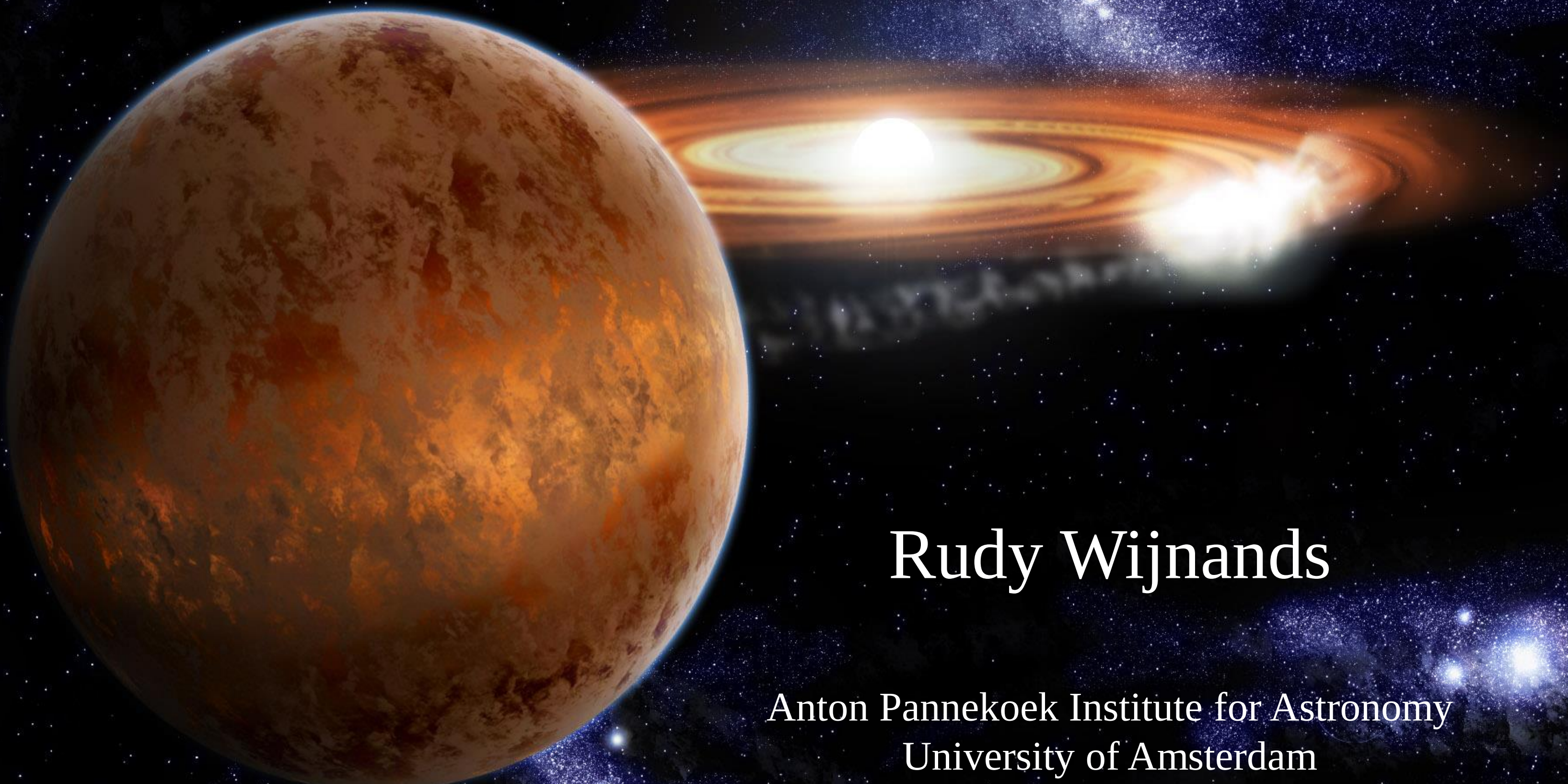
Sub-Eddington accreting neutron stars



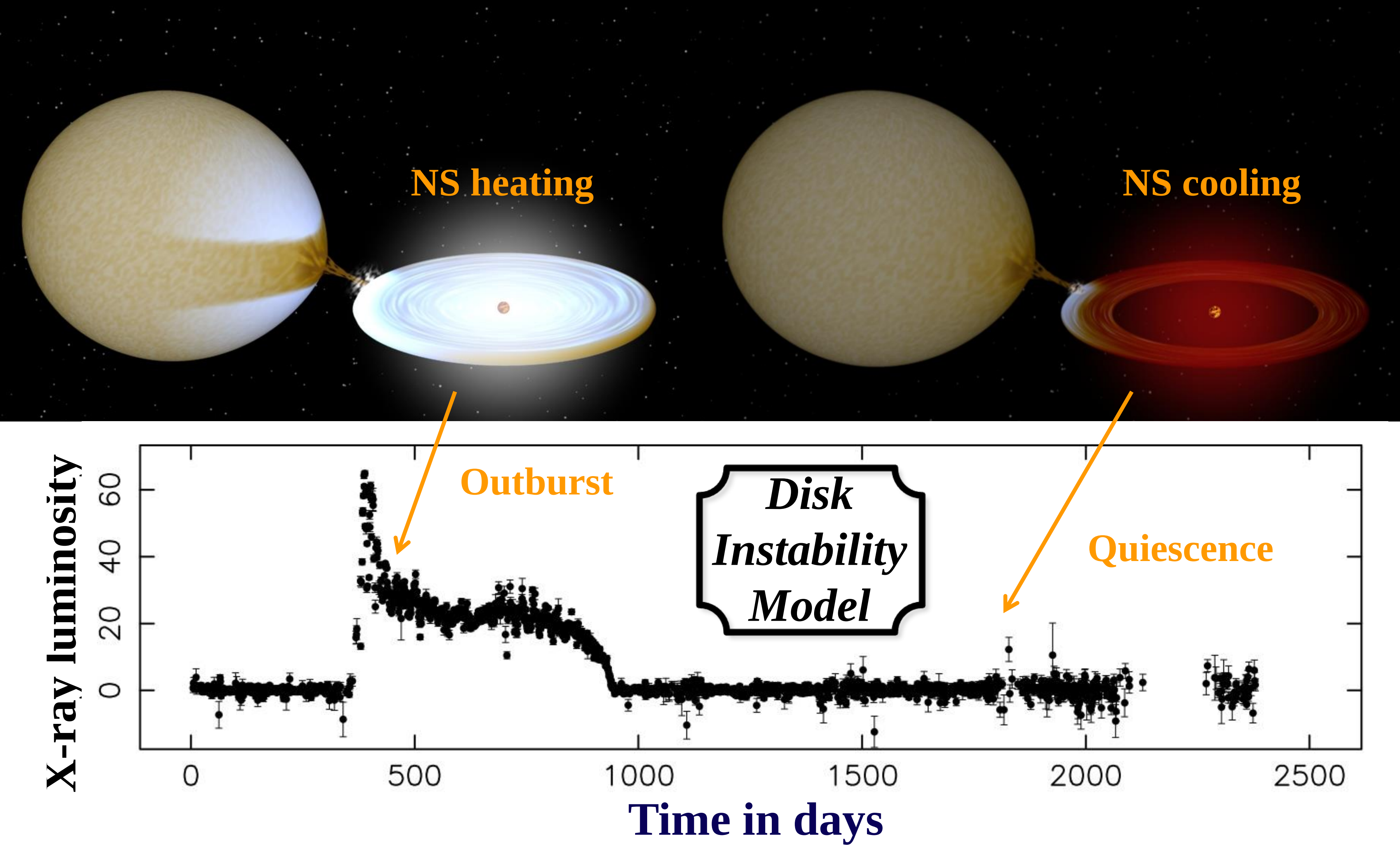
Rudy Wijnands

Anton Pannekoek Institute for Astronomy
University of Amsterdam

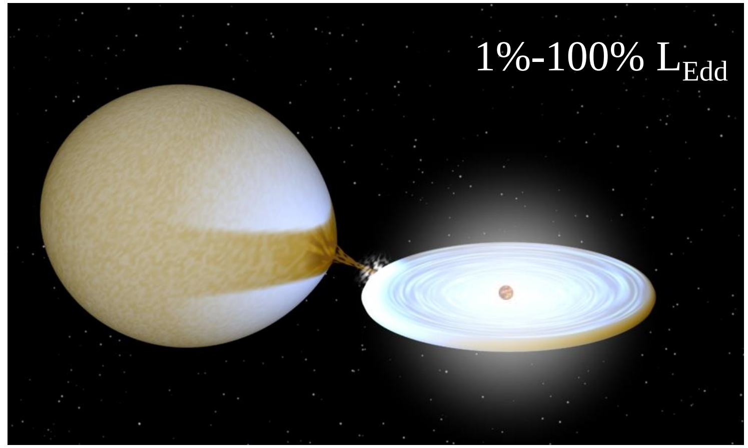
15 December 2015

Texas Symposium 2015, Geneva

Low-mass X-ray binary transients



Outburst

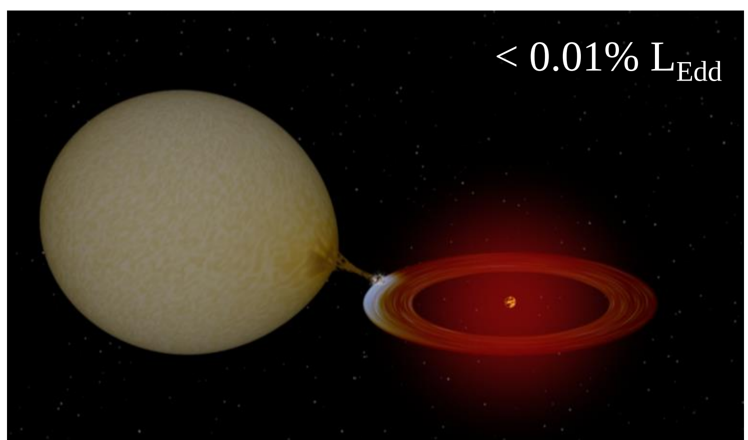


Bright but short

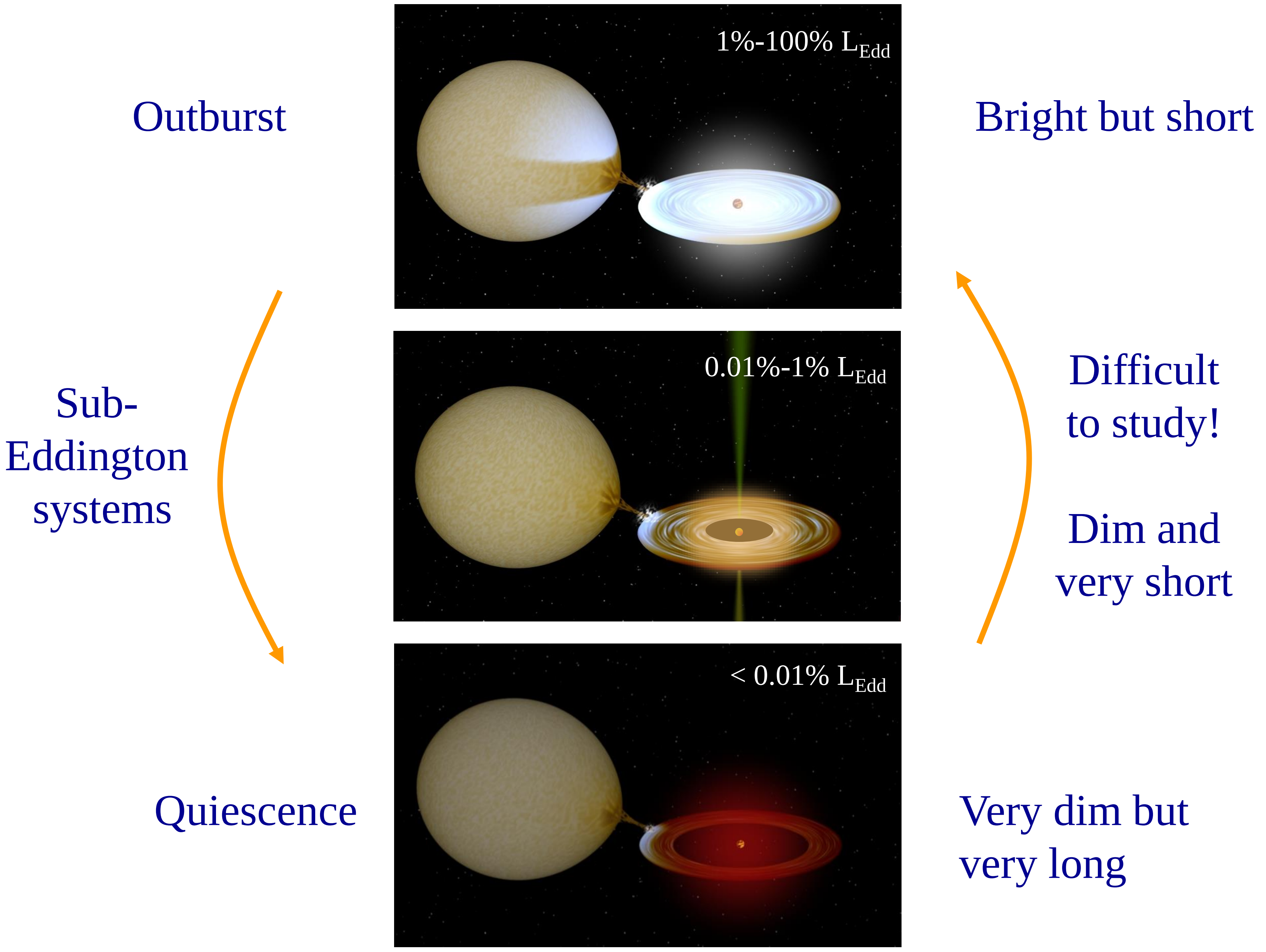
Both states quite
well studied!

How about the
intermediate regime?

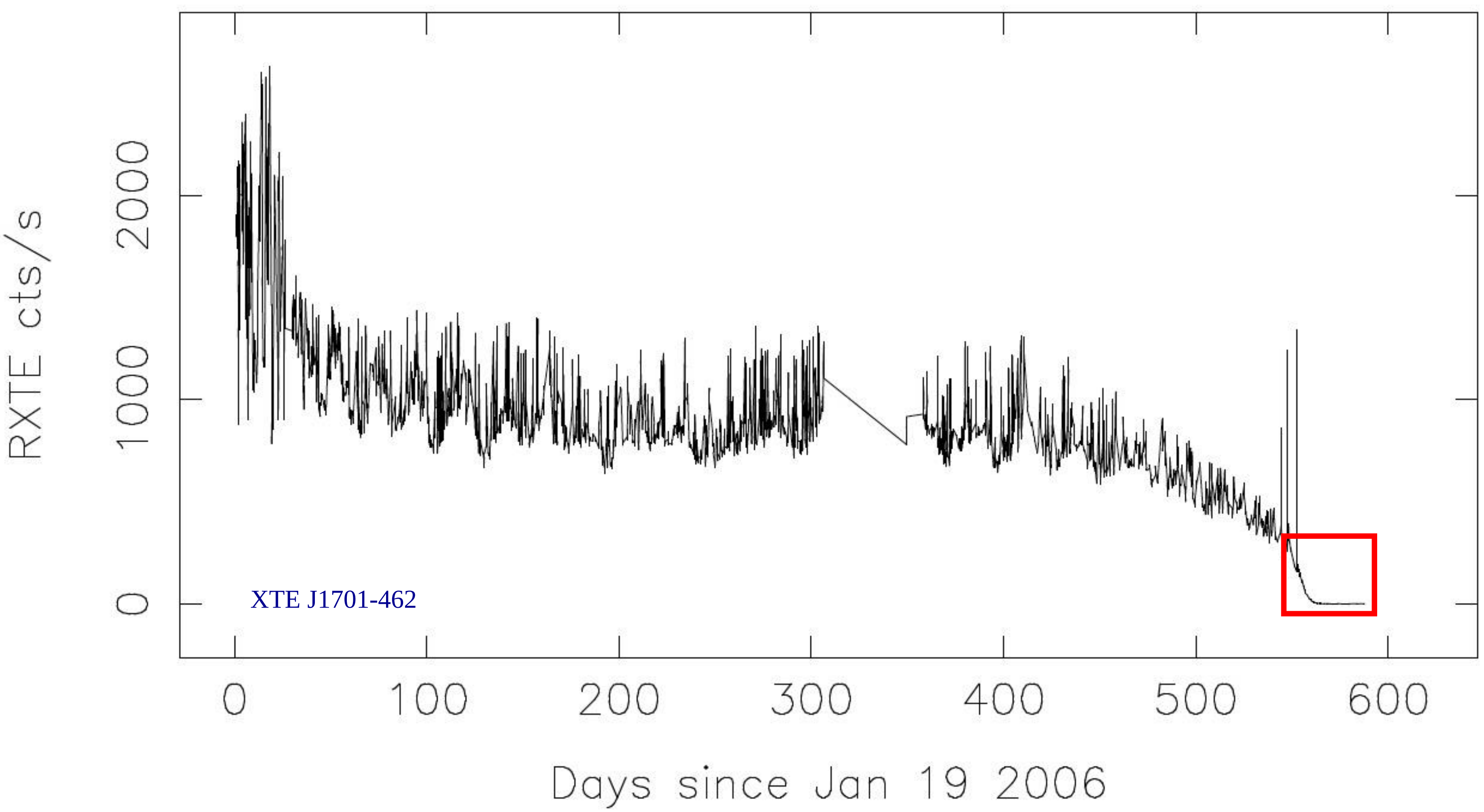
Quiescence



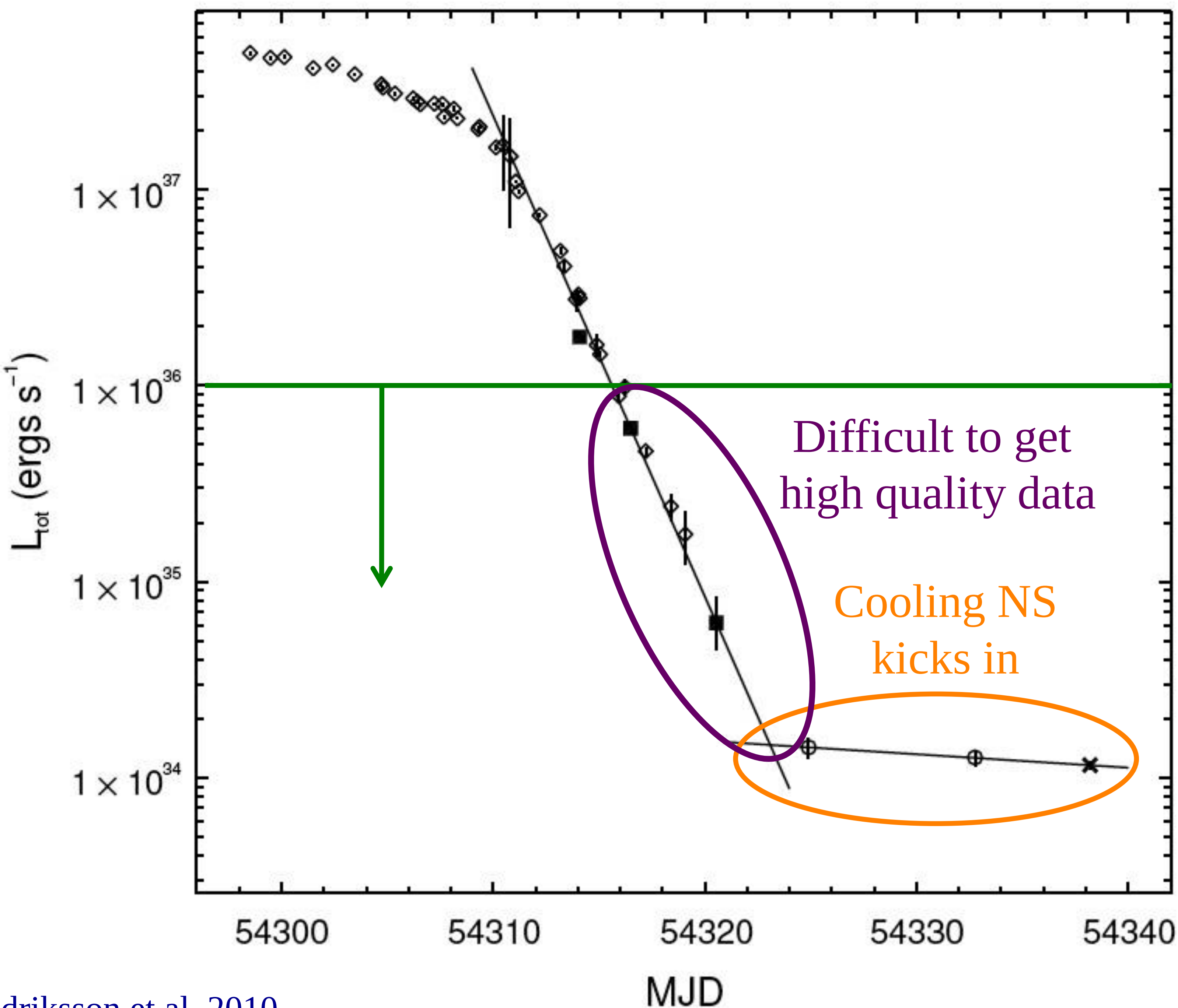
Very dim but
very long


Outburst
1%-100% L_{Edd}
Bright but short
Sub-Eddington systems
0.01%-1% L_{Edd}
Difficult to study!
Dim and very short
Quiescence
< 0.01% L_{Edd}
Very dim but very long

Final decay phase of bright transients



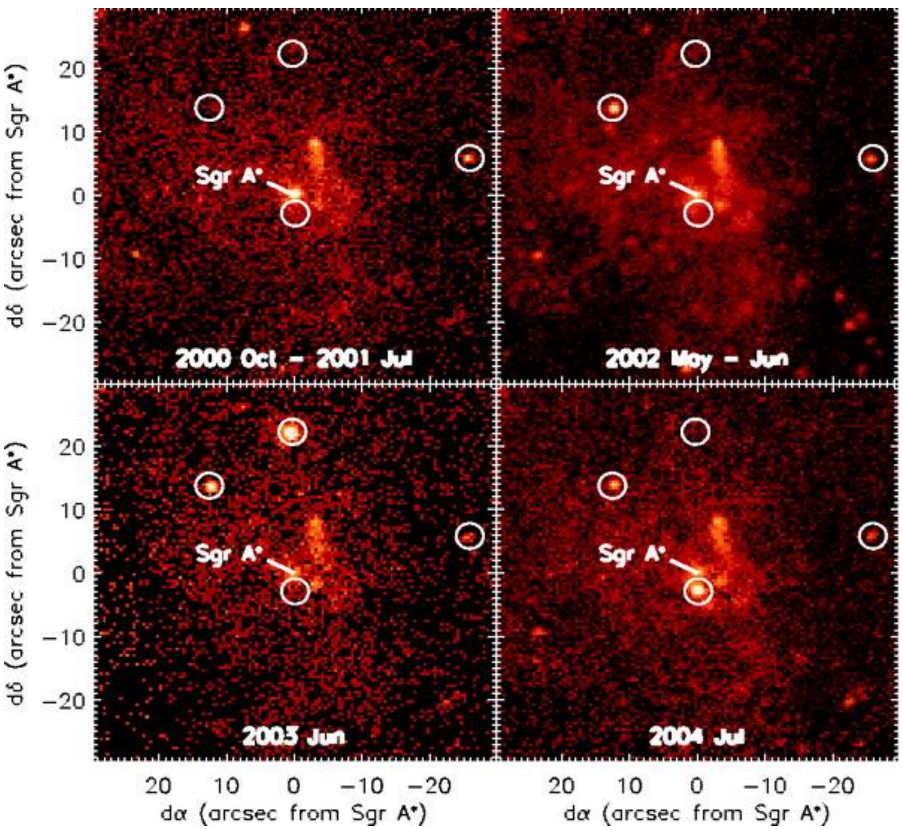
Disadvantage: it might only last for days



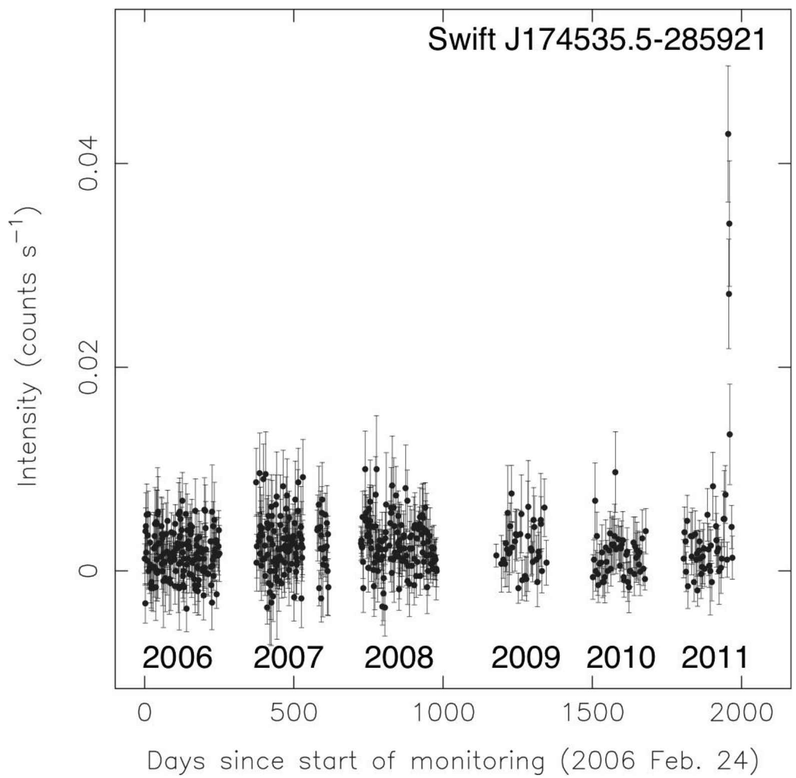
Fridriksson et al. 2010

Very-faint X-ray transients

- Never become brighter than 10^{36} erg s^{-1}
  - Difficult to find and typically only have low quality data
  - Outbursts tend to be brief so difficult to obtain data



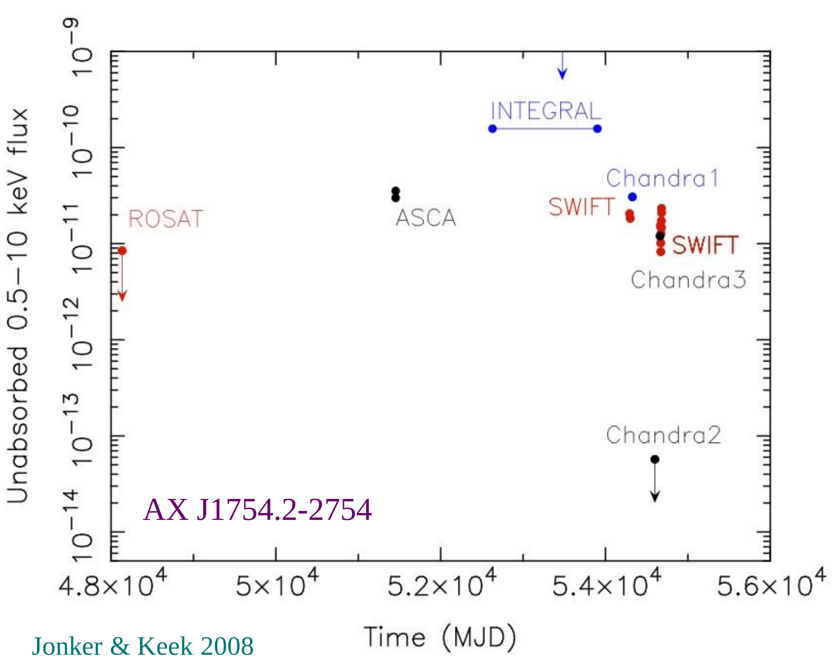
Muno et al. 2005



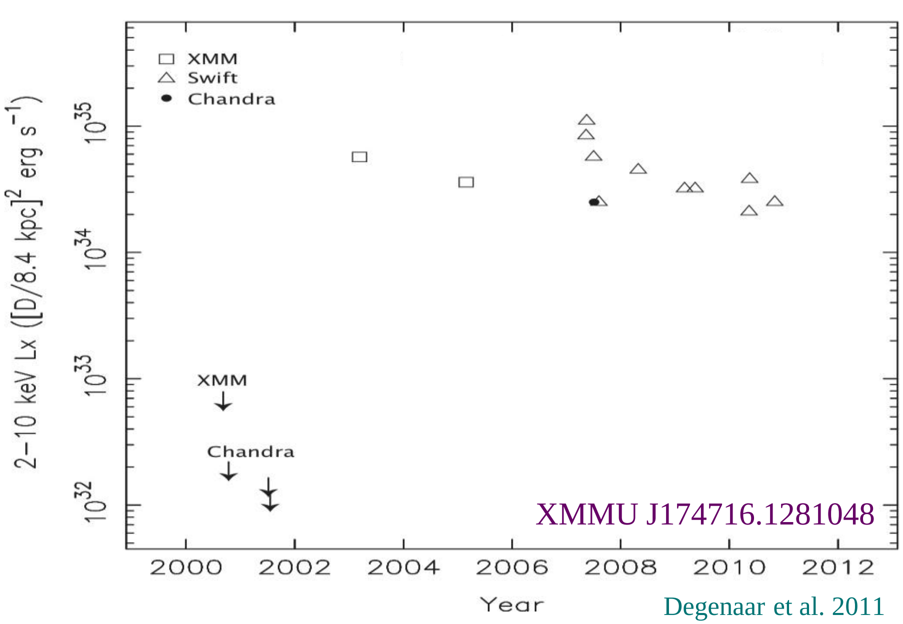
Degenaar & Wijnands 2010

(Quasi-)stable subluminous systems

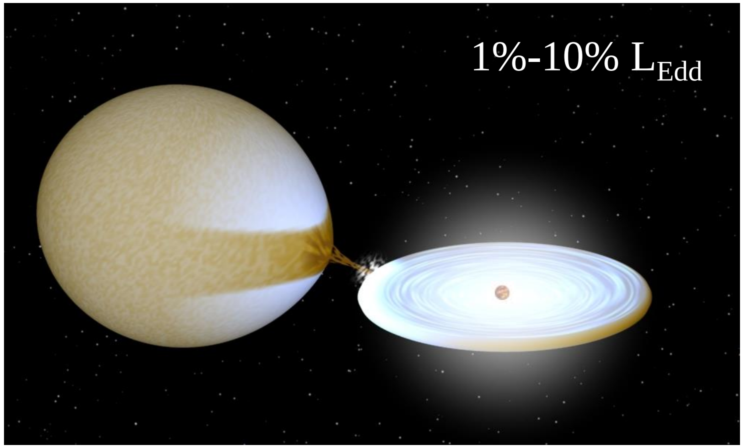
- Several NS systems are persistently subluminous
- Several NS transients are quasi-stable at very low luminosities
- This allows for more detailed studies

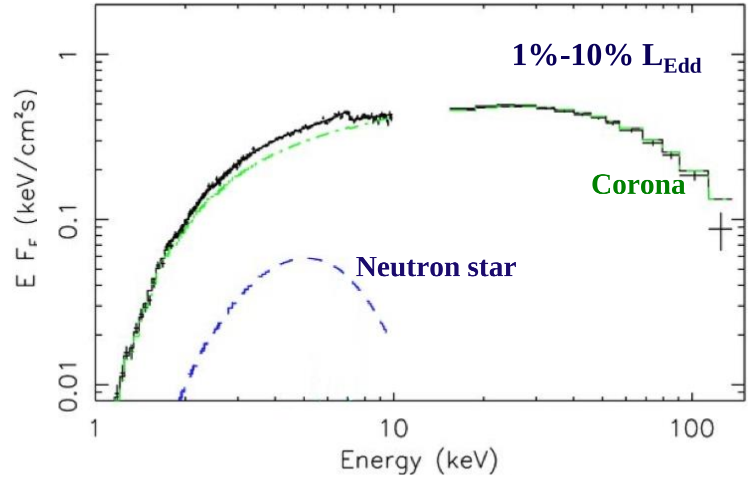


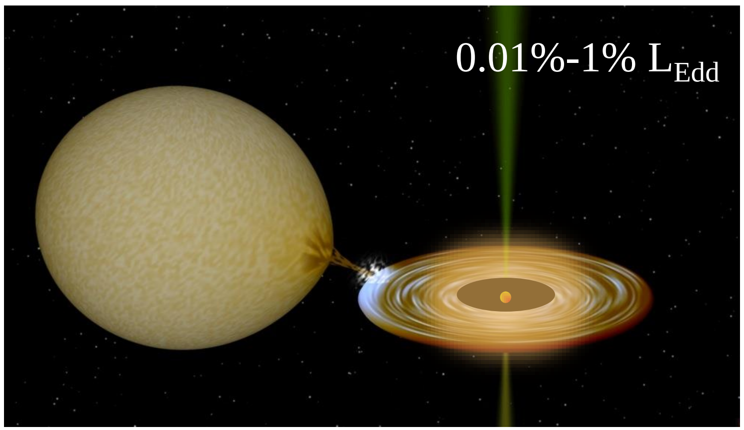
Jonker & Keek 2008



Degenaar et al. 2011







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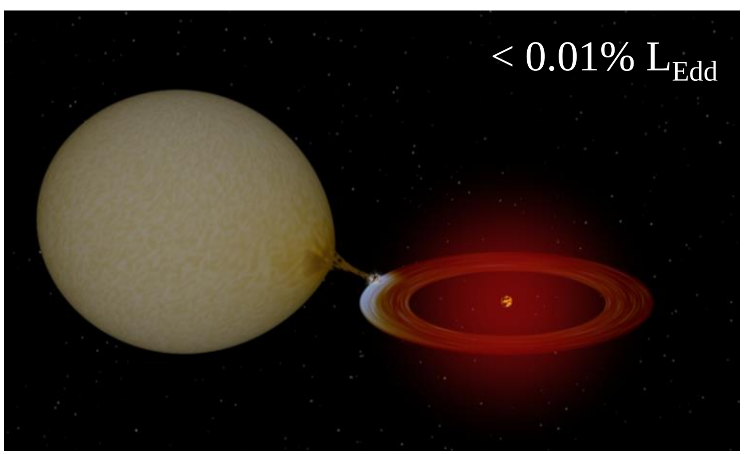
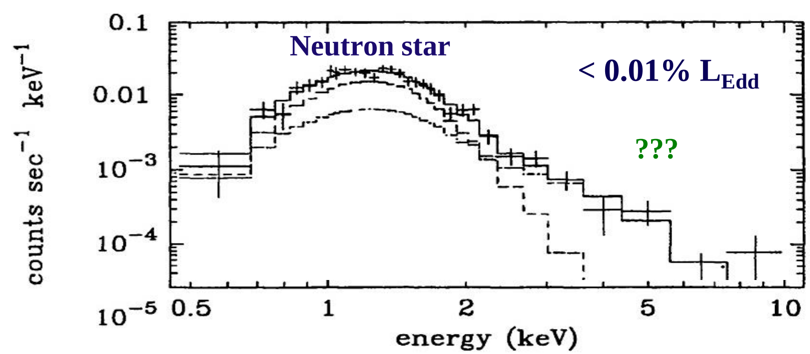
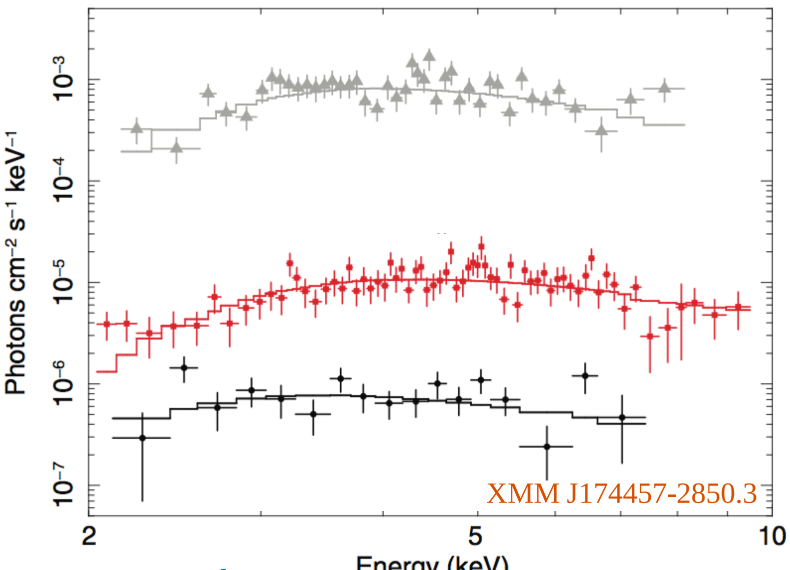




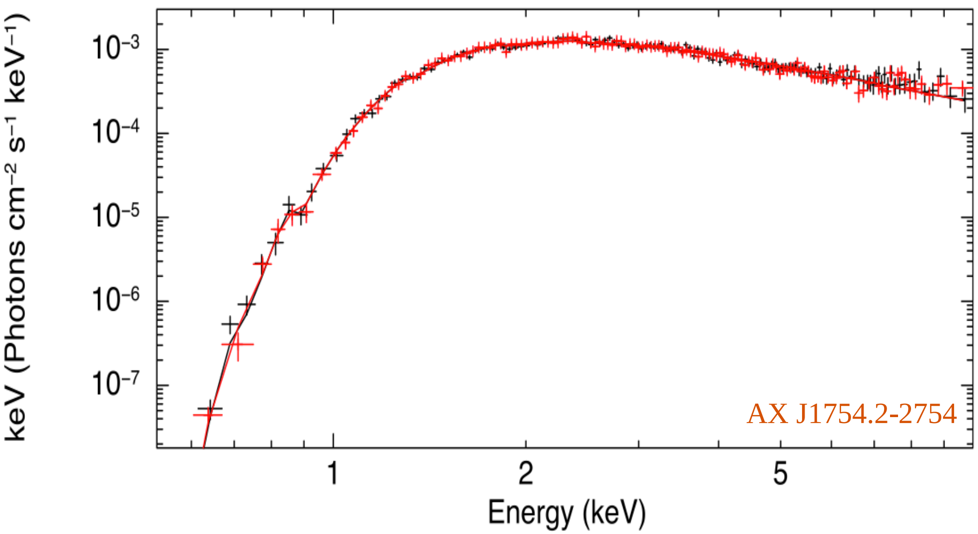
Note: 1 type out of 3 possibilities

Studying the X-ray spectra

- Usually the data have low quality
  - Very few photons
- Only simple models can be fitted to the spectra
  - Typically power-law model ($E^{-\Gamma}$, Γ = photon index)
- Sometimes high(er) quality data are obtained!

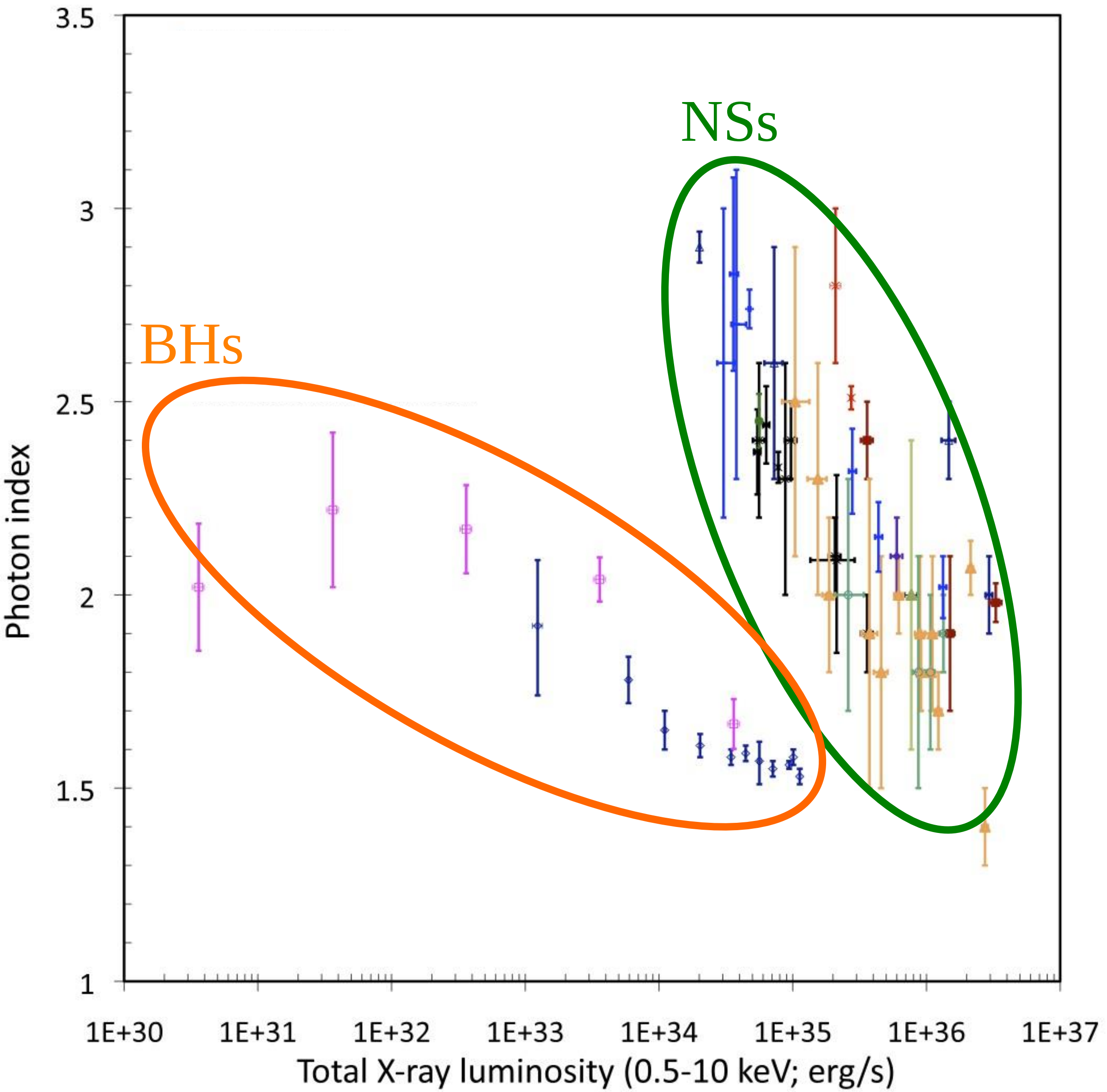


Degenaar et al. 2014



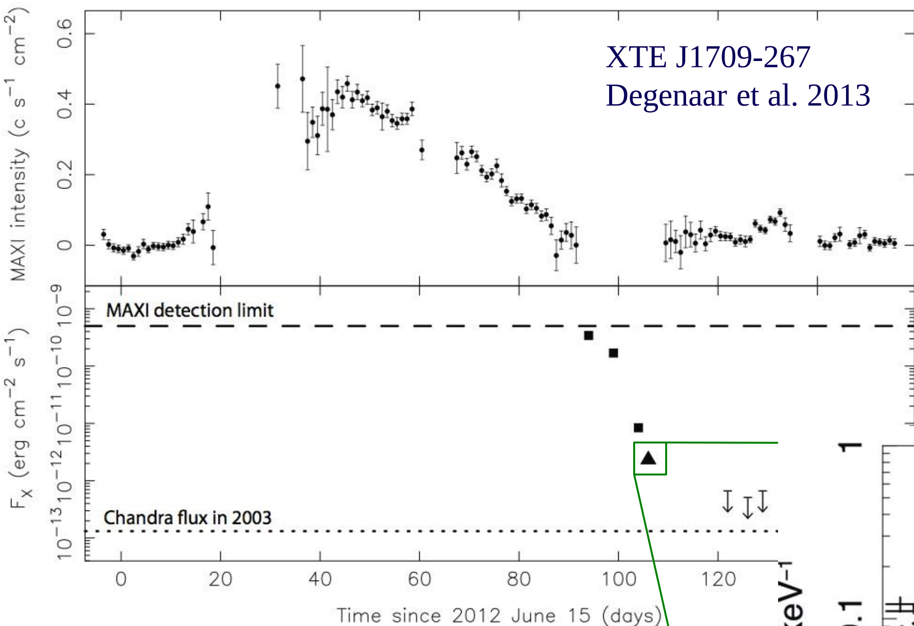
Armas Padilla et al. 2013

Evolution of the photon index

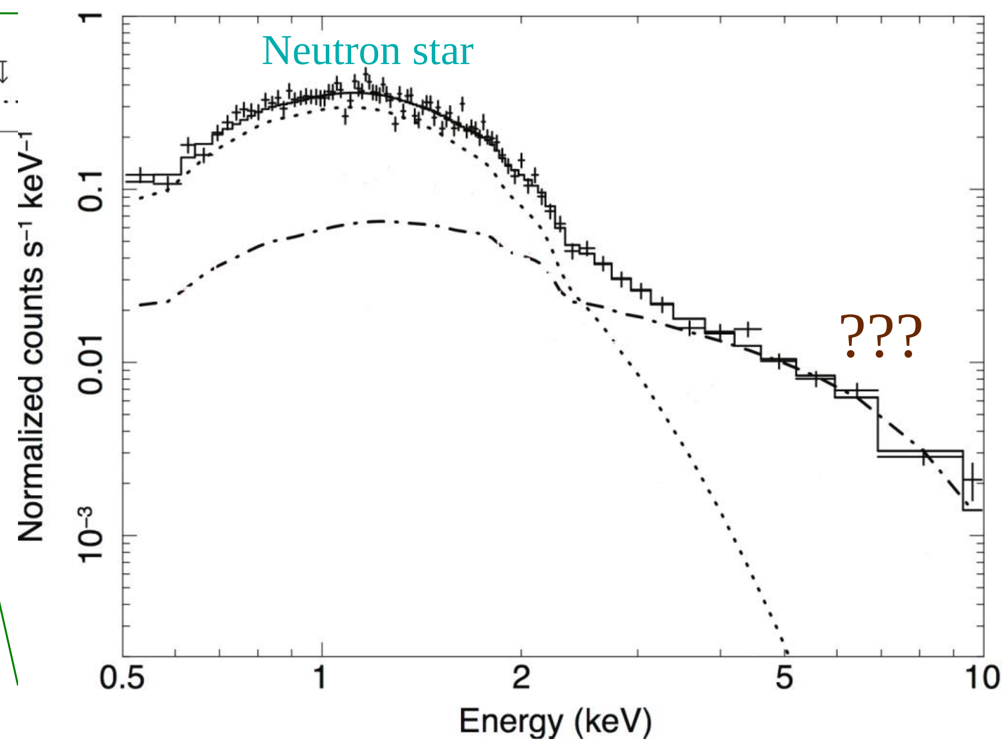


Wijnands et al. 2015

Neutron star becomes visible



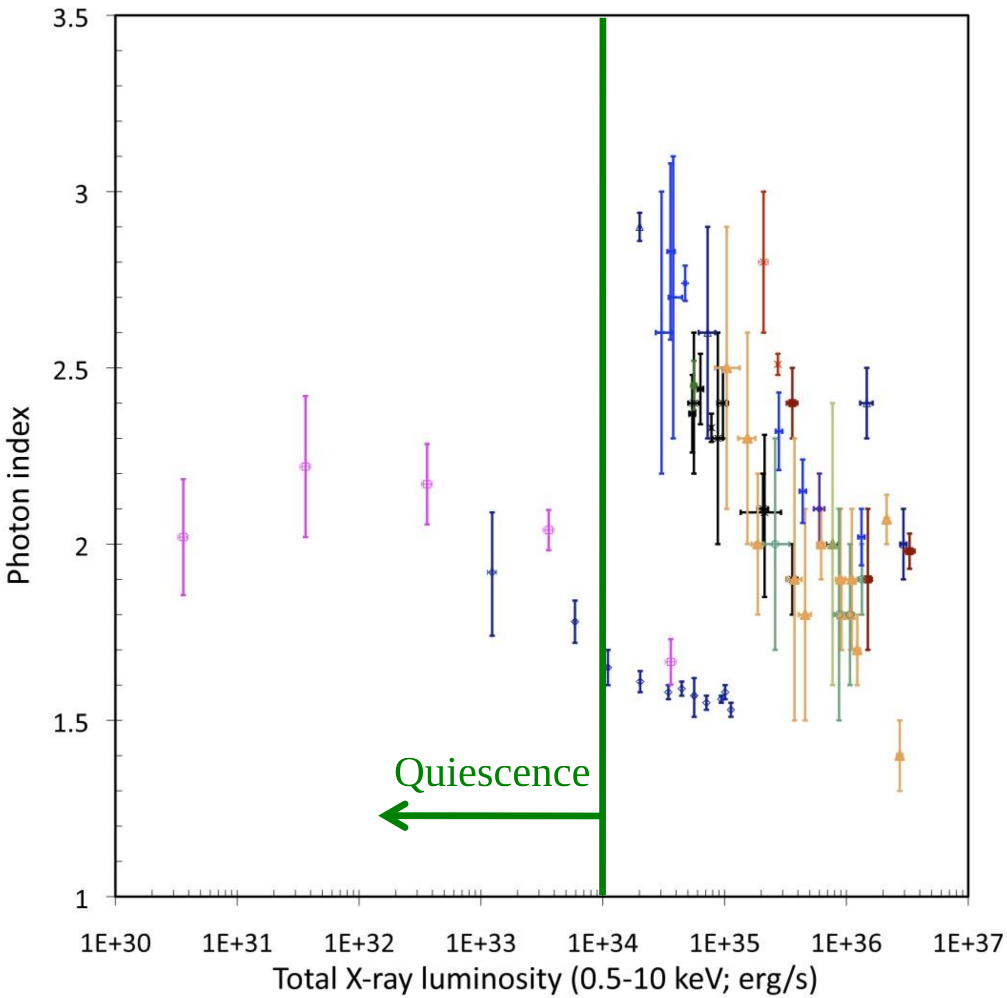
Appearance of strong black-body component, likely from low level accretion onto the NS surface, causes the spectrum to soften



When NS component added to the model, power-law becomes much harder (photon index 1-1.5)!

NSs at extremely low accretion rates

- So what at lower (< 10^{34} erg s^{-1}) luminosities?

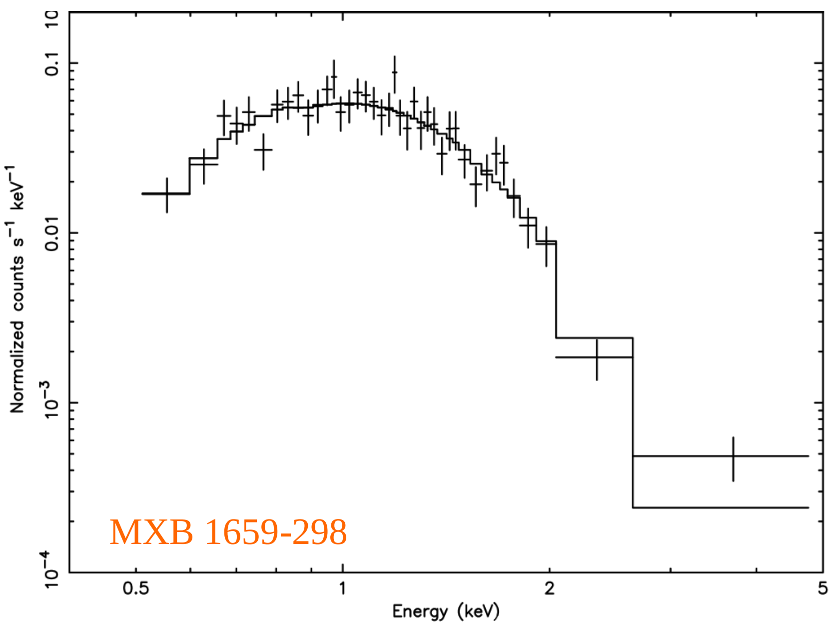


Wijnands et al. 2015

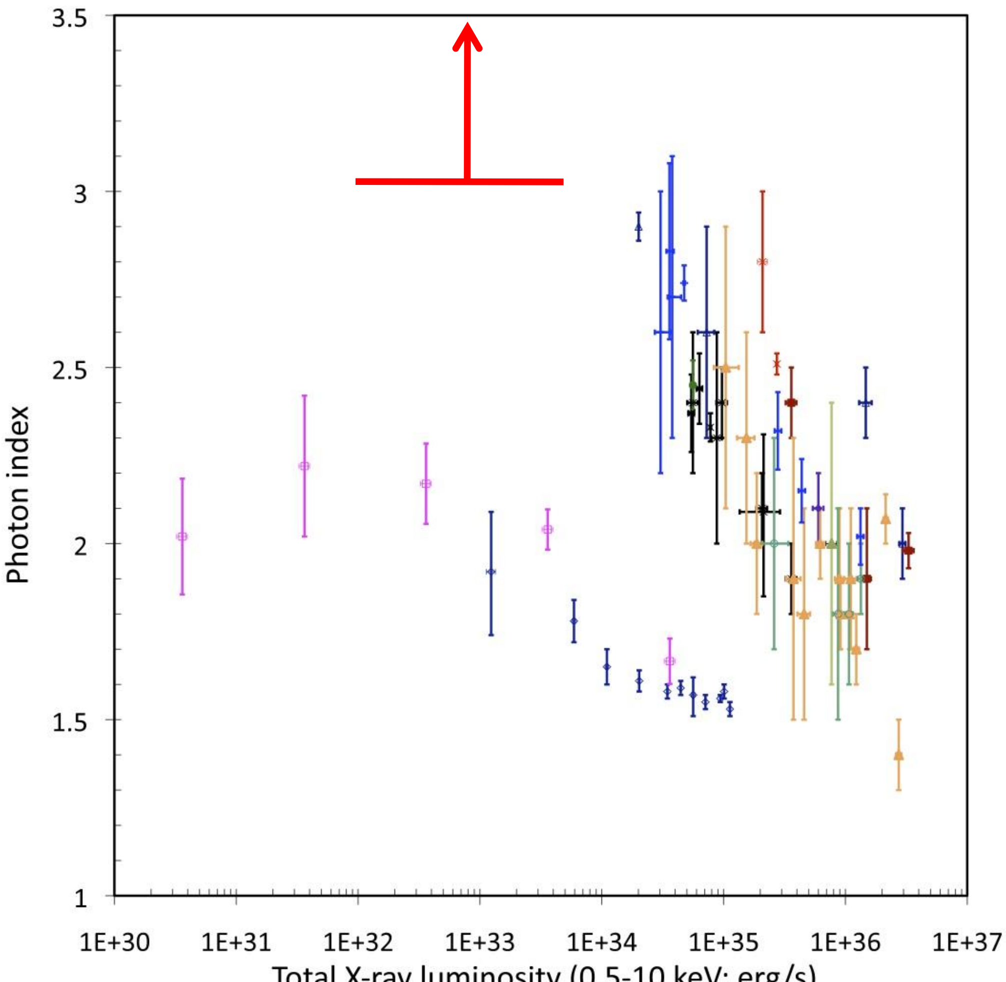
- Three options
  - Accretion totally switches off: “true” quiescence
    - Spectrum dominated by soft component
    - Cooling studies of accretion-heated neutron stars
  - Low-level accretion continues
    - Spectra very similar to those of the sub-Eddington systems!
    - Soft component with very hard power-law (Γ ~1-1.5)
  - Magnetic field effects state?
    - Power-law dominated spectrum, very hard
    - Connection with the ‘transitional ms pulsars’?

NSs at extremely low accretion rates

- True quiescence = no accretion onto the neutron star
- Cooling NS studies



Wijnands et al. 2003, 2015



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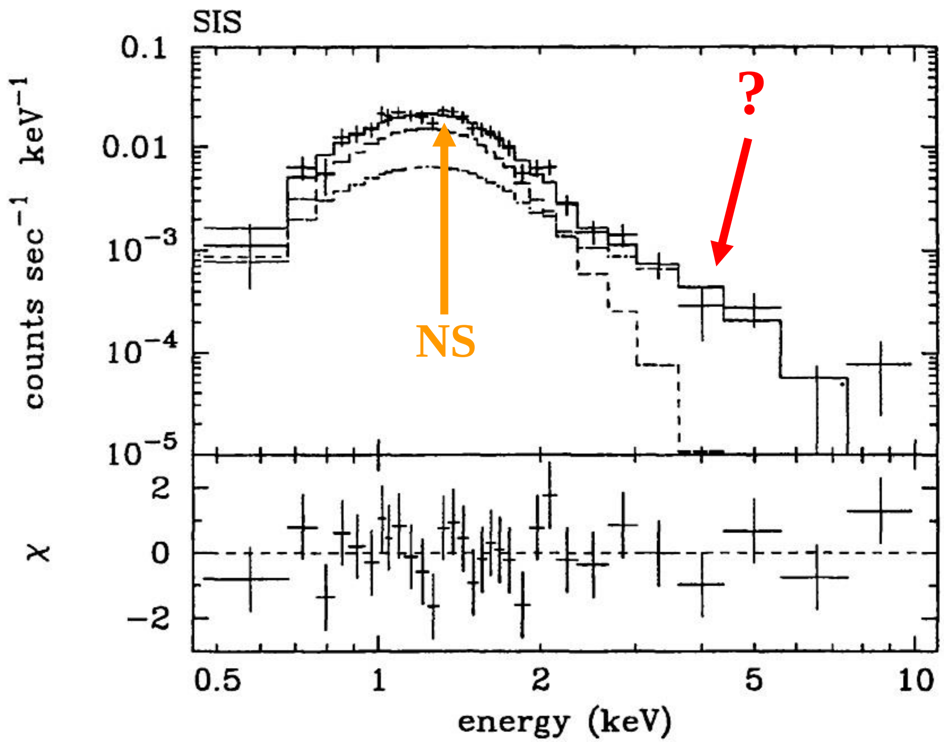
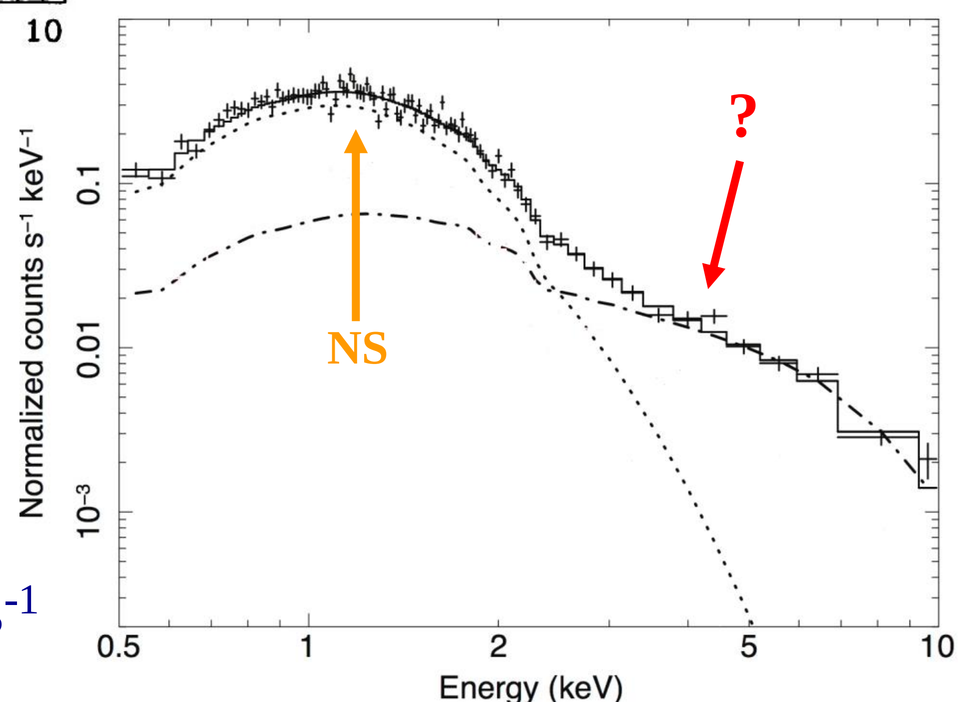
Comparison of spectra

Asai et al. 1998



$10^{32\text{-}33}$ erg s^{-1}

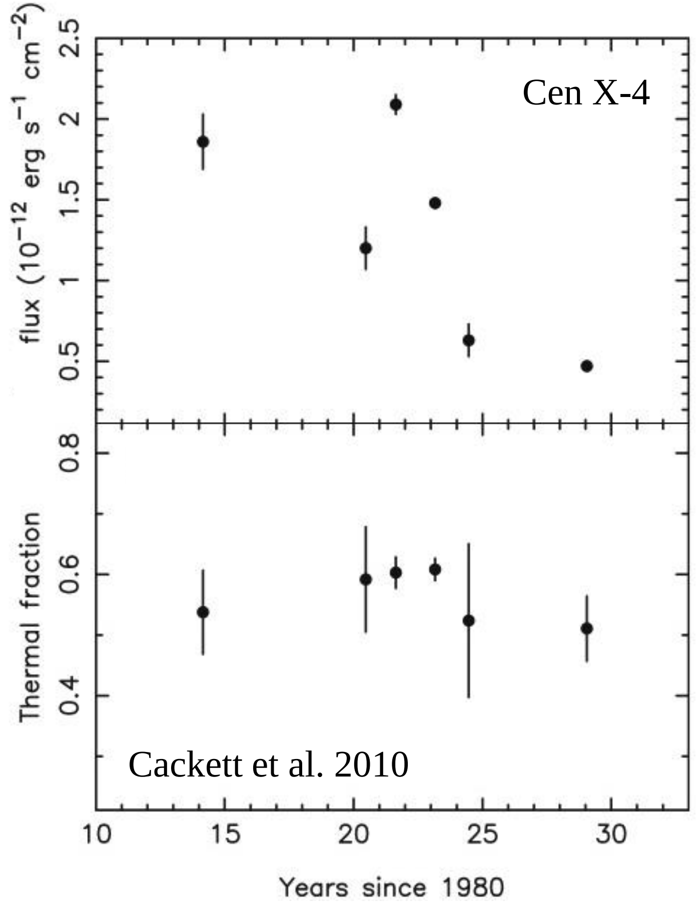
Degenaar et al. 2013



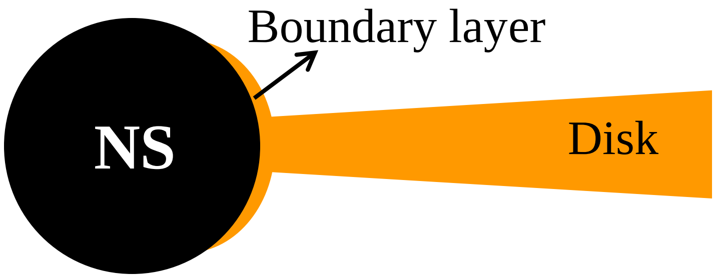
$10^{34\text{-}35}$ erg s^{-1}

Very similar spectral shape!

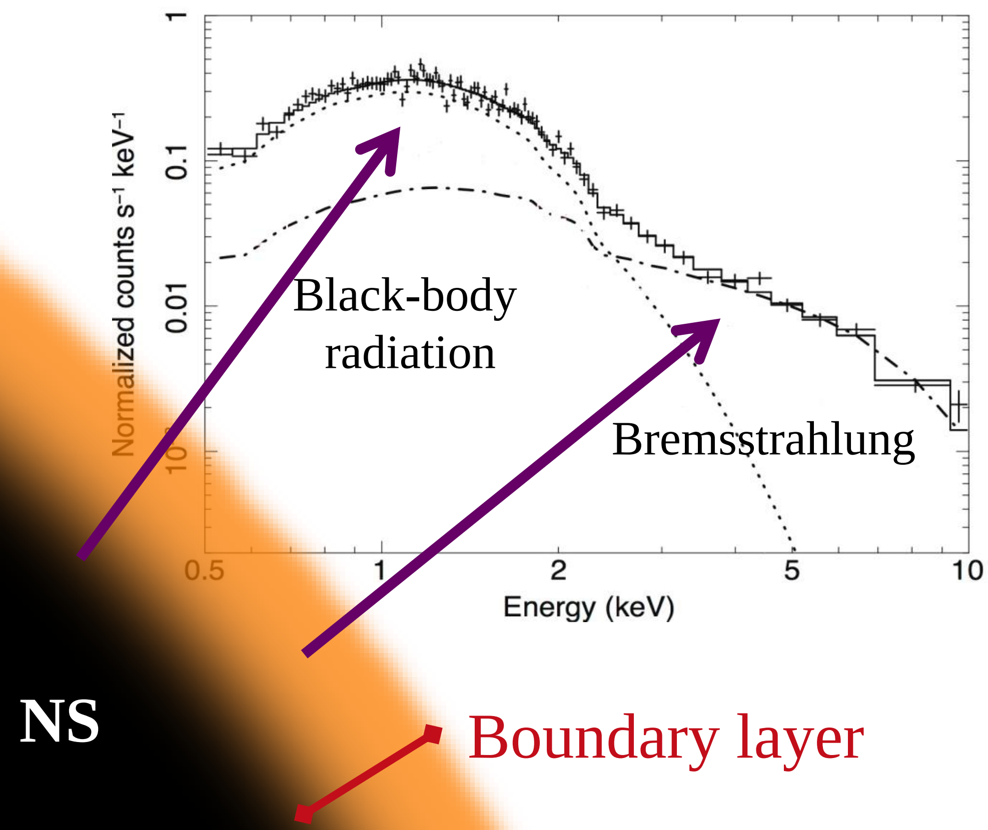
- Intimate connection between the soft and the hard power-law components
  - Roughly equal flux (0.5-10 keV) in both components over a large luminosity range
    - By combining quiescent data with data from sub-Eddington systems
    - $L_x = 10^{32}$ to 10^{35} erg s^{-1}
  - Likely soft and hard components originate from the same process
    - Very low level accretion onto NS!
    - Exact origin of the power law?
    - Boundary layer accretion?
      - Just a toy model idea!
      - E.g., D'Angelo et al. 2015

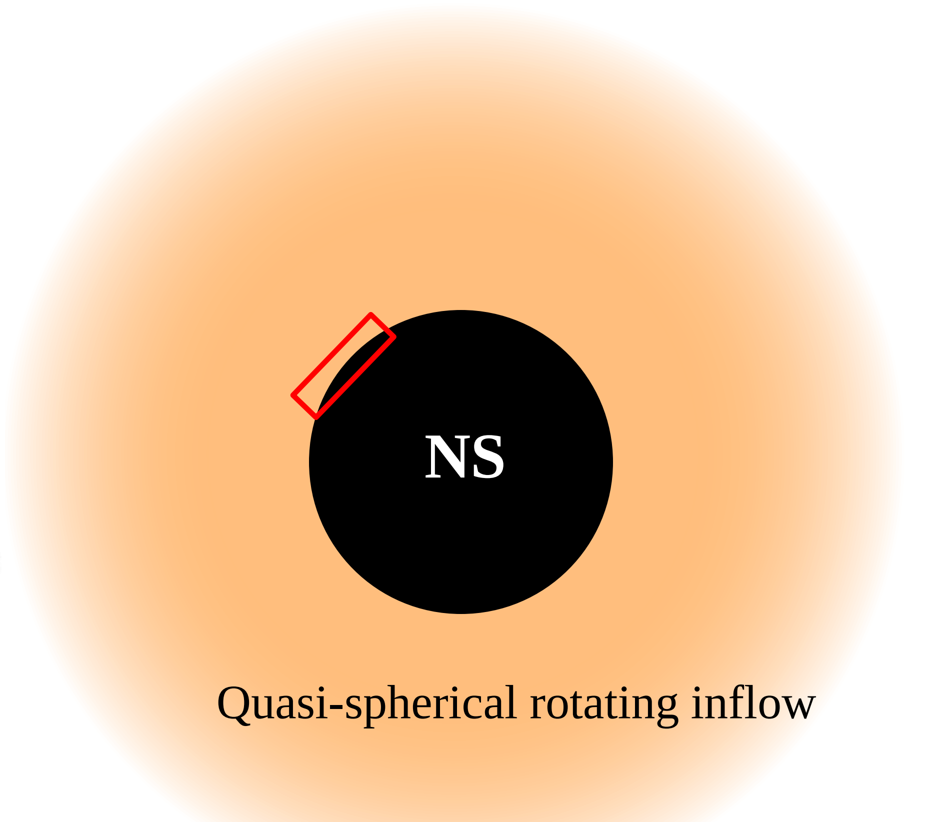


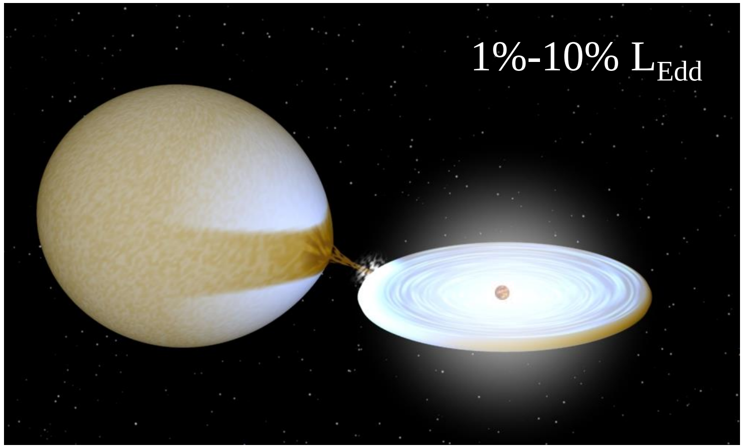
Boundary layer accretion

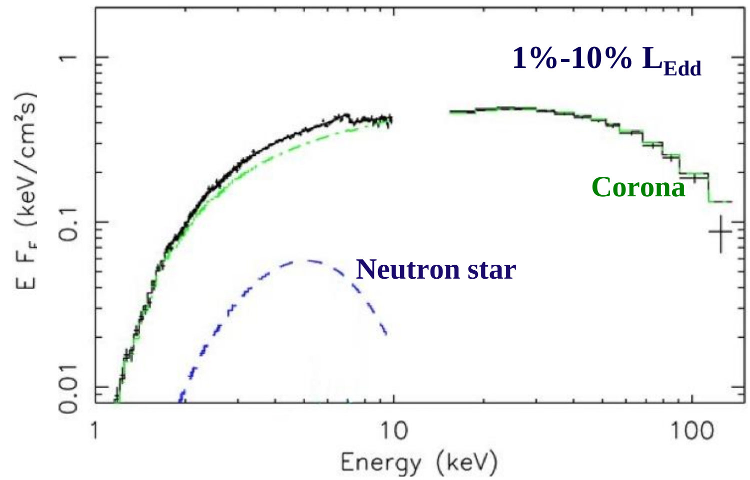


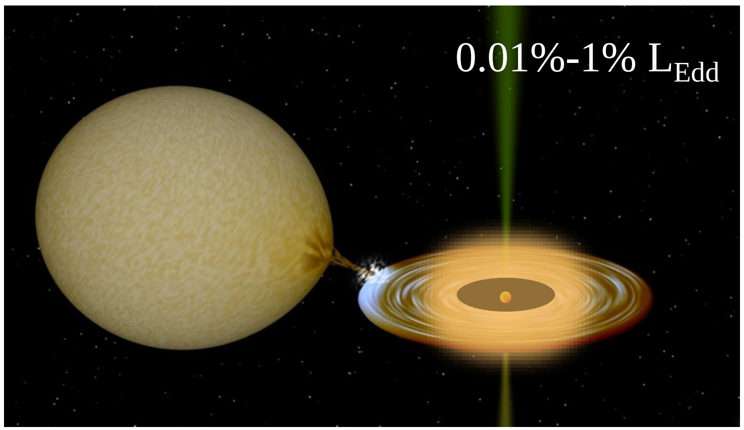
Boundary layer at high accretion rate assuming disk accretion



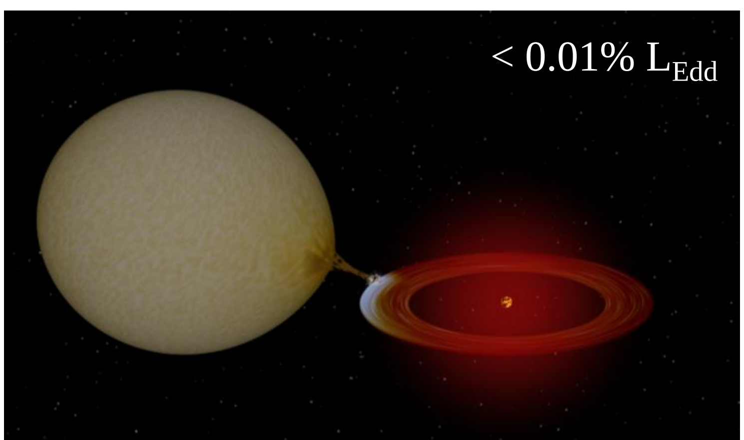


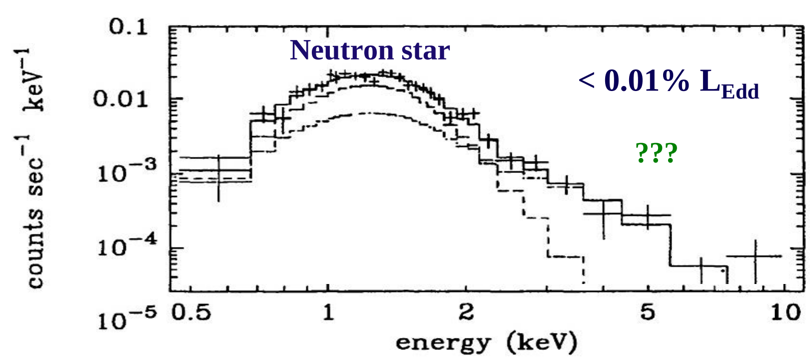

1%-10% L_{Edd}

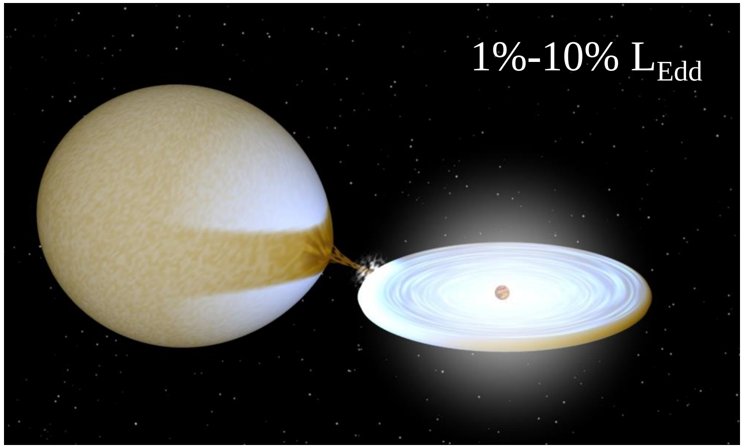

1%-10% L_{Edd}
Corona
Neutron star
E F_E (keV/cm²s)
0.01
0.1
1
1
10
100
Energy (keV)

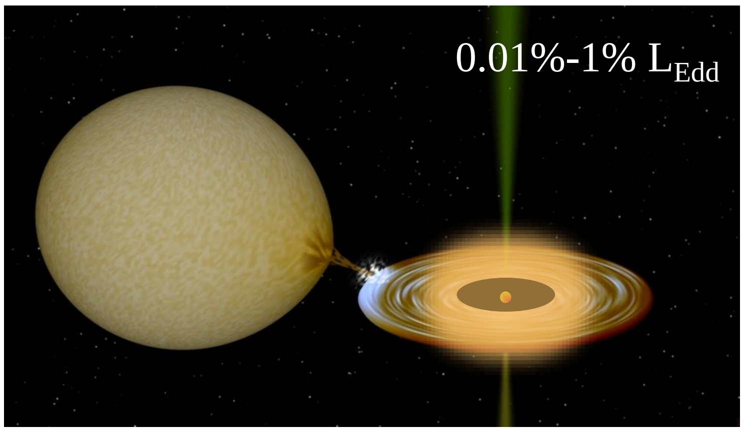

0.01%-1% L_{Edd}

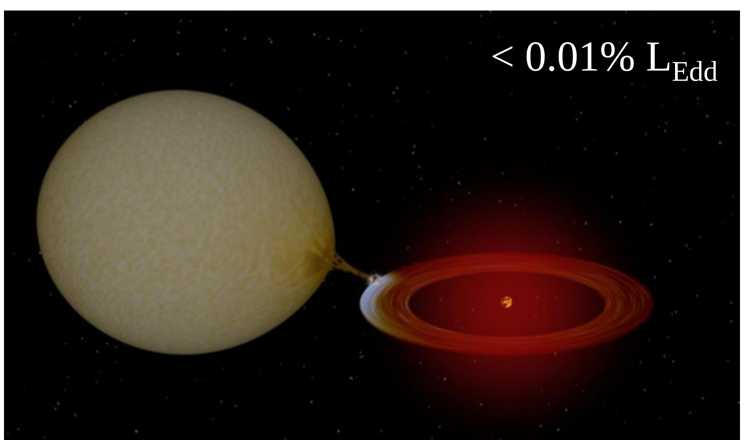
???

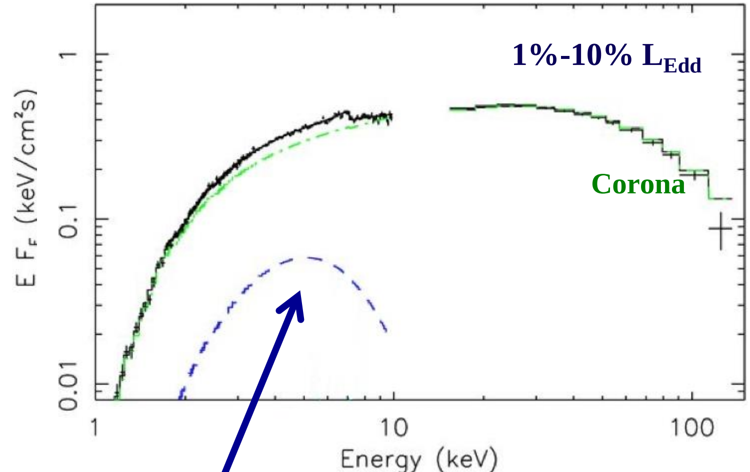

< 0.01% L_{Edd}

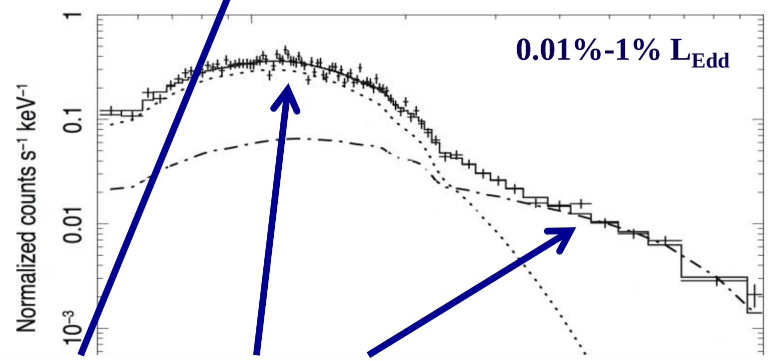

Neutron star
< 0.01% L_{Edd}
???
counts sec^{-1} keV^{-1}
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
0.5
1
2
5
10
energy (keV)



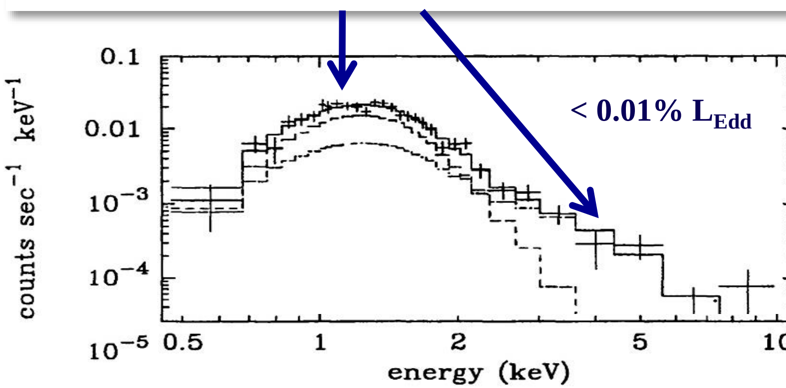








All accretion onto NS surface!



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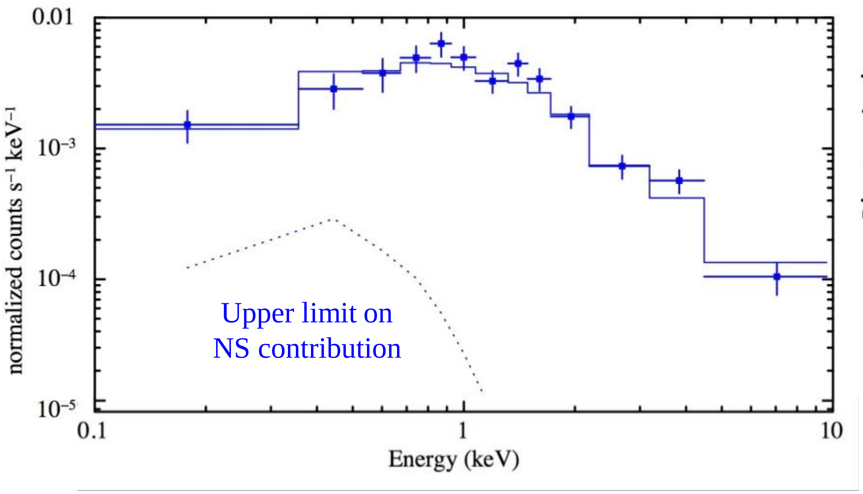
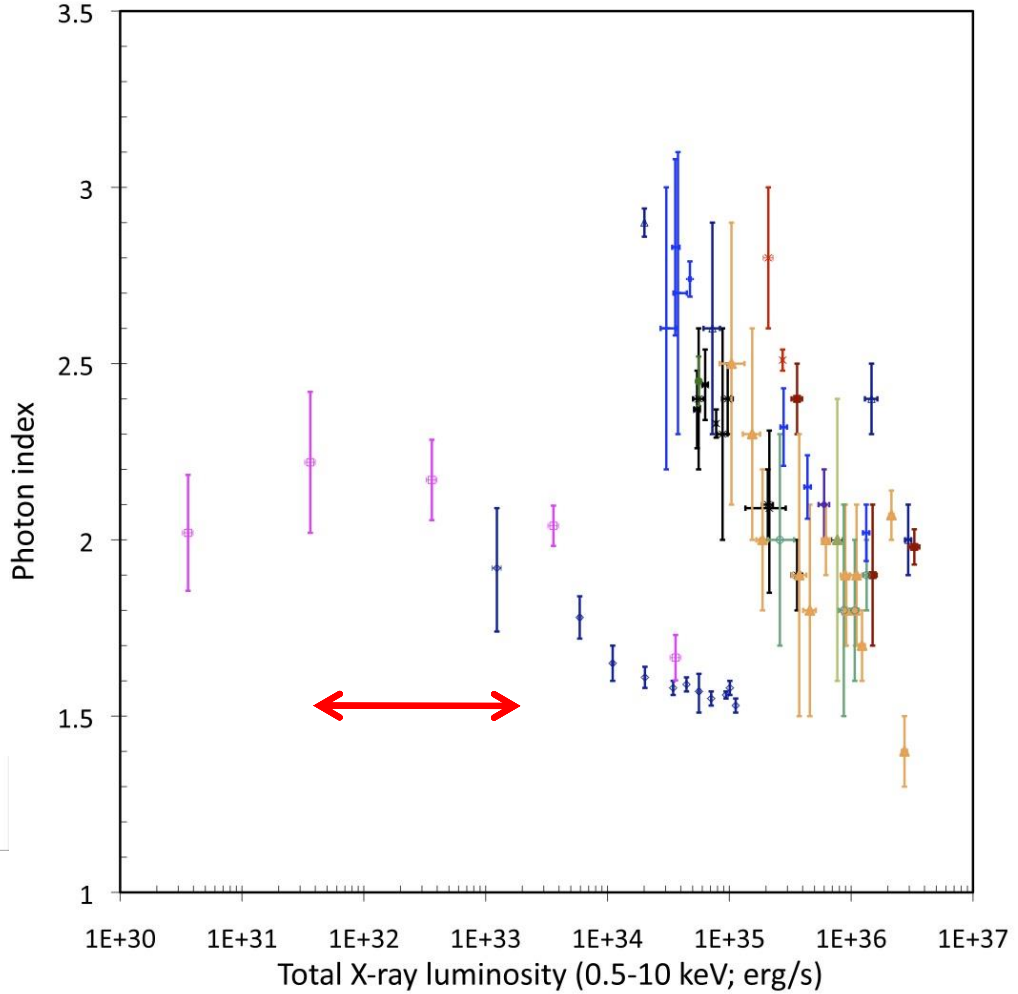
NSs at extremely low accretion rates

- Weird power-law dominated state; connection with transitional ms pulsars?
- Systems that have a magnetic field?
  - Magnetic accretion?



Heinke et al. 2009
Wijnands et al. 2015



Transitional millisecond pulsars

- Neutron star binaries (4 known) that switch between a millisecond radio pulsar phase and an accreting phase
  - Similar hard spectra and luminosities as very hard quiescent systems
  - Magnetic accretion? Propeller regime?

Papitto et al. 2013

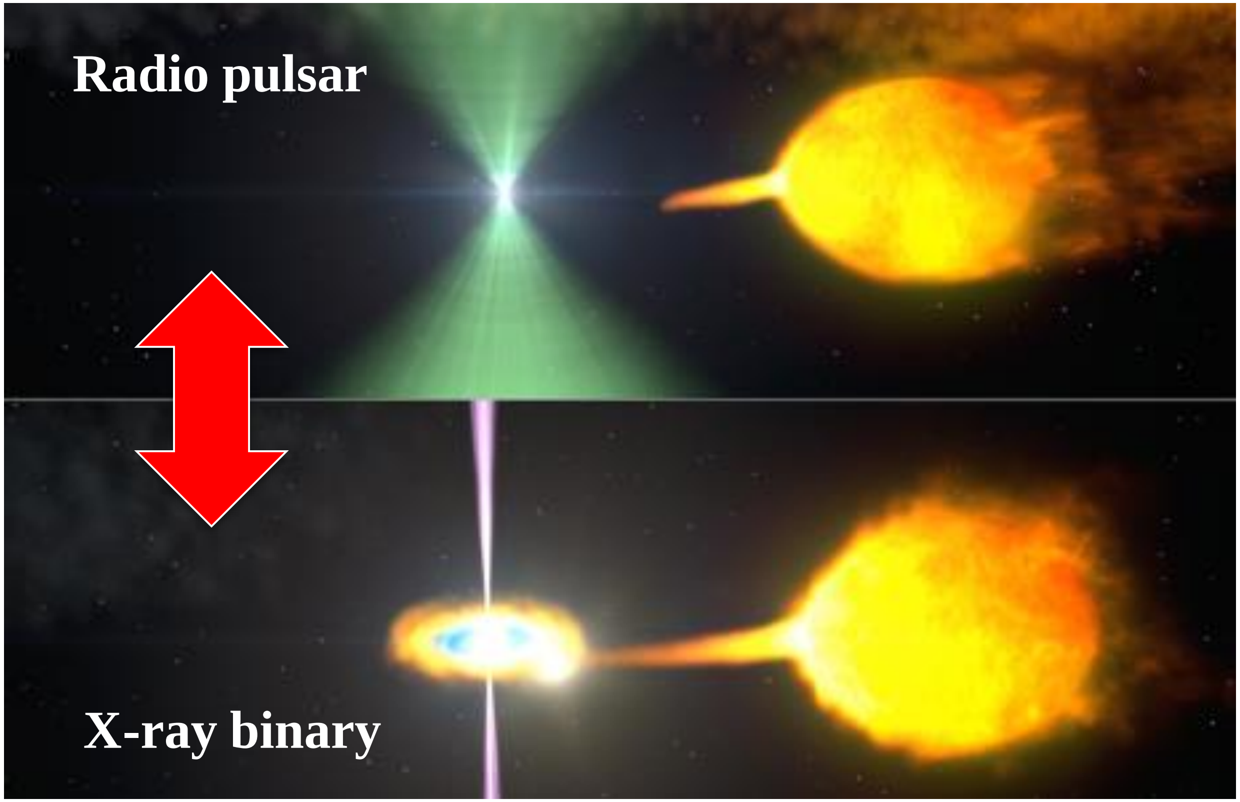
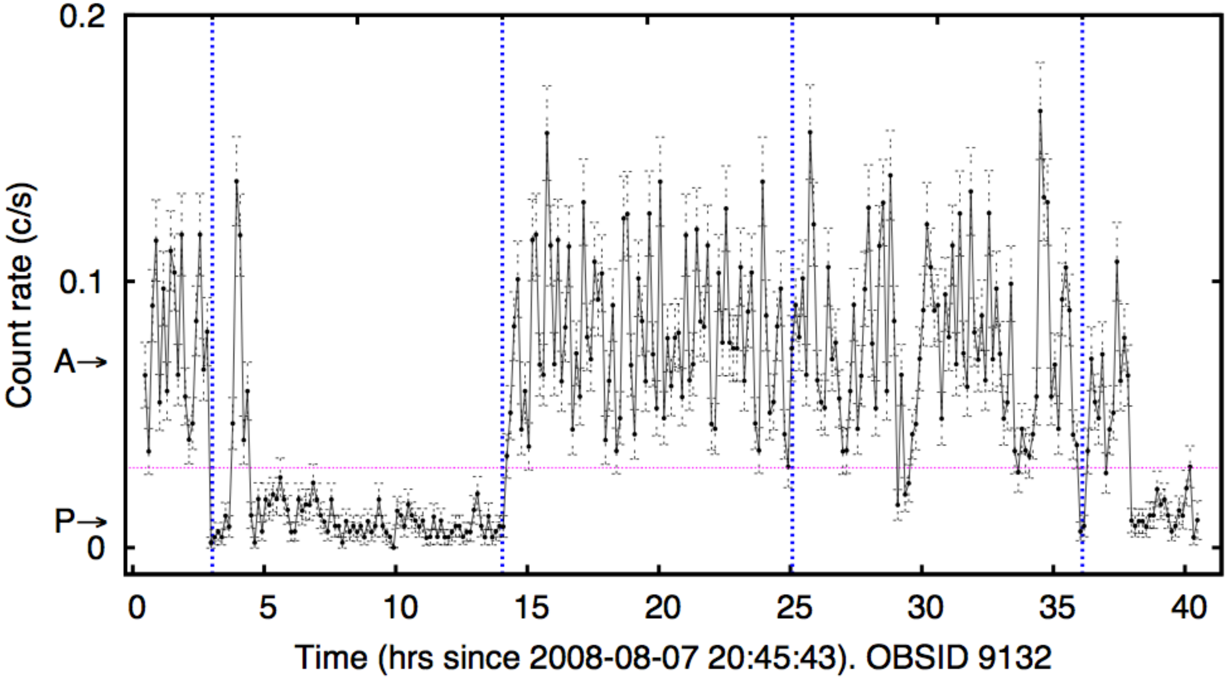
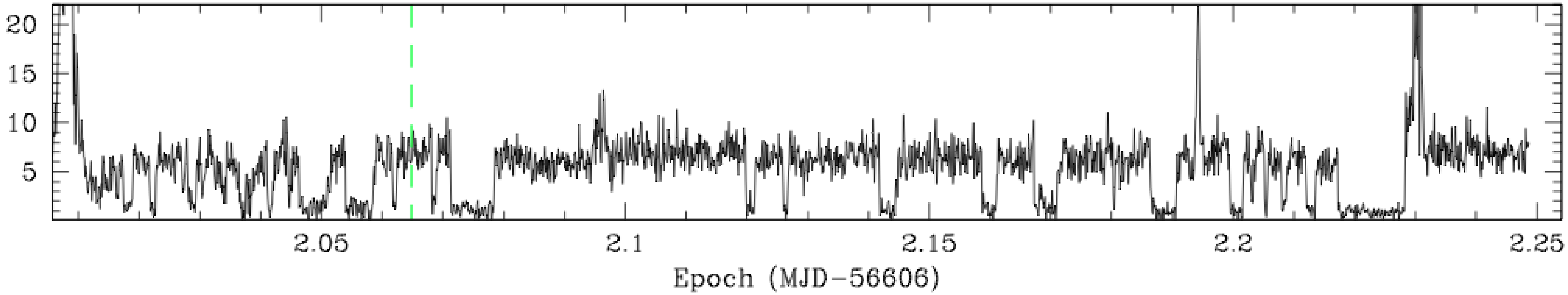


Image credit: NASA

Mode switching at low luminosity



M28I
Linares et al. 2014



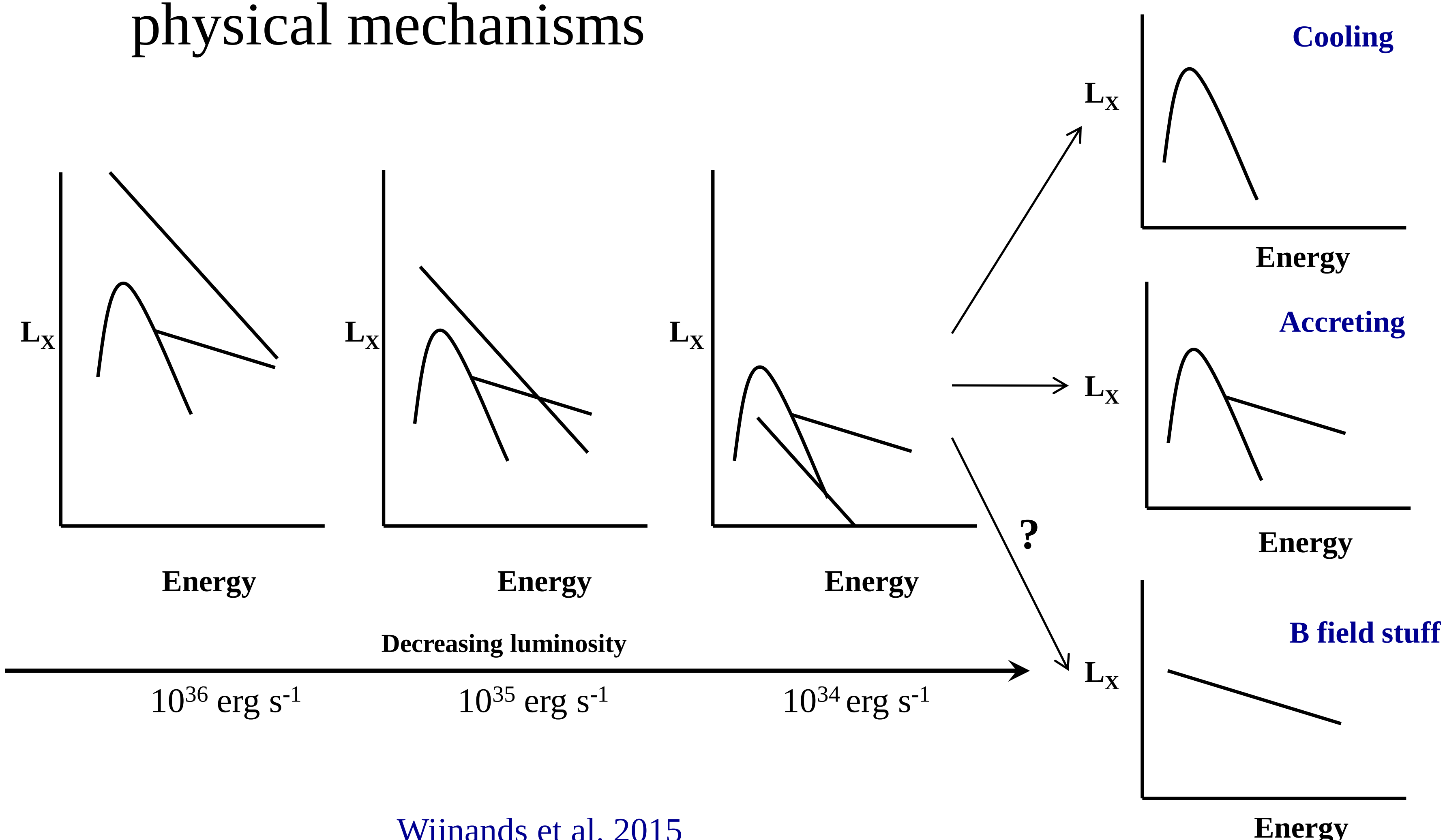
PSR J1023+0038 Bogdanov et al. 2015

Main uncertainties

- Unclear if those hard quiescent spectra are causes by the same mechanism as the transitional system spectra
  - Very low quality data for the quiescent systems
  - Typically much farther away than the transitional systems
    - One has to worry (a lot) about selection effects
- At low accretion rate the accretion is not through a disk but through a radial/quasi-spherical, rotating radiatively inefficient inflow
  - Unclear how magnetic accretion happens in such cases
    - Unclear how accretion happens even in absence of a magnetic field
  - What causes the mode switching?

Final model of the spectral evolution

- Power-law comes from (up to three) different physical mechanisms



Wijnands et al. 2015

Conclusions

- Studying low accretion rates is very important
  - Difficult to study and get high quality data
    - But making progress! New types of NS studies can be done now!
  - Neutron star is a very important player
  - The hard, power-law component is also due to accretion onto the surface of the neutron star!
    - Boundary layer accretion?
- Connection with very low accretion rates
  - Propeller accretion?
    - Neutron star magnetic field could become an important player
  - Boundary layer accretion?
    - Neutron star has no magnetic field?
  - Cooling neutron star if accretion has fully halted
- Lot of uncertainties in the data and models