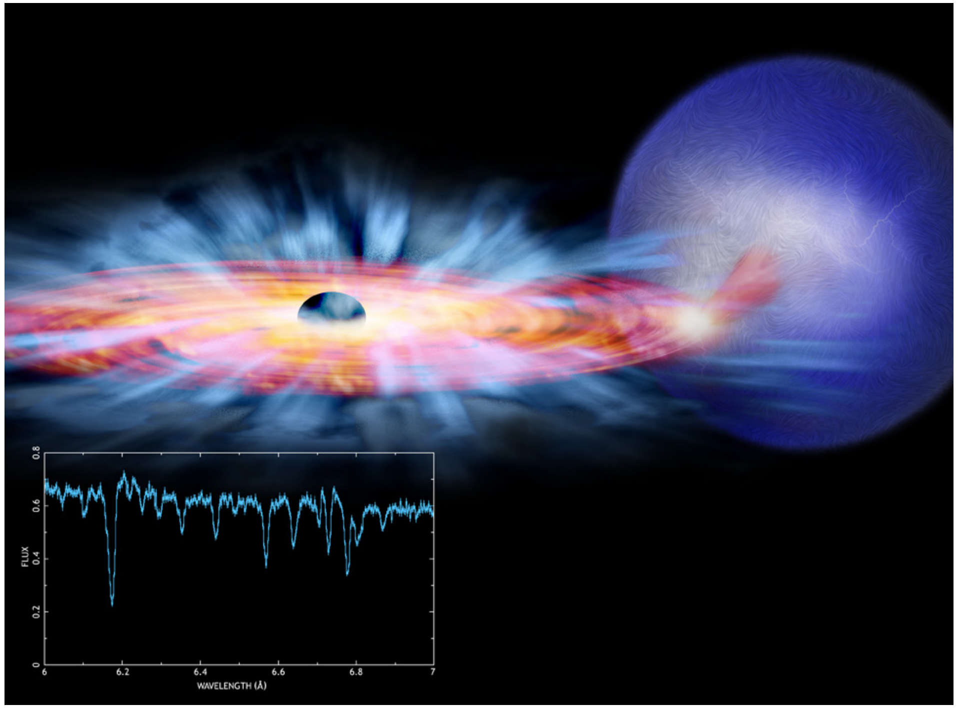
High-resolution X-ray spectroscopy from X-ray binaries

María Díaz Trigo

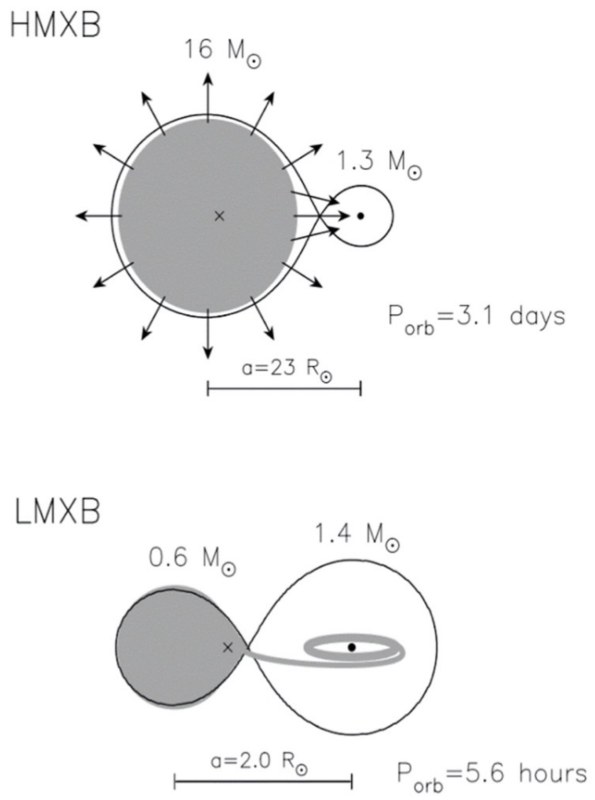
X-ray binaries



Credit: Illustration: NASA/CXC/M.Weiss;
X-ray Spectrum: NASA/CXC/U.Michigan/J.Miller et al.

- Important for understanding **stellar evolution** (especially in the era of gravitational waves)
- Great laboratories to study **mass accretion and jet formation**
- Test-beds for **general relativity**
- Variability timescales from milliseconds to days / months imply that we can see **changes in accretion processes in real time** (for example, jet formation/quenching, accretion state changes…)

High and low mass X-ray binaries

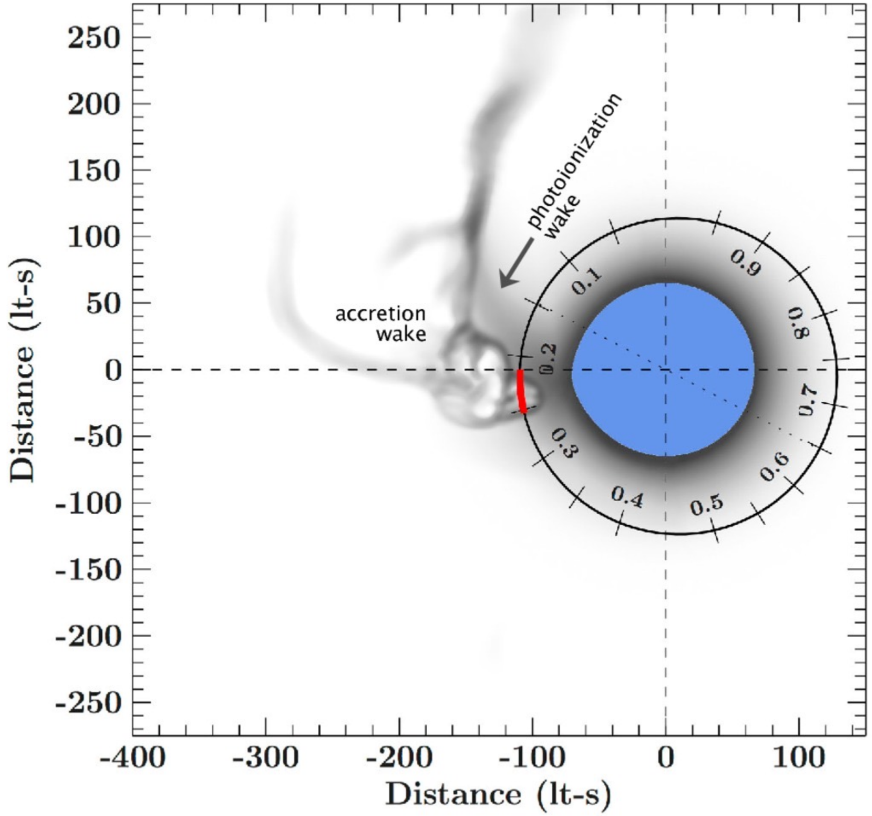


- "High mass" and "low mass" refer to the mass of the companion star
  - HMXBs: companions of > 10 M_{Sun}
  - LMXBs: companions of < 1.5 M_{Sun}
- Accretion via:
  - Roche lobe overflow (disc-fed systems)
  - Wind (wind-fed systems)

  (but note that accretion discs may form in wind-accreting systems without invoking Roche lobe overflow, El Mellah et al. 2019)

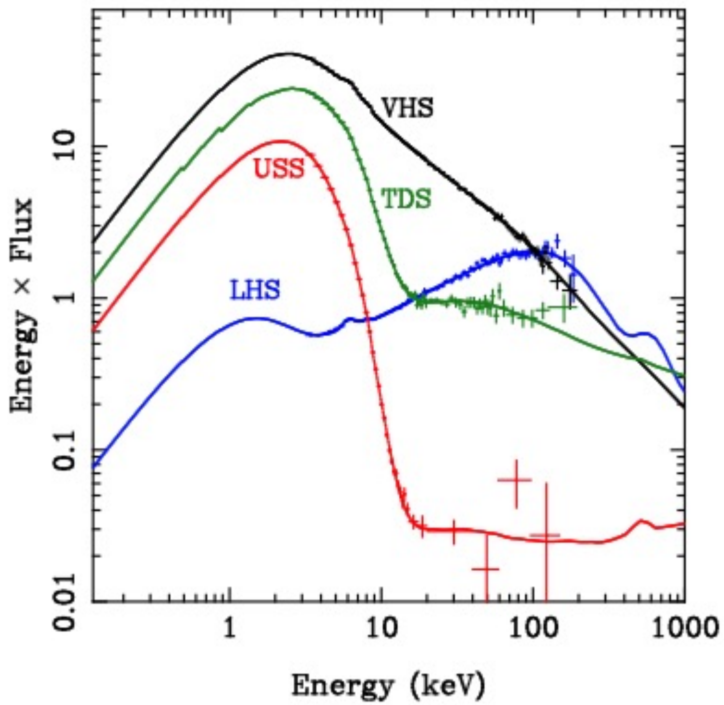
High and low mass X-ray binaries

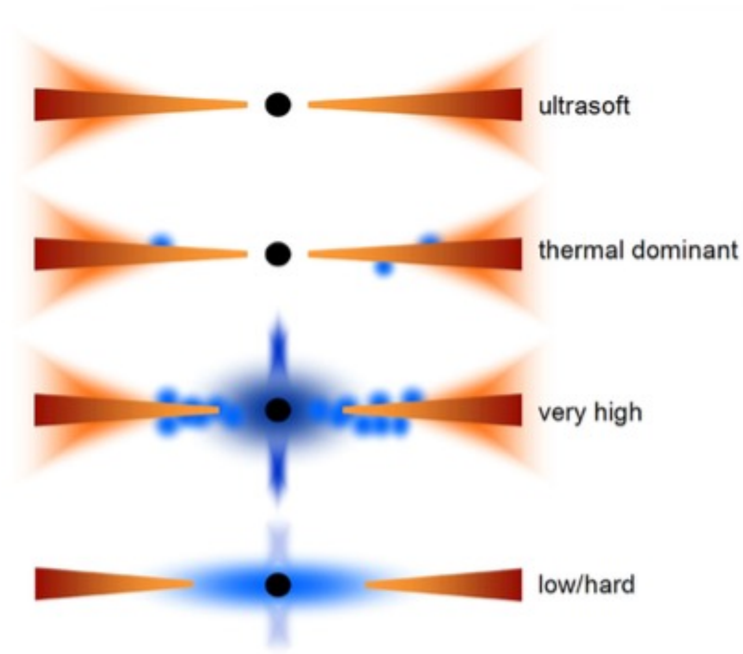
- **HMXBs**: studies of the stellar wind and the effect of irradiation and gravitational pull from the compact object on the wind
- **LMXBs**: studies of the accretion disc (disc atmospheres, coronae, absorption dips, reflection) and the compact object (e.g. bursts, gravitationally redshifted lines)



Grinberg et al. 2017

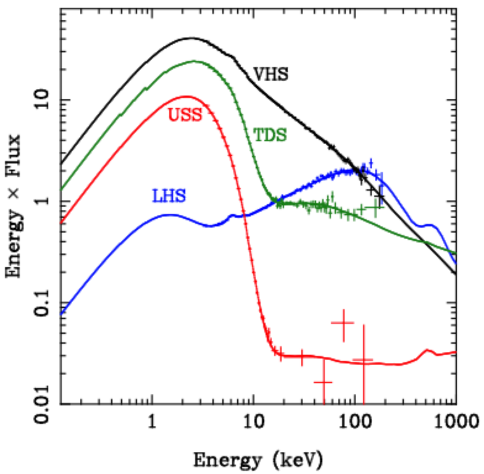
Accretion states



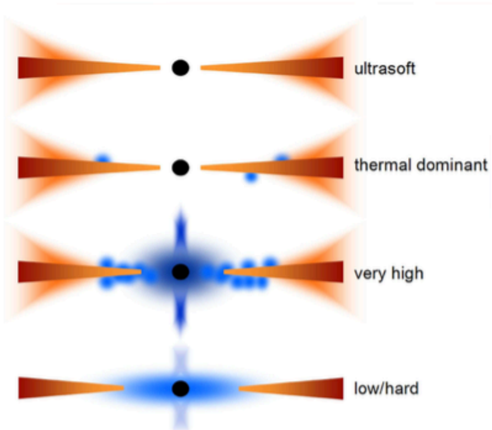


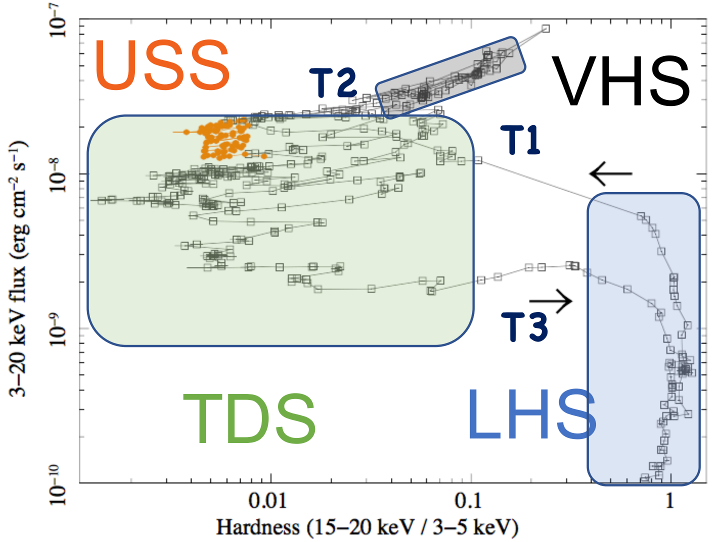
Done et al. 2007

Accretion states



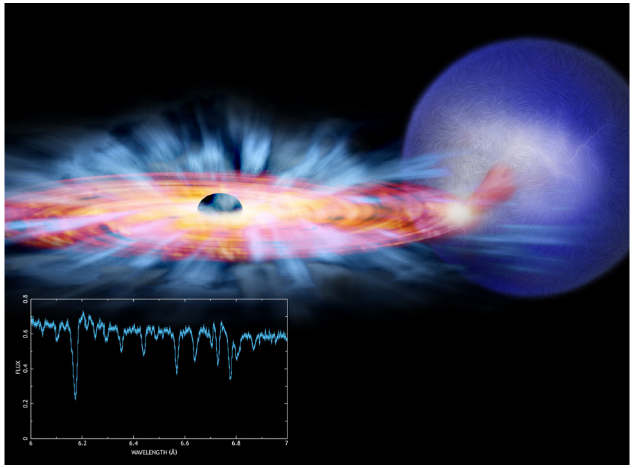
Done et al. 2007

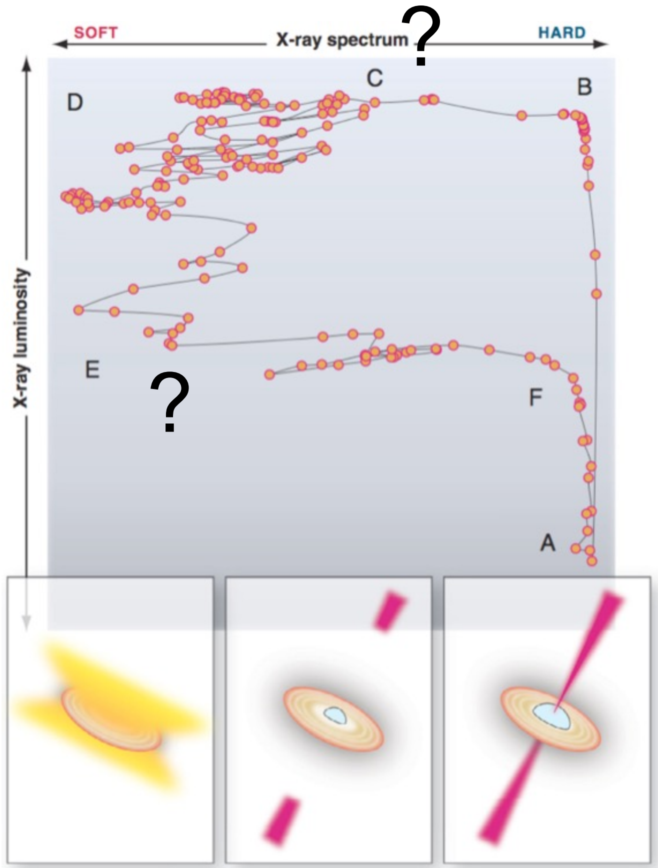




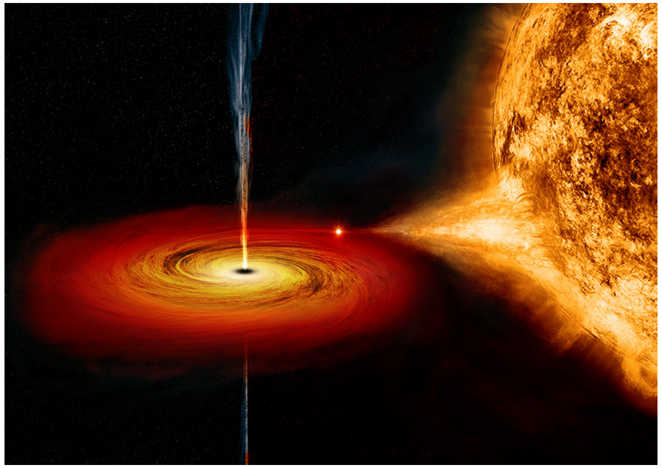
Adapted from Uttley et al. 2015

Accretion states





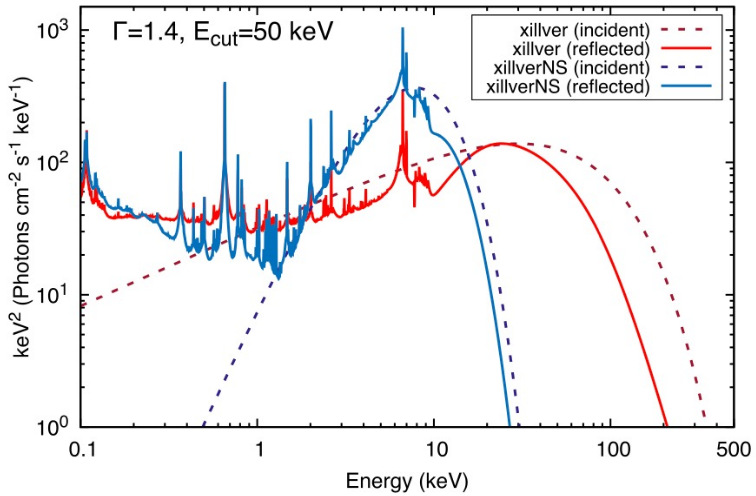
Fender et al. 2014



X-ray binaries at high spectral resolution in X-rays

- Plasma dynamics
  - Is the plasma inflowing/outflowing?
  - Radial and orbital dependence (determine masses of compact objects!)
  - Vertical structure
  - Systemic velocity (supernovae kick-offs?)
  - Turbulent velocity
- Plasma density and column density
- Plasma temperature and ionisation
- In some cases determine element abundances

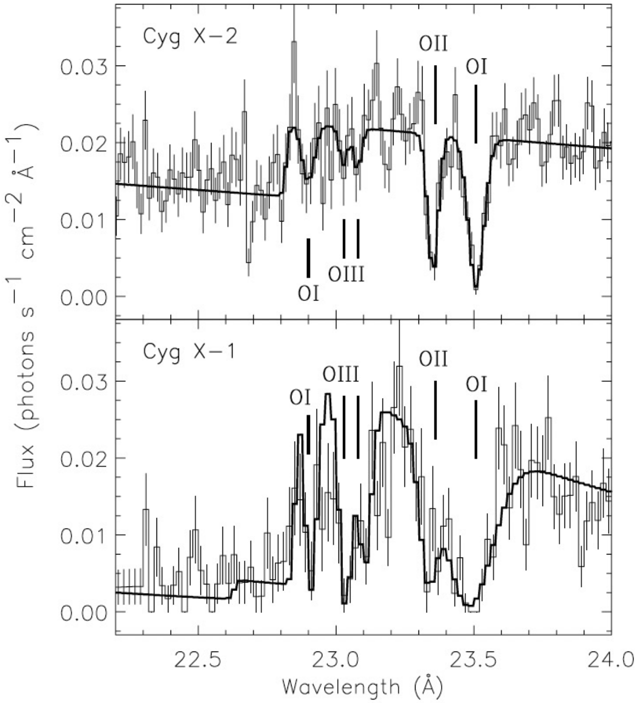
Reflection from the inner disc



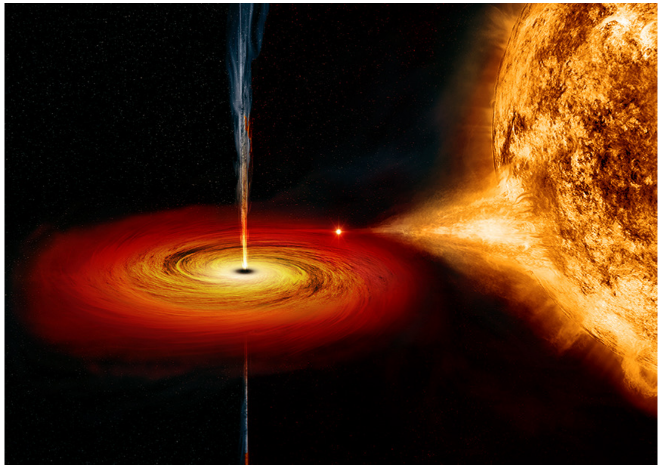
Garcia et al. 2022

(see Javier Garcia's talk)

Studies of the ISM

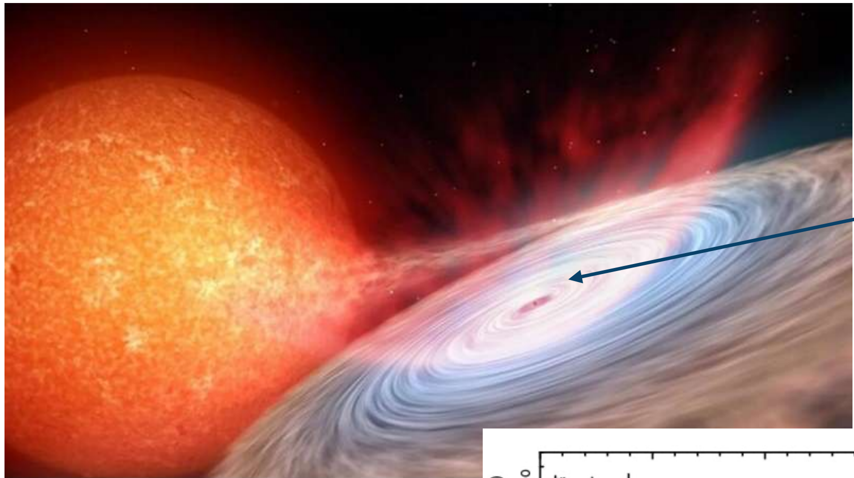


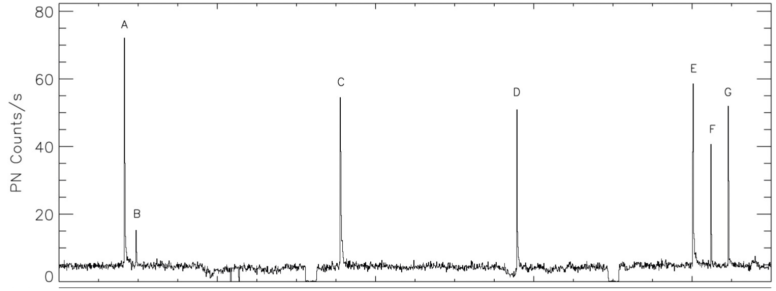
Juett et al. 2004

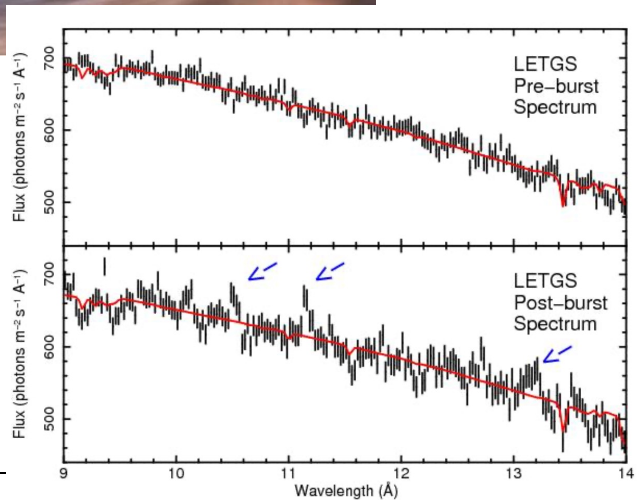


(see Ioanna Psadaraki's talk)

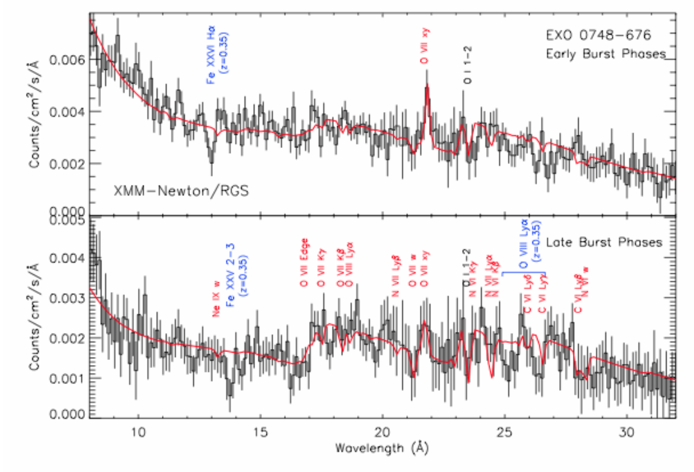
Bursts from the neutron star







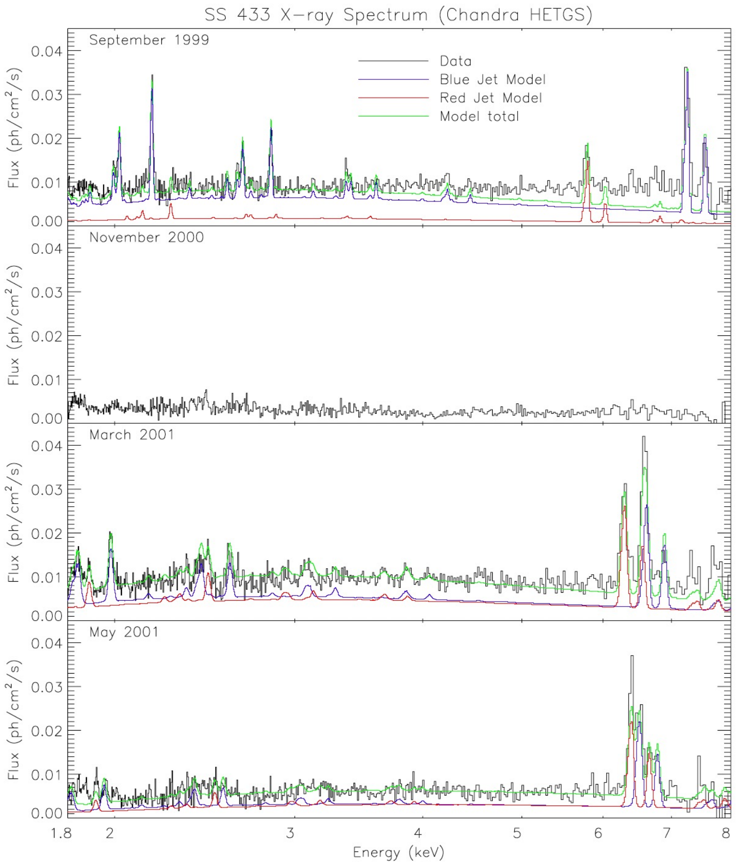
Pinto et al. 2014

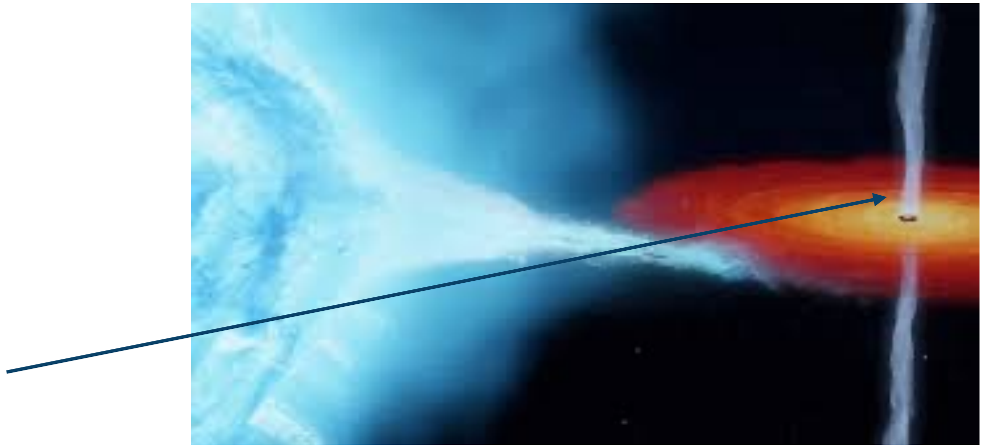


Cottam et al. 2002

Jets

Marshall et al. 2013





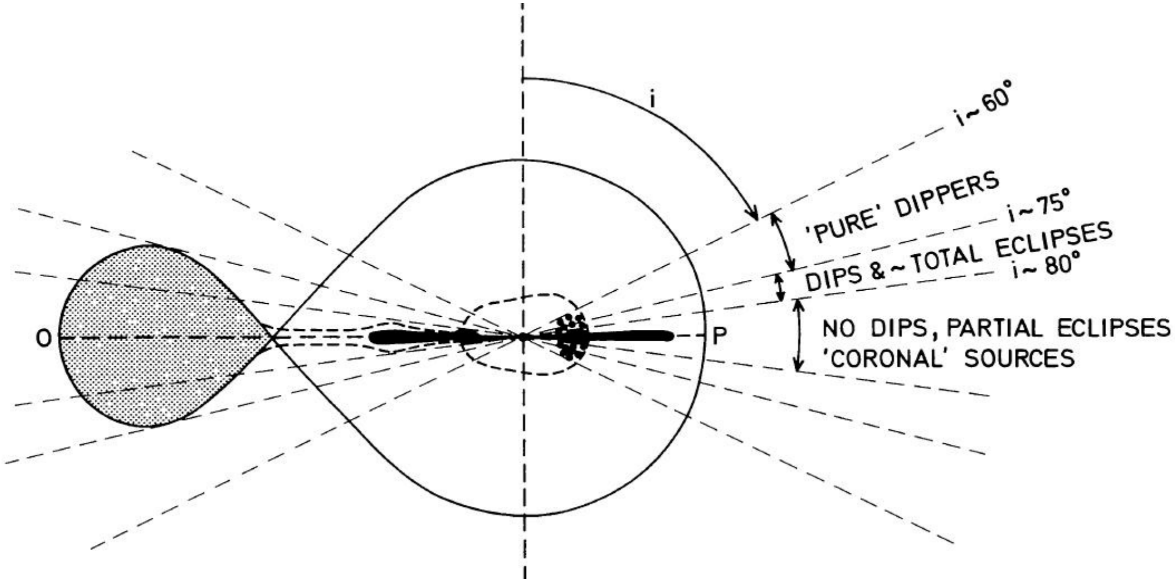
- Doppler-shifted lines from precessing jets
- X-ray emission lines arise in hot thermal plasma in the jet at distances of 10^{12} - 10^{13} cm from the compact object
- Jet opening angle 5x smaller than for optical lines

LMXBs

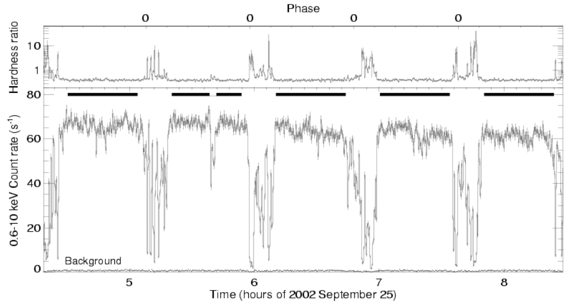
- High-inclination sources: disc atmospheres and winds (see Peter Kosec’s talk)
- Radial velocities: determine mass of the compact object
- Disc reflection (see Javier Garcia’s talk)
- ISM studies (see Ioanna Psdaraki’s talk)
- Neutron star bursters: effect of bursts on accretion discs, neutron star photospheres
- Circumbinary material
- Accretion streams

...

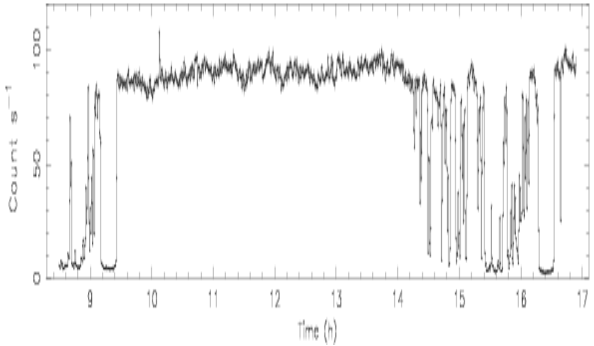
LMXBs: dipping sources



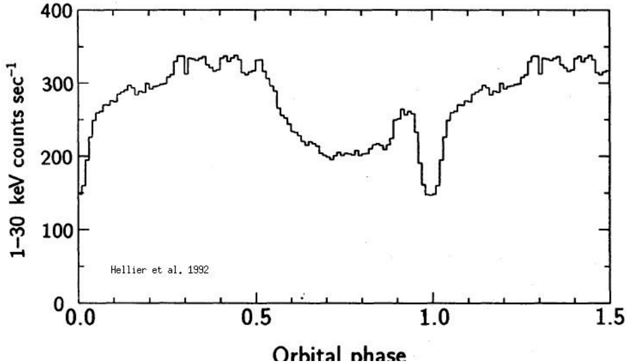
Frank et al. 1987



60-75 deg. 'Pure' dippers
(Boirin et al. 2004)



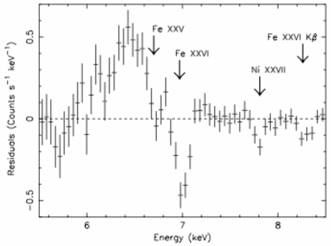
75-80 deg.
Dips & 'total' eclipses
(Sidoli et al. 2001)



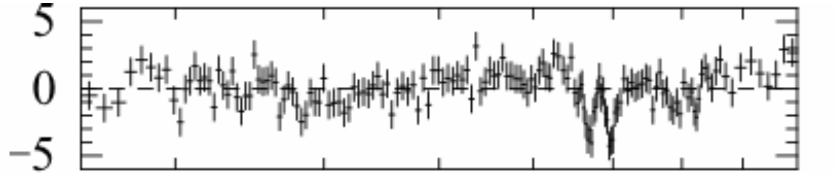
80-90 deg.
No dips, partial eclipses

LMXBs: disc atmospheres

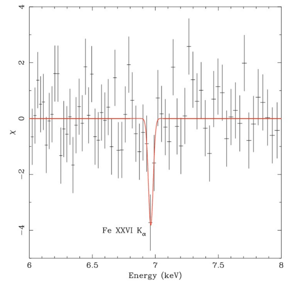
- Highly ionized absorption lines observed in sources at high inclination
- Implies plasma's equatorial shape (like a pancake!)
- Scale height: increases to ~0.1-0.2 (h/r) with irradiation (compared to Shakura-Sunyaev disc)
- Vertical and/or radial stratification within the atmosphere (see Her X-1 on P. Kosec's talk!)



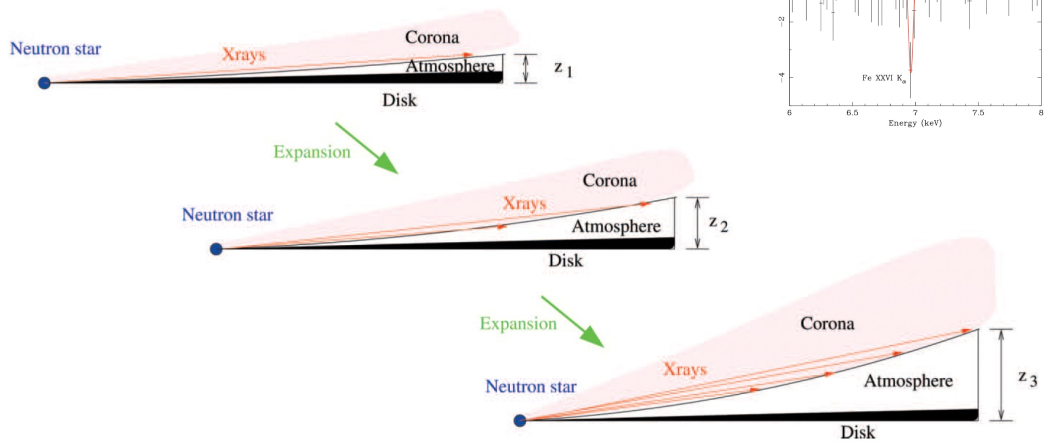
Parmar et al. 2002



Hyodo et al. 2008

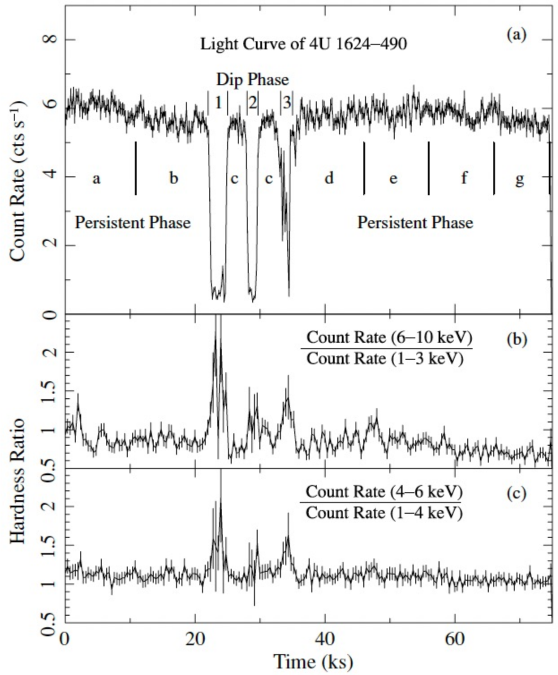


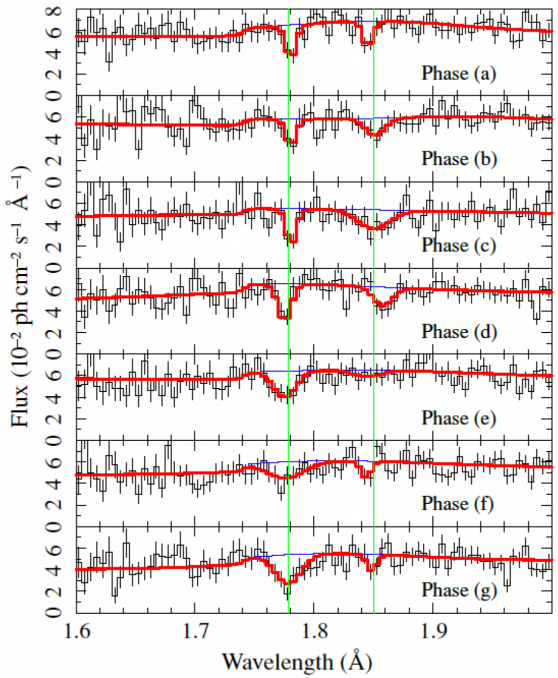
Iaria et al. 2007

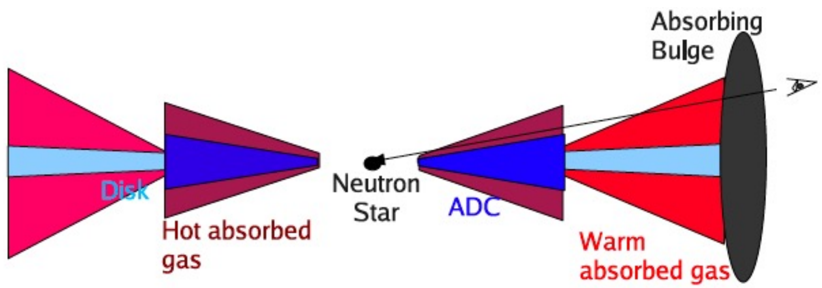


Jimenez-Garate et al. 2002
(see also Krolik 1981, Ko & Kallman 1991…)

Mapping plasmas
(orbital and radial dependence)

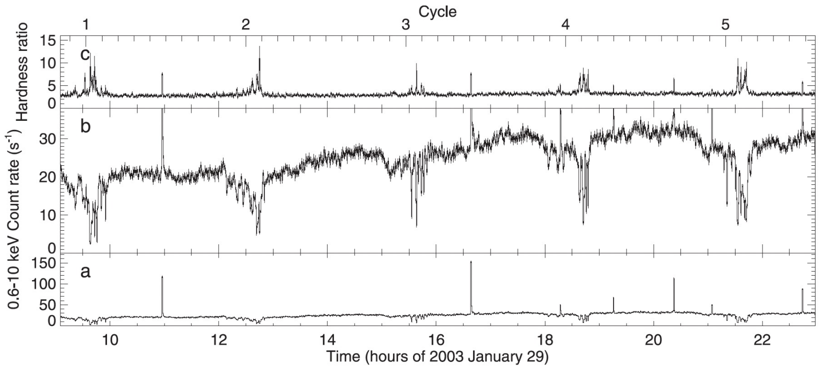




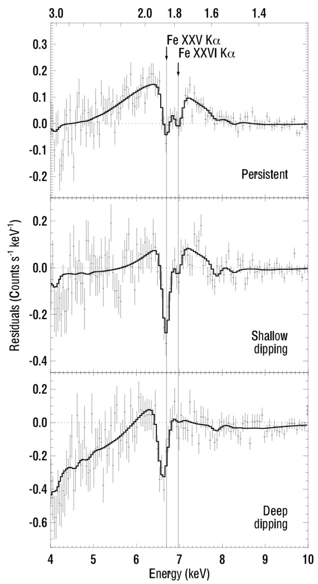


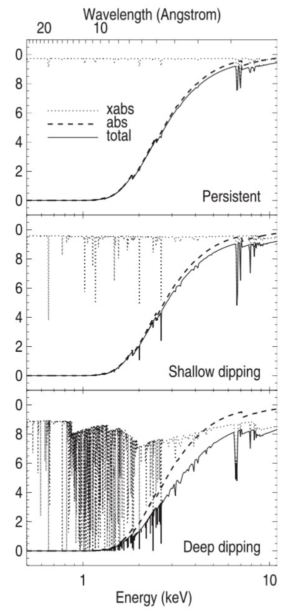
Xiang et al. 2009

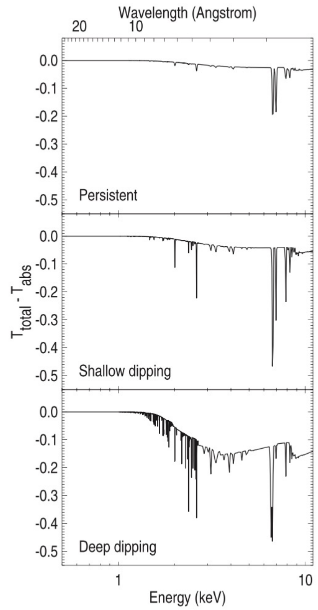
Mapping plasmas: multi-phases



Boirin et al. 2005

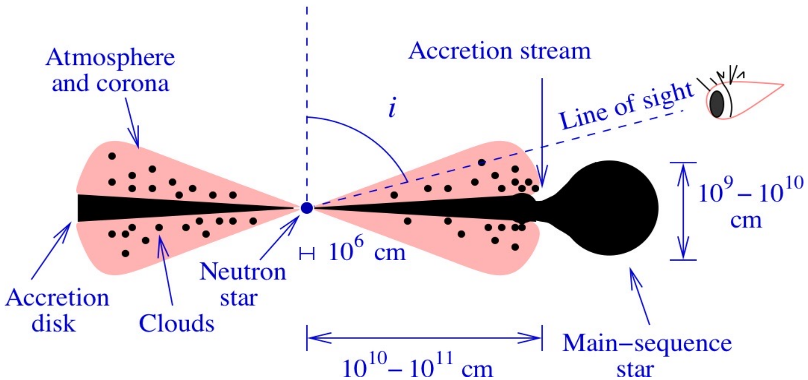




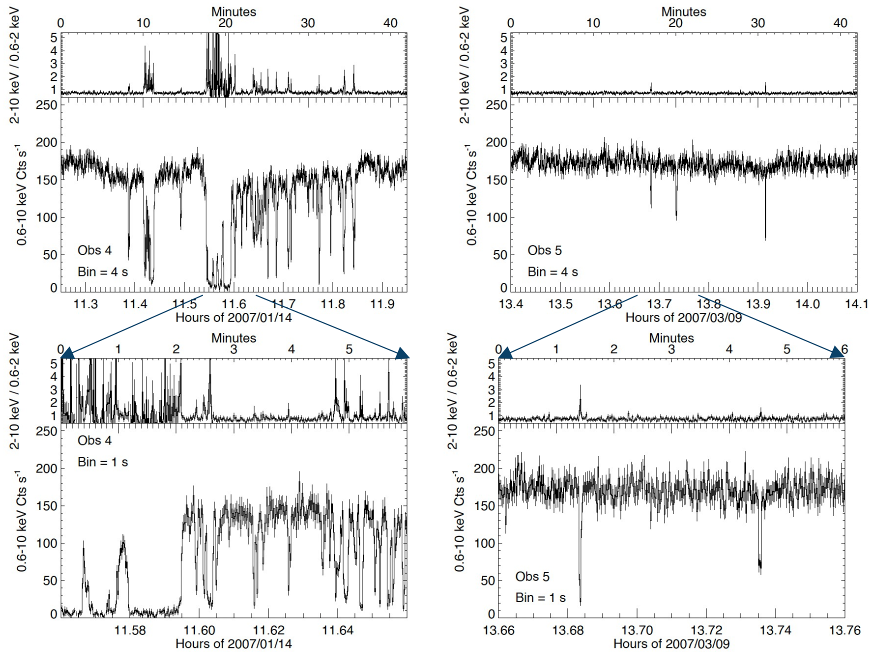


Complex changes in the light curves and spectral continuum modeled via changes in photoionized plasmas. All sources at high inclination show similar changes *(Boirin et al. 2005, Díaz Trigo et al 2006)*

Mapping plasmas: multi-phases / clumps?



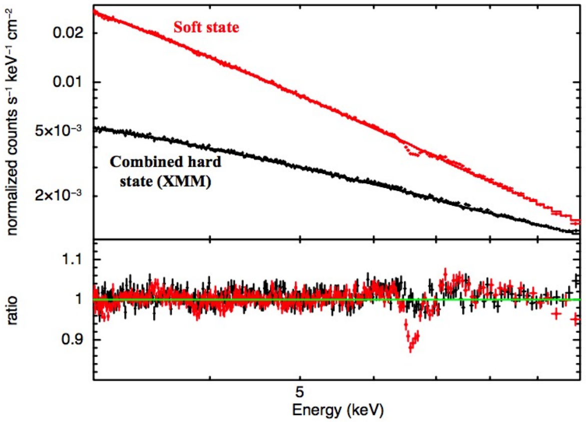
Jimenez-Garate et al. 2002



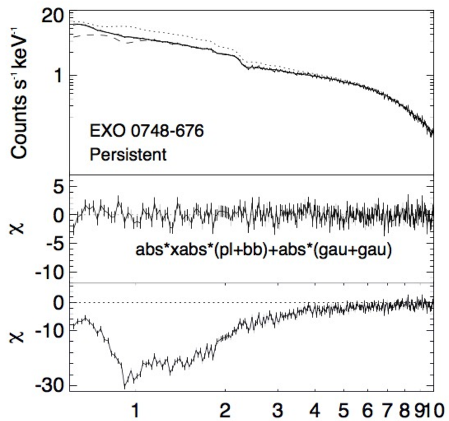
Díaz Trigo et al 2009

Dips that are uncorrelated with the orbital phase could be produced by orbital clouds crossing the line of sight (size > 10^6 cm)

Mapping plasmas: variability with accretion state

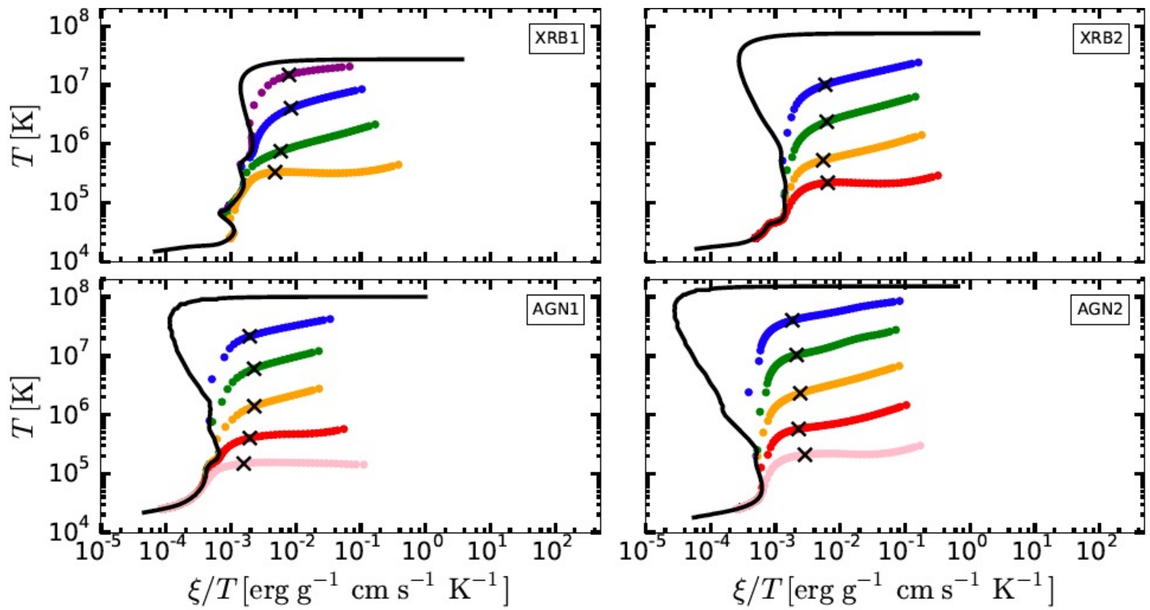


Ponti et al. 2014



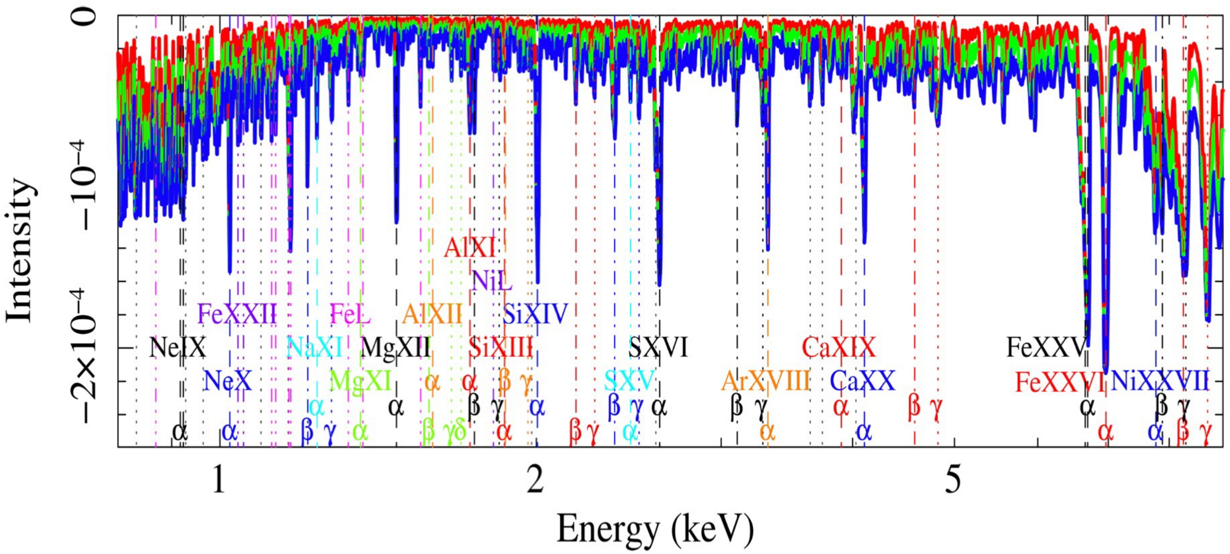
Diaz Trigo et al. 2006
(see also van Peet 2009)

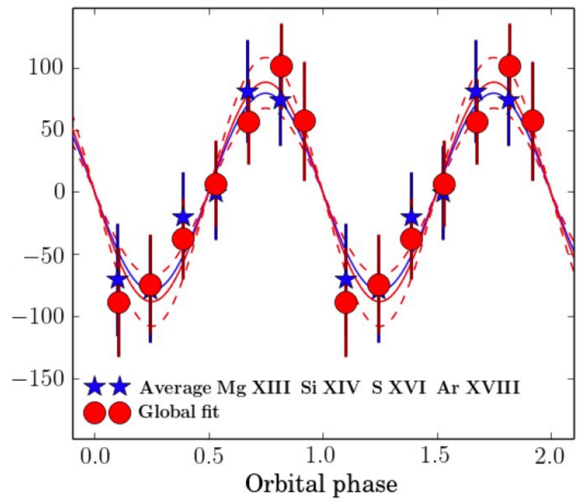
Dyda et al. 2016



Spectral hardness determines:
1) the amount of flux available for ionisation of given ions
2) the shape of the "thermal stability curve" (thermally stable regions or equilibrium states of a photoionised plasma)

Radial velocities





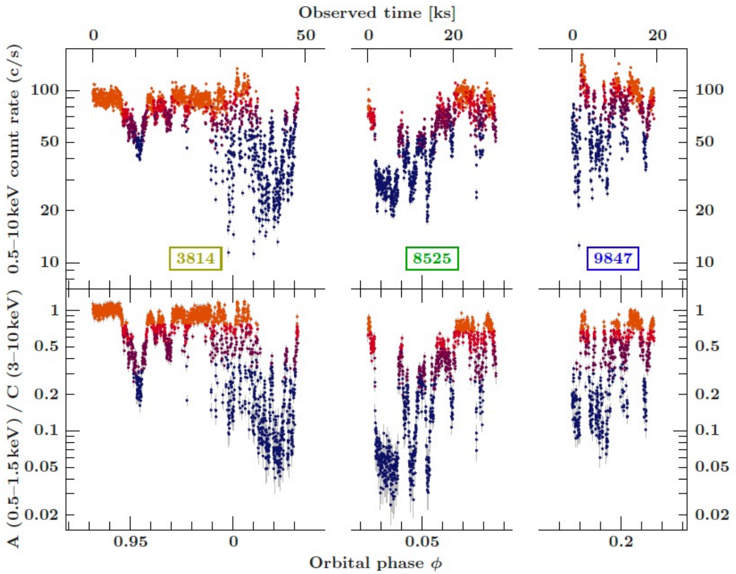
Ponti et al. 2019

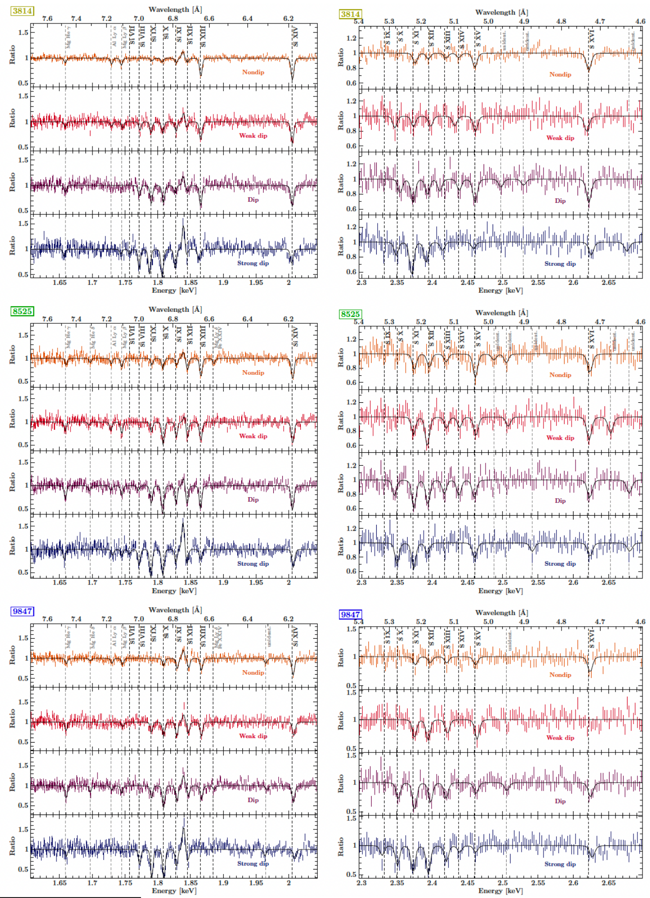
HMXBs

- Stellar winds:
  - Mass loss rates and terminal velocities from stellar winds poorly known
  - Understanding wind clumping crucial to determine mass loss rates (see L. Oskinova's talk)
- Studies in HMXBs:
  - Focused winds
  - Accretion/photoionisation wakes
  - Clumps
  - Shocks?
  - Connection to super-Eddington accretion (Ultra-luminous X-ray sources, see P. Kosec's talk)

(Cen X-3 presented in J. Rodes-Roca's talk)

Mapping plasmas: multi-phases / clumps

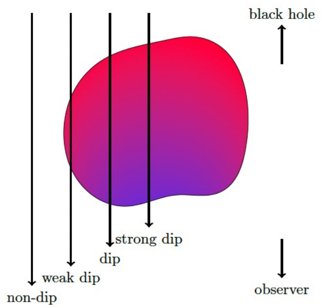




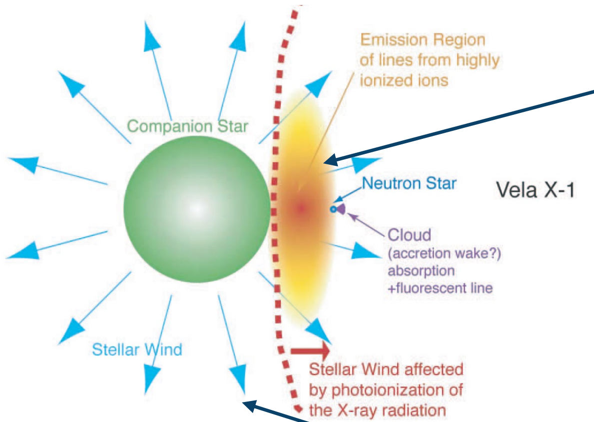
Cyg X-1

(variability attributed to clumps in the stellar wind)

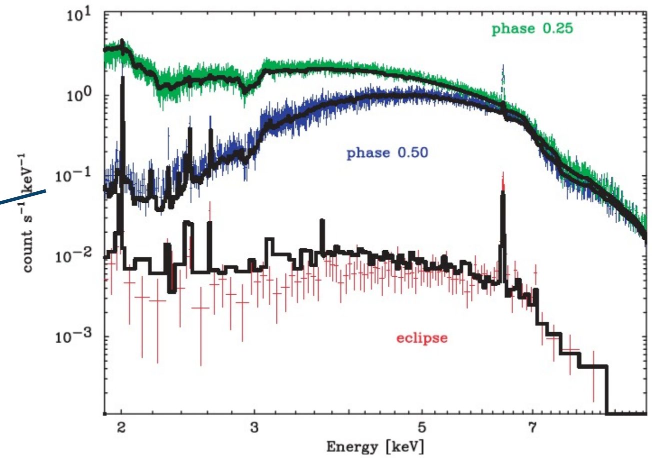
Hirsch et al. 2019
(see also Hanke et al. 2009,
Hell et al. 2013,
Miskovikova et al. 2016)



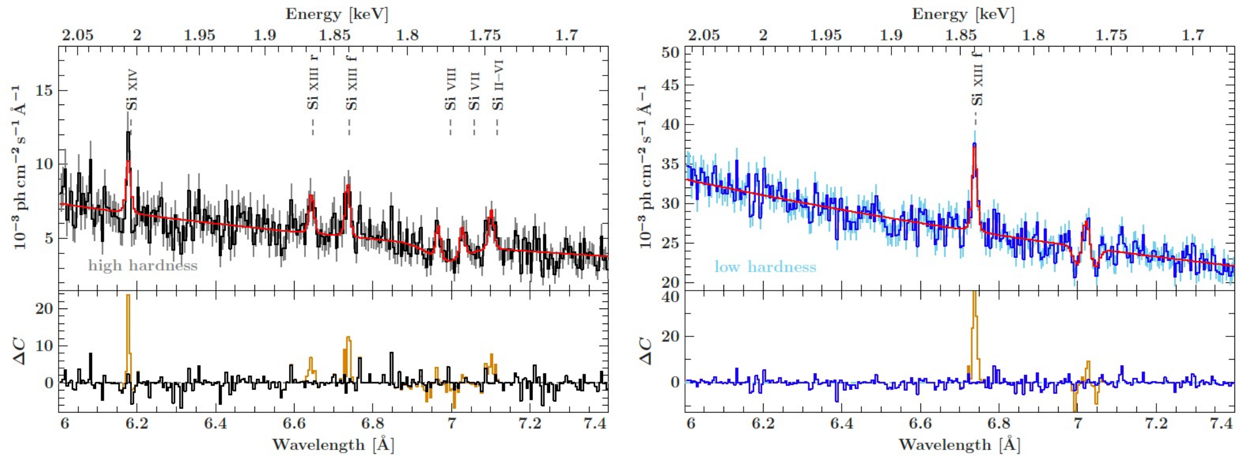
Accretion wakes, photoionisation, shocks…



Vela X-1



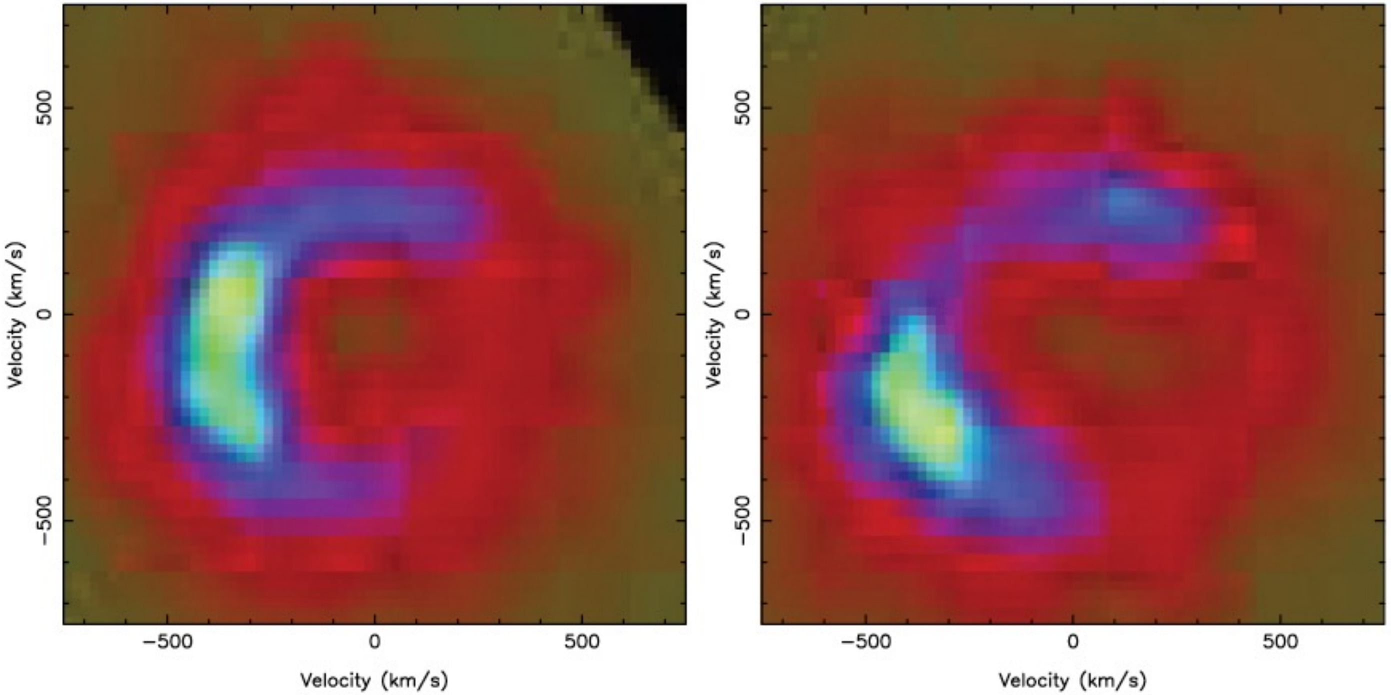
Watanabe et al. 2006



Grinberg et al. 2017

Some open questions and “resolving” them with high-resolution X-ray spectroscopy

What high spectral resolution can give you



Cornelisse et al. 2013

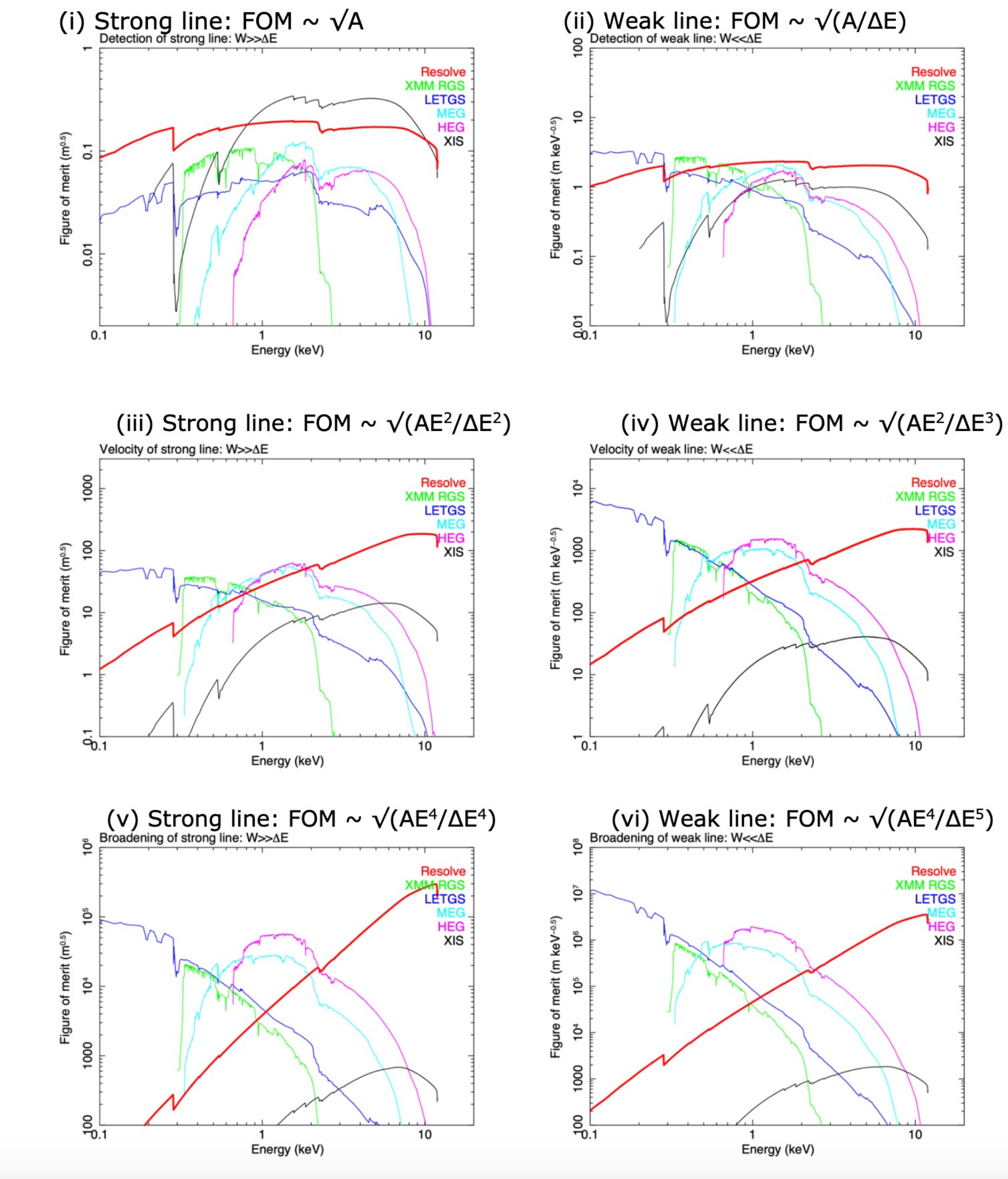
Could we get a Doppler map of a NS X-ray binary in X-rays?

(while waiting for a X-ray interferometer in space, Uttley et al. 2020)

XRISM

XRISM/Resolve (X-ray calorimeter)

Parameter	Requirement
Energy resolution	7 eV (FWHM)
Energy scale accuracy	± 2 eV
Residual Background	2 x 10^{-3} counts/s/keV
Field of view	2.9 x 2.9 arcmin
Angular resolution	1.7 arcmin (HPD)
Effective area (1 keV)	> 160 cm^2
Effective area (6 keV)	> 210 cm^2
Cryogen-mode Lifetime	3 years
Operational Efficiency	> 90%



XRISM Quick Reference Guide

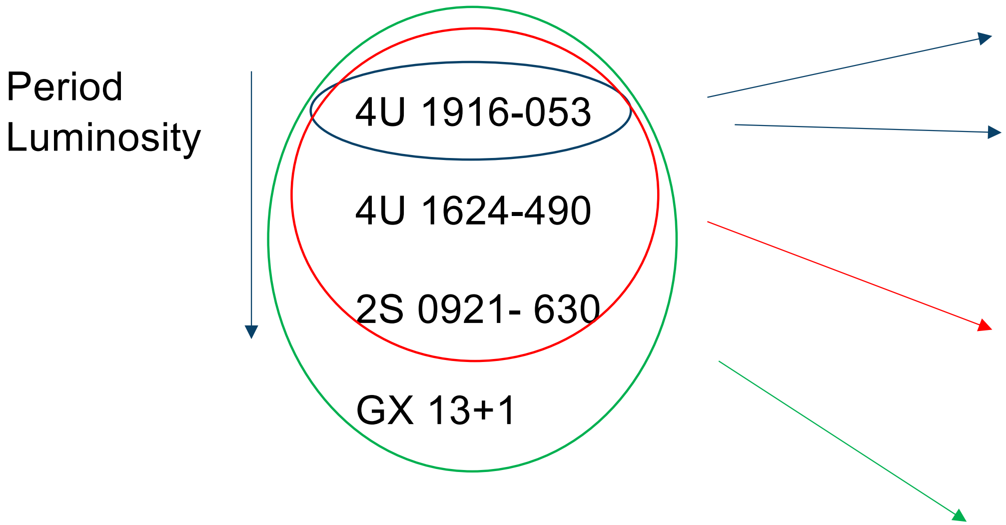
XRISM PV Phase XRBs

Target	Exp. Time (ks)
4U 1916-053	50
4U 1624-490	50
GX 13+1	30
Cyg X-1	100
SS 433	80
Cyg X-3	40
Cen X-3	90

Target	Exp. Time (ks)
2S 0921-630	80
Cir X-1	40
Vela X-1	70

Range of compact objects (BH, NS), stellar companions (wind or disc fed) and accretion rates

LMXBs with XRISM



Gravitationally redshifted atmospheres

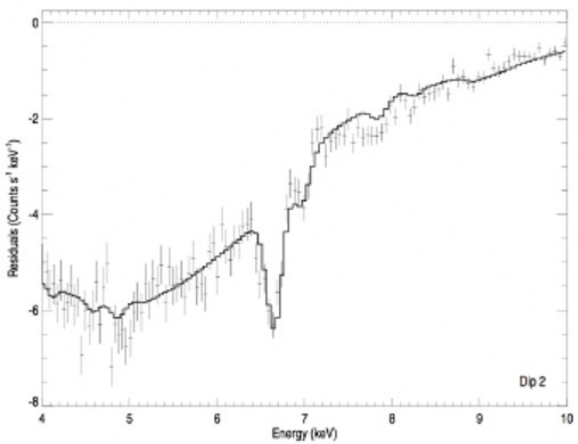
Bursts effect on disc atmosphere

Clumps / multi-phase plasma

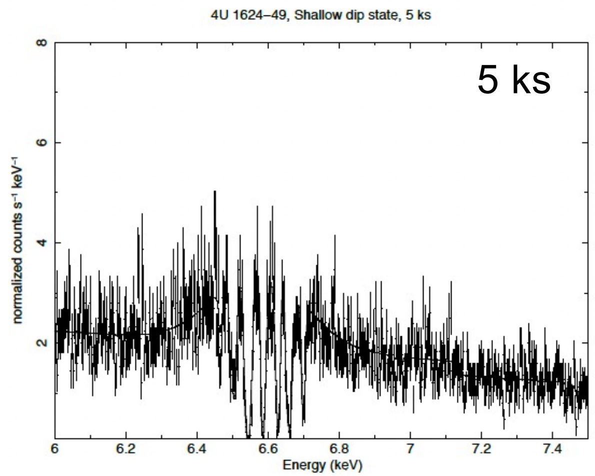
Geometry of atmospheres

Test wind launching mechanisms
(as a function of XRB size/luminosity)

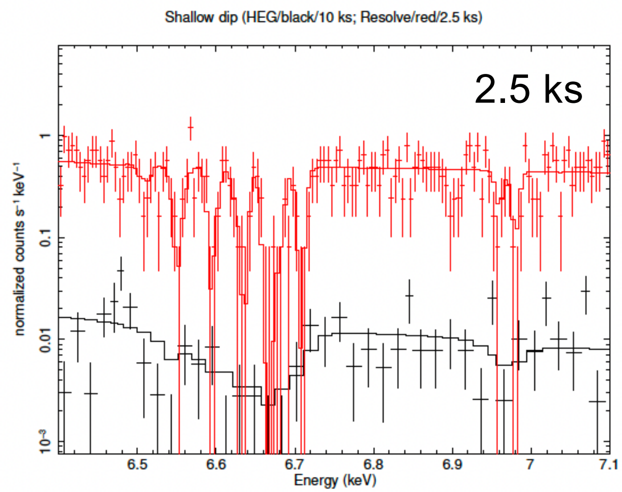
LMXBs with XRISM



XMM / EPIC (black, CCD)



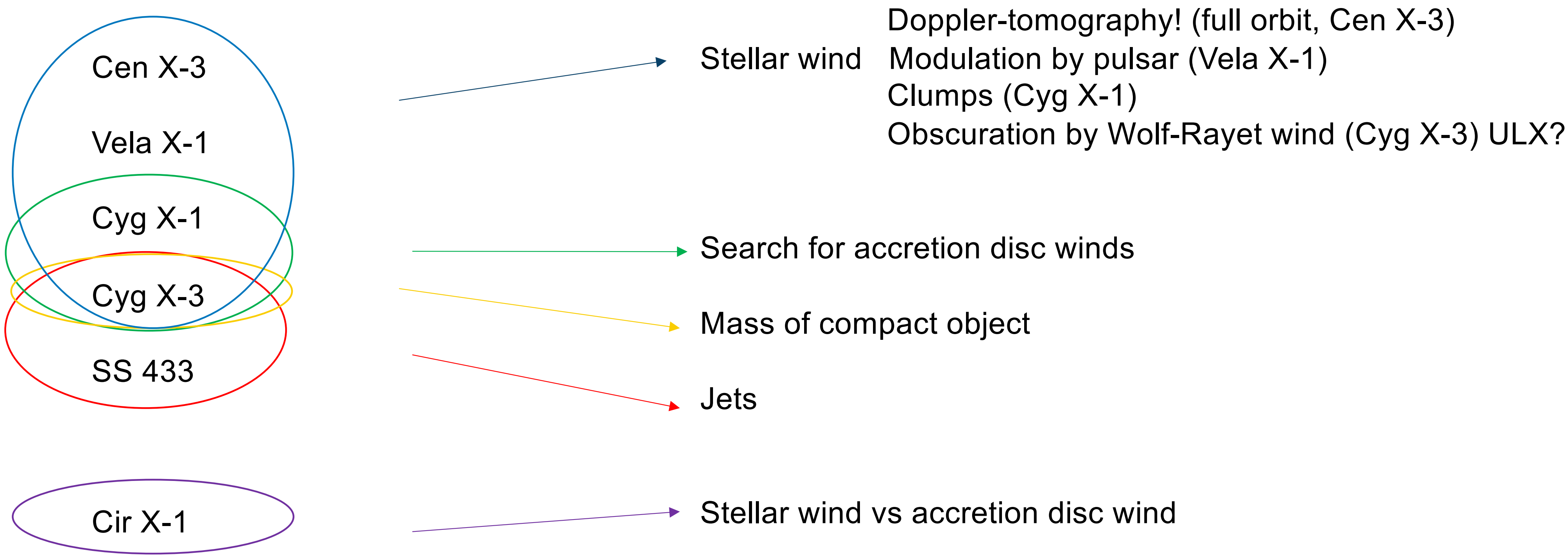
XRISM / Resolve (black, calorimeter)



XRISM / Resolve (red, calorimeter)
Chandra / HEG (black, grating)

Map for the first time Fe L and Fe K simultaneously at high resolution!

HMXBs with XRISM



Beyond the PV phase

Nature Astronomy — Review

Accretion physics at high X-ray spectral resolution: New frontiers and game-changing science

P. Gandhi,[1] T. Kawamuro,[2] M. Díaz Trigo,[3] J.A. Paice,[1,4] P.G. Boorman,[5,1] M. Cappi,[6] C. Done,[7] A.C. Fabian,[8] K. Fukumura,[9] J.A. García,[10] C.L. Greenwell,[1,3] M. Guainazzi,[11] K. Makishima,[12,13,14] M.S. Tashiro,[15] R. Tomaru,[7] F. Tombesi,[16,17,18,19] Y. Ueda[20]

Summary

Past 20 years:

- Established the presence of several, mainly photoionised, plasmas above the accretion discs (atmospheres) and outflowing (winds)
- Orbital-phase dependence
- Vertical and radial stratification
- Variability of the plasmas with the continuum illumination
- Theoretical efforts on RHD/MHD simulations

Future:

- Put all ingredients together to fully map the "disc" structure (including scattering and shielded regions and winds)
- Use variability at diverse timescales to study multi-phase winds (both disc and stellar)

Fellowships in Germany or Chile

Here you can find all the information related to the ESO Fellowship Programme and the recruitment process.

The application deadline is every year on October 15.

If you are interested in applying for the ESO Fellowship in Germany or Chile, please read carefully the instructions for applicants.

For a general overview of the ESO Fellowship Programme please download the ESO Fellowship brochure and click on the topics below for further details.

What makes it unique	Mission and Vision	How we support you
Duration and Frame of the Programme	Fellows' Research	Fellows and ESO Projects
Development Programme	Recruitment Process	Remuneration and Benefits