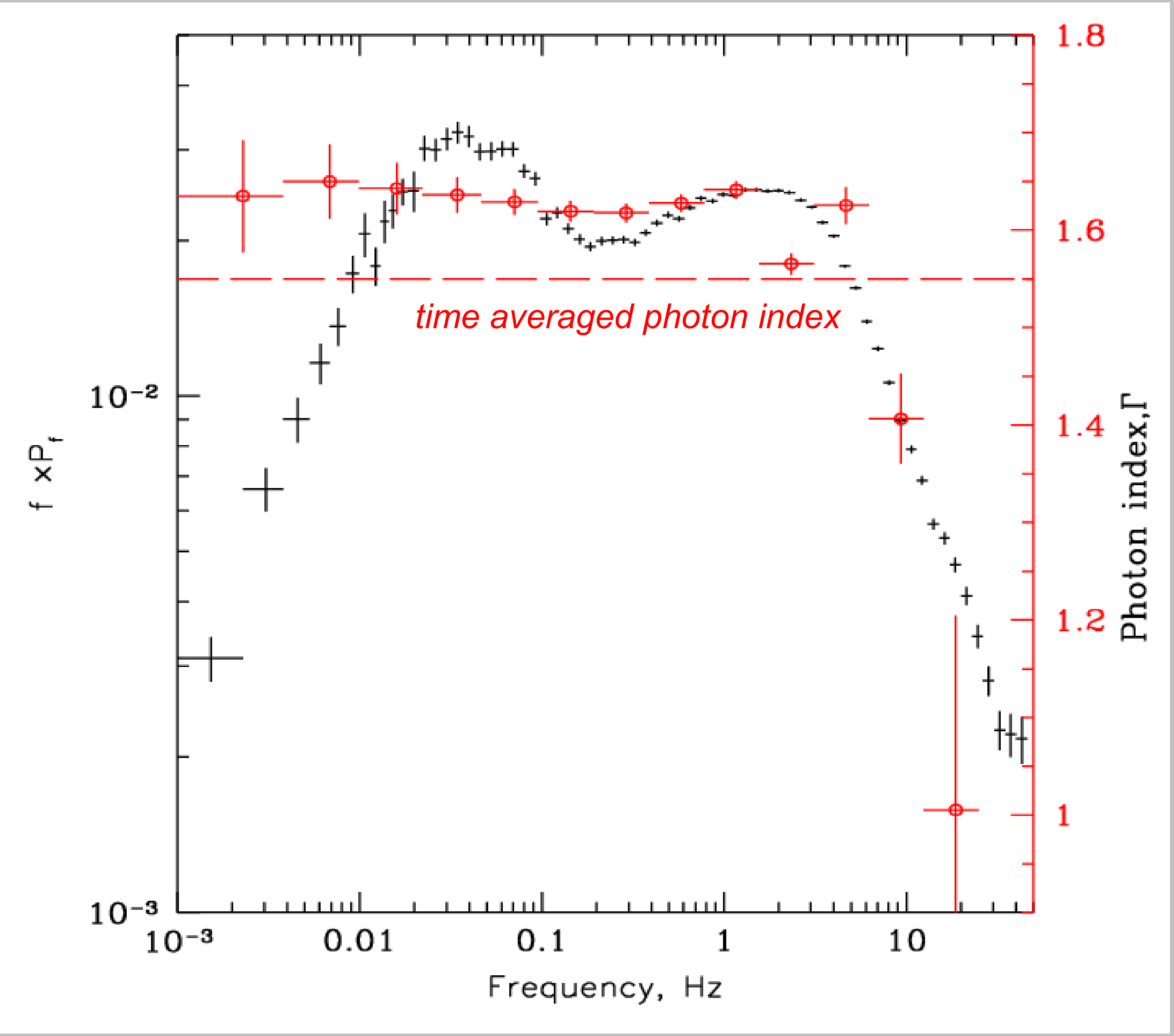


Fe line and continuum variability differs!



See also application to AGNs (e.g. MCG 6-30-15)
e.g. Vaughan & Fabian 2004, Papadakis et al. 2005

GX 339-4



1.8
1.6
1.4
1.2
1
10^{-2}
10^{-3}
10^{-3}
0.01
0.1
1
10
Frequency, Hz
f ×P_f
Photon index,Γ
time averaged photon index

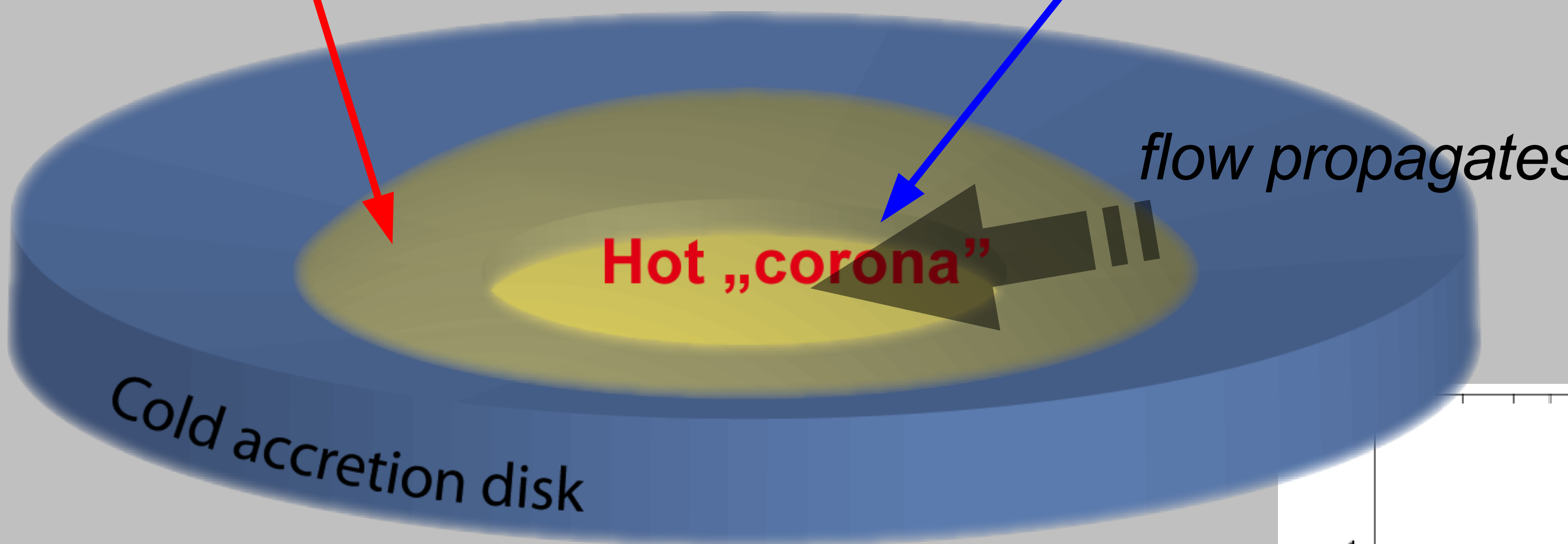
Summary of facts from freq. resolved spectroscopy:

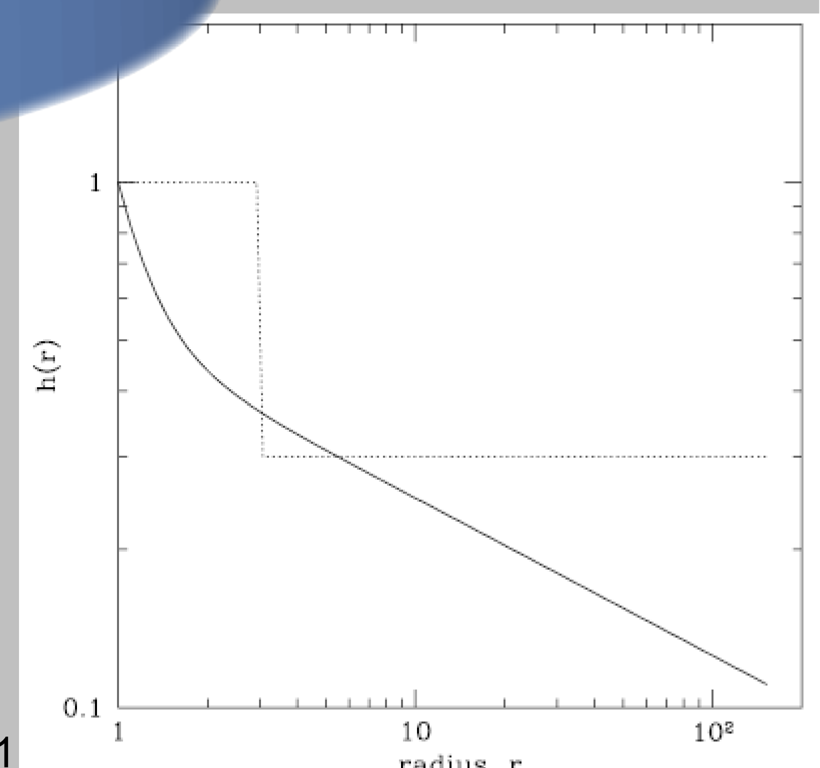
1. At high freq. - variability spectrum is progressively harder

2. At high freq. variability of the fluorescent line is dumped

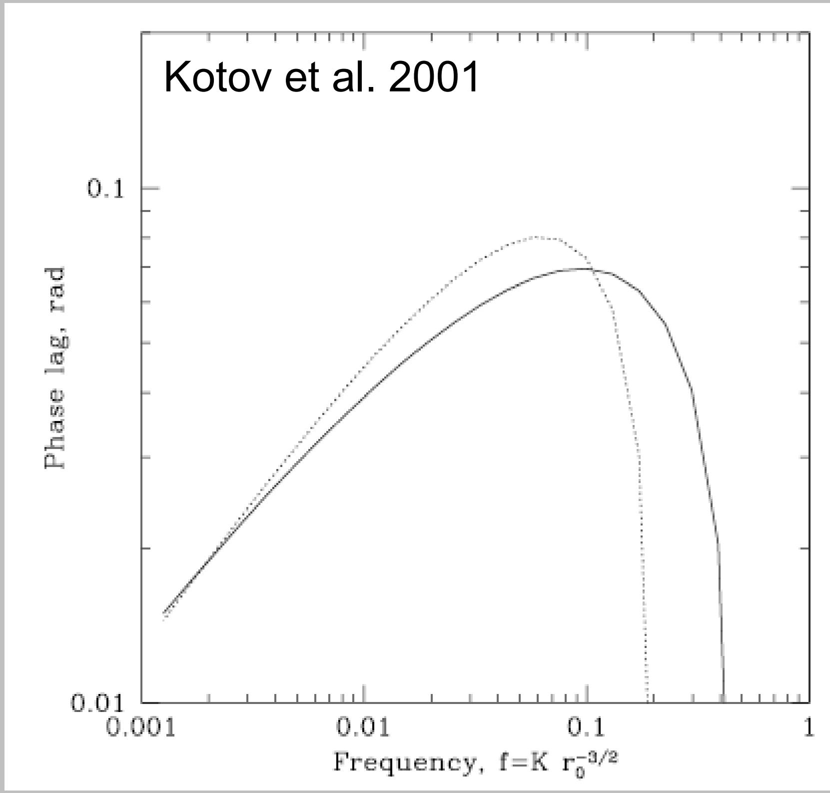
Outer regions are «softer» (e.g. due to close reprocessor/refregirator)

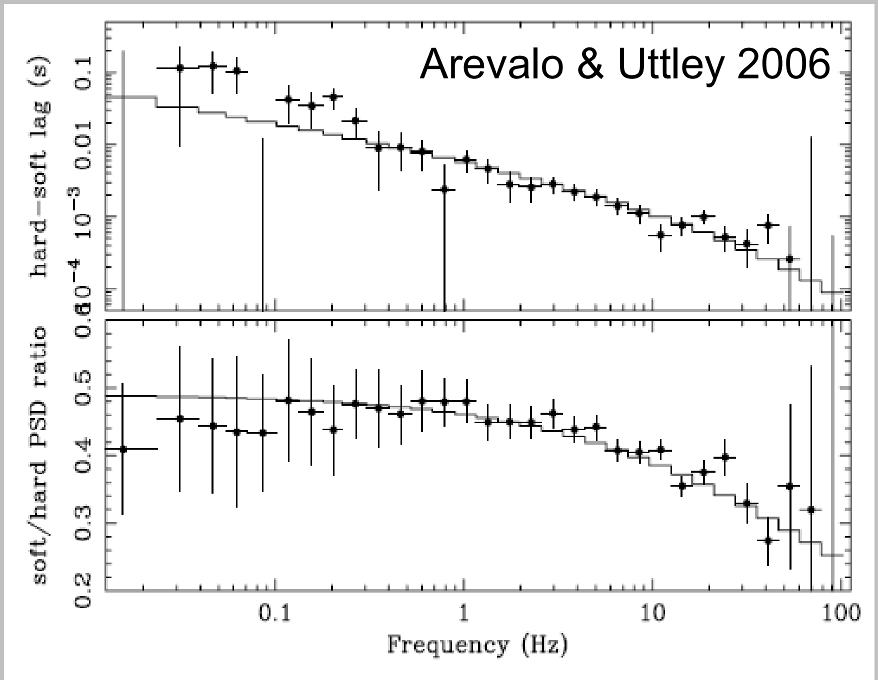
Inner region are «harder», e.g. due to larger energy release and further distance from refregirator

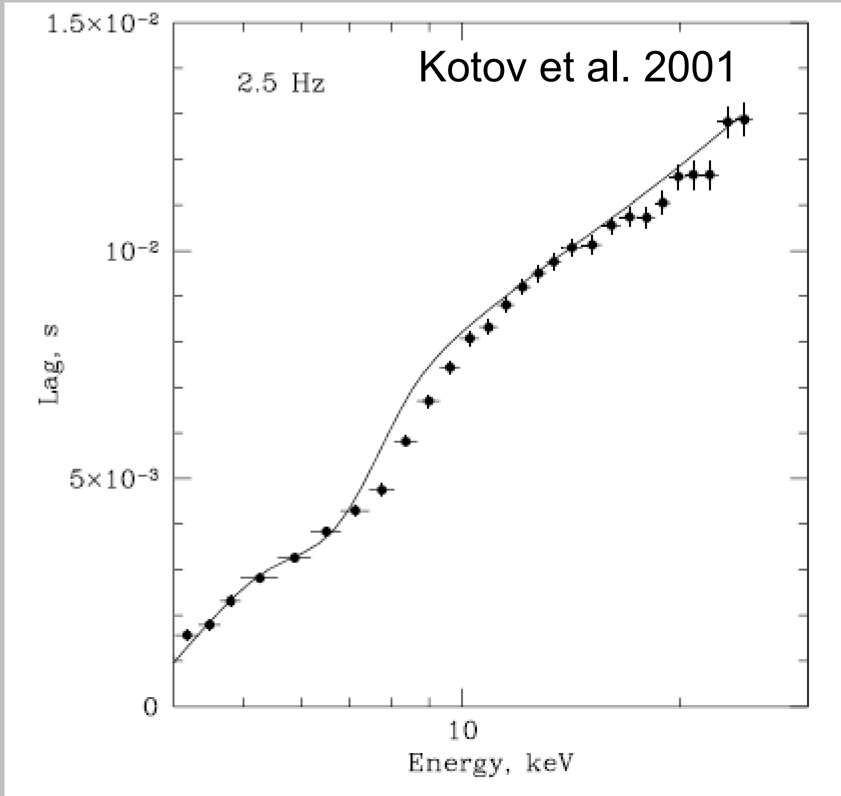




Kotov et al. 2001







Frequncy dependent lags naturally appear in the flow propagation model.

Condition: Harder spectra emerge at smaller radii

Summary of simple variability model (flow propagation)

1. Variable X-ray flux is caused by variable mass accretion rate

2. Variations are inserted at any radii on dynamical or viscous time scales at these radii

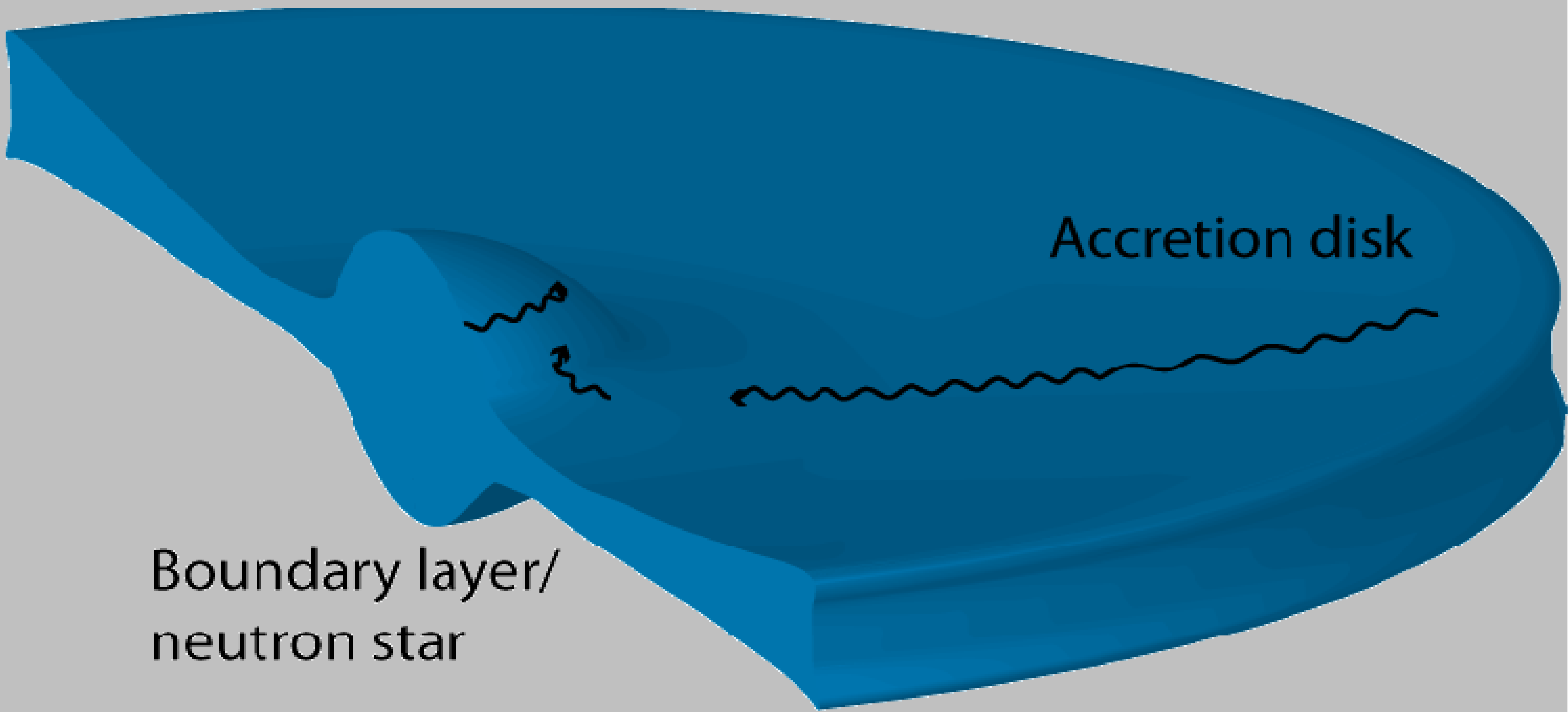
3. Variable photon flux emerges from the inner regions

4. The innermost regions are the hardest

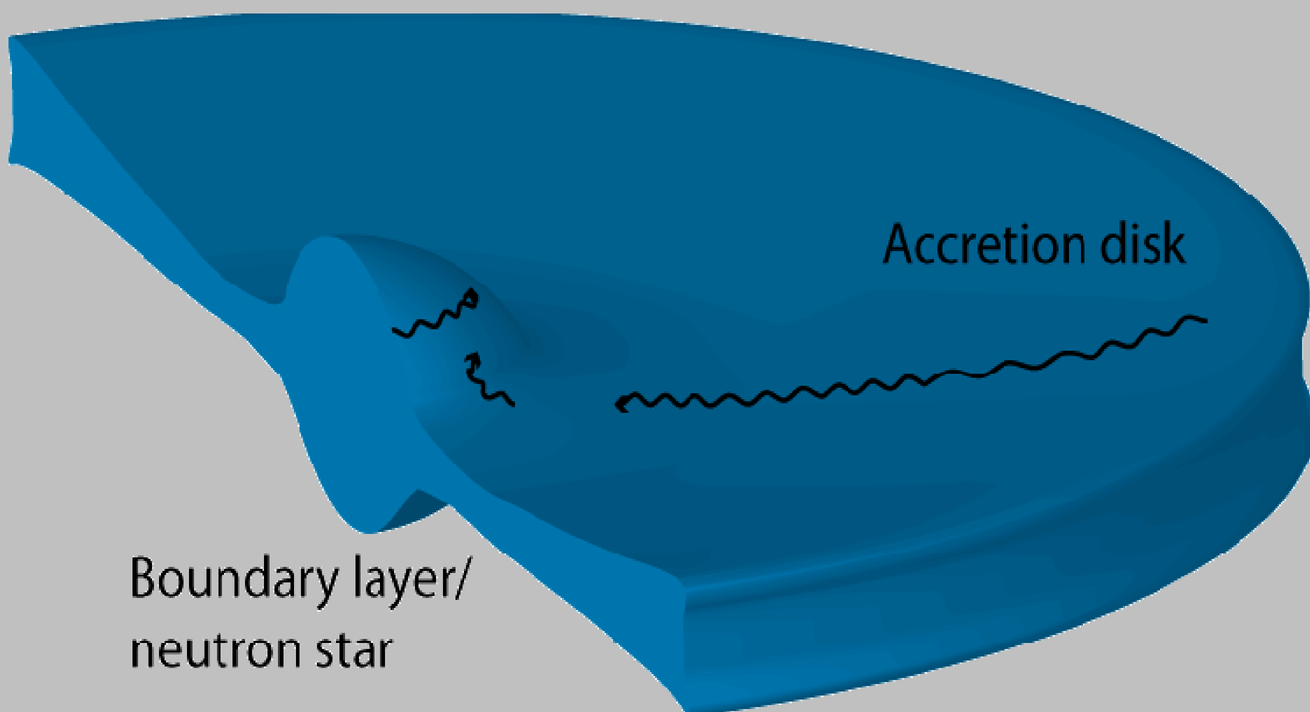
5. Optically thick accretion disk is stable (does not vary its flux)

Extracting physics using variability information

NS with weak magnetic field



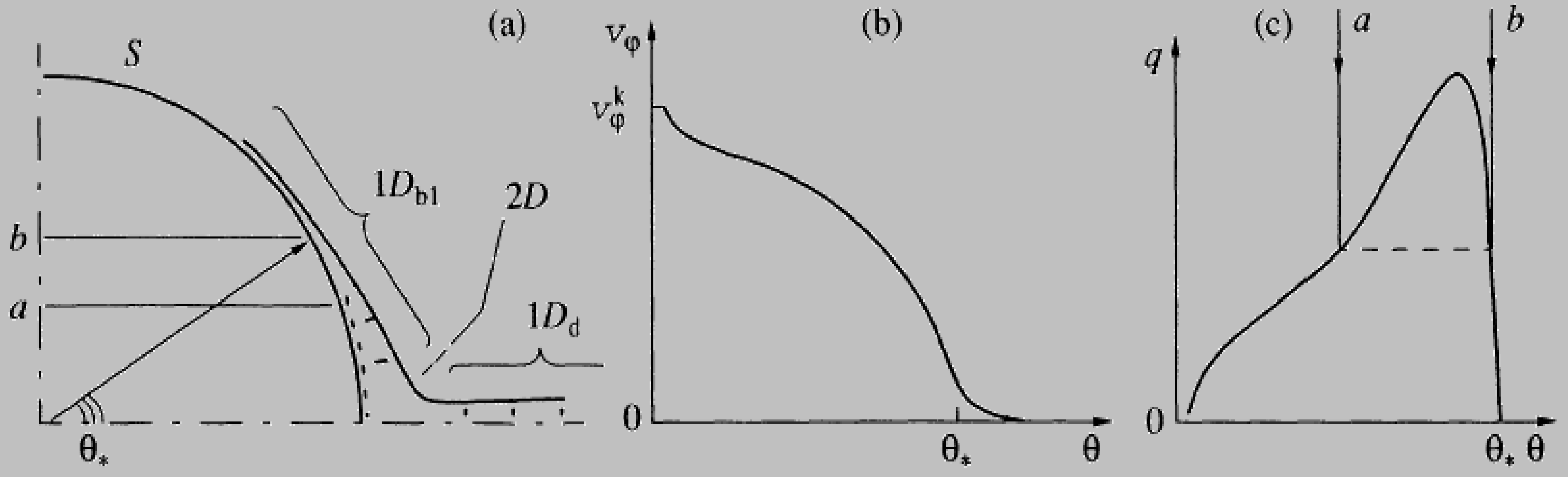
Naive accretion disk/boundary layer scheme



1. Matter rotates in the disk, moves inwards

2. Then it goes into the BL, drifts up/downwards. Settles to the NS surface

Boundary/spreading layer (Inogamov & Sunyaev 1999)



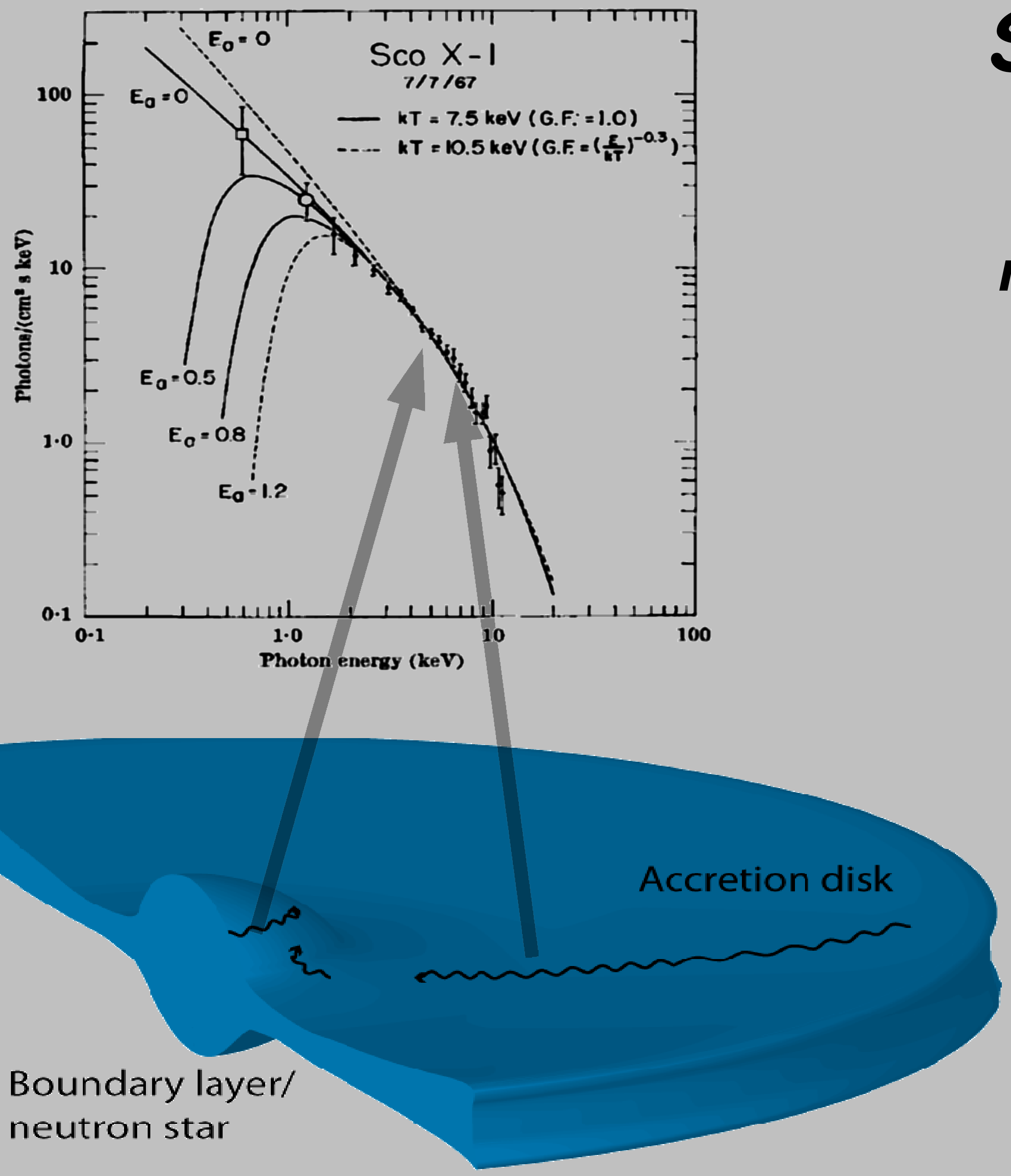
- <u>Radiation dominated</u>

How we can study the BL emission?

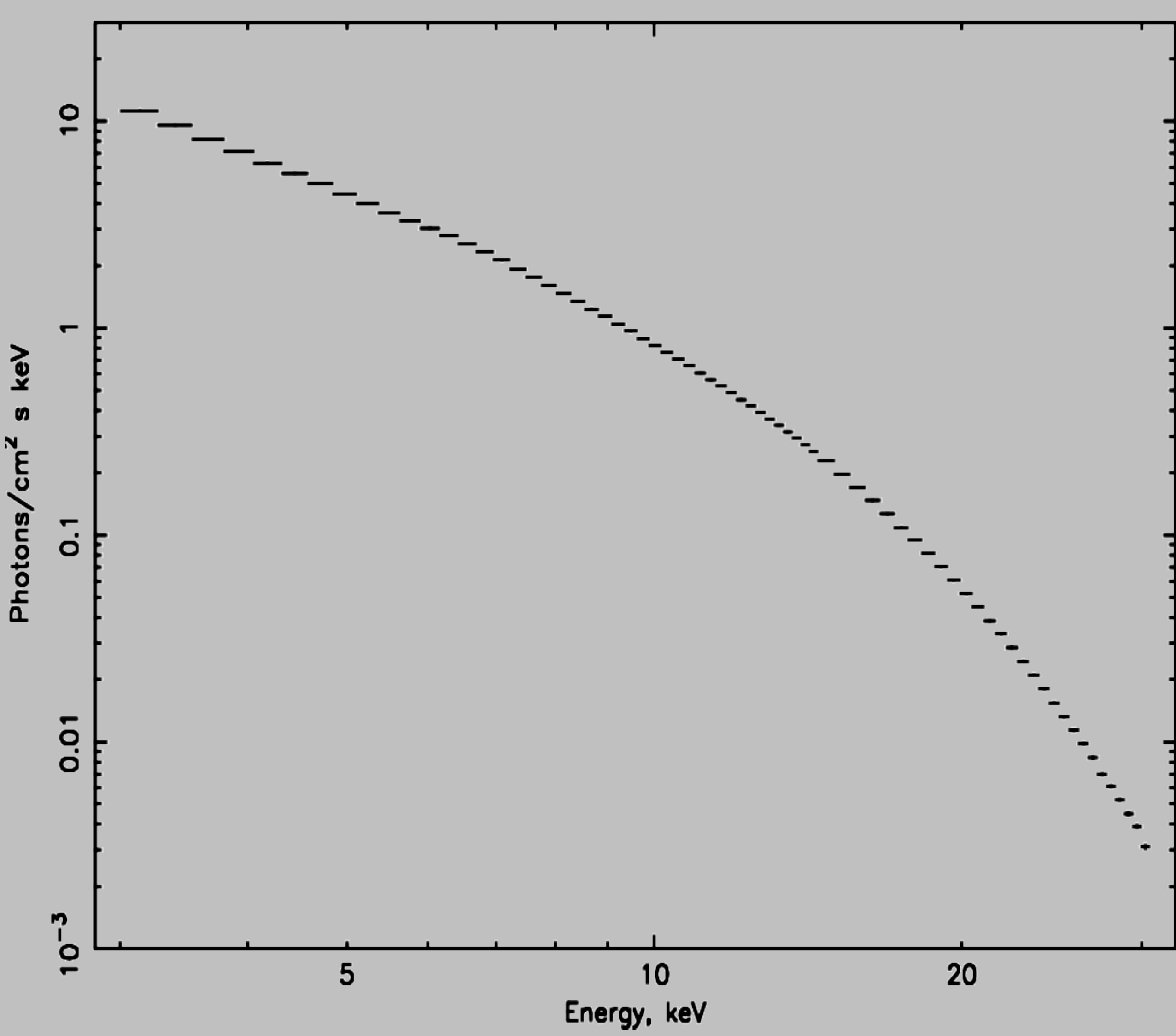
Sco X-1

Rocket measurements (~300 cm^2)

Rappaport et al. 1969



Sco X-1



Latest satellite measurements (~6400 cm^2)

Separation of two components is far from obvious

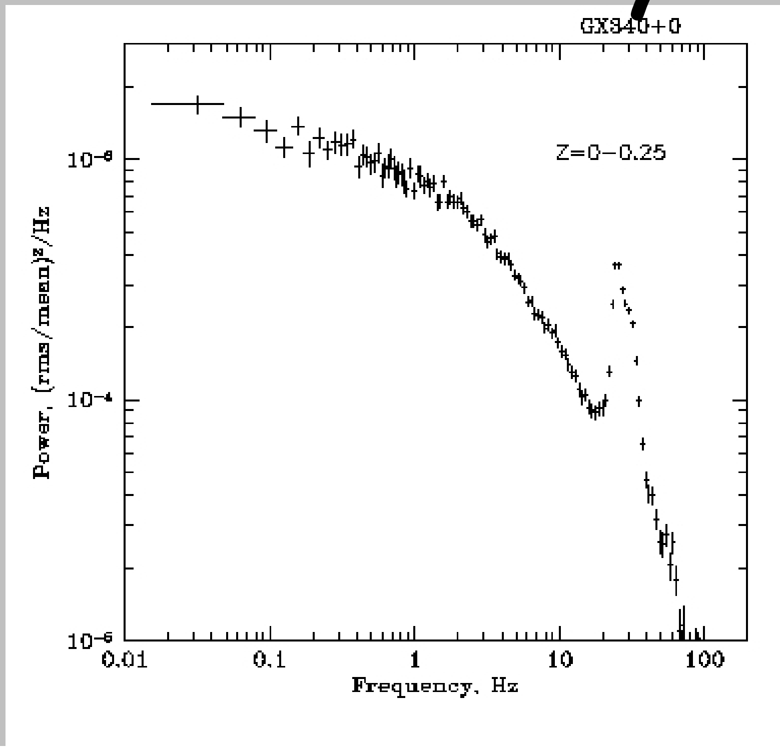
ACCRETION DISK

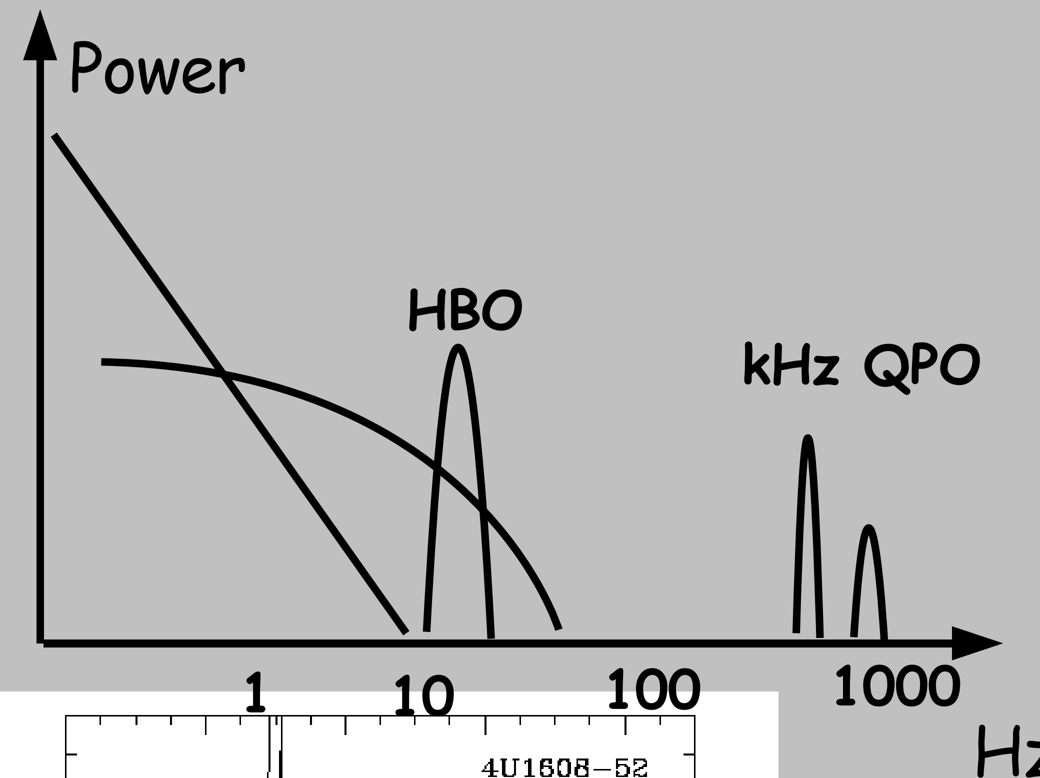
BOUNDARY LAYER

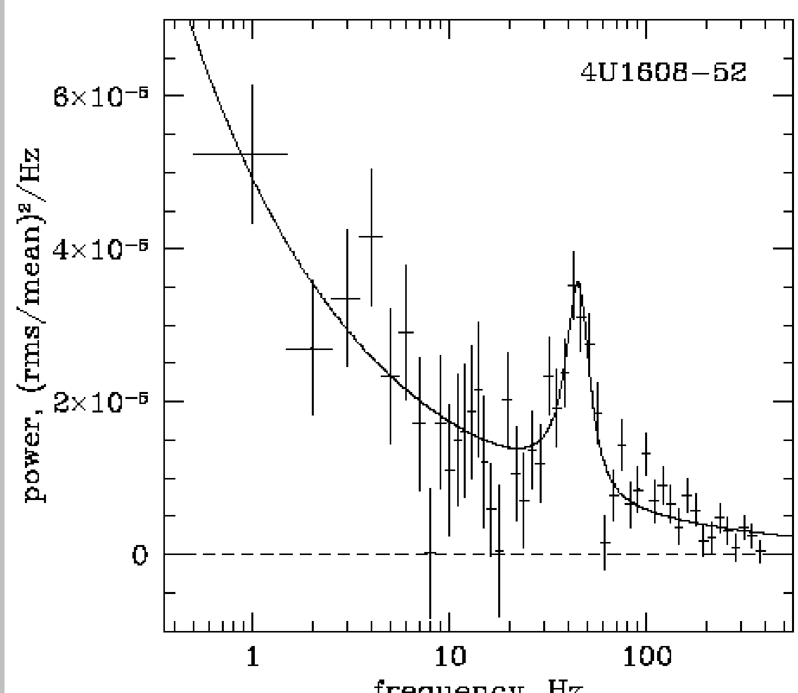
BOUNDARY LAYER

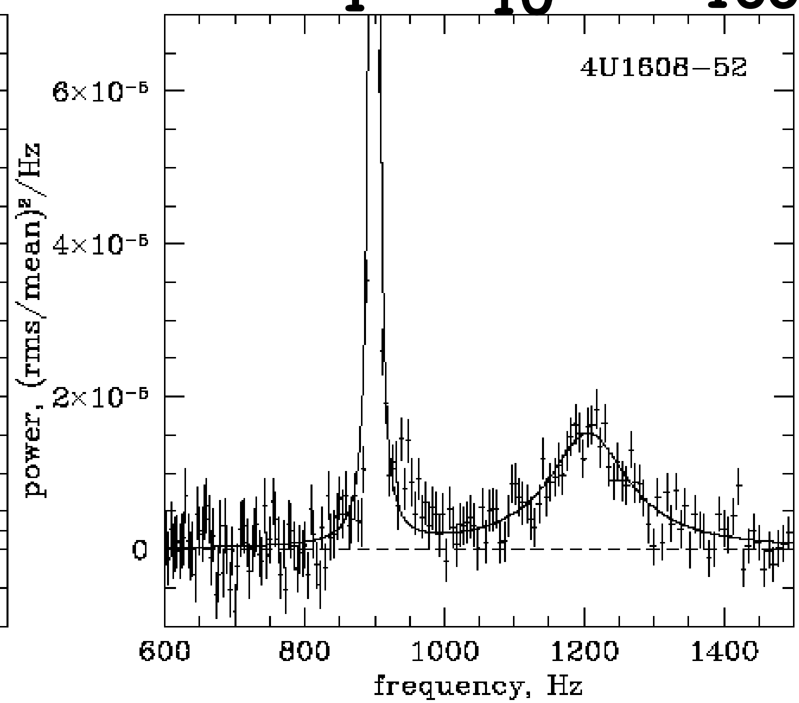
ACCRETION DISK

Variability of bright NS LMXBs

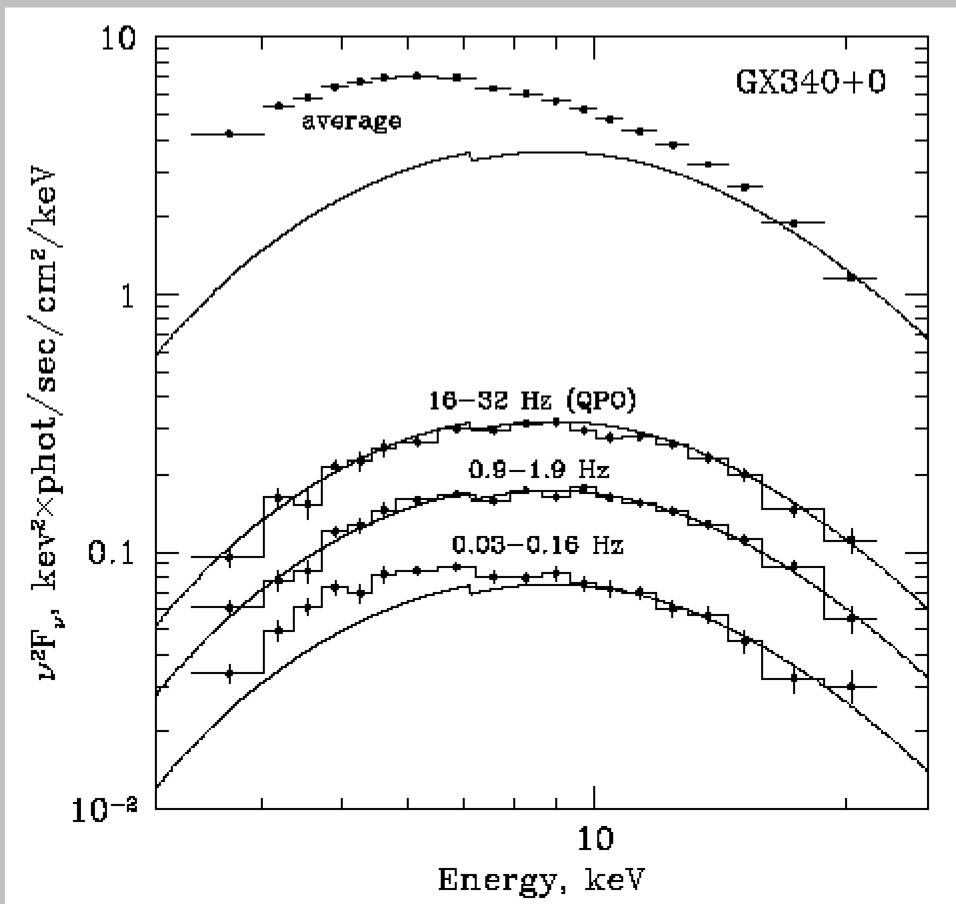


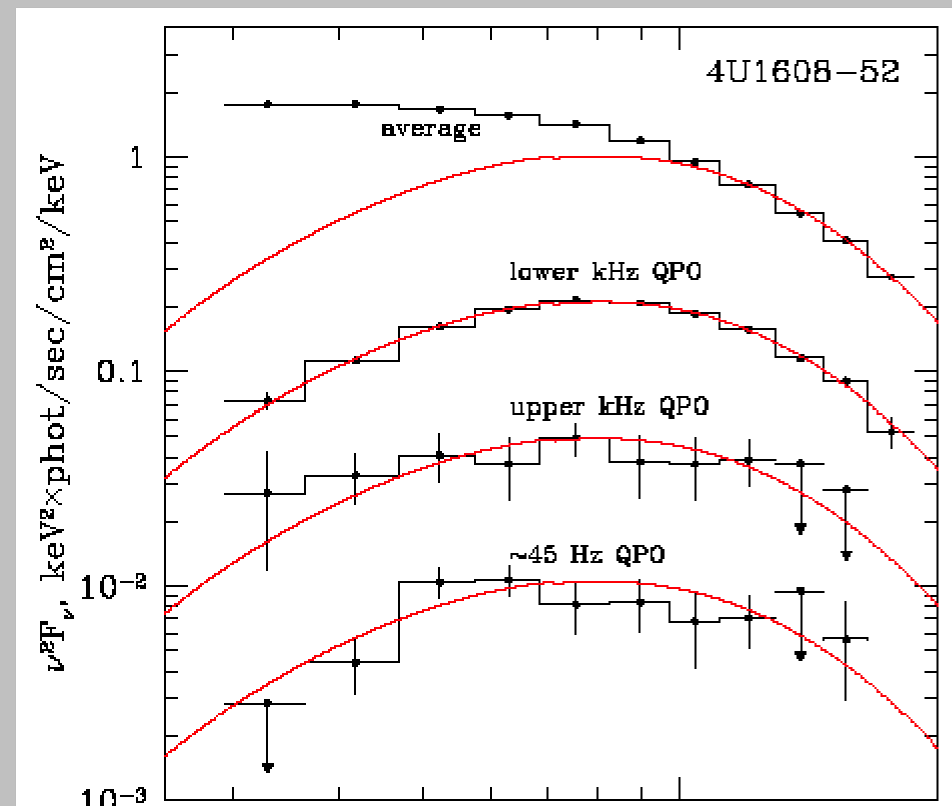






Frequency resolved spectra of bright LMXBs



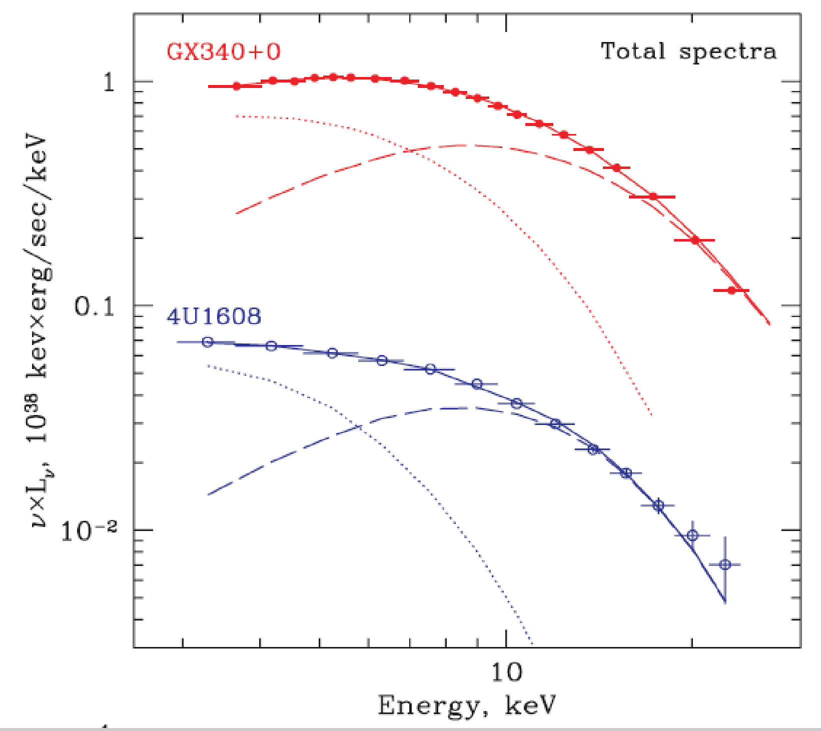


Energy, keV

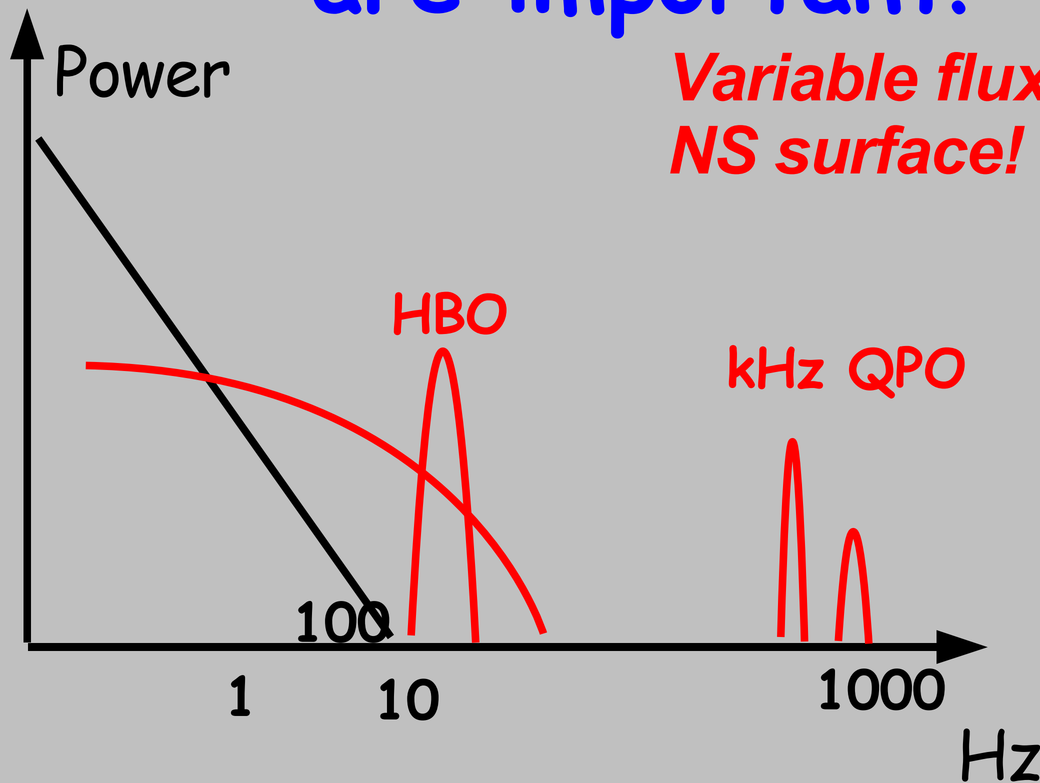
Frequency resolved spectra

1. Coherence ~1
2. Time(phase) lags <<1
2. Achromatic – do not depend on frequency

Almost unique interpretation - variability of one spectral component as a whole

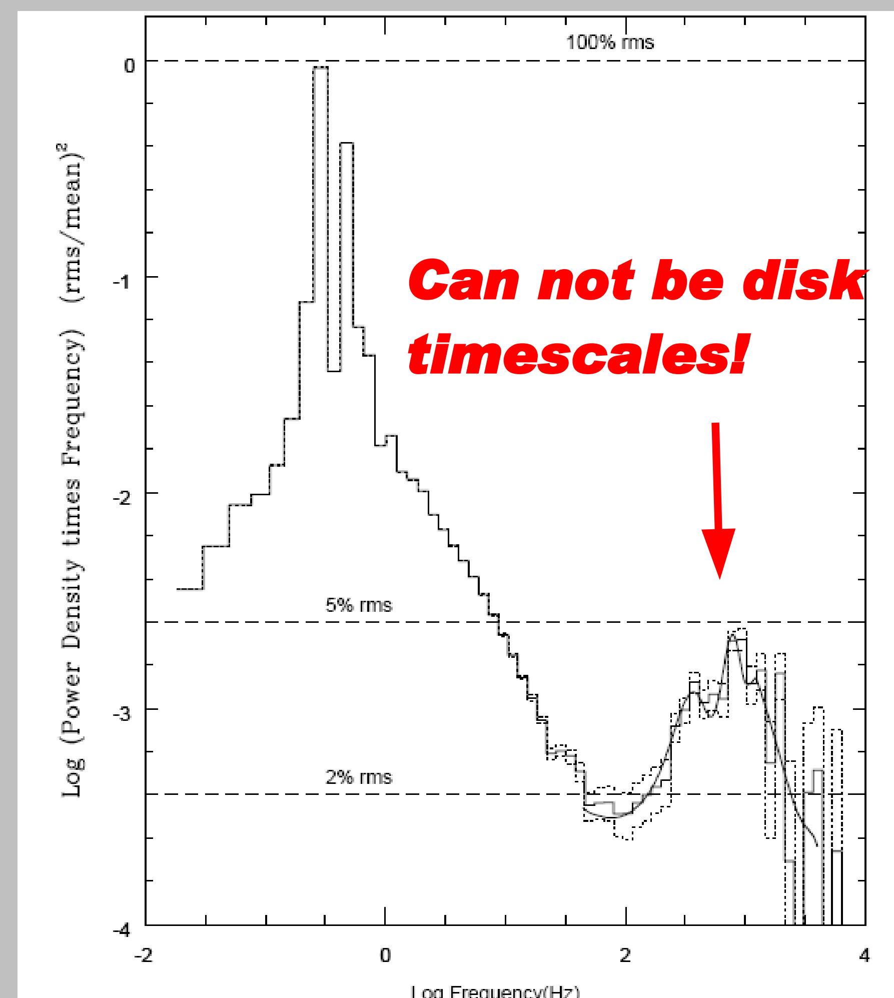


Processes on NS surfaces are important!



Variable flux physically emerges from NS surface!

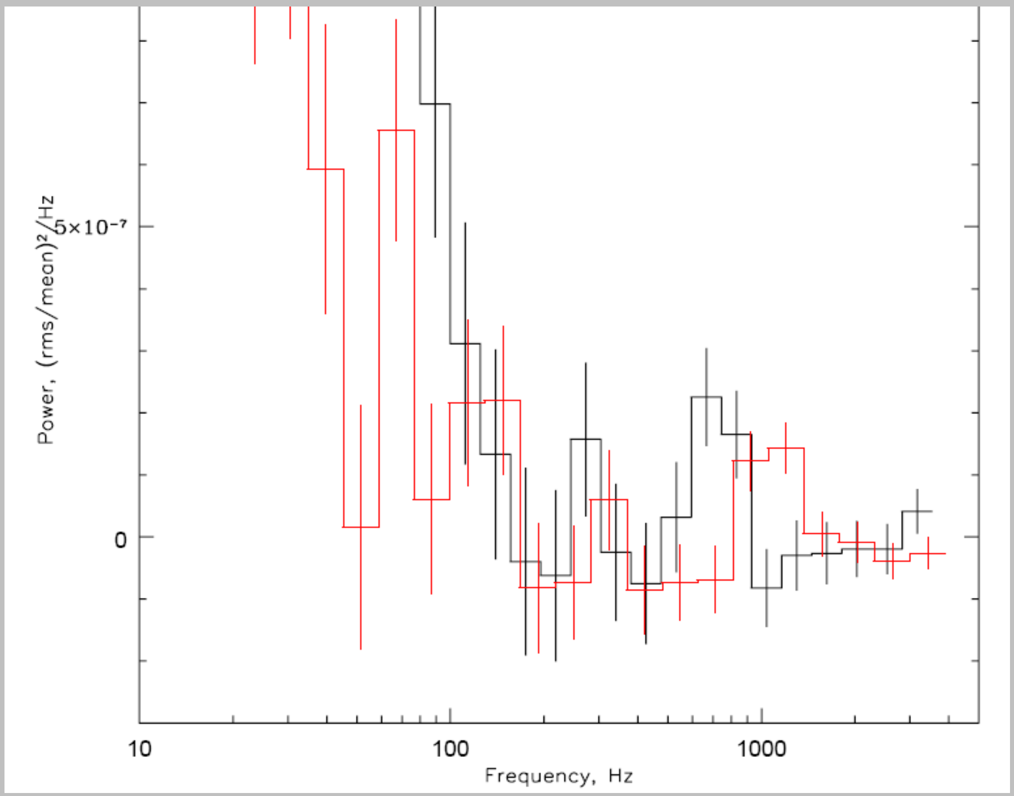
Jernigan et al. 2000

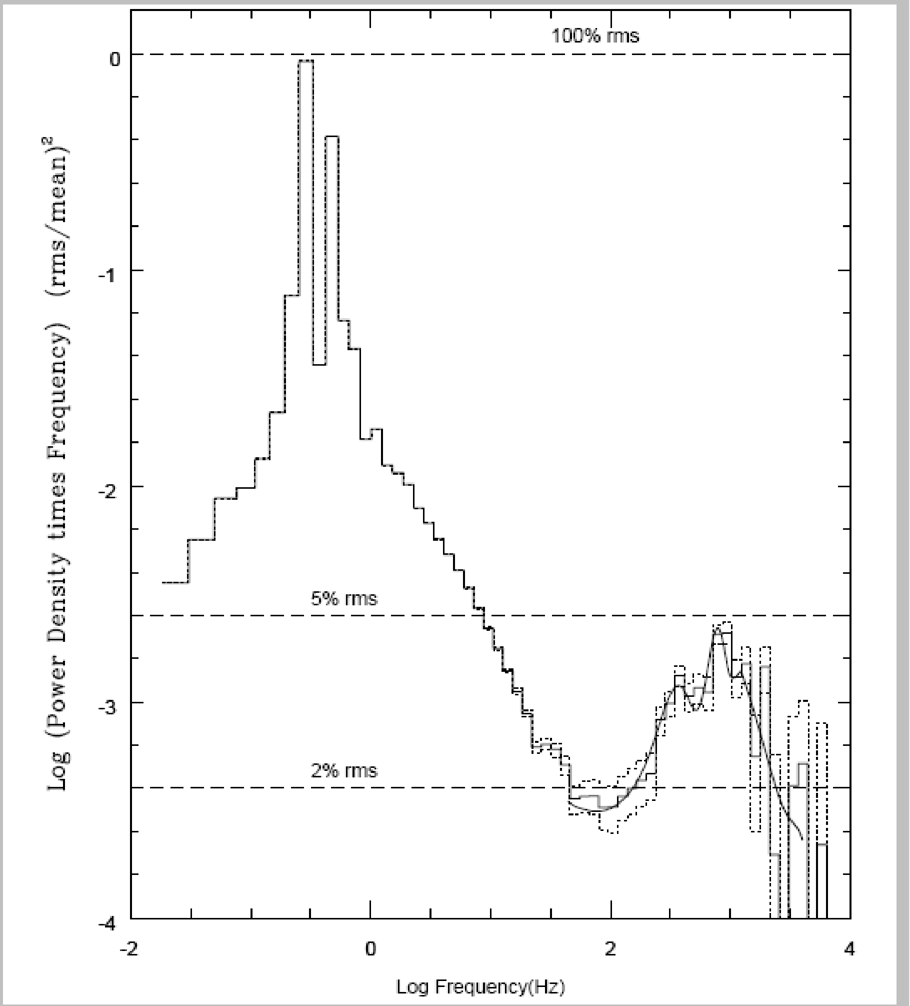


More examples - power of Cen X-3 (accreting pulsar with large magnetosphere)

Many more....

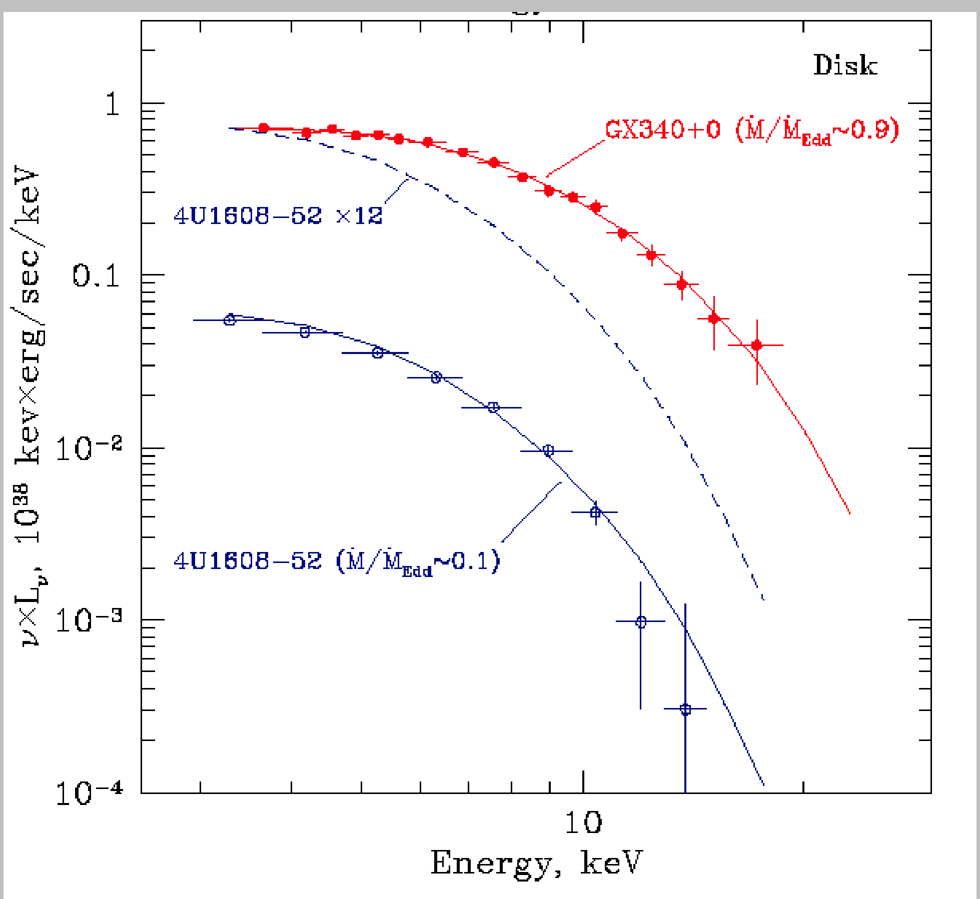
Processes on NS surfaces are important!

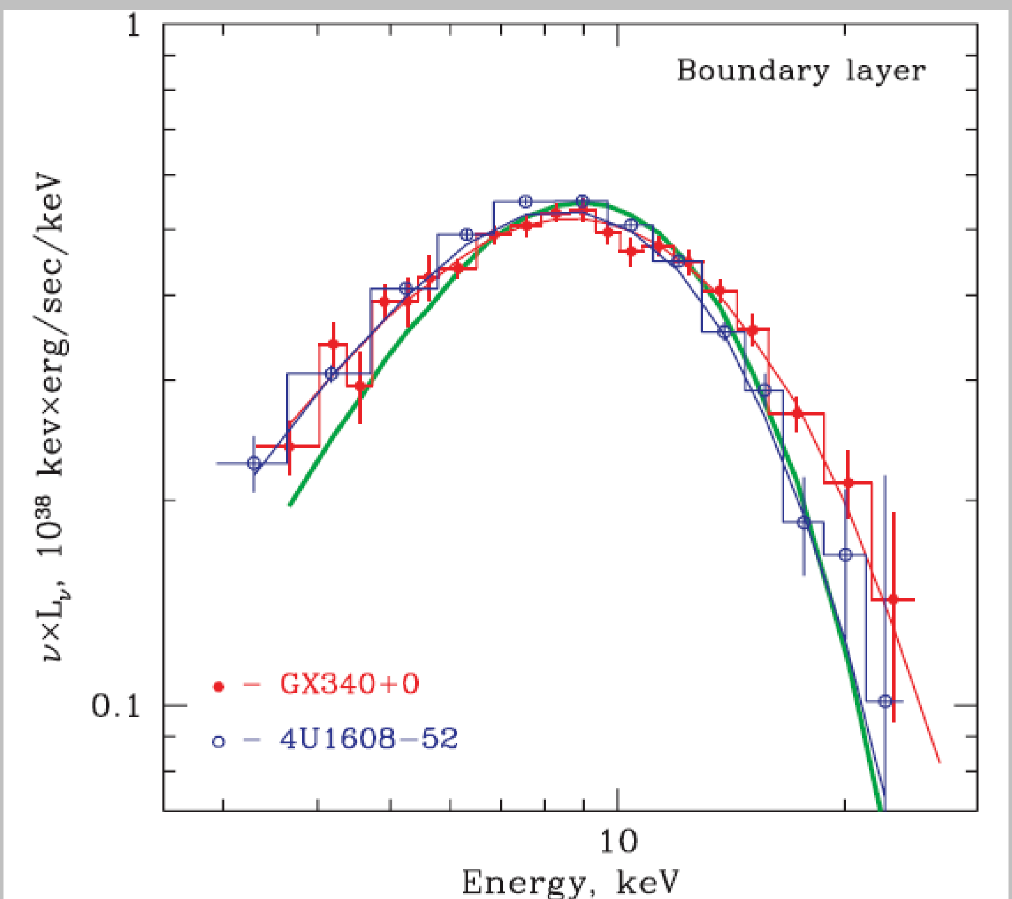




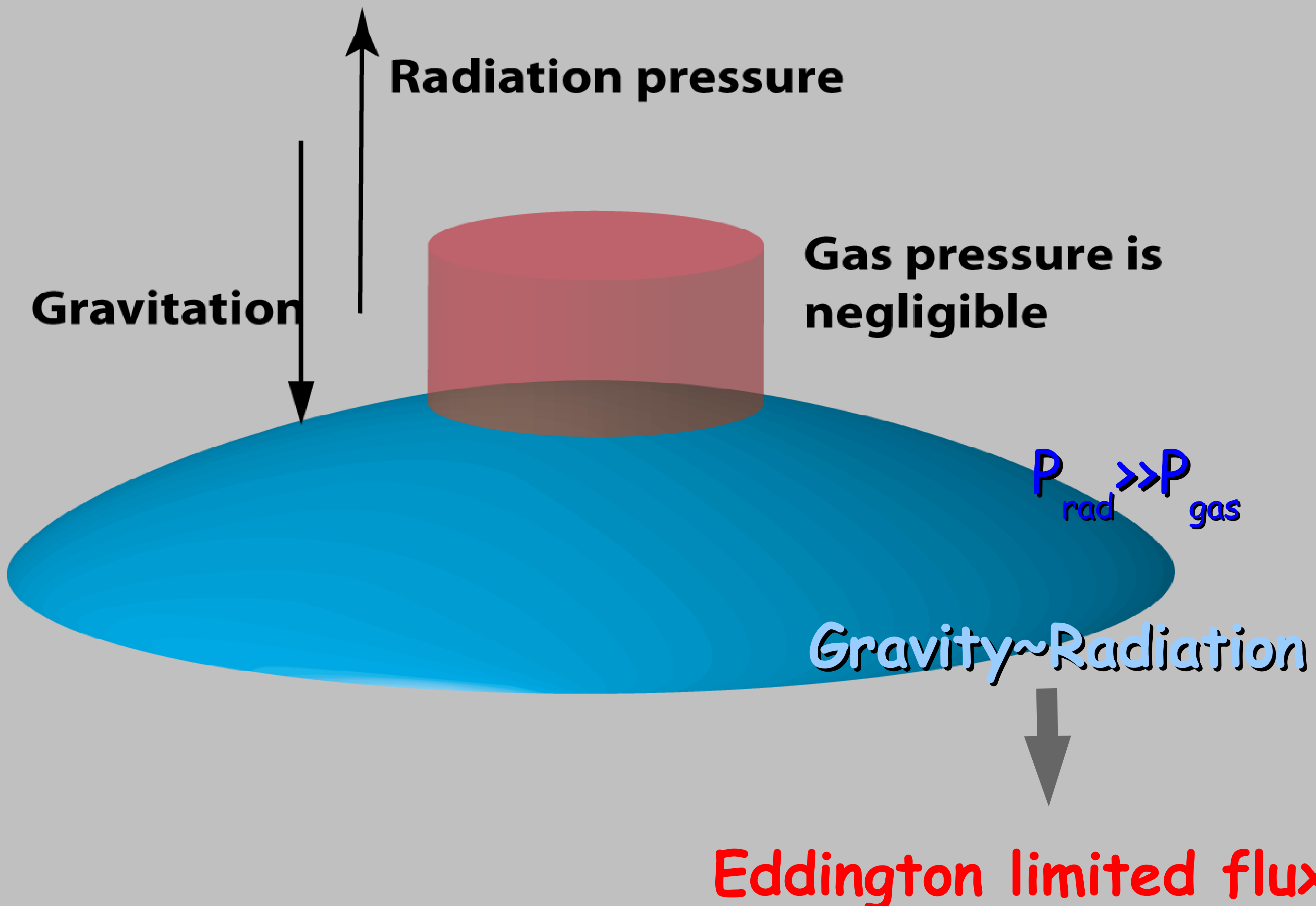
Factor 10 in LMXB luminosity:

1) Temperature of AD changes ~accordingly
2) Shape of the boundary layer spectrum is ~constant

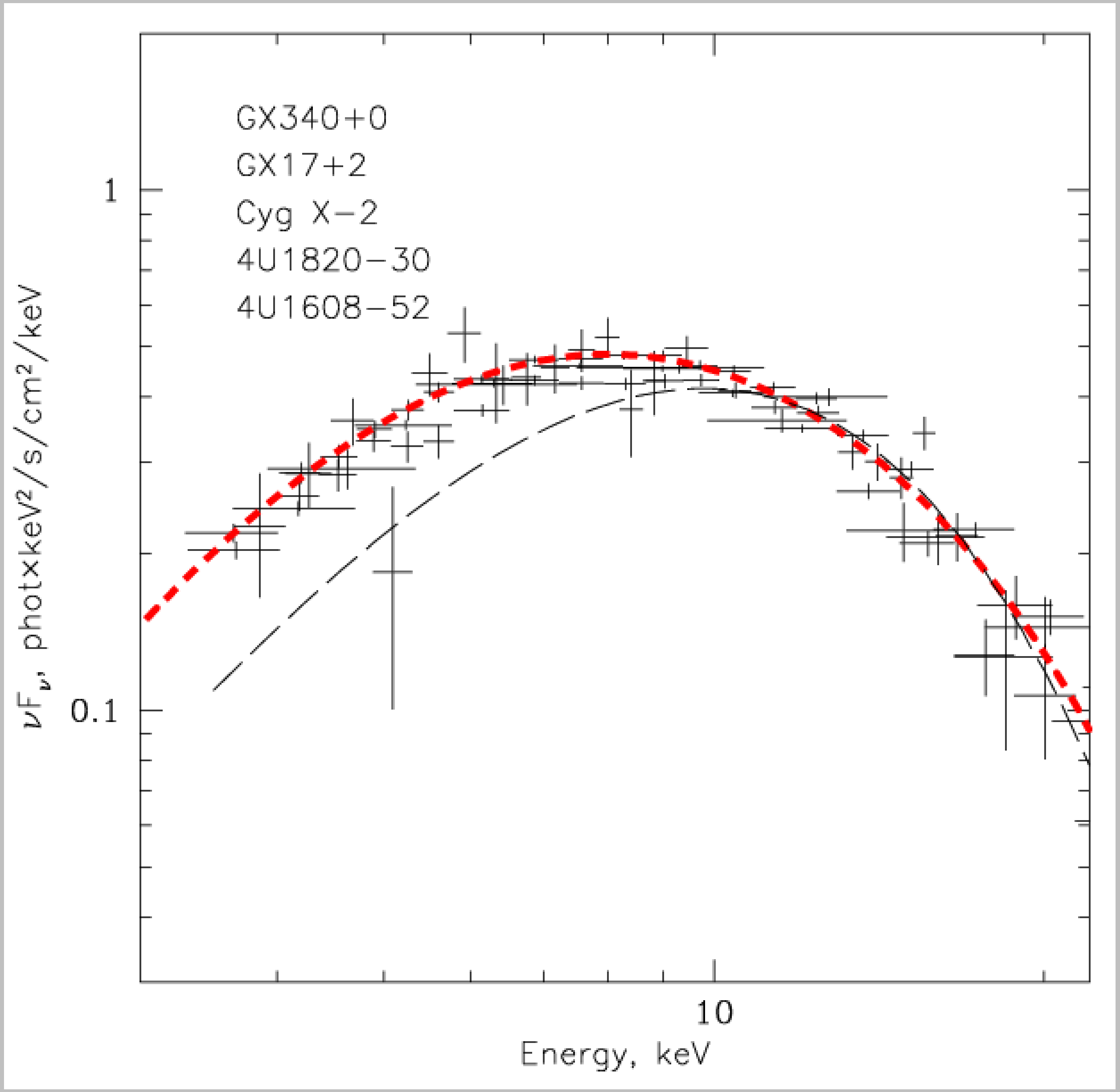




Boundary layer statics



Boundary layer spectrum

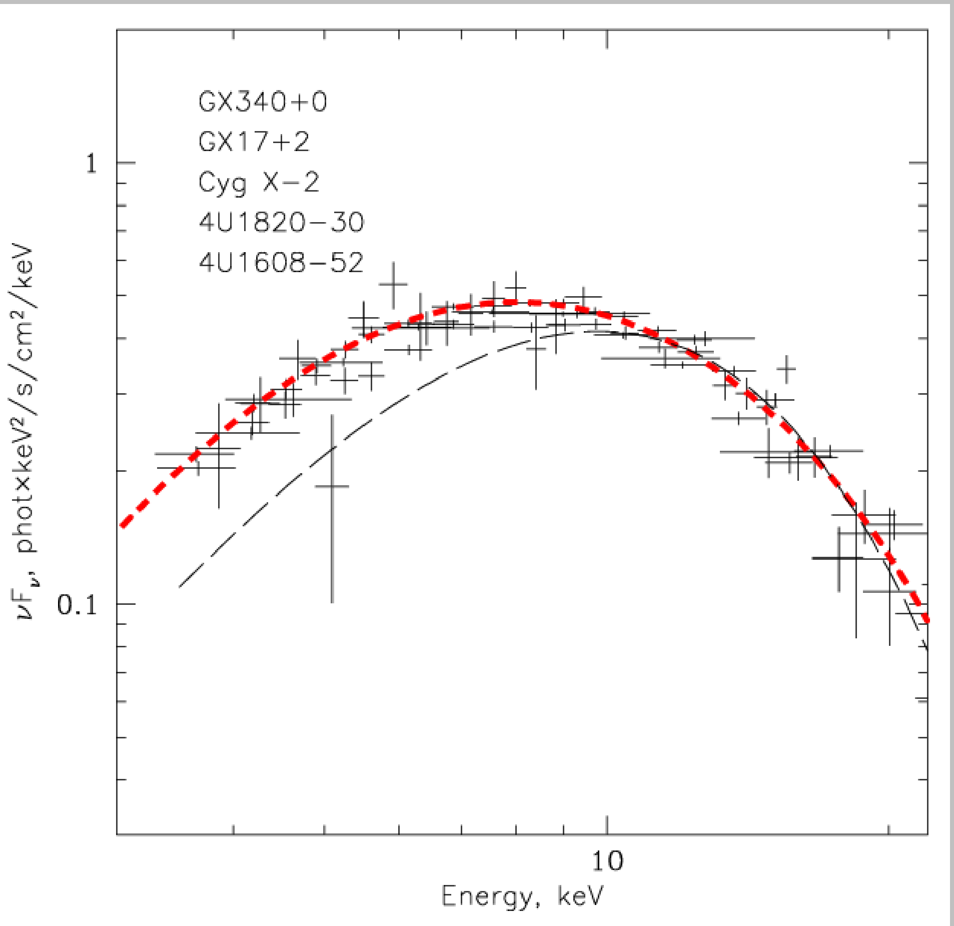


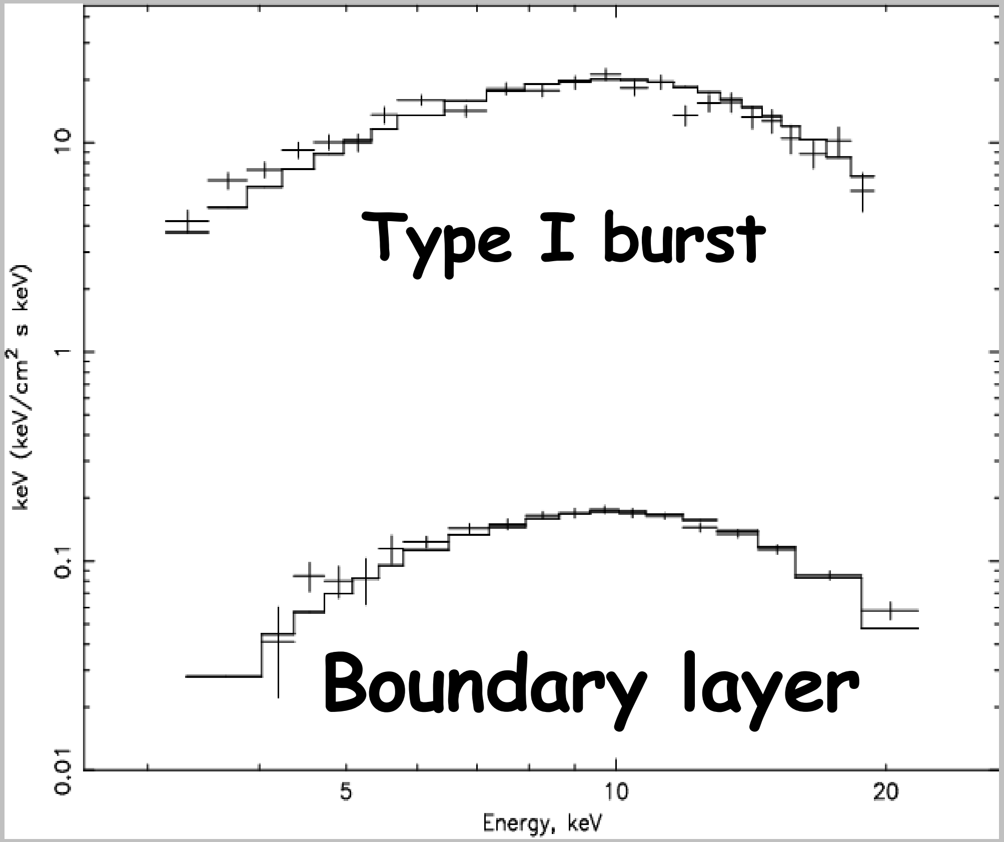
5 different sources

Accretion rate differs ~10 times

Color temperature kT ~ 2.4 keV

Eddington limited spectra of BL/NS



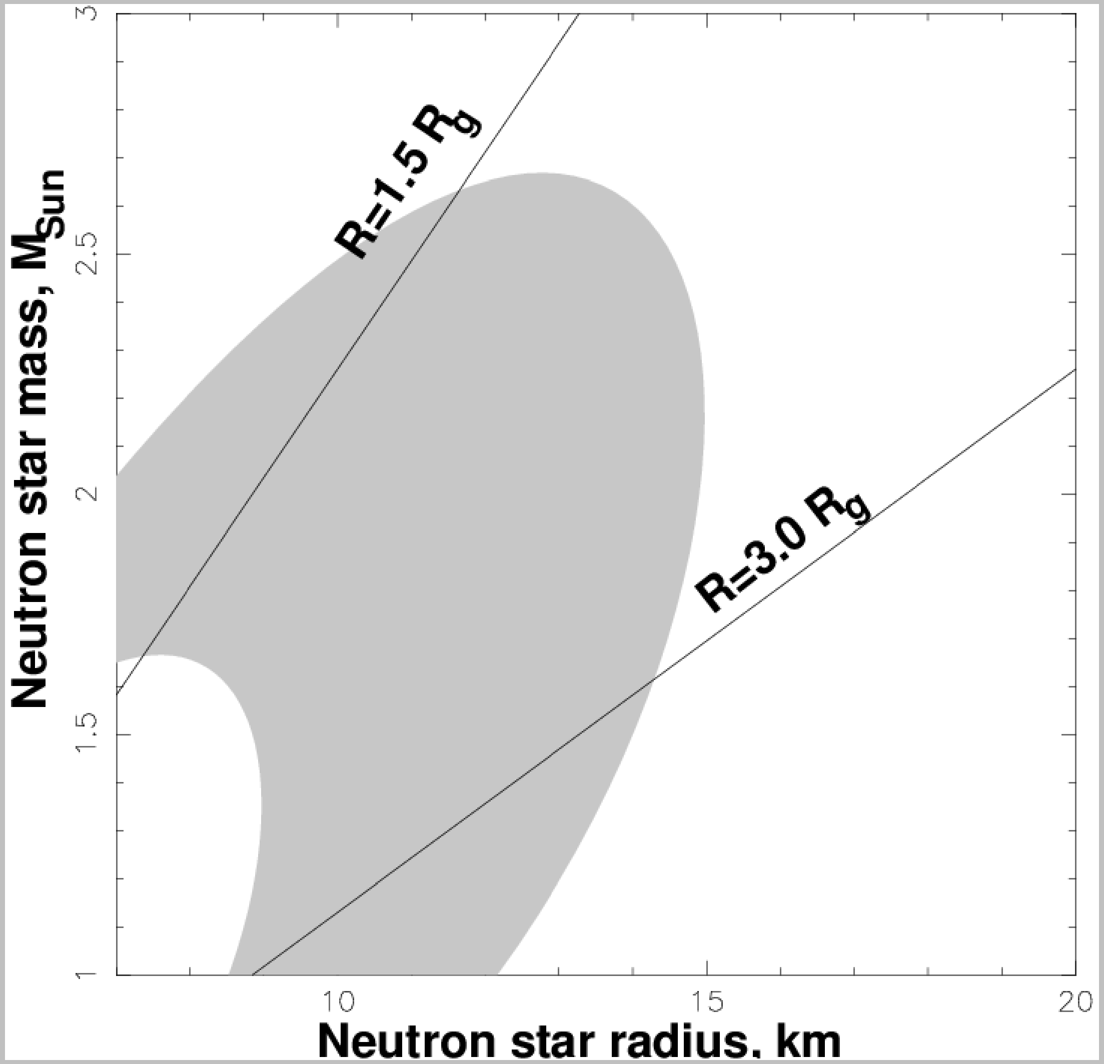


Neutron star parameters

Measurement of
Eddington flux value
in optically thick case

$$T^4 \sim GM\,R^{-2}$$

GR corrections



Complications:

1) Hardening factor
2) Centrifugal force

Summary

0.0 Variability provide very important part of the information about astrophysical phenomena!

0.1. I gave one example of its usage – NS mass/radius relation from the spectrum of the boundary layer

1. ~All observational properties of XRB variability can be explained in the framework of propagating fluctuations model:
a) Variable X-ray flux is a result of variable instant mass accretion rate
b) Variations are inserted at any radii on dynamical or viscous time scales at these radii

3. Variable photon flux physically escape from the inner regions: in BH binaries – from the accreion flow, in NS binaries – from NS surface

4. Optically thick accretion disk is stable (does not vary its flux) even at the highest Mdot