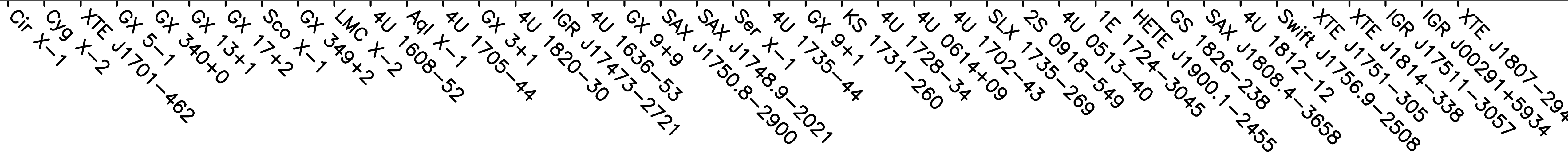
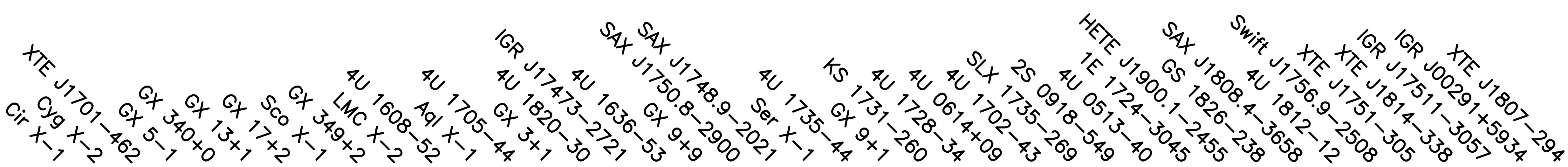


A ranking scheme for neutron-star low-mass X-ray binaries

Jeroen Homan, Joel Fridriksson, & Ron Remillard

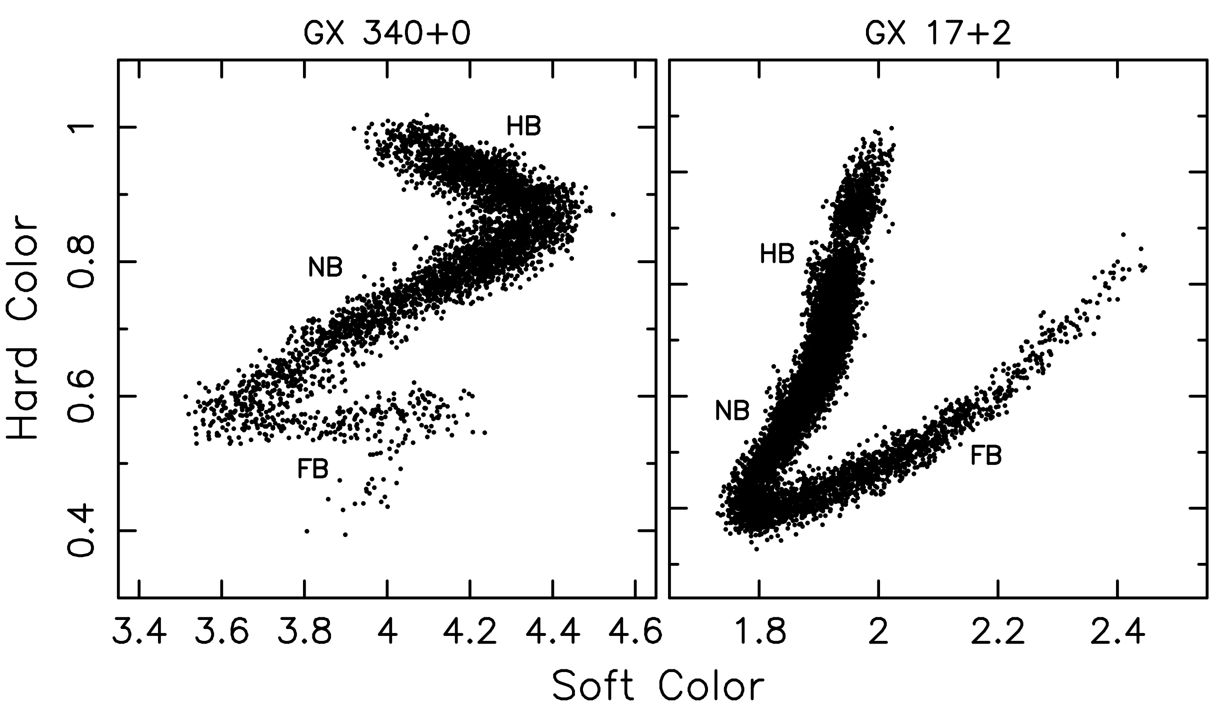


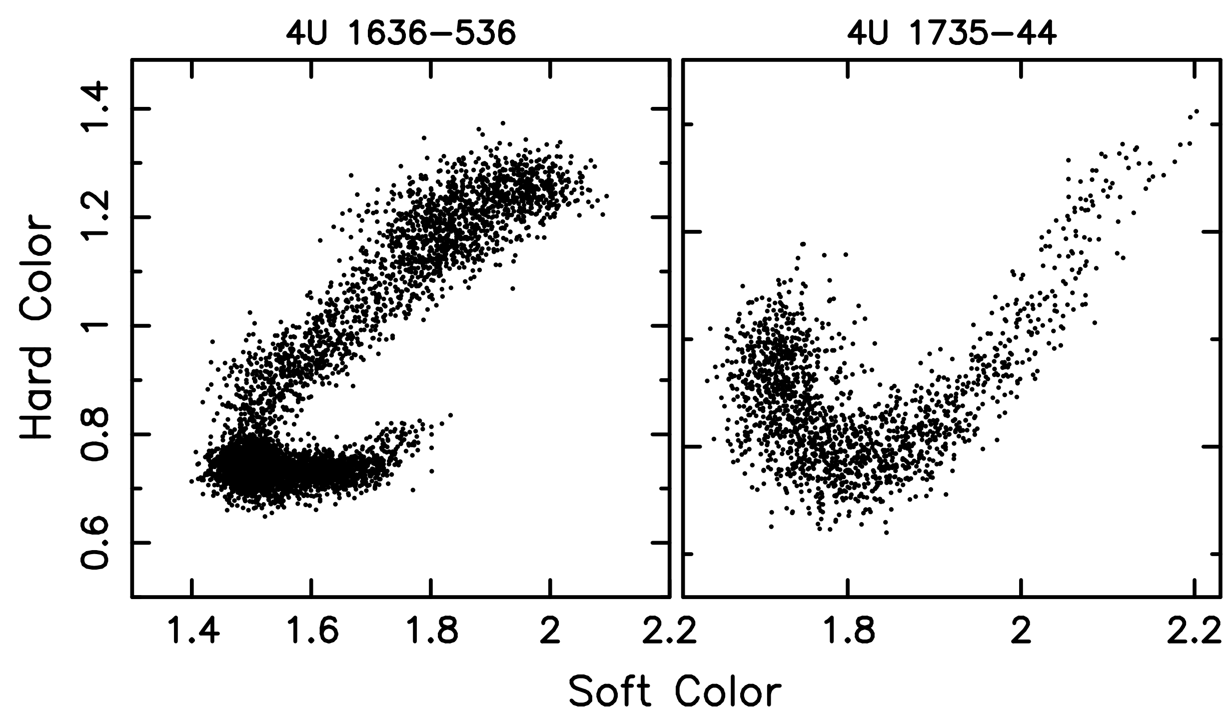
As most of you know, neutron star low-mass X-ray binaries as class show a wide range of X-ray properties. A lot of studies of neutron star X-ray binaries focus on how these properties change in individual sources. While much can be learned from this, it is also important that we take a more global approach. In particular, how do the X-ray properties evolve when we compare a large sample of sources with different mass accretion rates? What will this teach us about accretion onto neutron stars? To make such a comparison we need to create a framework that allows us to rank a large number sources in terms of mass accretion rate, and this is what I will talk about today.

This majority of this work was done by Joel Fridriksson with contributions from myself and Ron Remillard.

Cir X-1, Cyg X-2, XTE J1701-462, GX 5-1, GX 340+0, GX 13+1, GX 17+2, Sco X-1, GX 349+2, LMC X-2, 4U 1608-52, Aql X-1, 4U 1705-44, GX 3+1, 4U 1820-30, IGR J17473-2721, 4U 1636-53, GX 9+9, SAX J1750.8-2900, SAX J1748.9-2021, Ser X-1, 4U 1735-44, GX 9+1, KS 1731-260, 4U 1728-34, 4U 0614+09, 4U 1702-43, SLX 1735-269, 2S 0918-549, 4U 0513-40, 1E 1724-3045, HETE J1900.1-2455, GS 1826-238, SAX J1808.4-3658, 4U 1812-12, Swift J1756.9-2508, XTE J1751-305, XTE J1814-338, IGR J17511-3057, IGR J00291+5934, XTE J1807-294

A ranking scheme for neutron-star low-mass X-ray binaries





Cir X-1, Cyg X-2, XTE J1701-462, GX 5-1, GX 340+0, GX 13+1, GX 17+2, Sco X-1, GX 349+2, LMC X-2, 4U 1608-52, Aql X-1, 4U 1705-44, GX 3+1, 4U 1820-30, IGR J17473-2721, 4U 1636-53, GX 9+9, SAX J1750.8-2900, SAX J1748.9-2021, Ser X-1, 4U 1735-44, GX 9+1, KS 1731-260, 4U 1728-34, 4U 0614+09, 4U 1702-43, SLX 1735-269, 2S 0918-549, 4U 0513-40, 1E 1724-3045, HETE J1900.1-2455, GS 1826-238, SAX J1808.4-3658, 4U 1812-12, Swift J1756.9-2508, XTE J1751-305, XTE J1814-338, IGR J17511-3057, IGR J00291+5934, XTE J1807-294

The work made use of a large amount of RXTE data and the ranking itself relies on very simply tools, namely X-ray color-color and hardness-intensity diagrams.

NS LMXBs: sub-classes

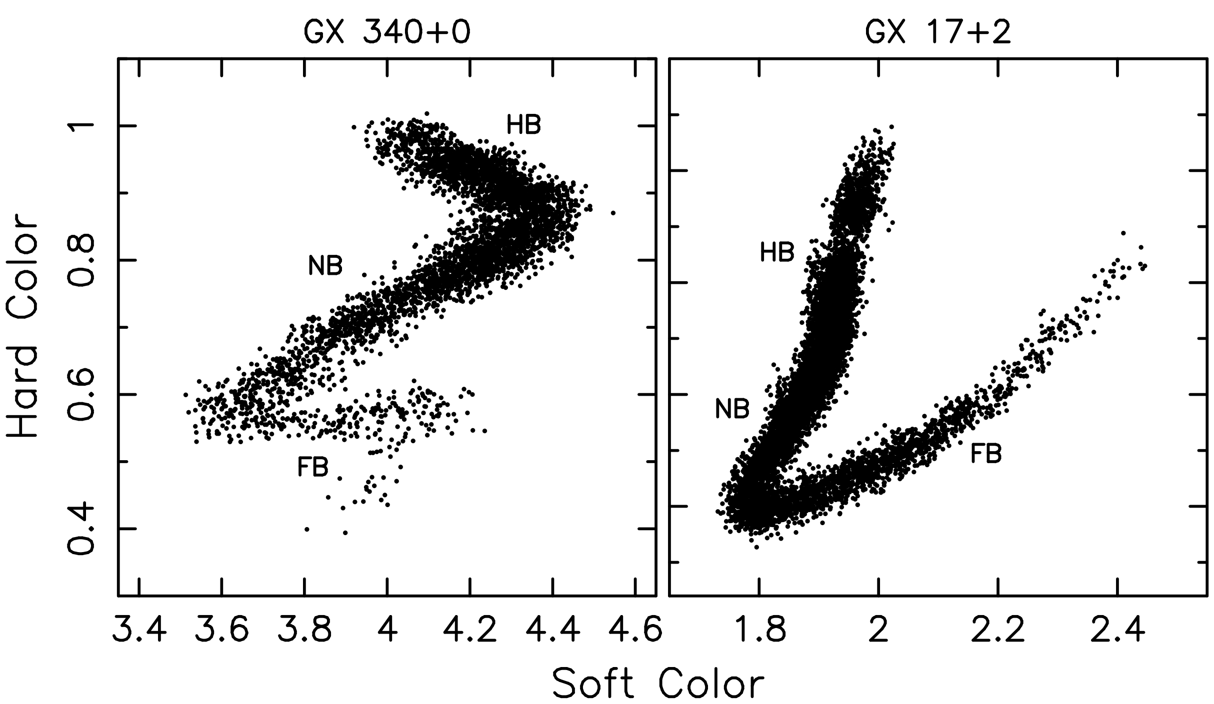
Astron. Astrophys. 225, 79–96 (1989)

ASTRONOMY AND ASTROPHYSICS

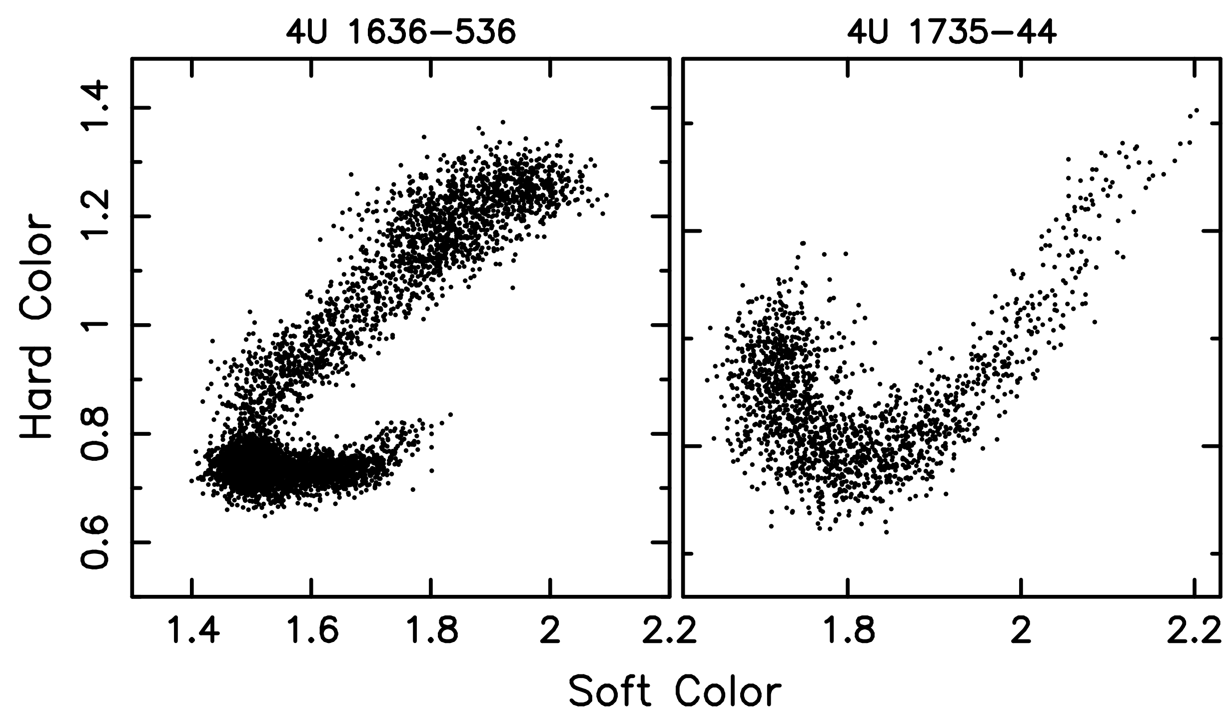
Two patterns of correlated X-ray timing and spectral behaviour in low-mass X-ray binaries

G. Hasinger[1] and M. van der Klis[2,3]

Z sources



Atoll sources

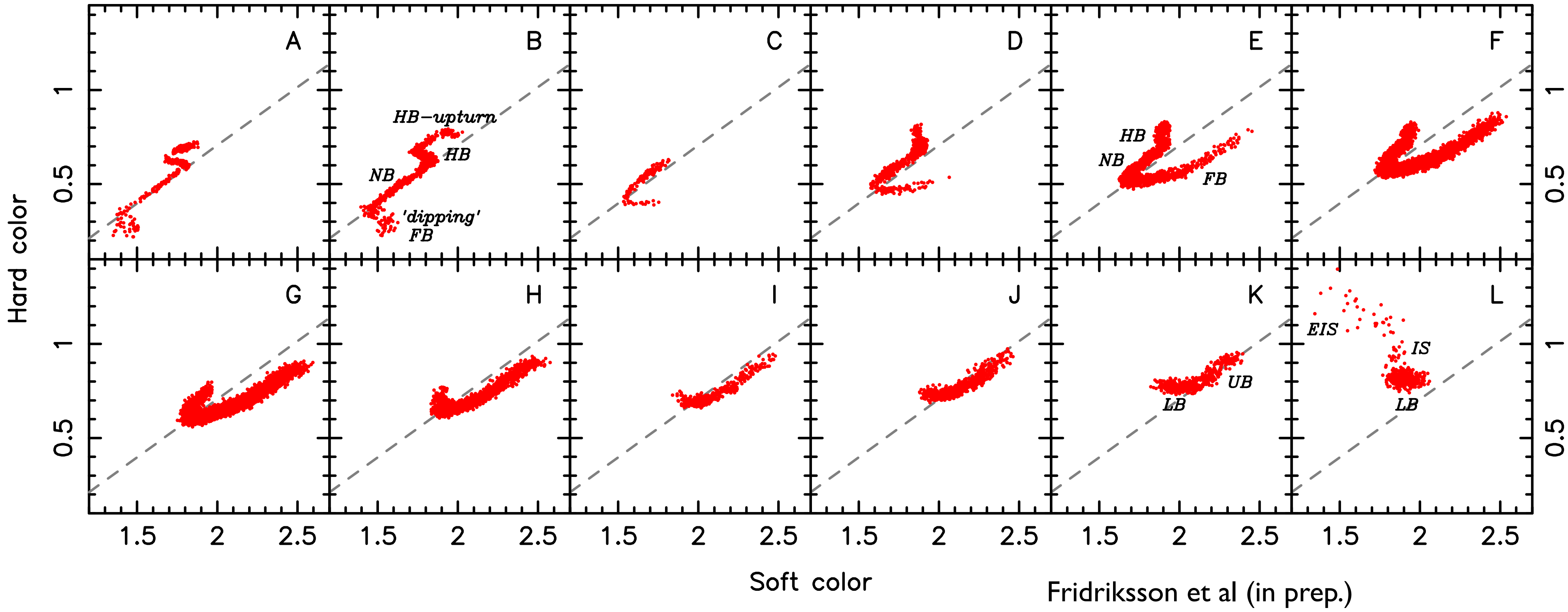


Let me first give a little background on previous efforts to rank neutron-star X-ray binaries. In 1989 Hasinger and van der Klis published a paper in which they defined different sub-classes of neutron star X-ray binaries, based on EXOSAT data. These sub-classes were defined based on the variability properties of the sources as well as on the shape of the tracks they traced out in color-color and hardness-intensity diagrams. Two main sub-classes were defined: the Z sources and the atoll sources. Here I show a few examples of color-color diagrams. As you can see, even within the two sub-classes there can be quite a variety in shapes.

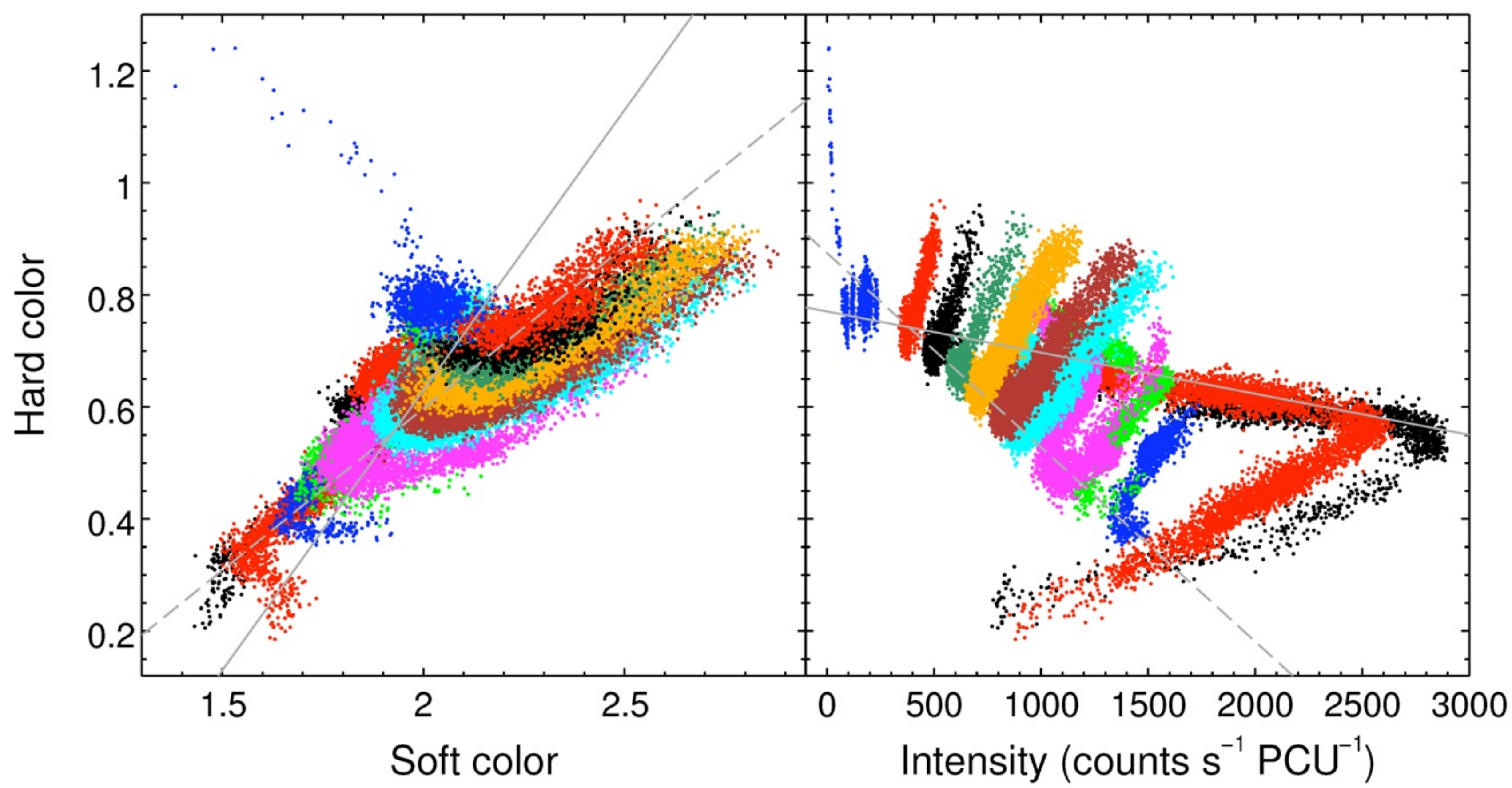
Based on the difference between the X-ray fluxes of the Z and atoll sources, it was pretty clear that mass accretion rate must be substantially higher in the Z sources. However, it was never clear what caused the differences within each subclass and if changes in mass accretion alone were able to explain the differences between Z and atoll sources.

Neutron star transient XTE J1701-462

Homan et al (2010)



Fridriksson et al (in prep.)

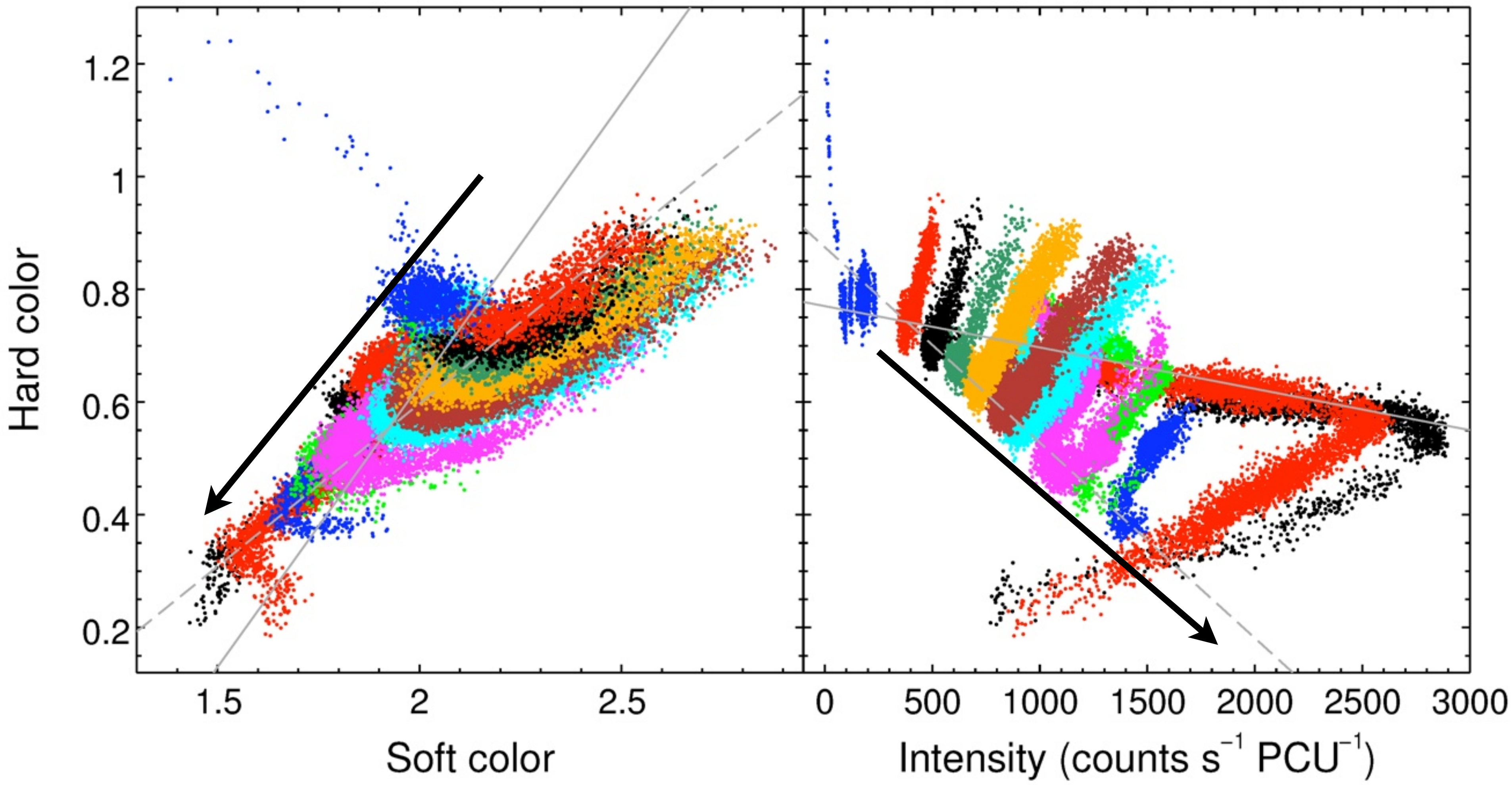


This became much clearer with the discovery of the neutron star transient XTE J1701-462 with RXTE in 2006.

During its outburst 1701 became the first source to be observed moving through all the neutron star LMXB subclasses. This can be seen in the color-color diagram here which shows different phases of the outburst. At the peak of its outburst 1701 showed behavior similar to that of the so-called Cyg-like Z sources - at lower luminosities it became a Sco-like Z source, and finally it became an atoll source, before returning to quiescence.

So for the first time, we saw how the various types of neutron-star LMXB behavior evolved into each other. In this Figure I show all the tracks in one plot: color-color on the left and hardness-intensity on the right. As you can see from the HID, the evolution of the tracks was accompanied by a substantial change in overall count rate

XTE J1701-462

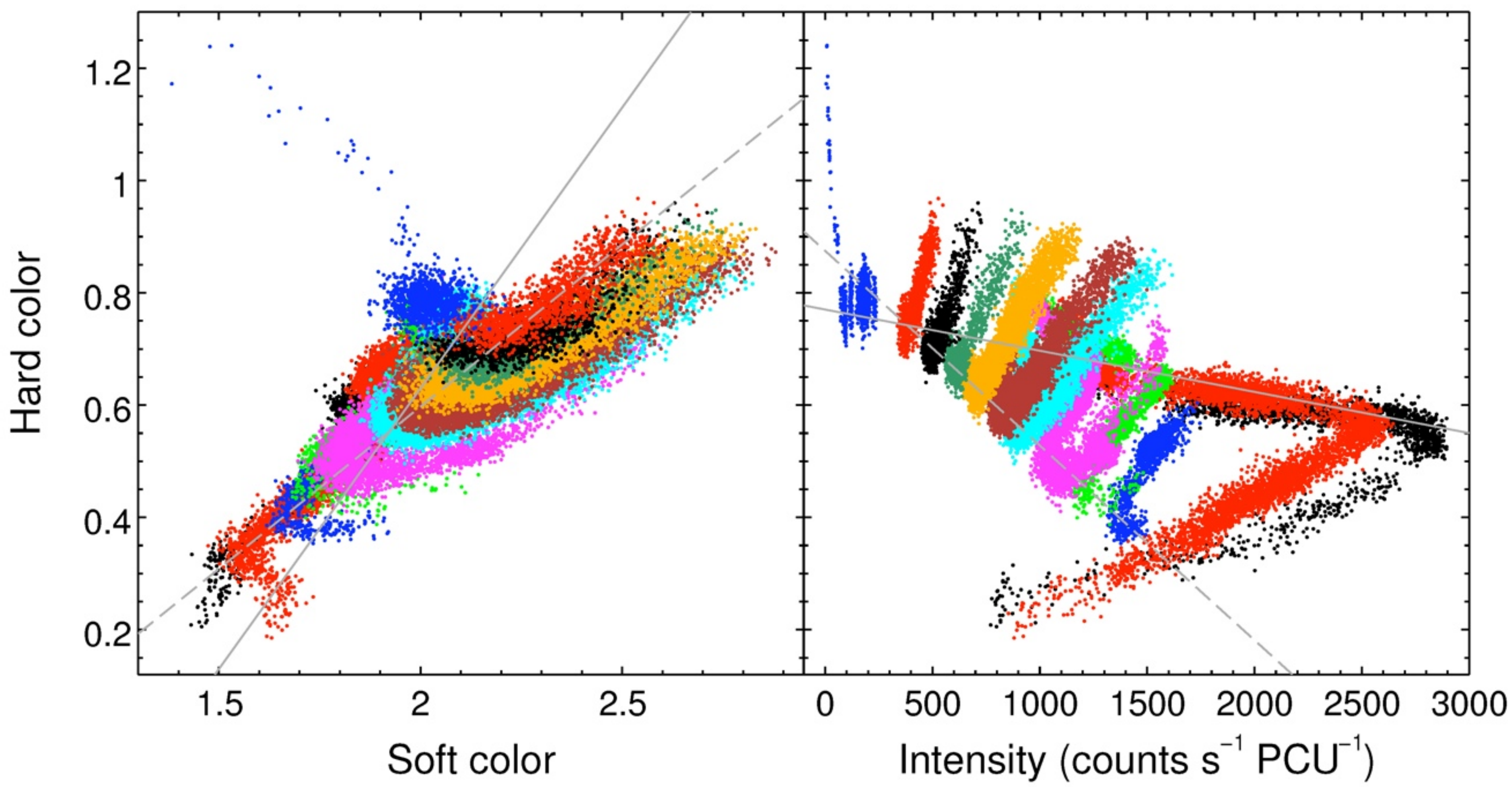


- Evolution from Eddington luminosities to quiescence
- $\dot{M}$-ranked sequence of CD/HID tracks (Lin et al. 2009)
- Can 1701 be used to get a relative $\dot{M}$ ranking for other NS LMXBs (without distance estimates and spectral modeling)?

So, with 1701 we were able for the first time to follow the evolution of a neutron star LMXB from near- or super-Eddington luminosities down to quiescence. Spectral fits strongly suggest that these subclasses can be linked by a single parameter, namely mass accretion rate, with the accretion rate increasing in the direction of these arrows.

The natural questions that then arises is: can we use this sequence of tracks to rank other NS LMXBs in terms of relative mass accretion rate or relative X-ray luminosities, simply by comparing the shapes of their CD/HID tracks to those seen in 1701? This would no require any knowledge of the distance nor would it depend one spectral modeling of any kind.

XTE J1701-462



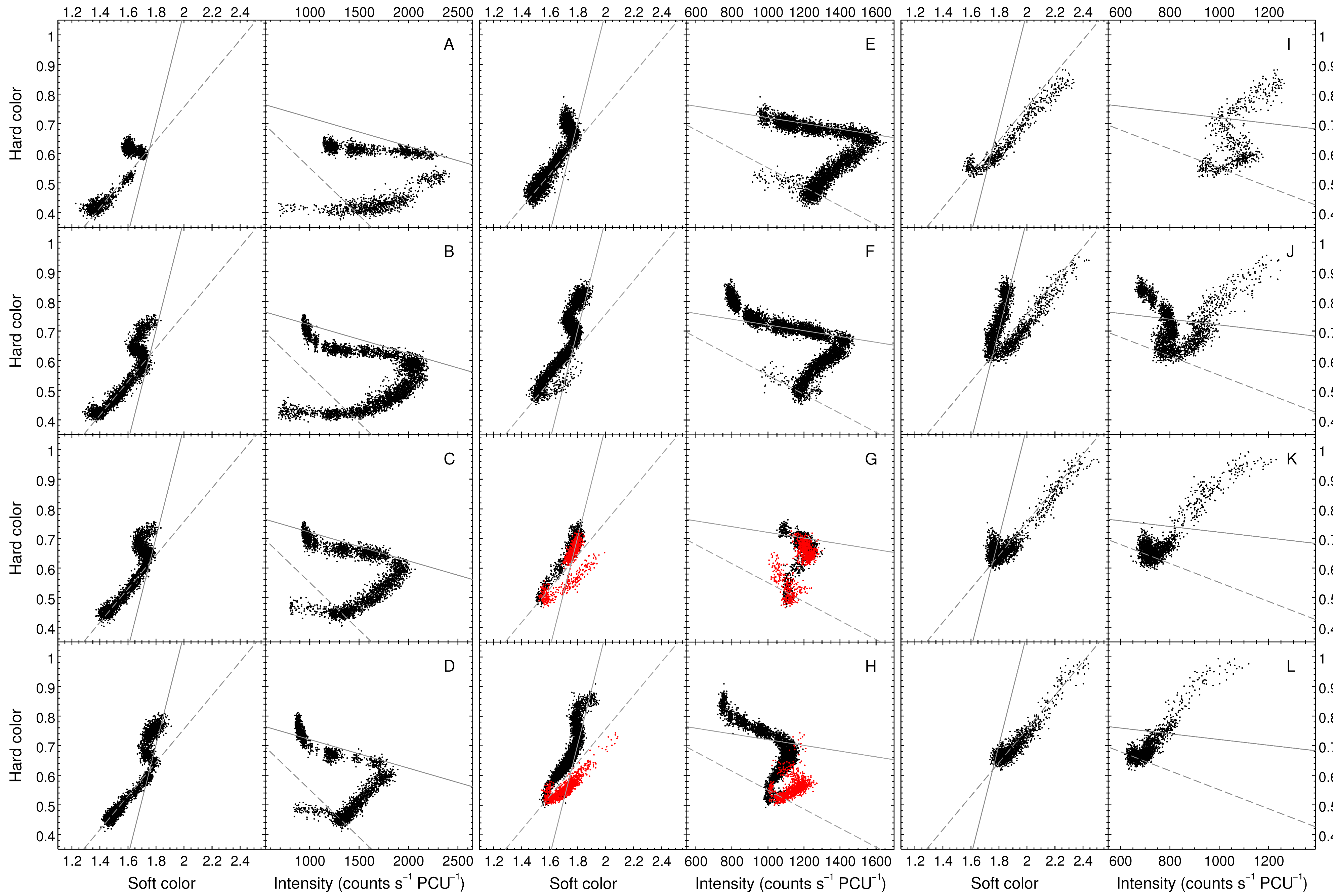
- Check: is similar behavior seen in other sources?
- At low luminosities: yes - comparison with atoll transients
- At high luminosities: unsure
  - Investigate sources with strong secular changes:
  - Cygnus X-2, Cir X-1, and GX 13+1

Before doing so, however, we need to check if we can observe similar evolution in other sources – to see if 1701 is representative of the class as whole. Seeing a sequence of tracks in only one source would be somewhat of a shaky foundation.

At low luminosities the answer is: probably yes. The atoll phase of 1701 was not very well covered, but comparison with many atoll transients suggest that 1701 was very similar.

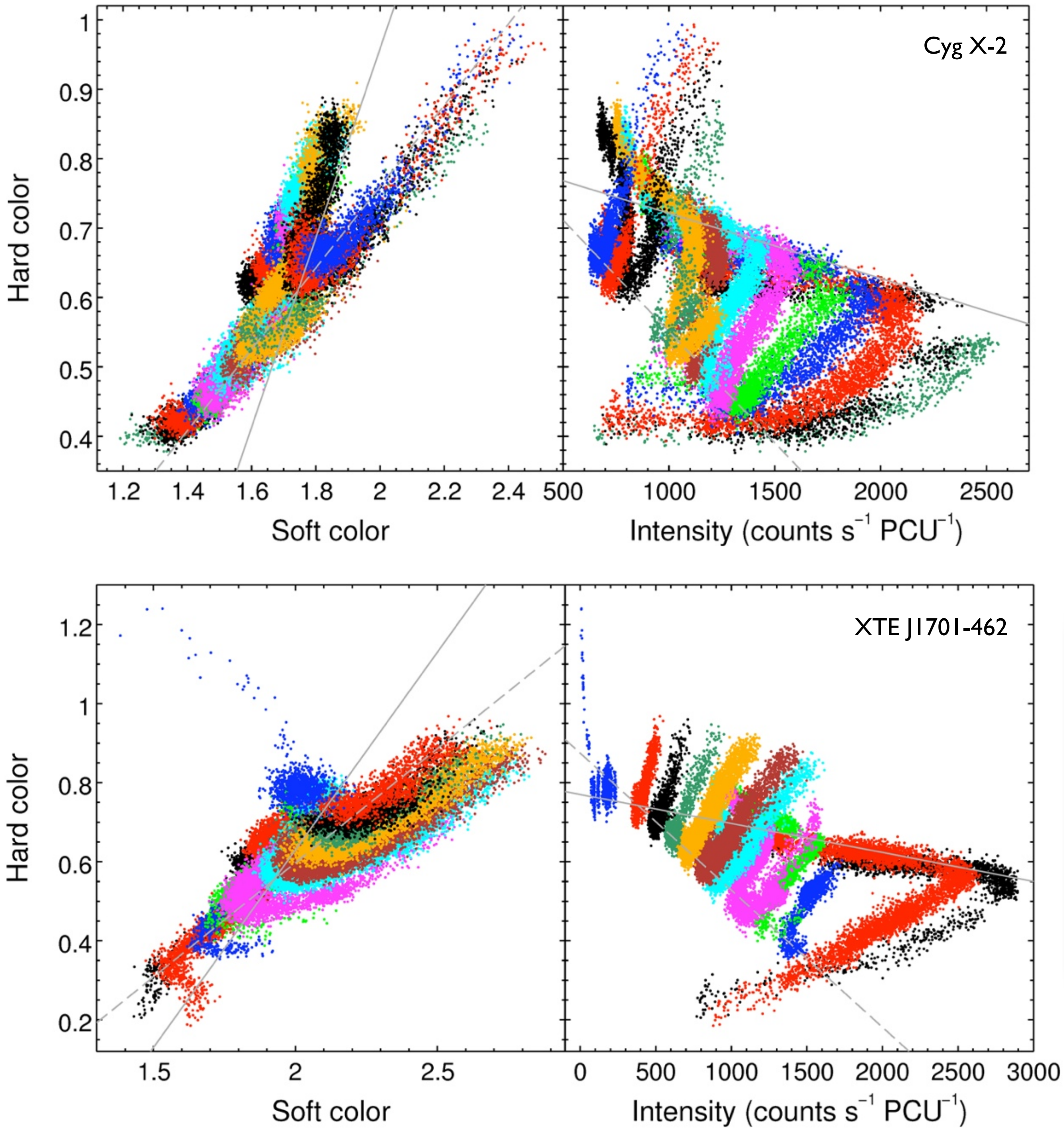
For the high luminosity part things are not so clear. To investigate this in detail we selected three sources which have historically been know to show strong secular changes in the shape and position of their tracks in the CD and HID: Cyg X-2, Cir X-1 and GX 13+1.

Cygnus X-2



Joel was able to a extract a nice set of tracks from Cyg X-2, which are shown here. Again, like in 1701, we see Cyg-like Z tracks at high count rates, and Sco-like Z tracks at lower count rates. Cyg X-2 didn't make it into atoll territory. The way the branches evolve, especially in the CD, and the order in which the various Z sources branches disappear is very similar to that seen in 1701.

Cygnus X-2



Cyg X-2
Cyg-like Z ↔ Sco-like Z

Cir X-1:
Cyg-like Z ↔Sco-like Z ↔ atoll

GX 13+1:
Cyg-like Z ↔ Sco-like Z

Here is the colored version, combining all tracks. The overall evolution when comparing to 1701 here below is very similar, except of course for the missing atoll stage in Cyg X–2. Also note how, like for 1701, the HID start to show increasingly strong intensity swings at higher count rates.

Cir X–1 and GX 13+1 showed behavior that was consistent with 1701. Cir X–1 changes between Cyg–like Z and atoll behavior, and GX 13+1 changes between Cyg–like Z and Sco–like Z tracks.

Next step: ranking neutron star LMXBs

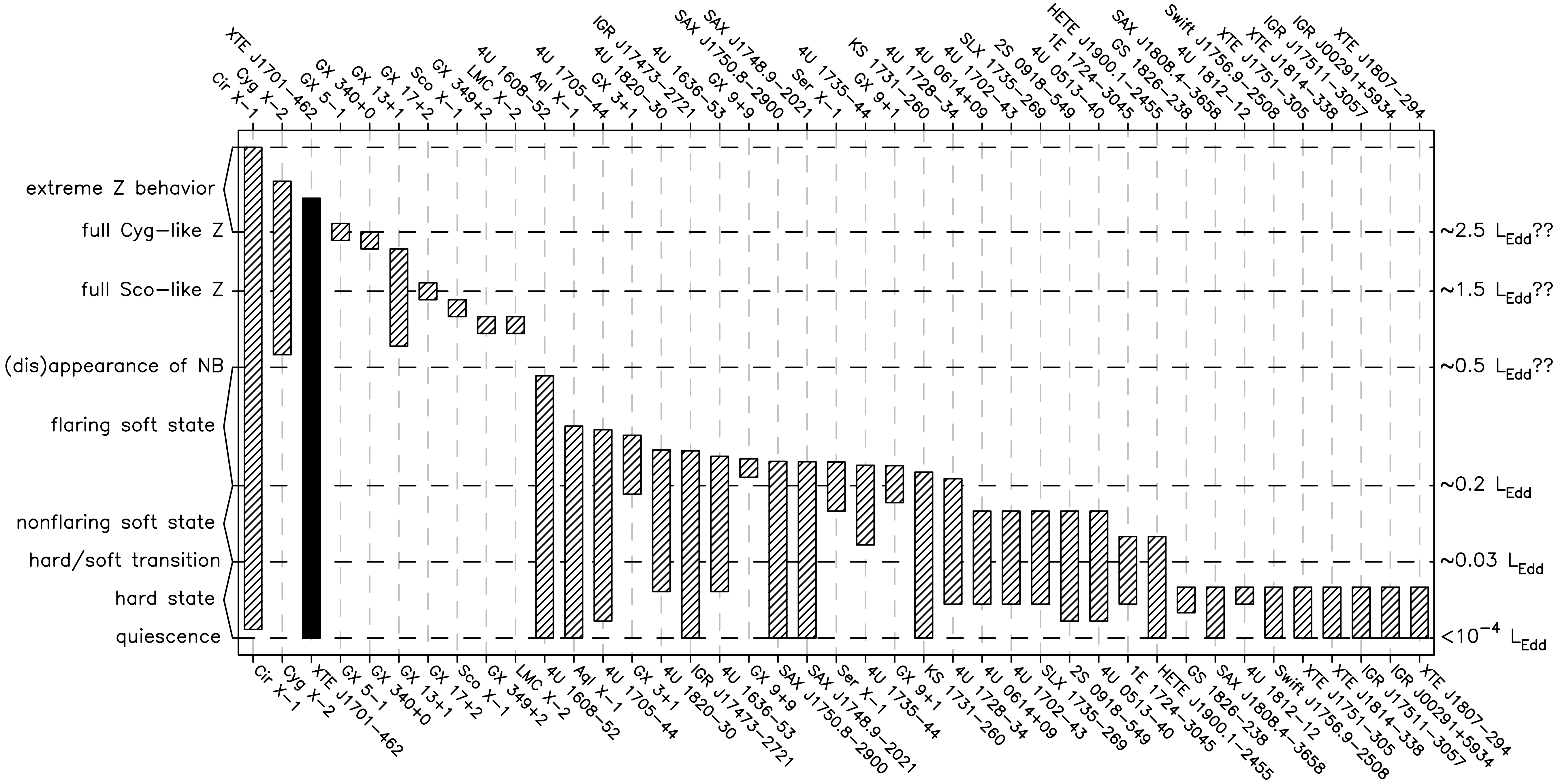
- Behavior of XTE J1701-462 might be representative of NS-LMXBs
- Rank 40+ NS-LMXBs based on CD/HID morphology (150+ ks with RXTE, no dipping/eclipsing sources)
- Ranking criteria: presence & orientation of Z/atoll states/ branches
- Assumption: mass accretion rate determines CD/HID morphology

So, we see very similar behavior at high luminosities in three other sources, suggesting that 1701 is representative of the class of neutron-star LMXBs as a whole. That means we can go on to the next phase, which is creating a relative ranking of other LXMBs.

We selected sources based on two criteria. First, sources had to be observed more than 150 ks with RXTE, and, second, the sources should not show dips or eclipses. This left us with a total of ~40 sources.

The ranking is morphology based. That is, we use the presence, orientation, and shape of the various Z and atoll branches in the CD and HID and see where they fall in the sequence observed in 1701. And of course, this ranking scheme assumes that luminosity or mass accretion rate determines the morphology of the CD/HID tracks as it did in 1701.

the ranking



Okay, so let me show you how we ranked the sources. Let me first briefly mention some of the criteria, for those of you who are familiar with the terminology. The states and branches are shown on the left, ordered on the luminosity in which they were seen in 1701. We start with quiescence on the bottom, followed by the atoll hard state, the appearance of the first Z source branched all the way up the Cyg-like Z behavior.

Using these criteria, we constructed the following bar plot. For each source we plot the range of states in which the have been observed. Transient sources go all the way to the bottom, representing quiescence. Cir X-1 is the highest ranked source in our sample. On the left are the Cyg-like sources, including the peak of 1701, the Sco-like Z sources, followed by the brightest atoll transients and some bright persistent atoll. At the right end we have a lot of millisecond X-ray pulsars, most of which never leave the atoll hard state.

What we would like, of course, is to have an absolute luminosity scale accompanying this. This is obviously very difficult, especially at the high end.

Testing and using the ranking scheme

- Test the ranking scheme - is the $\dot{M}$ scale the same for all sources?
  - get better distance estimates (VLBA) → luminosities
- Add more sources (<150 ks, dipping/eclipsing NS LMXBs)
- Study variability/spectral/bursting properties across entire range of mass accretion rate

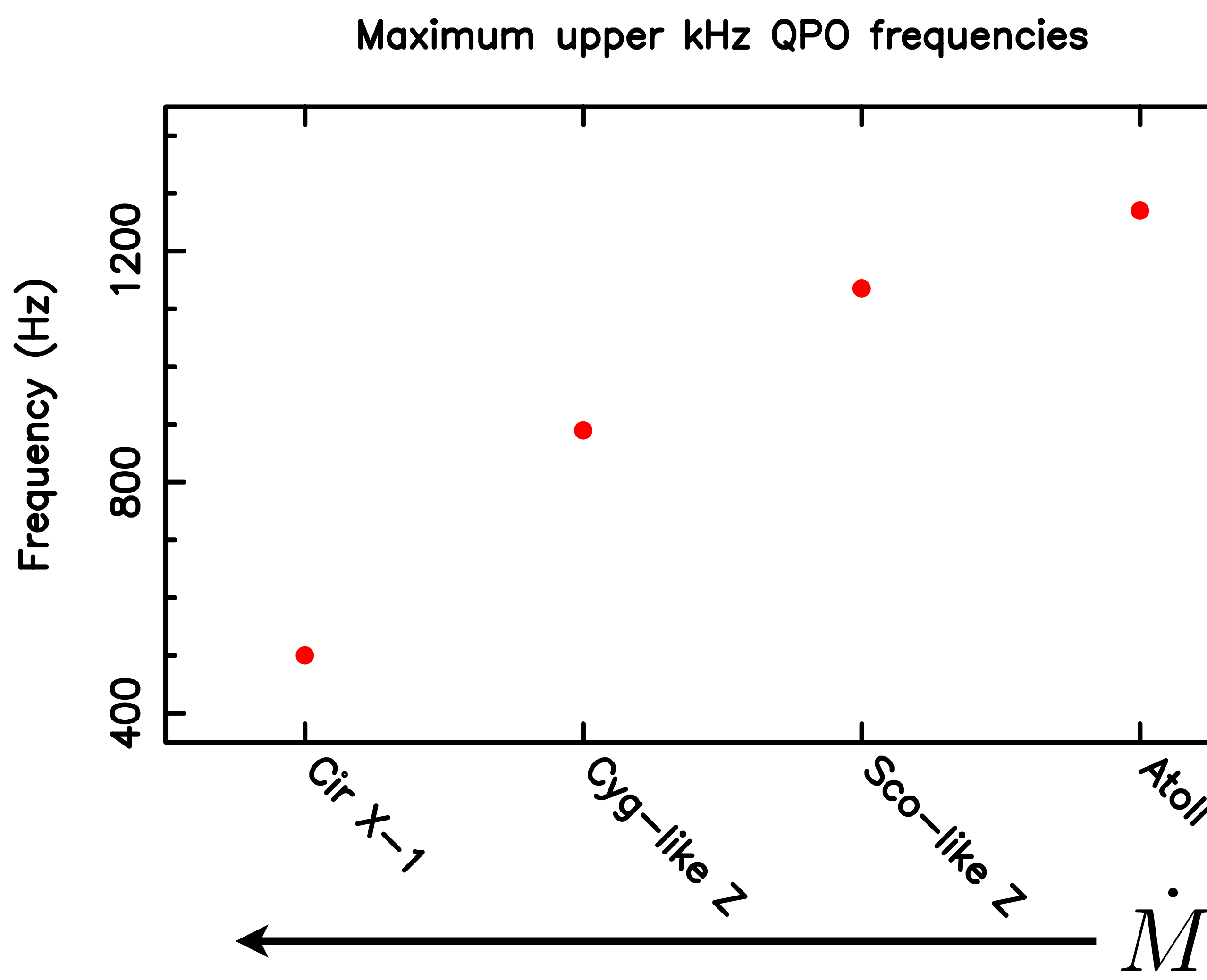
So, what's next? There basically two things we're working on right now.

First we want to test and refine our ranking scheme. For this we need to get better distance estimates, especially at the high luminosity end, to get luminosities and see if our ranking holds once we put in luminosities. We have already applied for VLBA time to get Z source parallaxes.

We also intend to increase the number of sources, by including dippers and sources with lower exposure times, to see if there might be sources that could invalidate the ranking.

At the same time we are also trying to use the ranking the see how properties such as spectra, variability and bursts vary globally as a function of mass accretion rate.

One example: variability



- Systematic shift in kHz QPO frequency ranges

Radiative stresses may play an important role

One thing were have recently started with is variability. Here is an example of some fast variability properties, namely the kHz QPOs.

In this plot I show the maximum observed upper kHz QPO frequencies as a function of sub-class, with mass accretion rate increasing in this direction. What we see is a systematic decrease in frequencies as the inferred mass accretion rate increases, suggesting that radiation from the neutron star is pushing back against the disk, leading to lower frequencies.

Now, this is just one example of what can be done. It's a first step – we think our ranking scheme provides new opportunities for understanding the role of mass accretion rate in the observed X-ray properties of neutron star X-ray binaries.