Overview of spectral change in NS-LMXB

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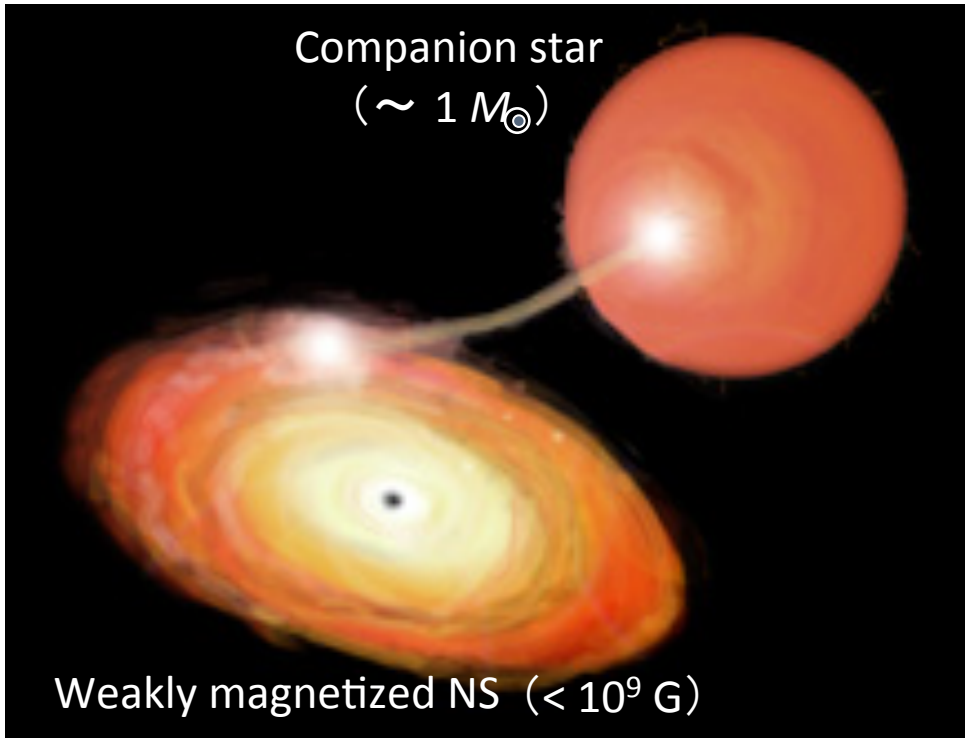
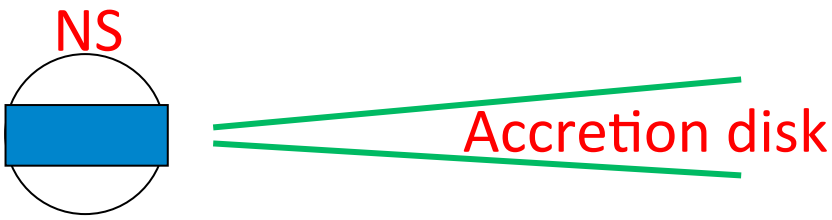




Low-Mass X-ray Binary (LMXB)

Neutron Star (NS) or black hole

Low-mass companion star

X-ray Emission:

Accretion disk

NS surface (boundary layer)

Today's topic:

Low/hard state

High/Soft state

- **Standard**
- **More luminous states**

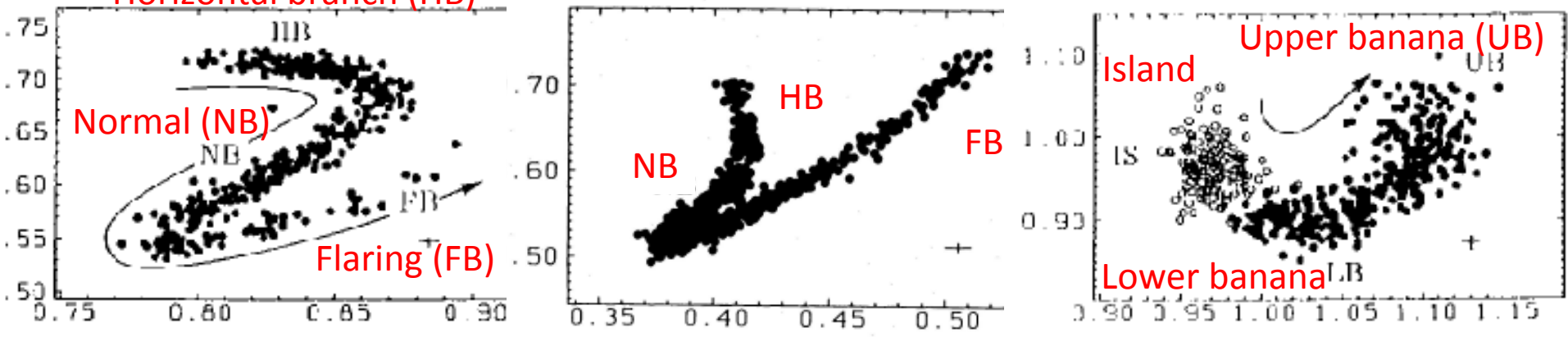
Eddington luminosity: 10^{38} erg/s

Z (Cyg-like "Z"), Z (Sco-like "ν") & Atoll sources/states

Haisinger et al. 1989

Hard Color

Color-Color Diagram (CCD)



Soft Color

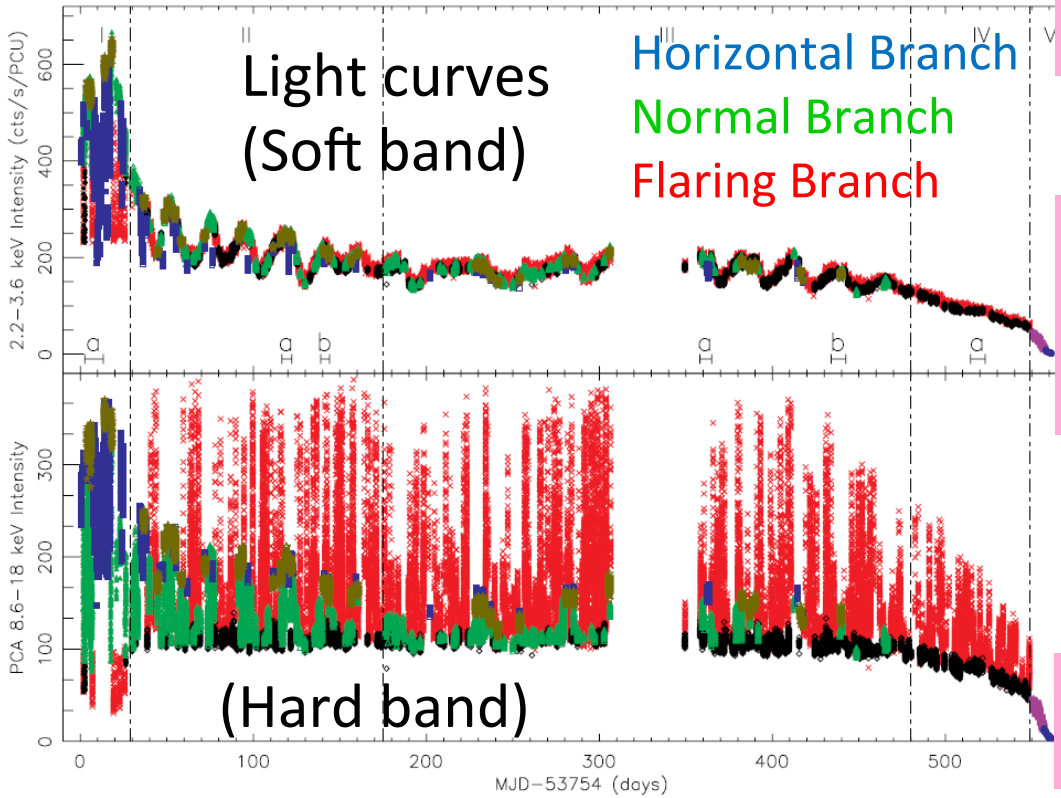
Mdot — High → Low

- NS-LMXBs show 3 different shapes in color-color diagram (CCD).
- Luminosity: Z sources (inc. Sco X-1): ~ Eddington, Atolls: quiescent ~ Eddington
- From higher to lower Mdot, the shape changes Z (Cyg), Z (Sco) and Atoll.
- However, at a certain Mdot, LMXBs seem to take all of HB, NB and FB.
  (e.g.) Cyg FB **does not** connect to Sco HB.

- Depending on Mdot, LMXBs trace different Z (Cyg), Z (Sco) and atoll states。
- Some parameter(s) other than Mdot determine HB, NB and FB.

Z (Cyg-like “Z”), Z (Sco-like “ν”) & Atoll sources/states

XTE J1701-422 (Lin et al. 2009)
MAXI J0556-332 (Sugizaki et al. 2013)

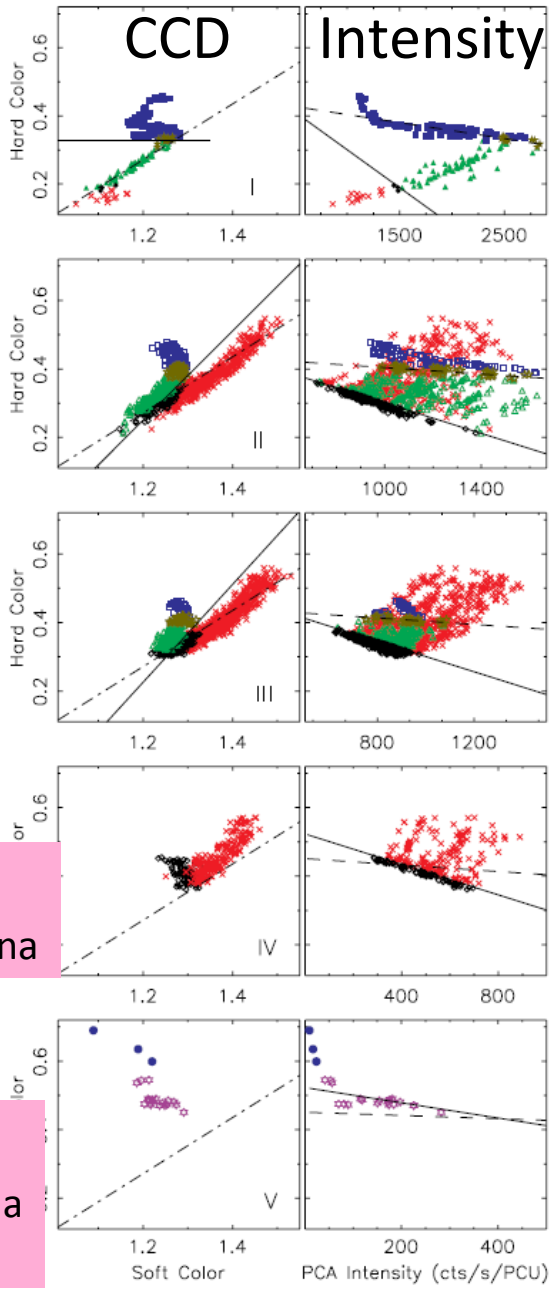


Cyg
- Horizontal
- Normal
- Flaring

Sco
- Horizontal
- Normal
- Flaring

Atoll
- Upper banana

Atoll
- Lower banana
- Island



- During outbursts, one LMXB exhibited all states from Z (Cyg), Z (Sco) and atoll states.
- Another parameter(s) control HB, NB and FB independent from Mdot.

Comparison with black hole binaries

Black hole binaries

Mdot

~Eddington

Slim disk

Very High

High/Soft

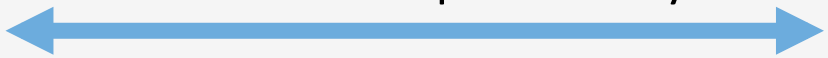
Low/Hard

Today's topic

NS-LMXBs

What physical parameters?

- NS & disk relation
- More radiation pressure by NS



Z (Cyg):

Horizontal, Normal, Flaring branches

Z (Sco):

Horizontal, Normal, Flaring branches

Atoll:

Upper banana

Atoll:

Lower banana

Atoll:

Island

3 Observational results

(HT+2014, in prep)

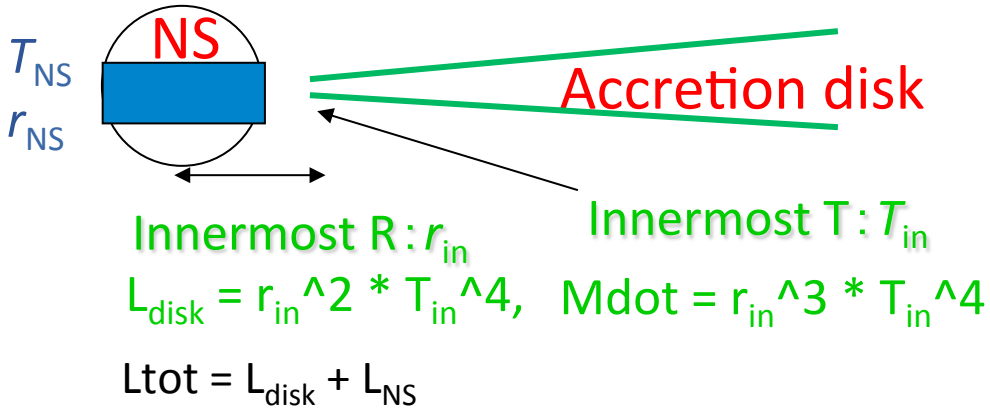
Datasets: RXTE/PCA, (Suzaku/XIS+PIN by Okada-san Poster No.11)

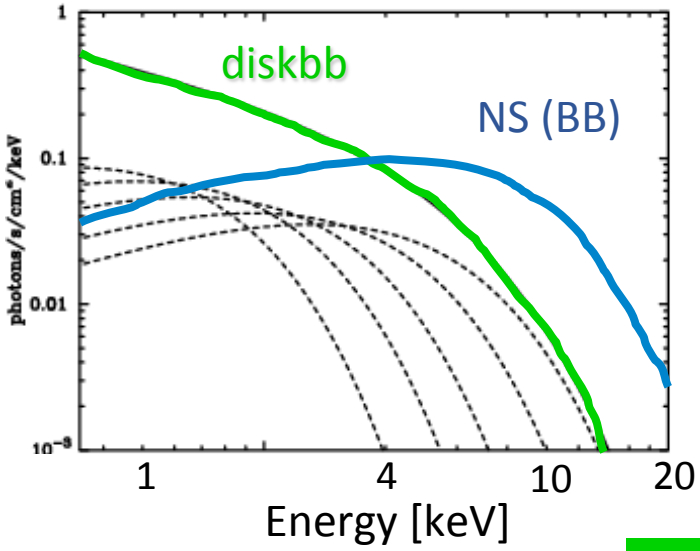
- All states of atoll (UB), Z (Sco-HB/NB) and Z (Cyg-HB/NB): Standard picture

spectra are basically well reproduced by **diskbb+BB** from accretion disk and NS.

(Mitusda et al. 1984
Makishima et al. 1989)

$L_{NS} = r_{NS}^2 * T_{NS}^4$





- L_{NS} relatively decreases as L_{disk} increases (L_{NS}/L_{disk} decreases as Ltot increases). (1)

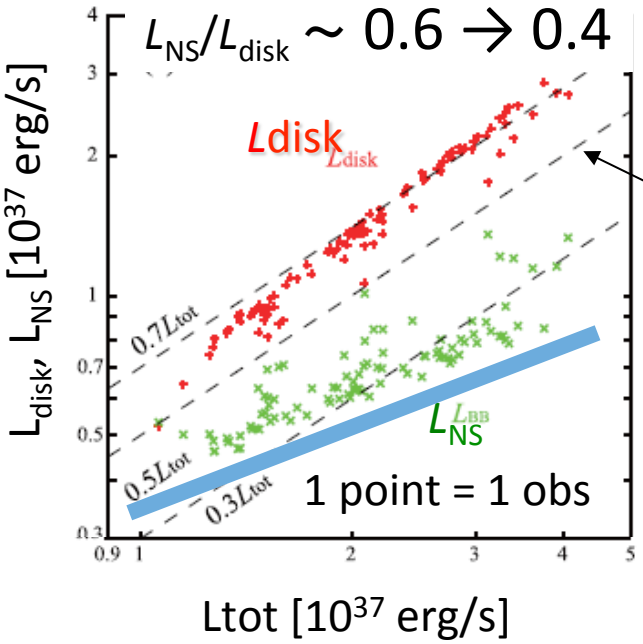
- Disk parameters fluctuating independent from Mdot in two ways. (2-a/b)

- Additional third component (blackbody) appearing between NS and disk. (3)

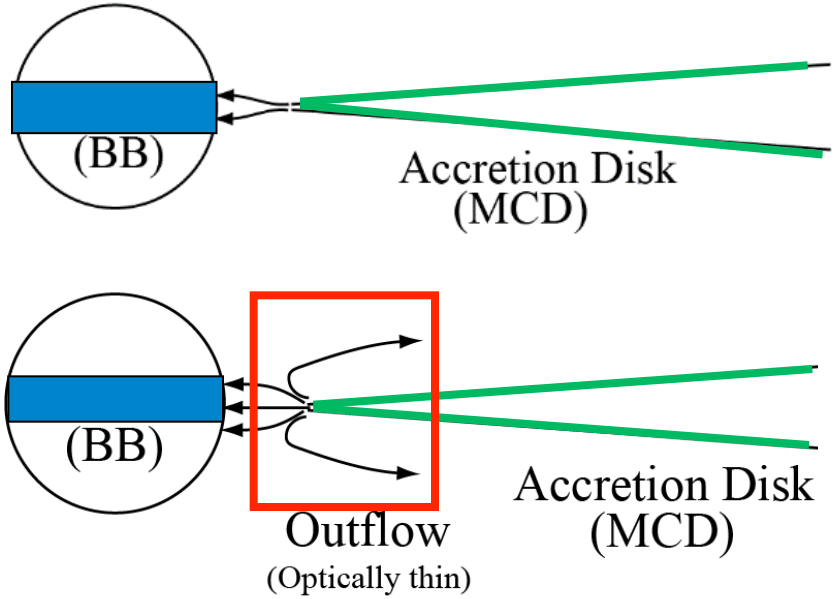
(1) shows existence of outflow
(2-a/b) makes atoll (UB) and Z (Sco/Cyg) behaviors in CCDs.
(3) confirms (2) ideas.

(1) L_{NS} relatively decreases as L_{disk} increases (L_{NS}/L_{disk} decreases as Ltot increases)

Atoll (UB) case (4U 1608-522)



$L \propto$ Ltot ~ Mdot



Gravitational energy → 1/2 Disk emission

Gravitational energy → 1/2 Rotational energy

Virial theorem

$$L_{disk} = \frac{GM\dot{M}}{2r\mathrm{in}} \propto \dot{M}$$

Released as NS emission $L_{NS} \propto \dot{M}$

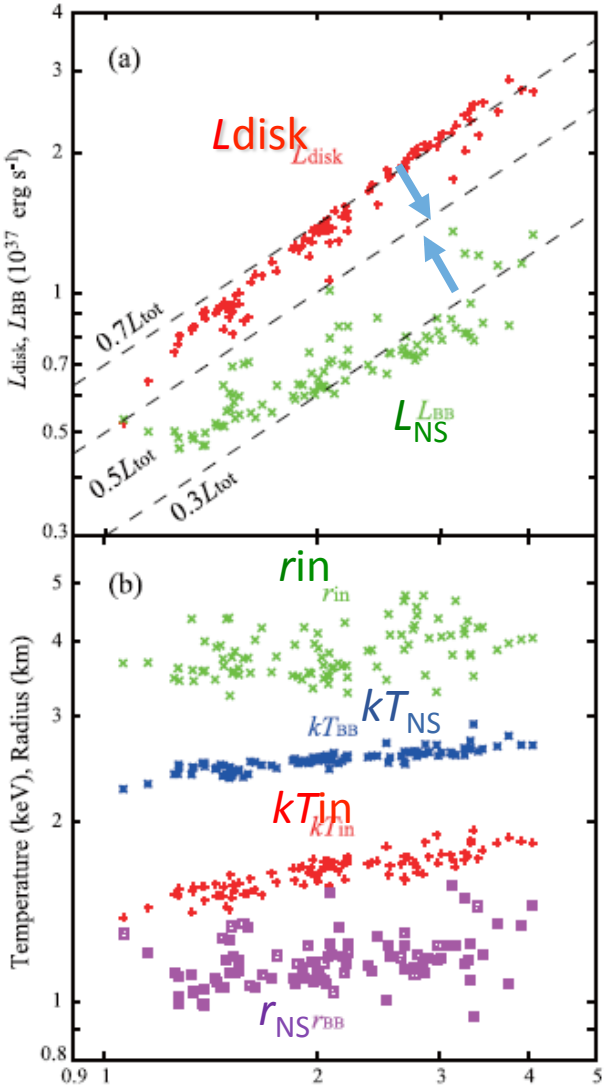
~20% fraction of matter does not accrete onto NS surface.

Outflow occurs (probably due to radiation pressure of L_{disk}+L_{NS}).

(2) Disk parameters fluctuating independent from Mdot

Atoll (UB) case
(4U 1608-522)

Relationship with Ltot



Look at deviations from average trend…

(2-a) L_{disk} decreases <=> L_{NS} increases.

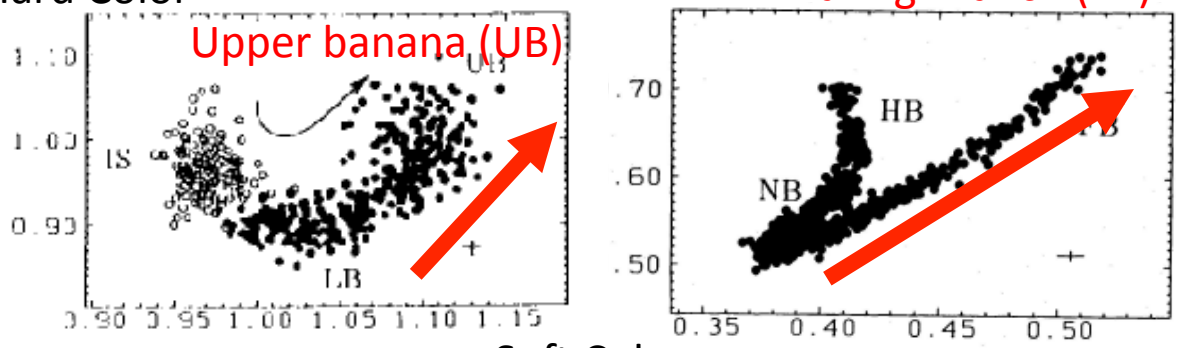
r_{in} increases & T_{in} decreases.

Spectra become harder and make UB/FB shape.

Hard Color

CCD

Flaring Branch (FB)

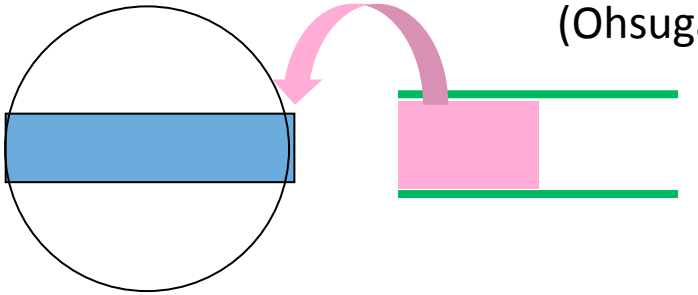


Soft Color

This emission is not emitted at disk but later at NS.

<= Photon trapping (due to high density & deep depth)?

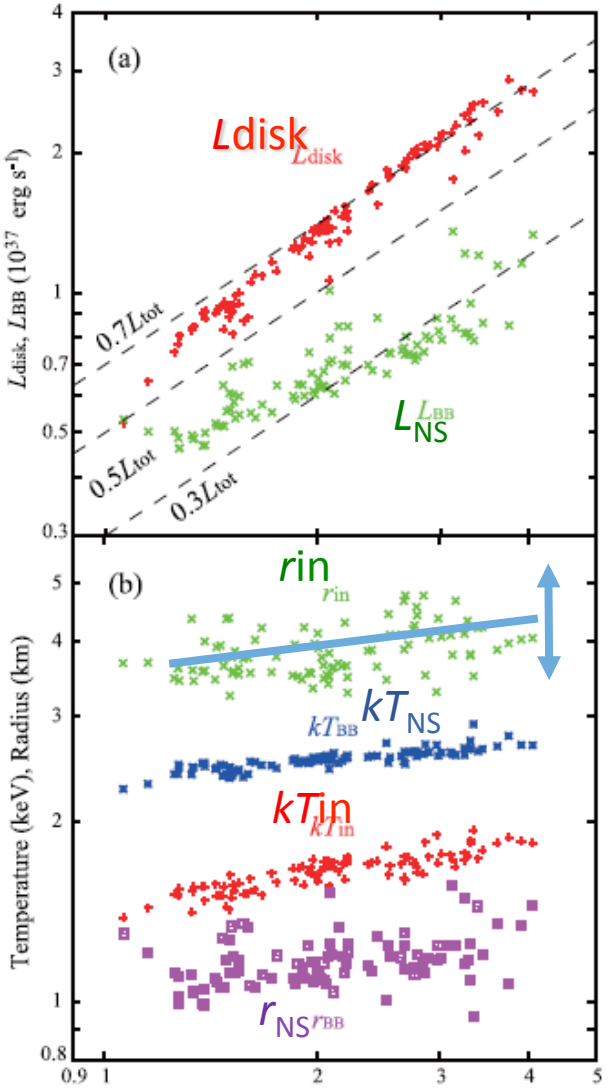
(Ohsuga et al. 2002)



(2) Disk parameters fluctuating independent from Mdot

Atoll (UB) case
(4U 1608-522)

Relationship with Ltot



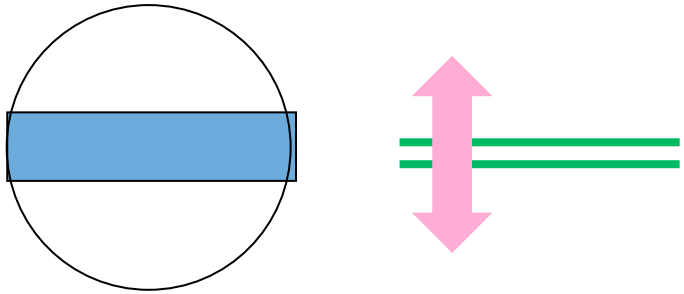
Look at deviations from average trend…

(2-b) r_{in} (and T_{in}) scatters in 2 dimensions, while L_{disk} does not scatter except for (2-a)

#r_{in} varies in both up and down, while (2-a) causes only 1 direction (r_{in} increase).

=> r_{in} & T_{in} change with keeping L_{disk} constant.

<= Hardening factor may change (due to disk geometrical thickness)?



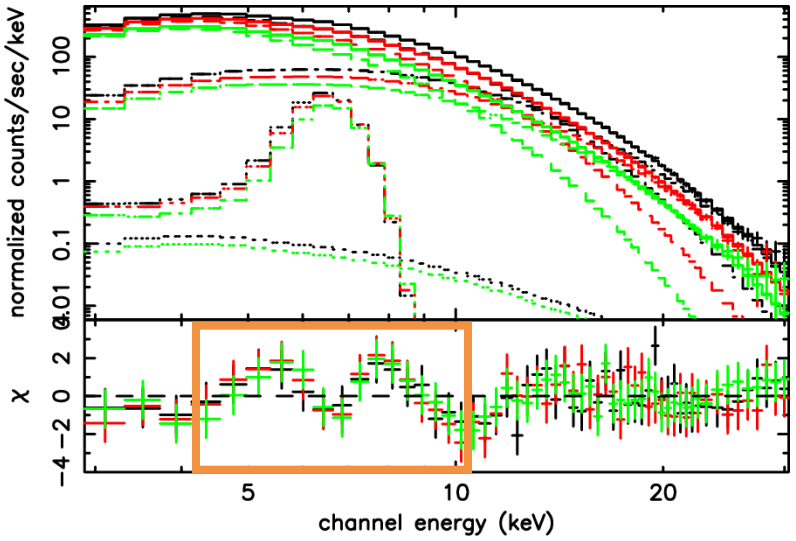
Independent from average trend (= Mdot), disk parameters change in two ways.
(2-a) L_{disk} & L_{NS} change simultaneously.
(2-b) Only r_{in} & T_{in} change

In CCDs
=> UB, FB
=> HB, NB

(3) FB requires additional third component (blackbody)

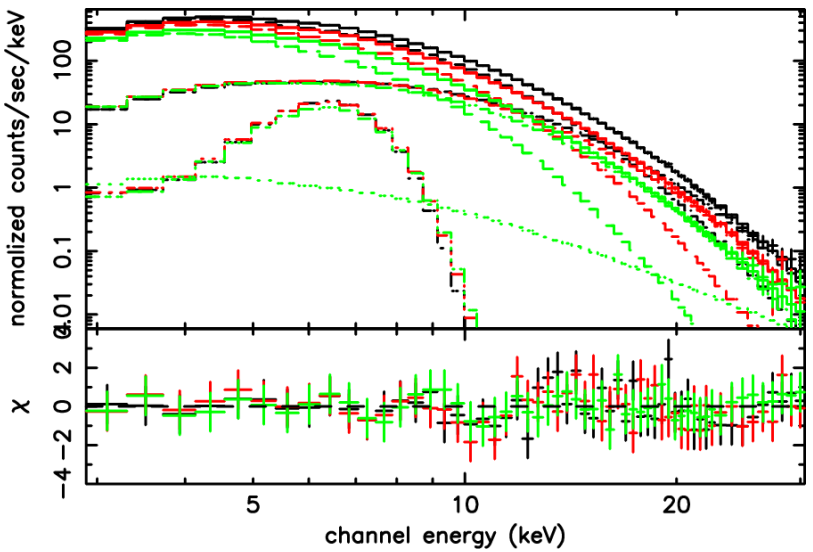
Z (Sco "ν") FB case: GX 17+2

diskbb+BB+**narrow line**



"M"-shape residual

diskbb+BB+**broad line???**



- Line width: ~1 keV
  (<0.2 keV@HB, NB)
- Equivalent Width: ~200 eV
  (5 times larger than HB, NB)

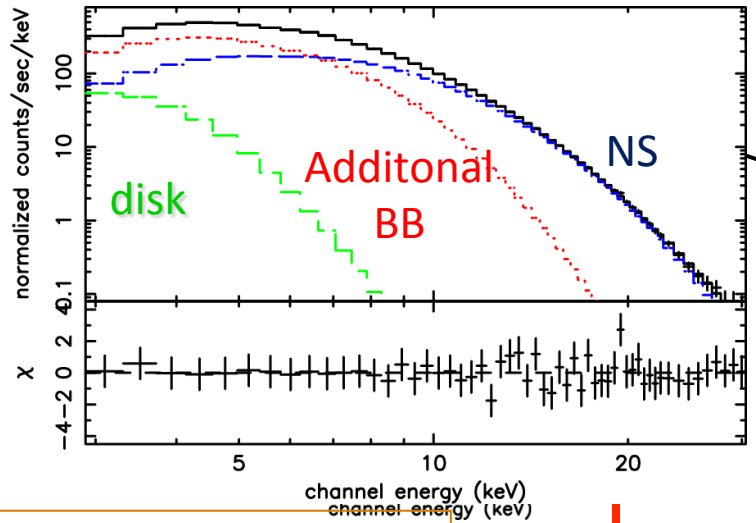
Different ideas of Compton scattering
(see Sugizaki+2014, Tutarchuk+2014)

Two components (disk+NS) needs too broad/strong line.
This broad feature is reproduced by **additional third BB emission**.

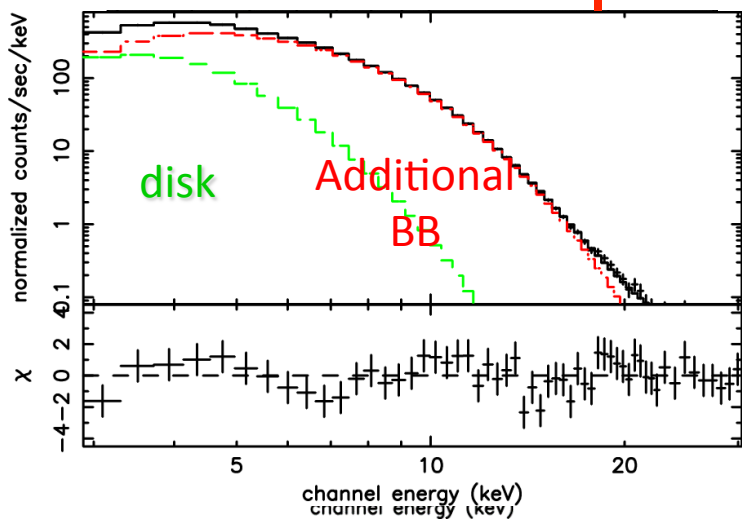
This new middle component could be optically thick region caused by photon trapping in (2-a) or outflow by L_{NS}.

(3) FB requires additional third component (blackbody)

Z (Sco-FB): GX 17+2



Z (Cyg-FB): GX 5-1



In FB, Sco & Cyg states are similar except for harder flux in Sco state.

→ Sco-FB requires additional middle BB .

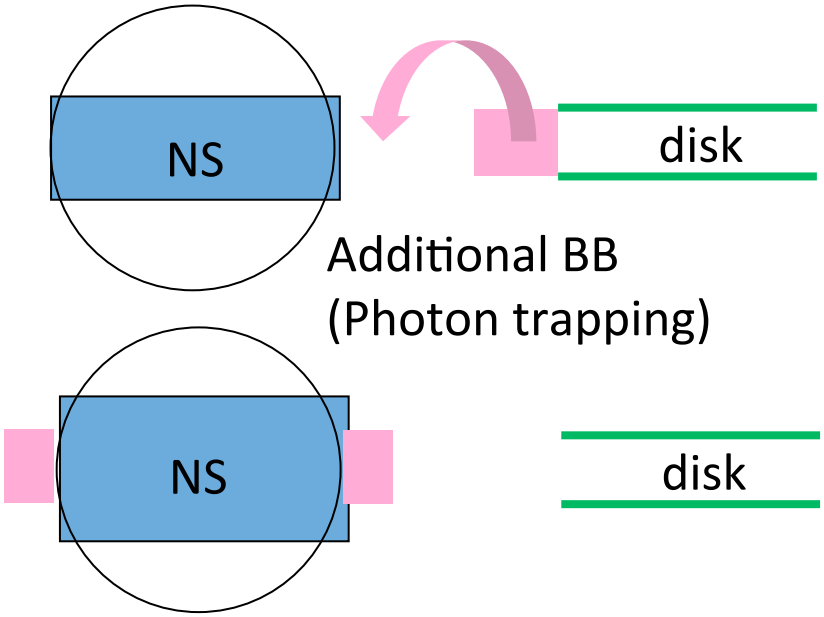
	GX 5-1
disk（Tin～sub keV、r_{in}～60 km）	Yes
BB（T_{BB}～1.3 keV、r_{BB}～20 km）	Yes
NS（T_{NS}～2.6 keV、r_{NS}～4 km）	No

Additional BB

middle r (size) & T between disk and NS.

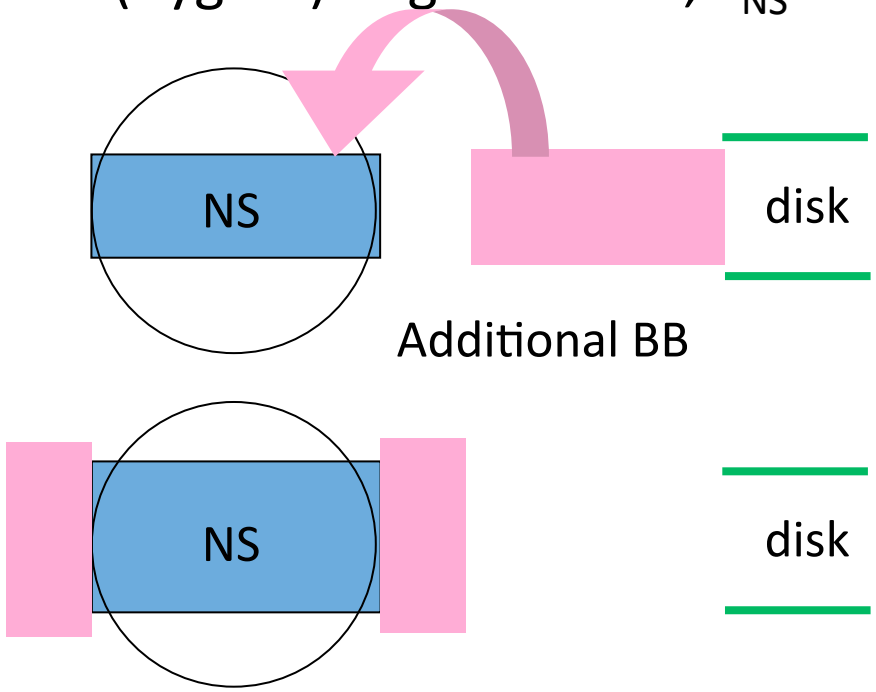
(3) FB requires additional third component (blackbody)

Z (Sco-FB): lower Mdot, $L_{NS} > L_{BB}$



Moderate amount of photon trapping
=> does not cover all NS emission.
=> Hard flux from NS is detected.

Z (Cyg-FB): higher Mdot, $L_{NS} < L_{BB}$



Huge amount of photon-trapping region
=> NS emission could be obscured
(even if emission exists).
=> Hard flux from NS disappears.

This new middle BB component could be optically-thick region caused by photon trapping in (2-a).

Summary

To reveal physical pictures of high/soft state of NS-LMXB in atoll, Z (Sco) and Z (Cyg), we analyzed RXTE/Suzaku data and obtained 3 observational results.

(1) Spectra are basically well reproduced by **diskbb+bb** from accretion disk and NS.
From L_{NS}/L_{disk} ratio, **the existence of outflow is detected** due to radiation pressure.

(2) Disk parameters fluctuate **independent from Mdot** in two ways.
(a) Inner part of disk could accrete before emitting (i.e., photon trapping)
(b) Hardening factor may change and result in fluctuation of only r_{in} & T_{in}.
And, (2-a) causes UB, FB behaviors of L_{disk}/L_{NS} decrease/increase.
(2-b) does HB, NB with outflow occurring from disk surface or before NS.

(3) Z-source FB requires **additional third component (if line, it is too broad/strong)** in the middle energy band between NS and disk.
This could be optically thick region caused by photon trapping in (2-a).
And, (3) could explain hard-flux increase/decrease in Z (Sco-FB) / Z (Cyg-FB) according to whether L_{BB} dominates L_{NS} or not.