Accretion disk winds in X-ray binaries

Peter Kosec

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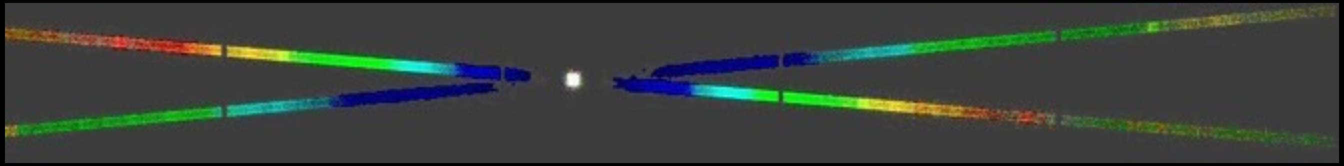


Accretion onto compact objects and disk winds

- Shakura & Sunyaev (1973) – theoretical prediction of outflows from accreting systems
- Plethora of possible launching mechanisms
  - Radiation pressure, line driving, magnetic forces, thermal driving

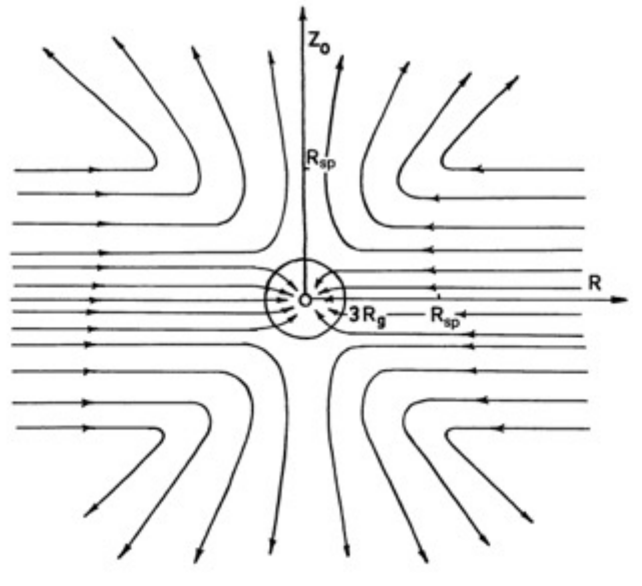


Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the Z-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins

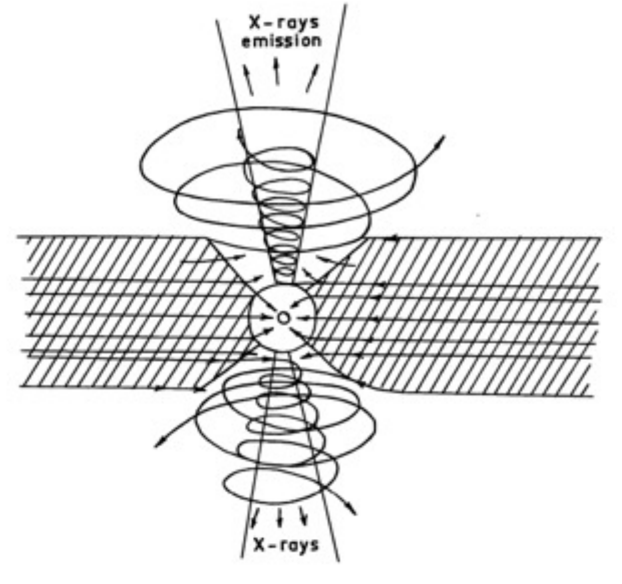
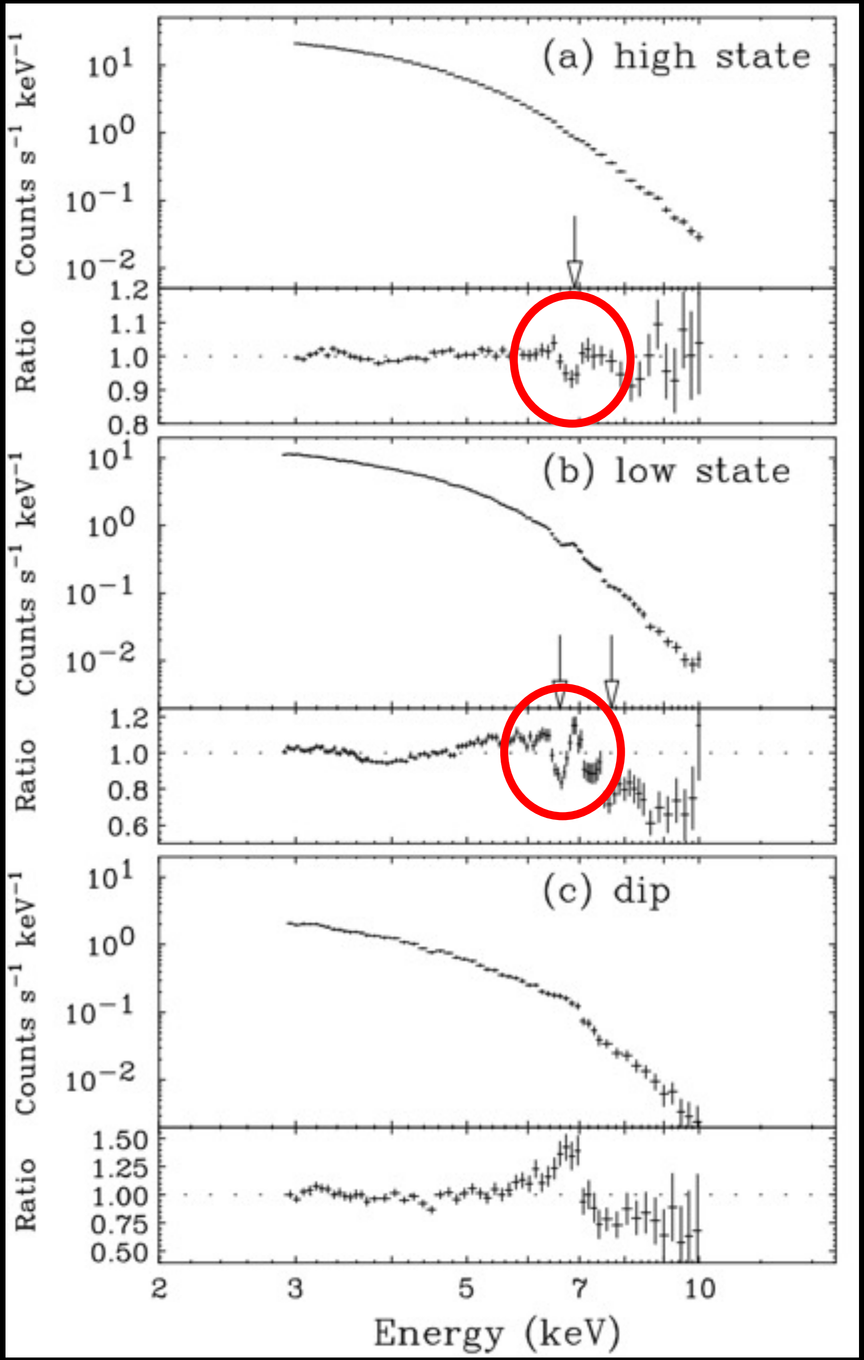


Fig. 9. The outflow of the matter from the collapsar at the supercritical regime of accretion

Discovery of X-ray binary disk winds

- Detected in late 90s observations with ASCA, but confirmed with gratings onboard Chandra (HETG) and XMM-Newton (RGS)

Ueda+98



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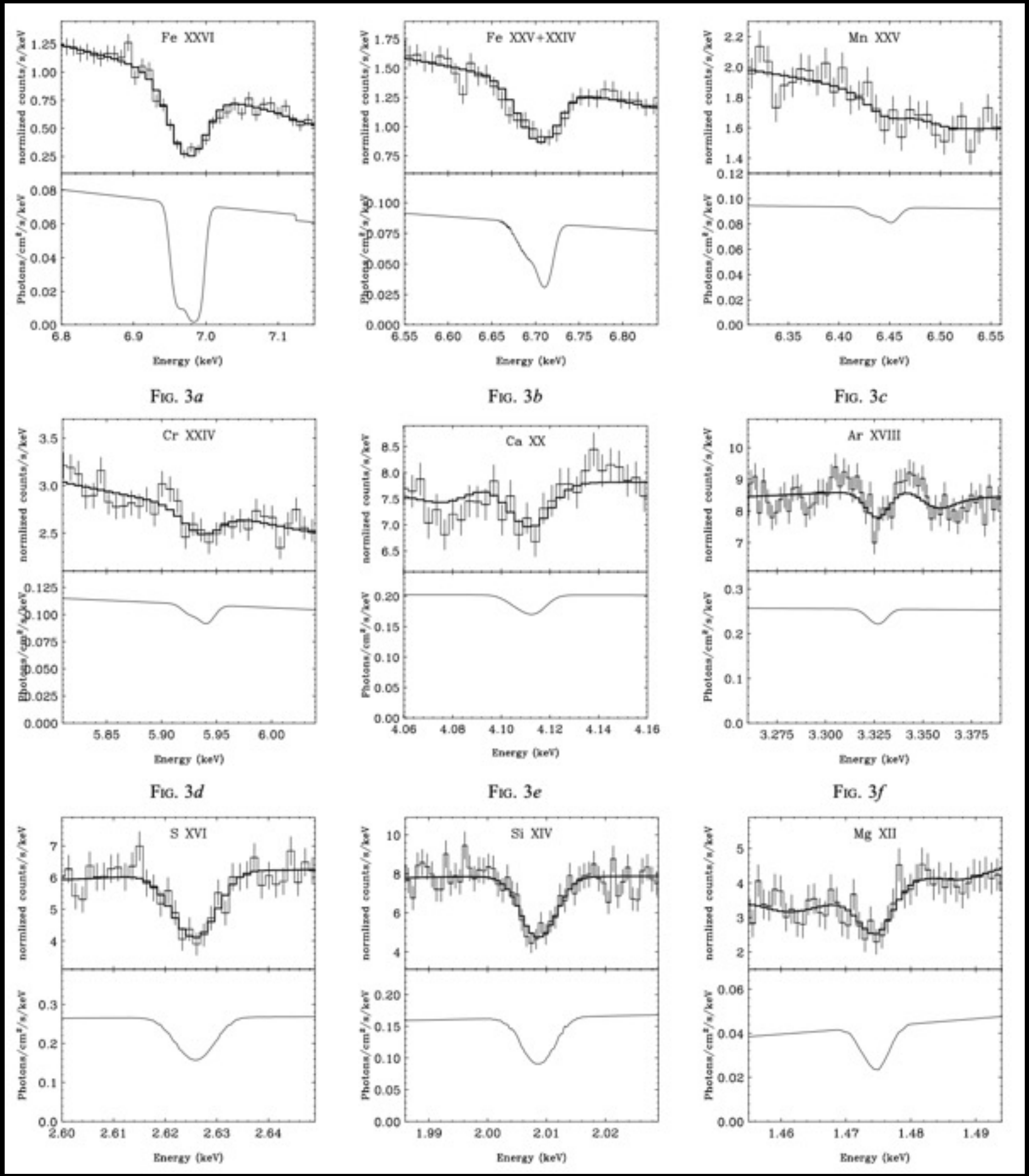
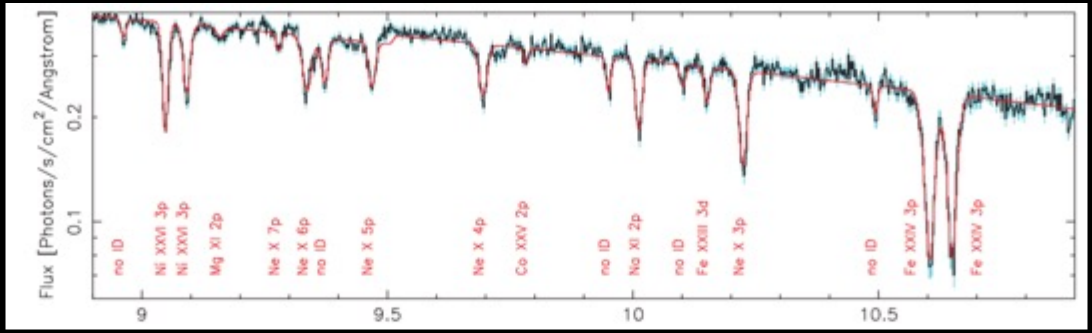
Ueda+04

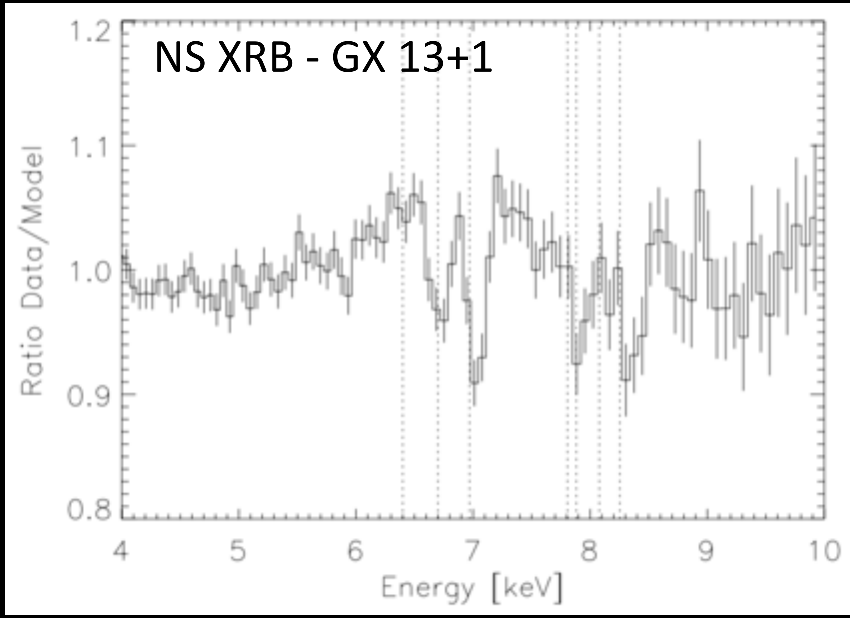


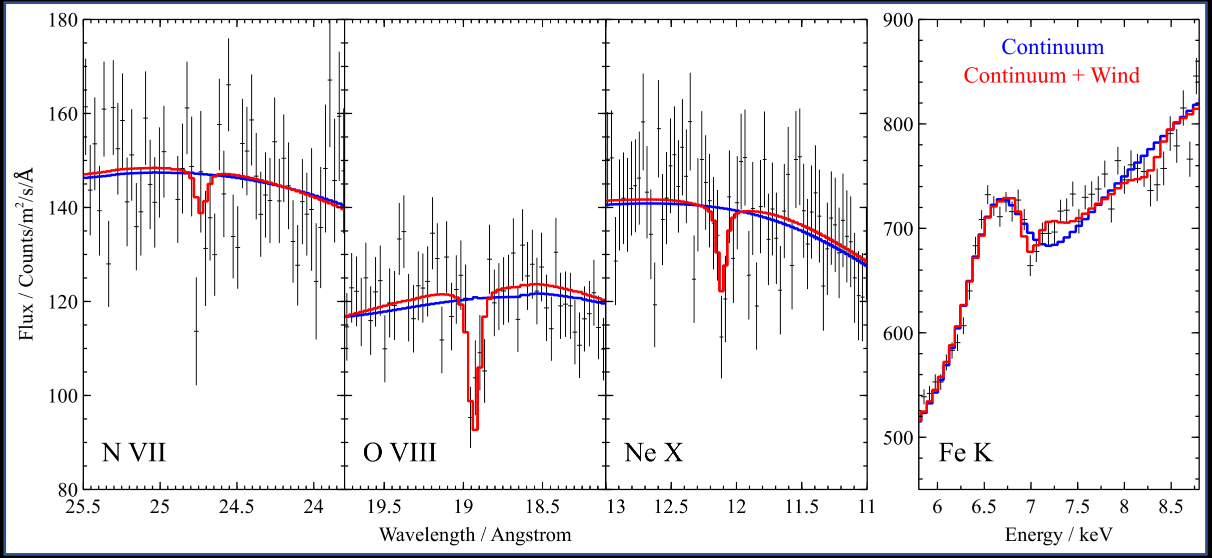
X-ray Binary wind ZOO

- X-ray winds detected in:
  - Black hole XRBs
  - Low-magnetic field neutron star XRBs
  - High-magnetic field X-ray pulsar (Her X-1)
- Usually show high column densities, high ionization, low velocities* (~1000 km/s)
- Outside XRBs: also seen in active galactic nuclei, tidal disruption events, white dwarfs

BH XRB - GRO J1655-40







X-ray pulsar – Her X-1

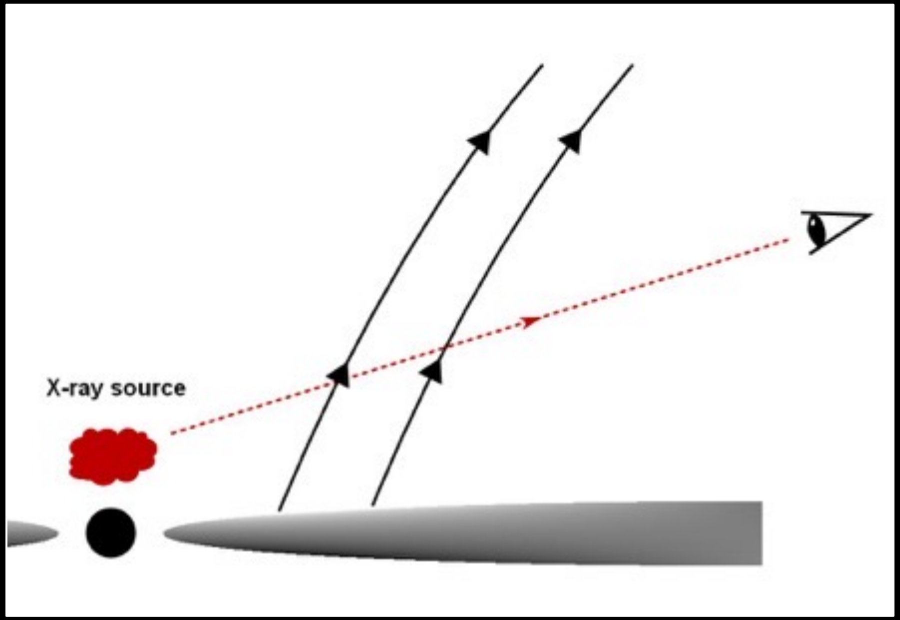
*exceptions apply

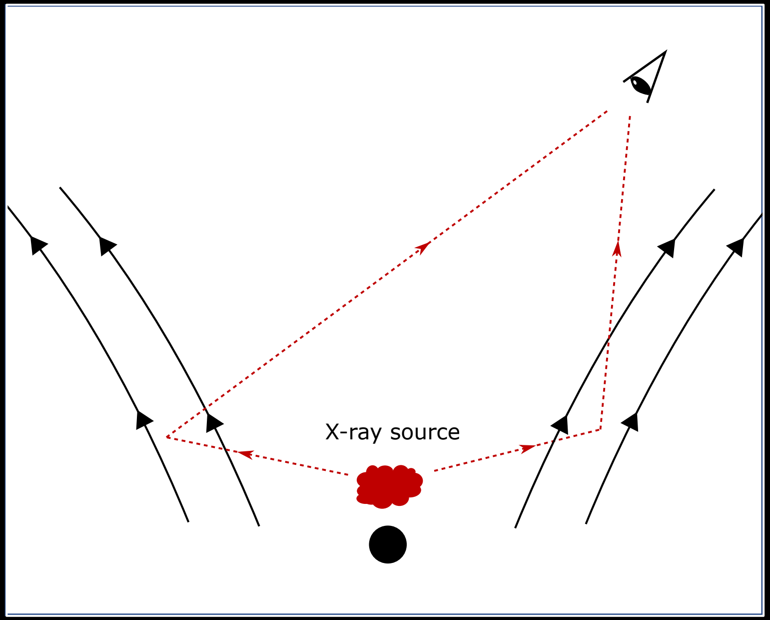
Miller+08, Diaz Trigo+12, Kosec+20

Disk winds – why do we care?

- Winds can carry away large fraction of originally infalling mass
  - Significantly modify accretion flows, evolution of X-ray binaries
- Winds from inner accretion flow (in some XRBs) can reach relativistic velocities (~0.1c) -> huge kinetic power
  - Significantly affect neighborhood of accreting systems

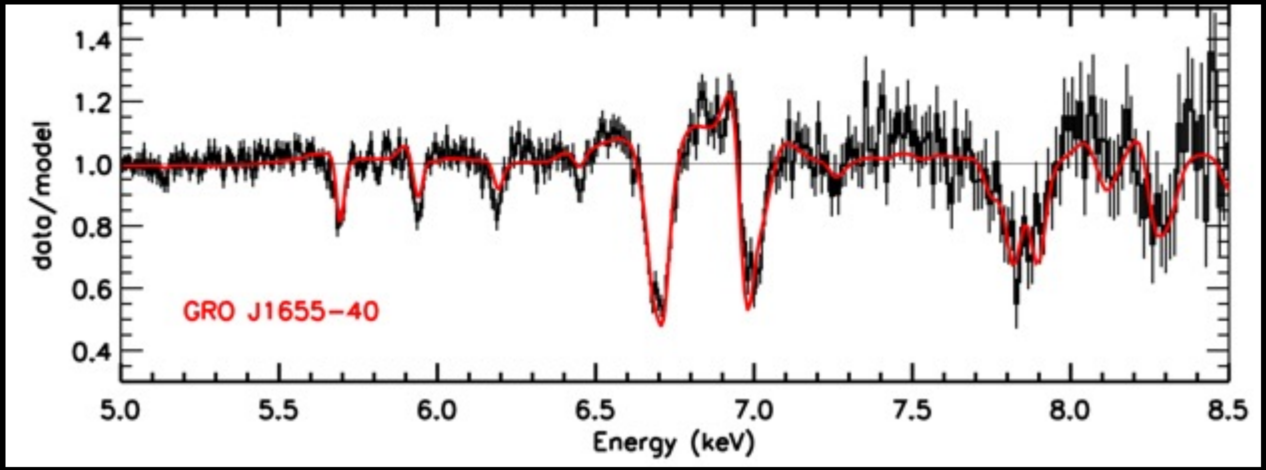
Studying ionized outflows with X-ray spectroscopy





- Absorption spectra particularly useful
  - But only sample wind at a single point!
- Can model wind re-emission to study 3D wind structure
  - Emission often weak, modelling can be degenerate

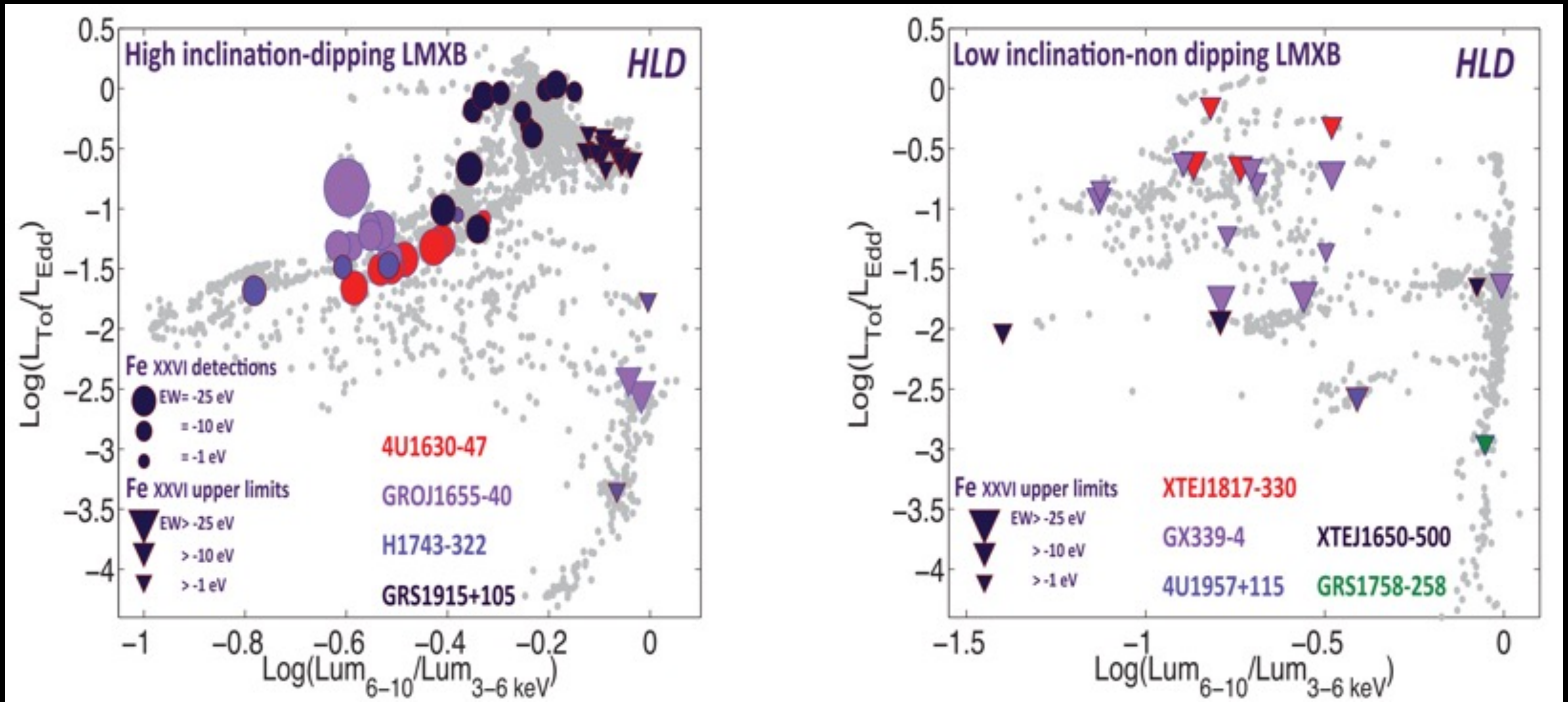
Miller+15



Wind geometry and time evolution

See also the following talk by M. Parra

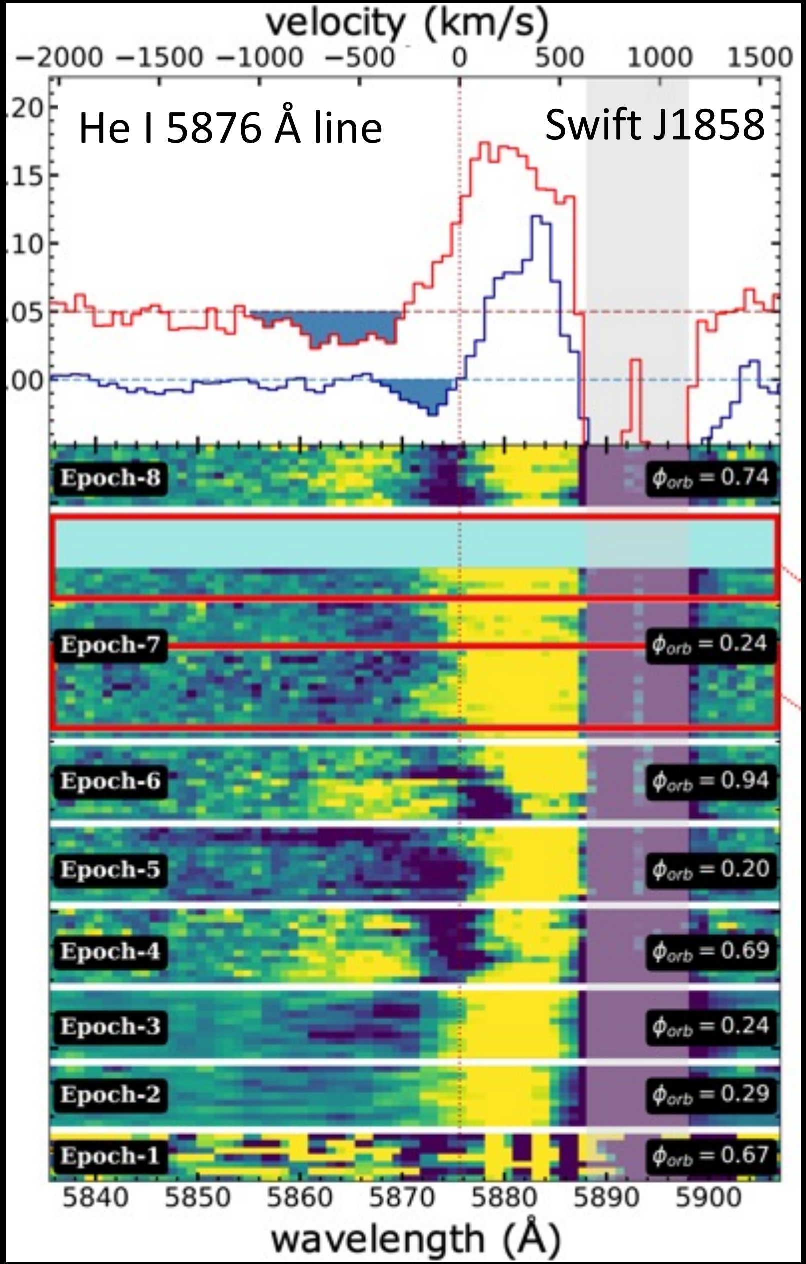
- Outflow detections in:
  - High-inclination XRBs -> outflow geometry not spherical but equatorial
  - Soft states -> Over-ionization of the wind? Thermal instability in hard states? No wind launching in hard states?



Ponti+12

More recently: outflows in X-ray binaries also seen outside X-ray band!

- Transient and persistent outflows (~1000 km/s) seen in optical, near-IR and UV band
  - Detected primarily in hard states of XRBs, but were also observed throughout some XRB outbursts



Castro Segura+22, also Munoz-Darias+18,+19,+20,+22

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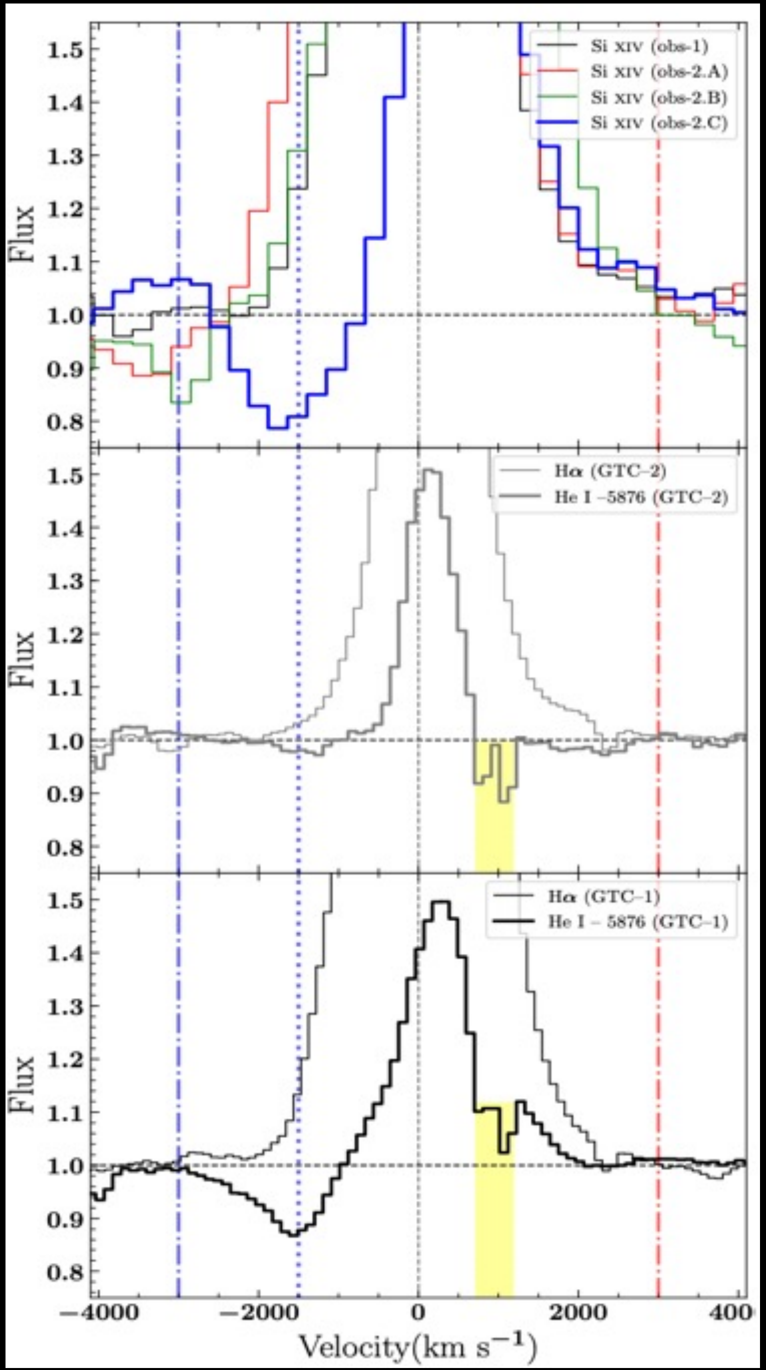
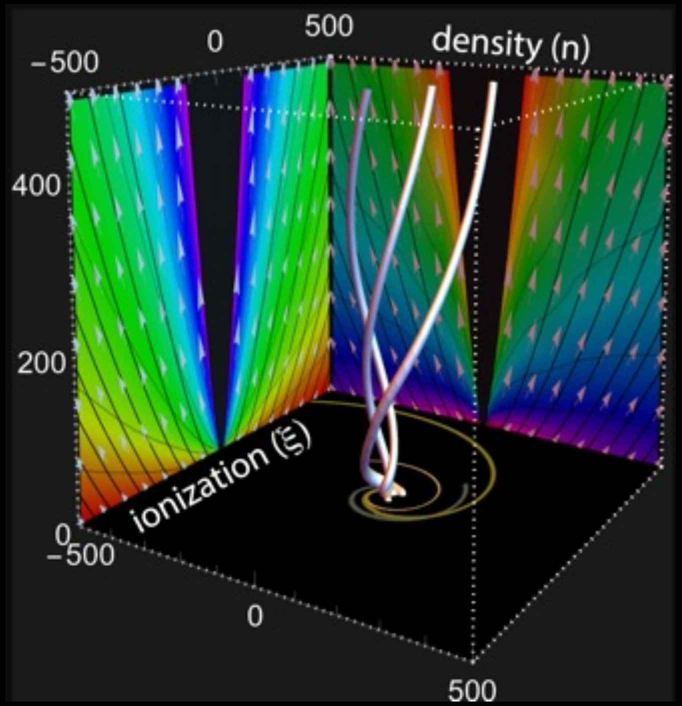
- Transient and persistent outflows (~1000 km/s) seen in optical, near-IR and UV band
  - Detected primarily in hard states of XRBs, but were also observed throughout some XRB outbursts
- Can co-exist with X-ray detected winds at the same time (V404 Cygni)
  - Possibly forming a complex multi-phase outflow, which can be detected both in X-rays as well as in UV/O/IR

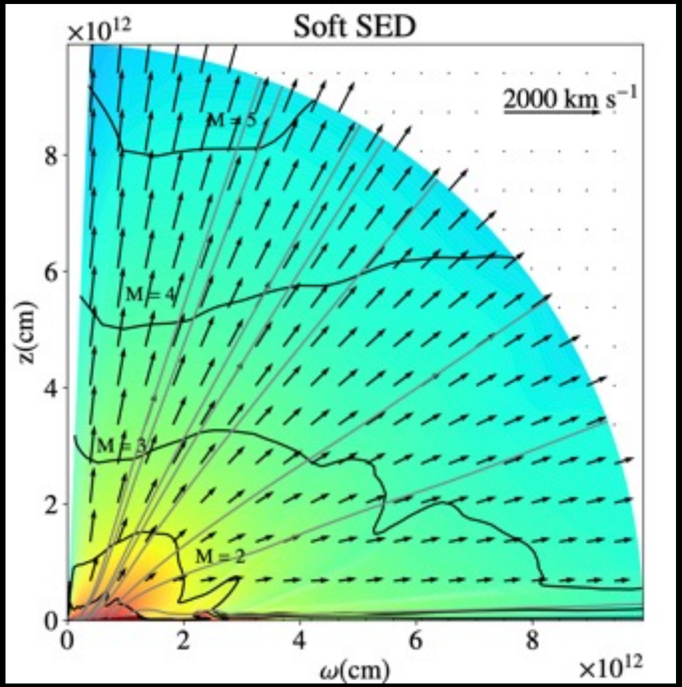
Castro Segura+22, also Munoz-Darias+18,+19,+20,+22



XRBs: possible wind driving mechanisms

- Radiation line pressure
  - Radiation pressure on many UV transitions
  - But: material cant be over-ionized by hard X-rays
- Magnetic driving
  - Wind launching along magnetic field lines for certain magnetic configurations
  - But driving force heavily depends on the magnetic field configuration and strength in the disk: difficult to study
- Compton heating/ thermal driving
  - Wind launched from outer disk irradiated by hard X-ray radiation
  - Produces low-velocity outflows (~1000 km/s)

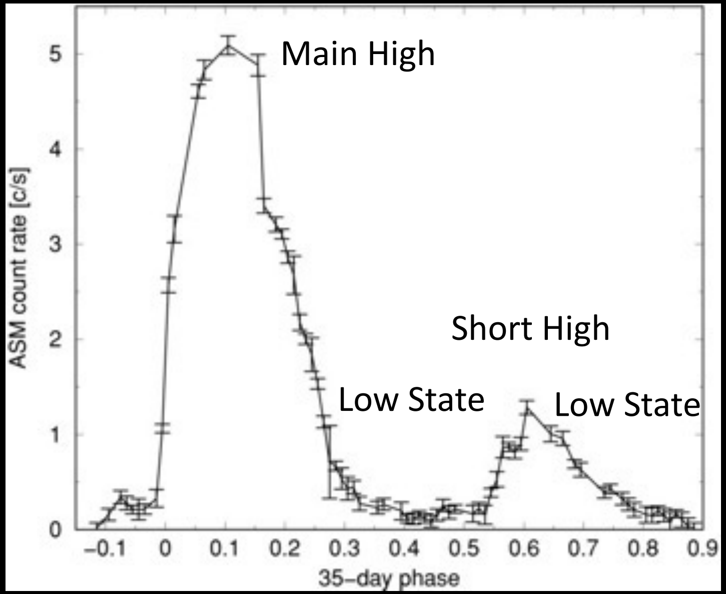




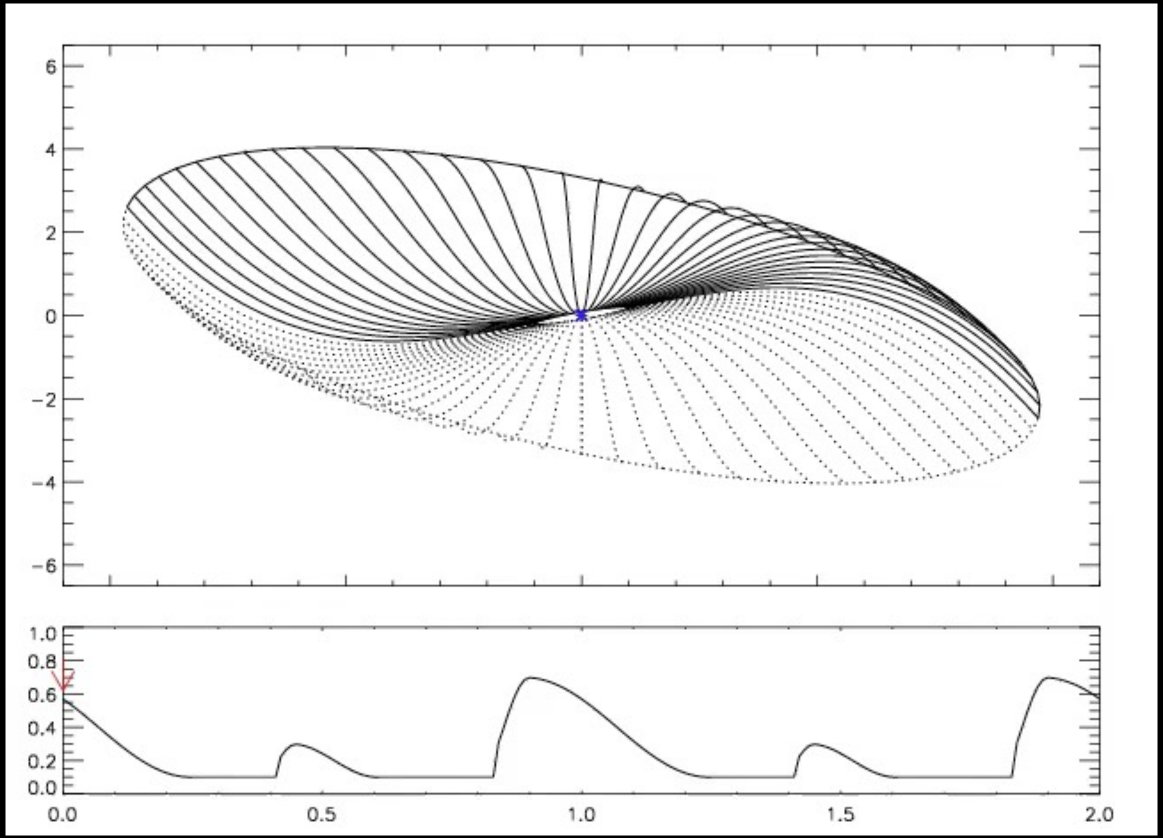
Blandford&Payne 82, Begelman+83, Proga+00, Fukumura+18, Higginbottom+20

Hercules X-1: leveraging the line of sight to study 3D wind structure

- Neutron star XRB with warped, precessing disk (35-day period): repeating high and low X-ray flux states
- Disk precession -> time-variable line of sight through ionized disk wind!



Leahy&Igna 2010, Kosec+20

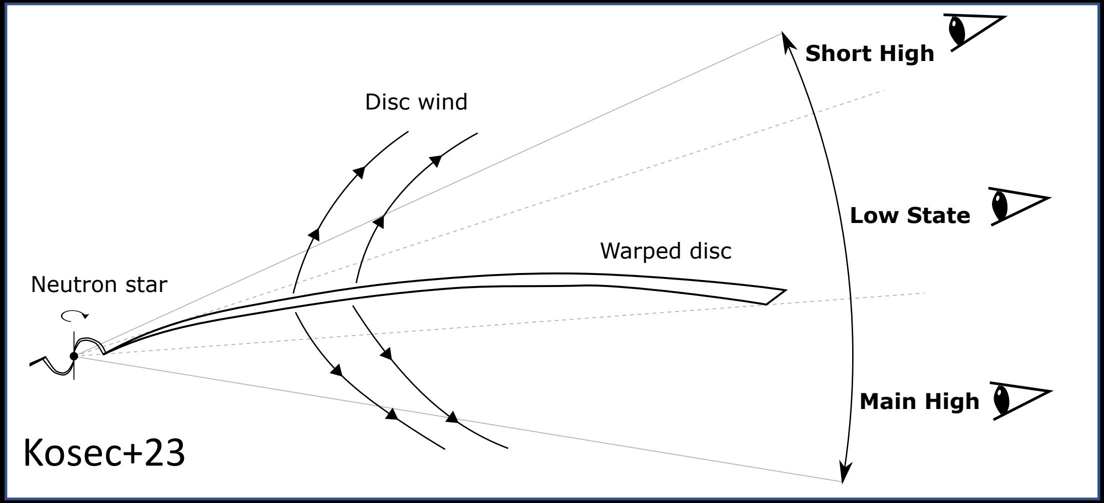


Courtesy of R. Hickox. Model from Leahy, Scott & Wilson (2000).

Her X-1: wind evolution with precession phase

- Large campaign to study wind properties with phase -> wind evolves with height above disk

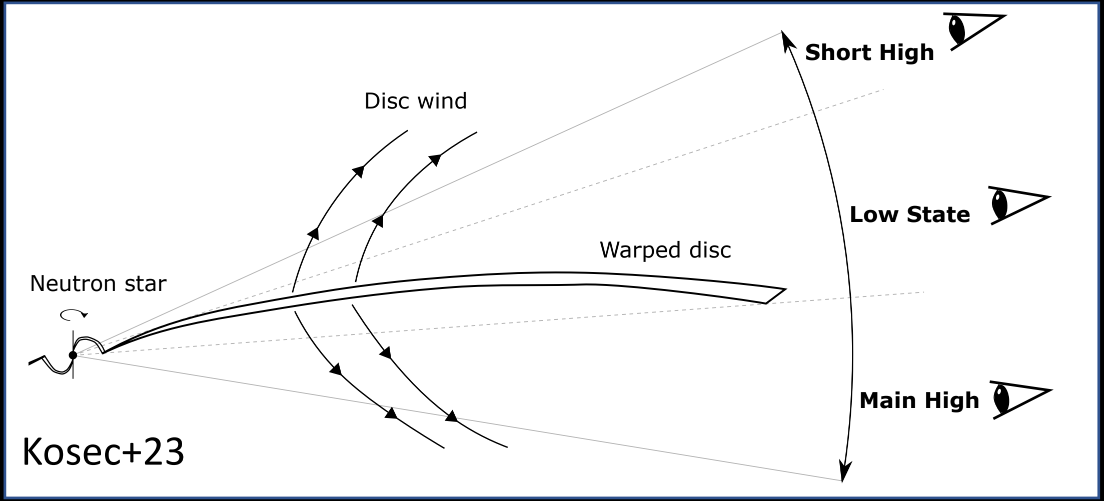
Precession cycle flux states

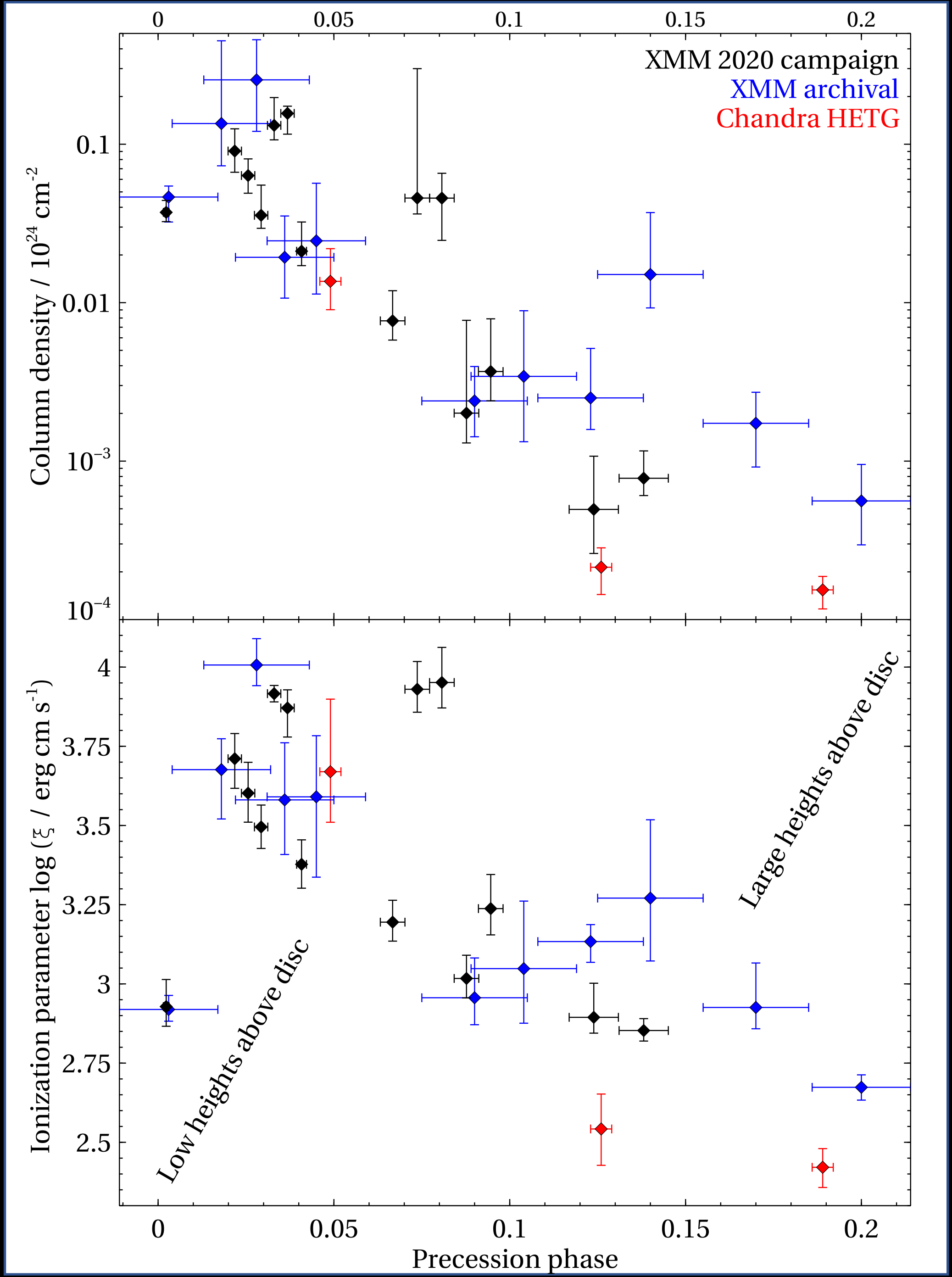


Her X-1: wind evolution with precession phase

- Large campaign to study wind properties with phase -> wind evolves with height above disk
- Column density strongly decreases with height
  - In agreement with XRB population studies and simulations
- Strong evolution in ionization parameter as well

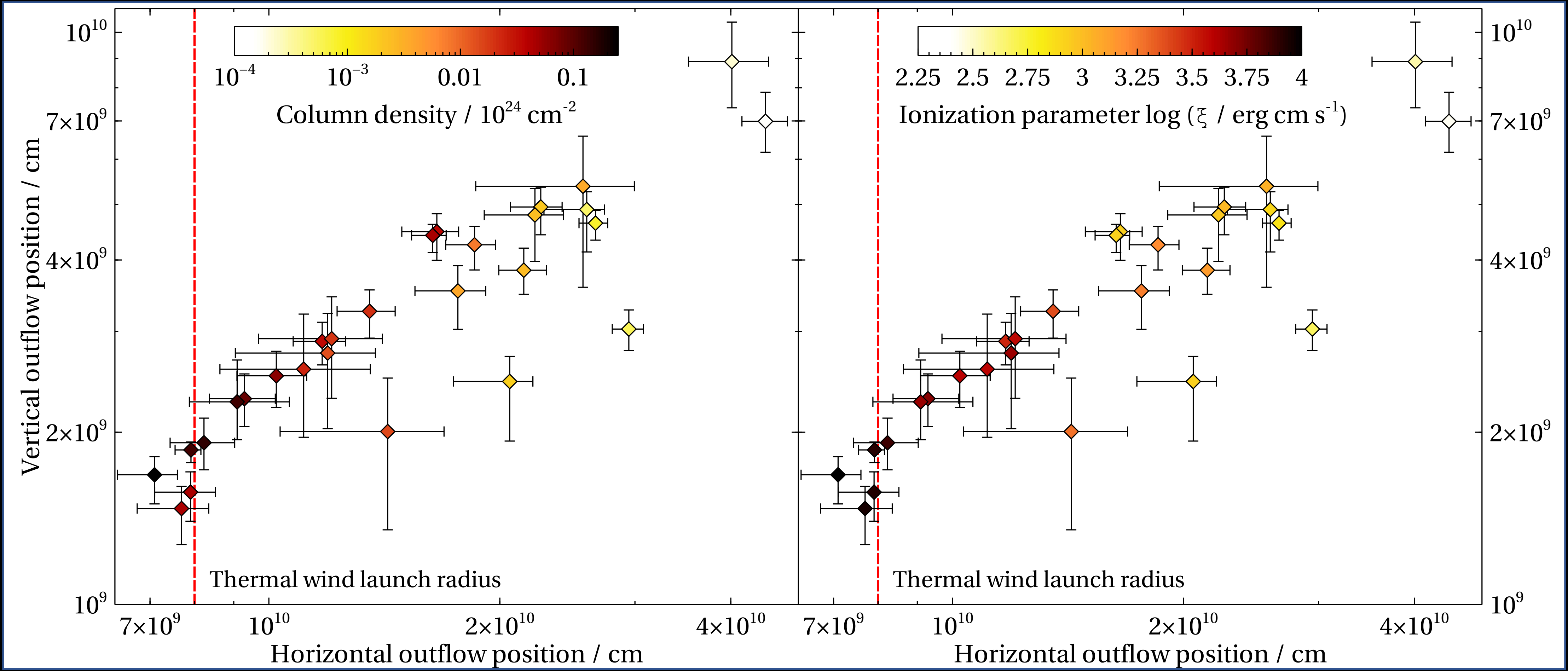
Precession cycle flux states





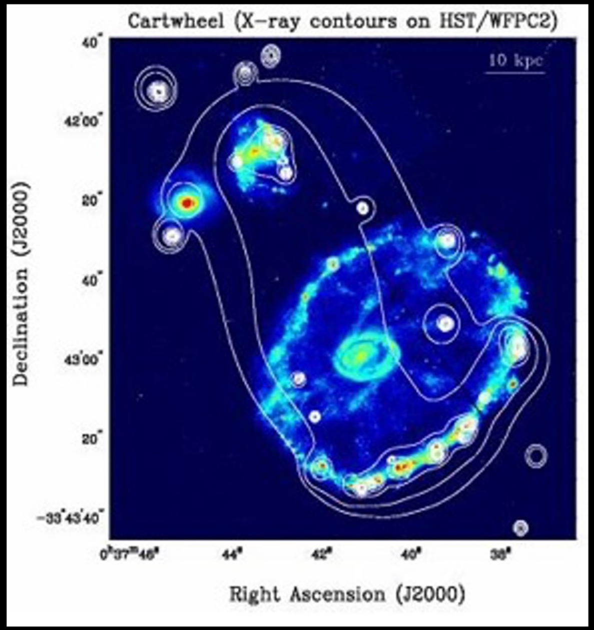
Her X-1: 2D map of a disk wind

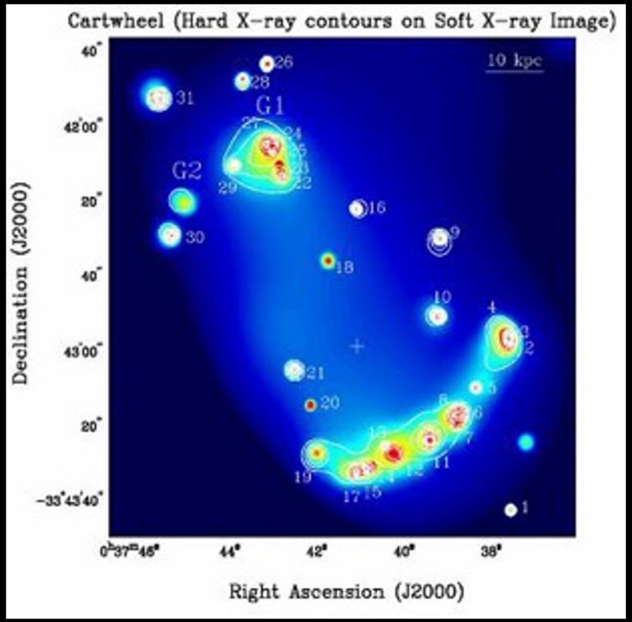
- Model the warped disk shape using estimated wind distances from the X-ray source -> obtain a 2D map of an accretion disk wind



Ultraluminous X-ray sources: the most extreme X-ray binaries

- (Extragalactic) non-nuclear objects with X-ray luminosity exceeding Eddington luminosity of a stellar-mass ($10\ M_S$) black hole ($\sim 10^{39}$ erg/s)
  - Intermediate mass black holes or super-Eddington accretion?





Gao+03

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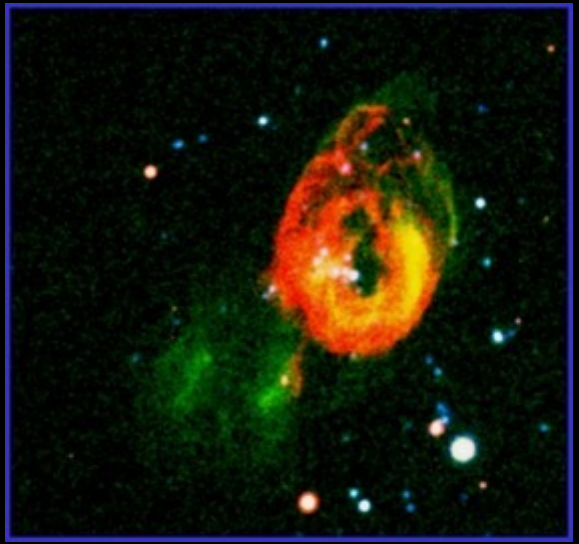
- Often found in star-forming regions and galaxies, and in massive (100s pc) bubbles of ionized gas



Pakull+08

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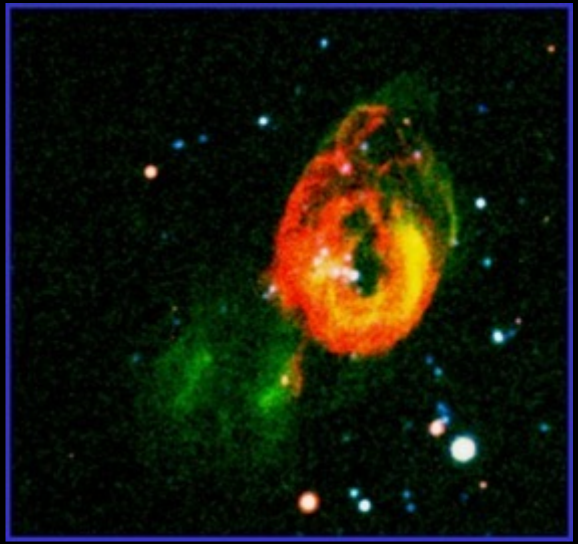
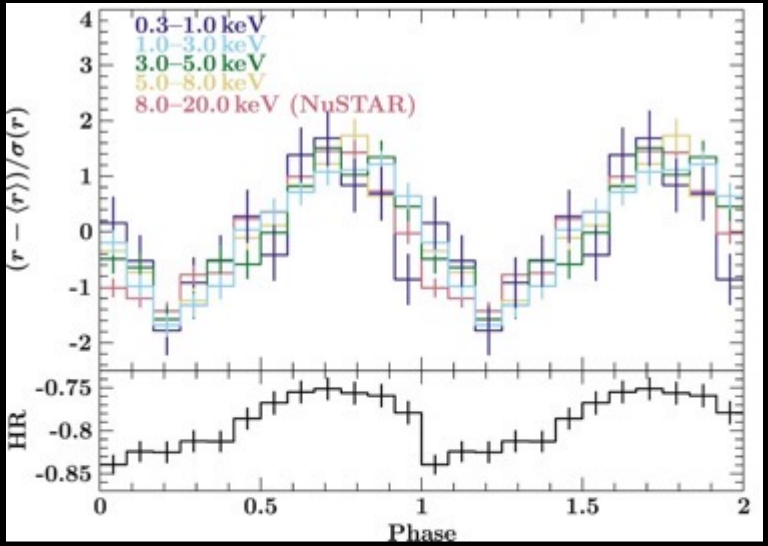
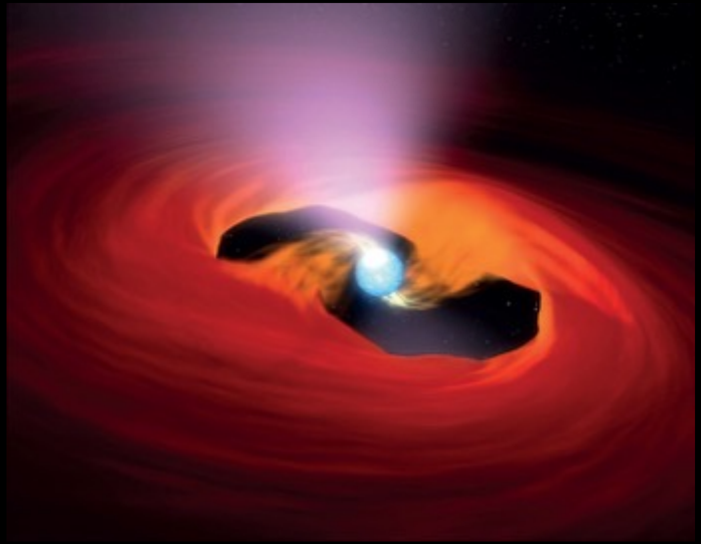
  - Intermediate mass black holes or super-Eddington accretion?
- Often found in star-forming regions and galaxies, and in massive (100s pc) bubbles of ionized gas
- Nowadays: at least majority powered by super-Eddington stellar-mass accretors (including neutron stars!)

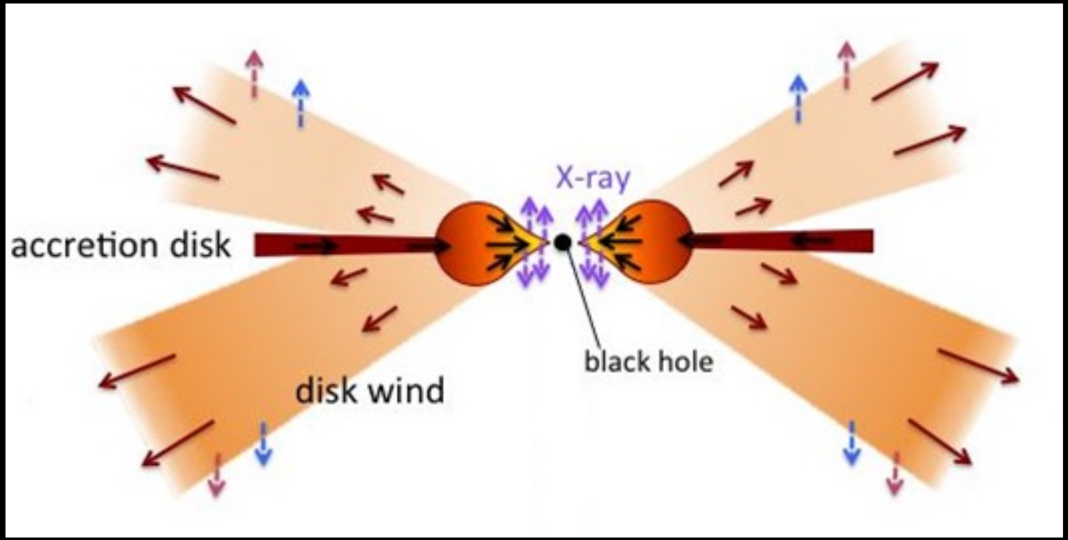




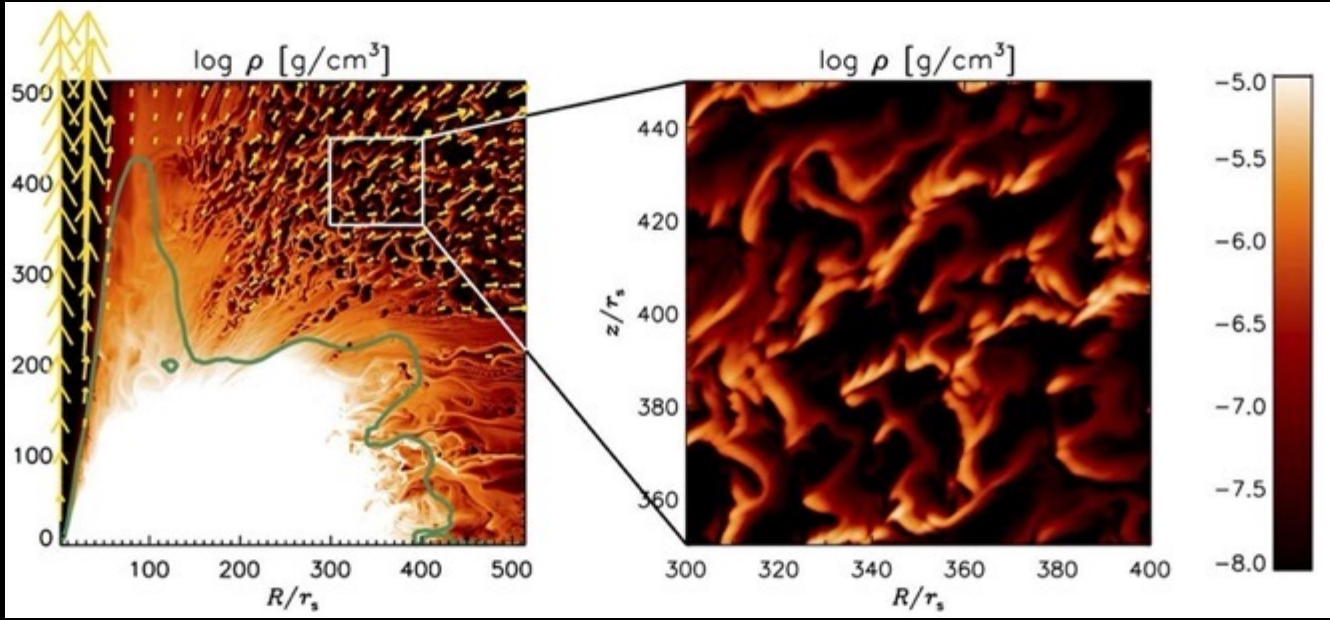


Pakull+08, Bachetti+14

Radiation-driven outflows



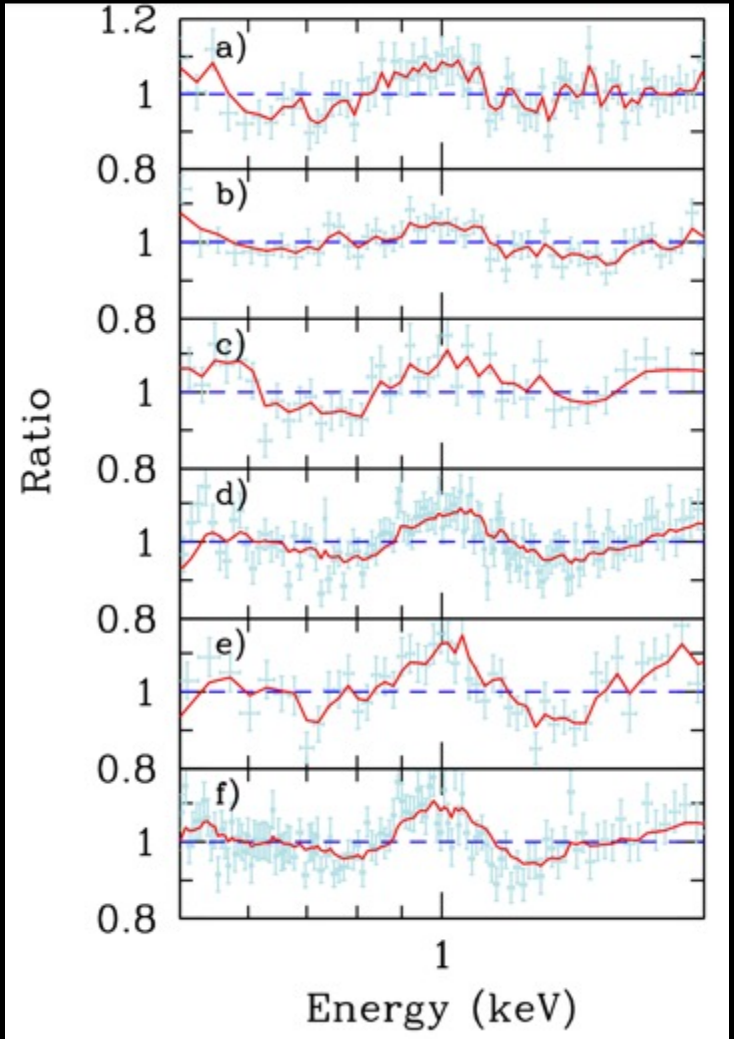
- Eddington limit: limit of maximum theoretical mass accretion rate onto a body:
    - $L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M \cong 1.3\times 10^{38} \left(\frac{M}{M_S}\right) \frac{erg}{s}$
- Naturally expect radiation-driven winds in systems accreting around or above the Eddington limit
- Radiation pressure highest in the inner flow regions -> the outflow very fast and energetic



Takeuchi+13, Fabrika+15

Detection of powerful winds in ULXs

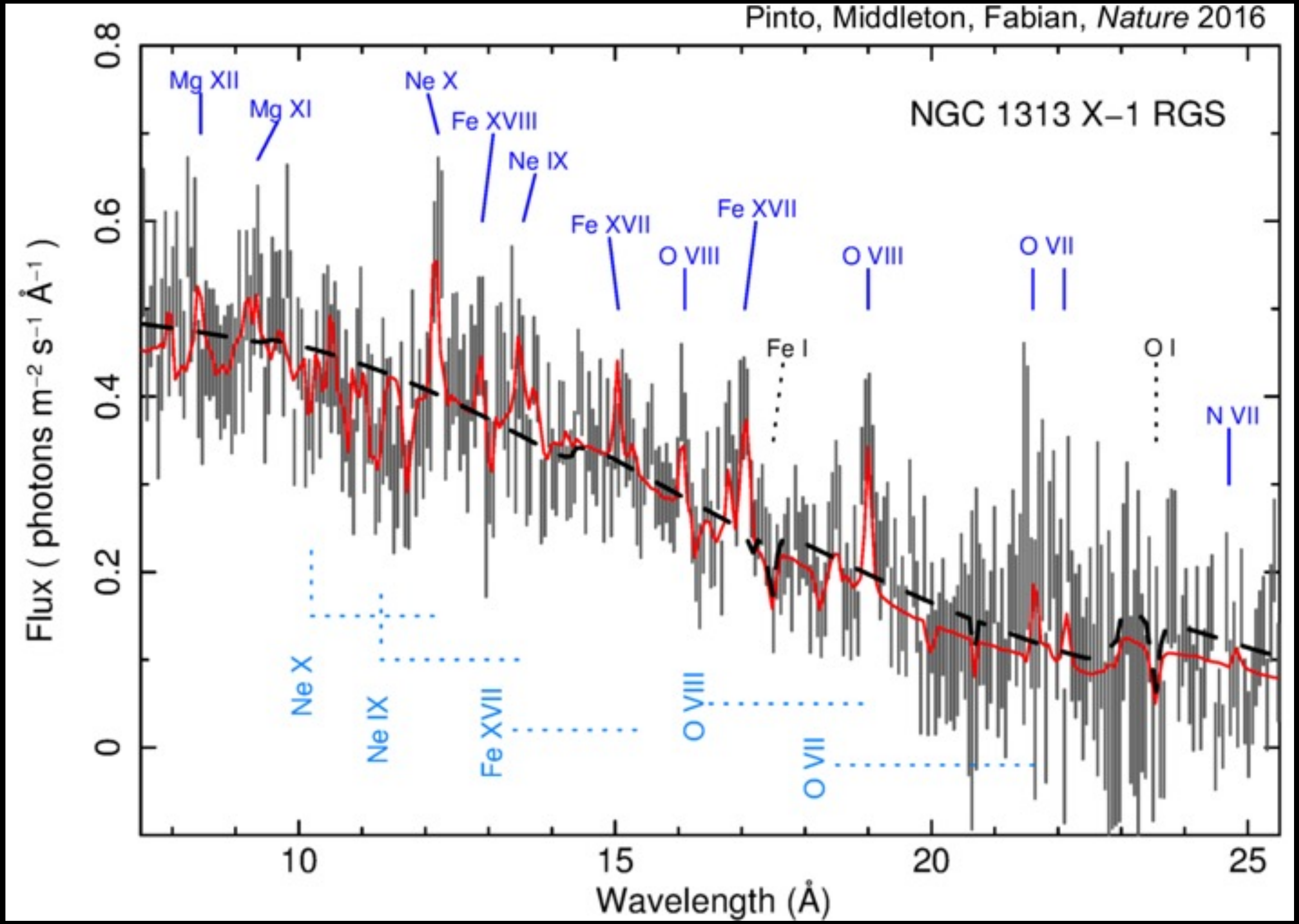
- Spectral features difficult to resolve with X-ray CCD instruments – need high spectral resolution (gratings)!
  - But: low X-ray fluxes



Middleton+15

Detection of powerful winds in ULXs

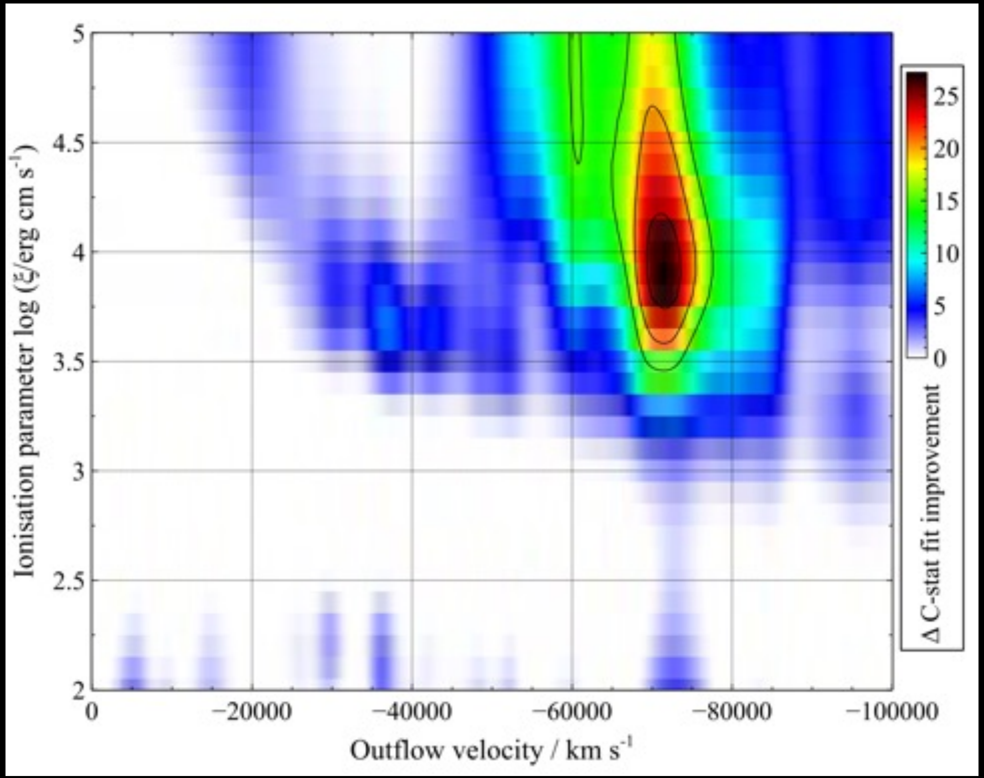
- Spectral features difficult to resolve with X-ray CCD instruments – need high spectral resolution (gratings)!
  - But: low X-ray fluxes
- Fast outflows found in a few ULXs with best quality X-ray datasets: NGC 1313 X-1, NGC 5408 X-1, NGC 55 ULX, NGC 247 ULX-1
- Observational signatures:
  - Strongly blueshifted (0.1-0.2c) absorption
  - Also detect rest-frame ionized emission

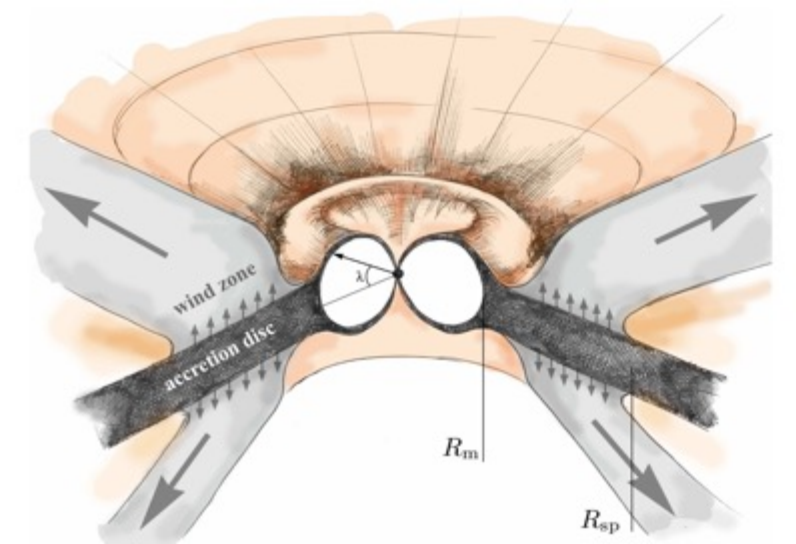


Pinto+16, Pinto+17, Pinto+21

Evidence for fast winds in neutron star ULXs

- NGC 300 ULX-1
  - Serendipitously discovered transient pulsating ULX
  - Systematic search of XMM-Newton and NuSTAR observations - 3.7σ evidence for a time-variable outflow at 0.22c
- Swift J0243 – the first Galactic neutron star ULX
  - Be/X-ray binary transient that reached $L_x > 10^{39}$ erg/s
  - Chandra grating spectra - evidence for an outflow at 0.22c

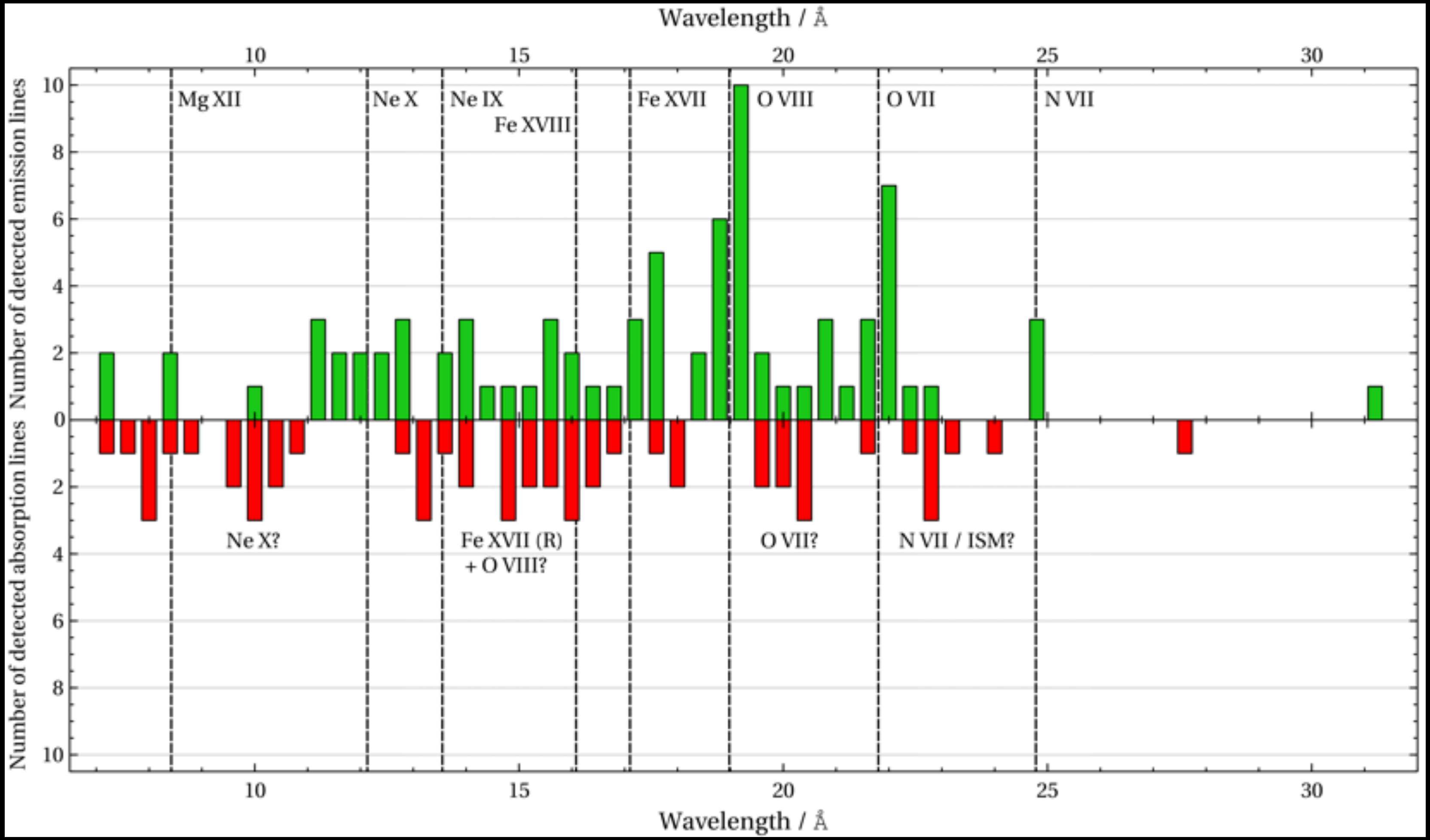




Kosec+18,
van den Eijnden+19,
Mushtukov+19

Ionized plasma in the population of ULXs

- Systematic study of 17 ULXs, search for emission and absorption lines
- Emission lines: strongly concentrated around rest-frame transitions of Mg, Ne, Fe, O, Ne -> low velocity plasma
- Absorption lines: mostly avoid the rest-frame transitions -> consistent with highly blueshifted absorption (0.1-0.2c) from fast winds



Kosec+18a, 21

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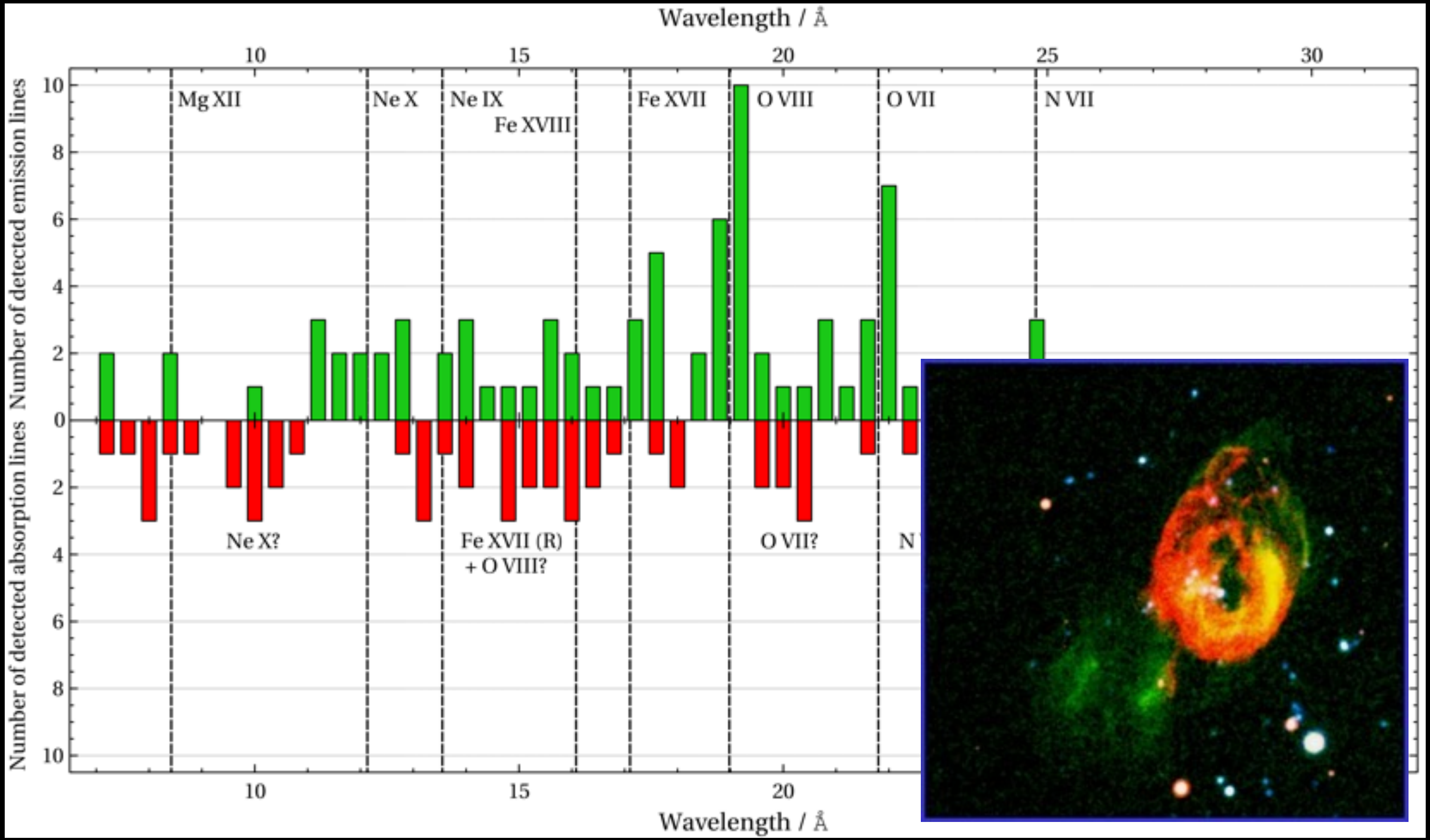


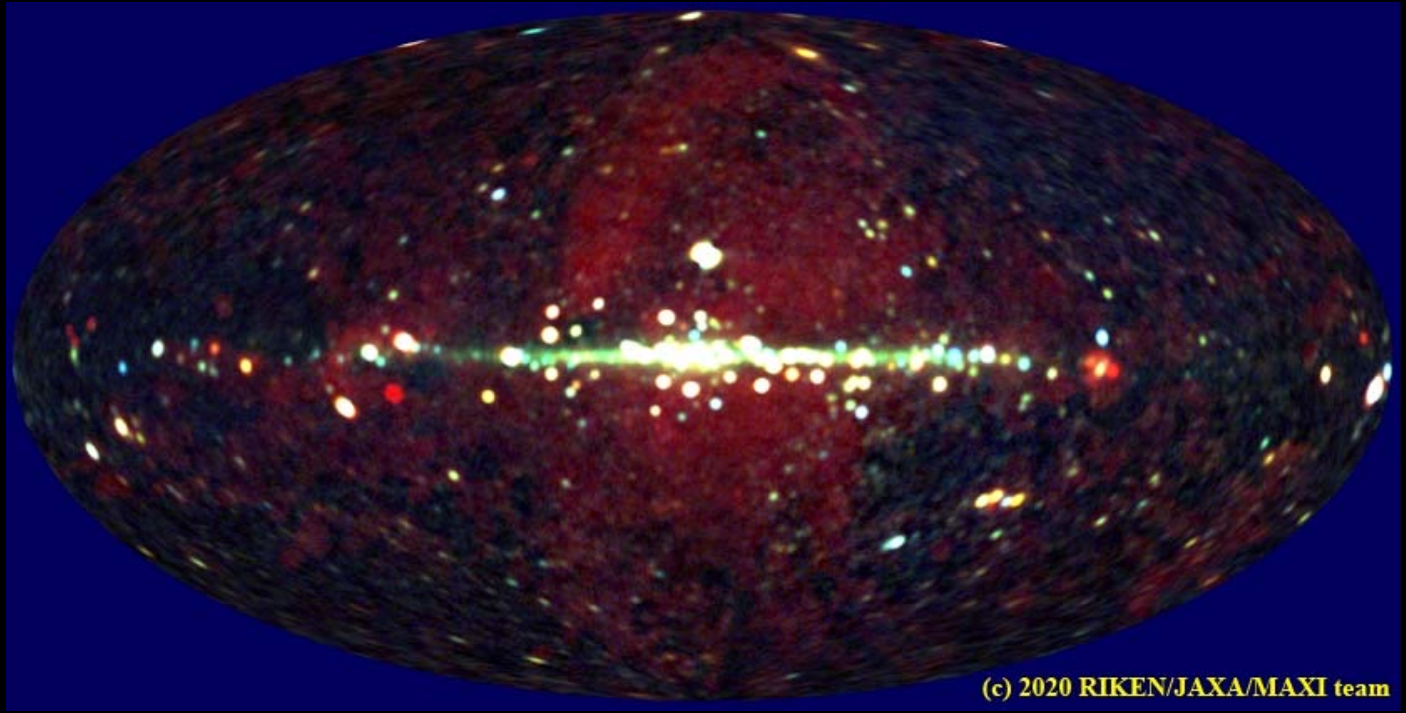
Kosec+18a, 21

Summary

- Disk winds: ubiquitous phenomena during certain stages of life of X-ray binaries
  - But show great complexity, complicating our understanding of their energetics and launching mechanisms
- Ultraluminous X-ray sources:
  - Powerful, relativistic outflows likely common among the population, as expected for super-Eddington accretors
- XRISM has potential to revolutionize the field of high-resolution spectroscopy
- For a recent review on HRXS of XRBs (with a focus on disk winds), see also Neilsen & Degenaar (2023)

High-resolution X-rays spectroscopy of X-ray binaries

- Low distance -> high flux -> high statistics!!
- But also, low compact object masses -> very fast variability timescales
- Many XRBs in our galaxy – many highly absorbed, but not all + many XRBs in Magellanic Clouds



High-resolution X-rays spectroscopy of X-ray binaries:
A biased review

- This talk: accretion disk winds in X-ray binaries (standard and ultraluminous)

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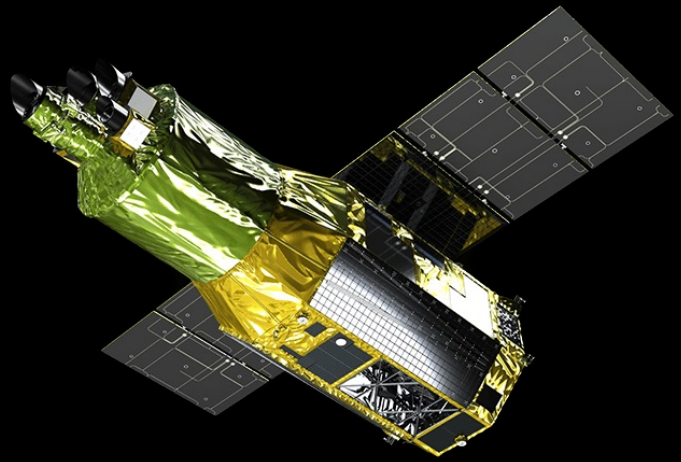
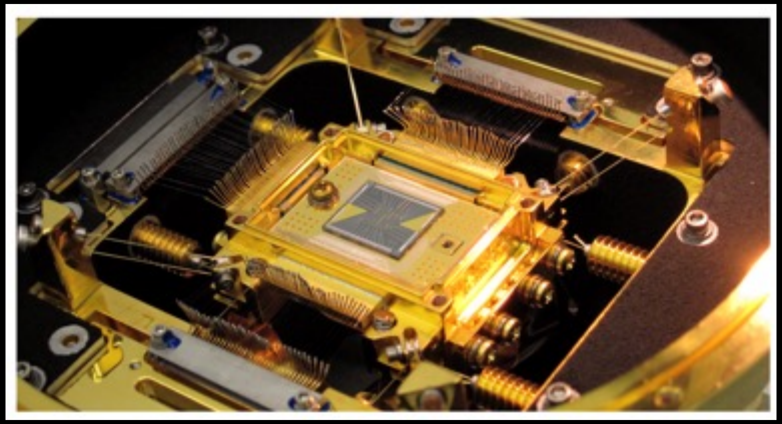
Future of high-resolution X-ray spectroscopy of XRBs: XRISM



- Expected to launch on August 26 (in just 23 days!!)
- Carrying the non-dispersive Resolve calorimeter – order of magnitude improvement in spectral resolution, alongside with significant effective area

Parameter	Requirement	Hitomi Values
Energy resolution	7 eV (FWHM)	5.0 eV
Energy scale accuracy	± 2 eV	± 0.5 eV
Residual Background	2 x 10^{-3} counts/s/keV	0.8 x 10^{-3} counts/s/keV
Field of view	2.9 x 2.9 arcmin	same, by design
Angular resolution	1.7 arcmin (HPD)	1.2 arcmin
Effective area (1 keV)	> 160 cm^2	250 cm^2
Effective area (6 keV)	> 210 cm^2	312 cm^2
Cryogen-mode Lifetime	3 years	4.2 years (projected)
Operational Efficiency	> 90%	> 98%



Takahashi+12, XRISM collaboration+20

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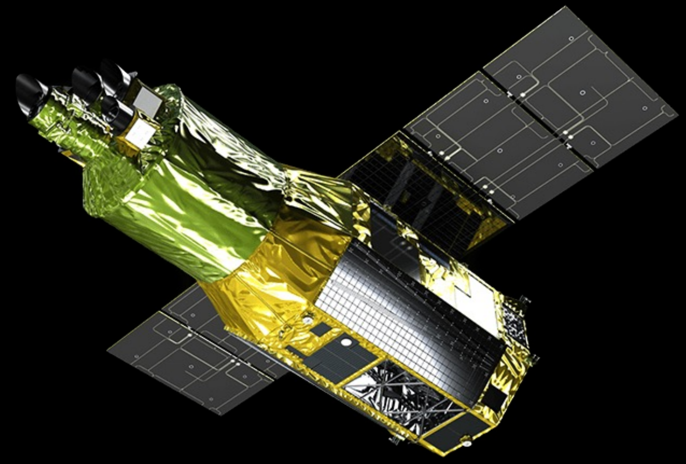

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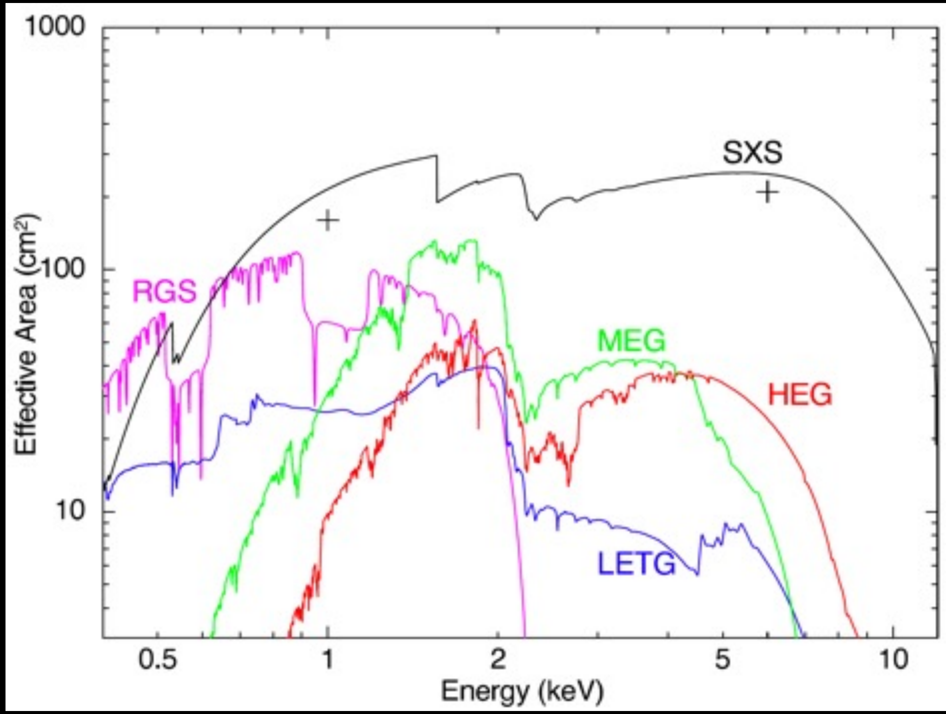
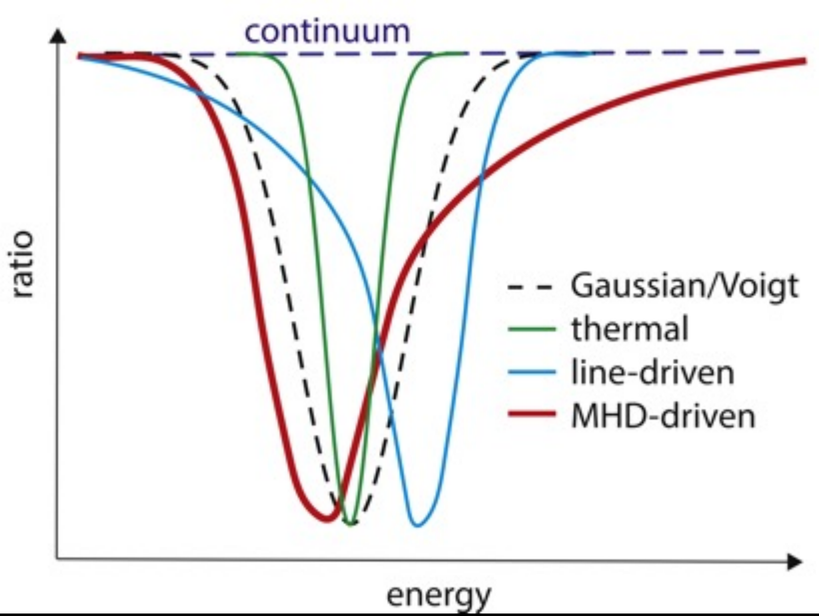


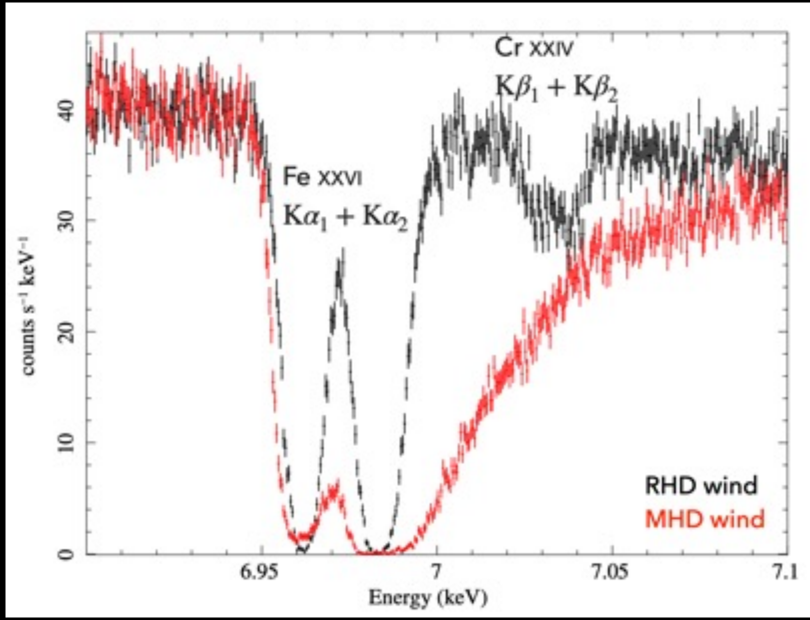
Takahashi+12, XRISM collaboration+20

Future: resolving individual wind lines with XRISM

- Superior XRISM resolution -> resolving the shapes of individual wind absorption lines
- Line shapes carry insights on outflow launching mechanisms
- Importantly: XRISM will have sufficient statistics to make these measurements for X-ray binaries



Prediction of line shapes from different launching mechanisms

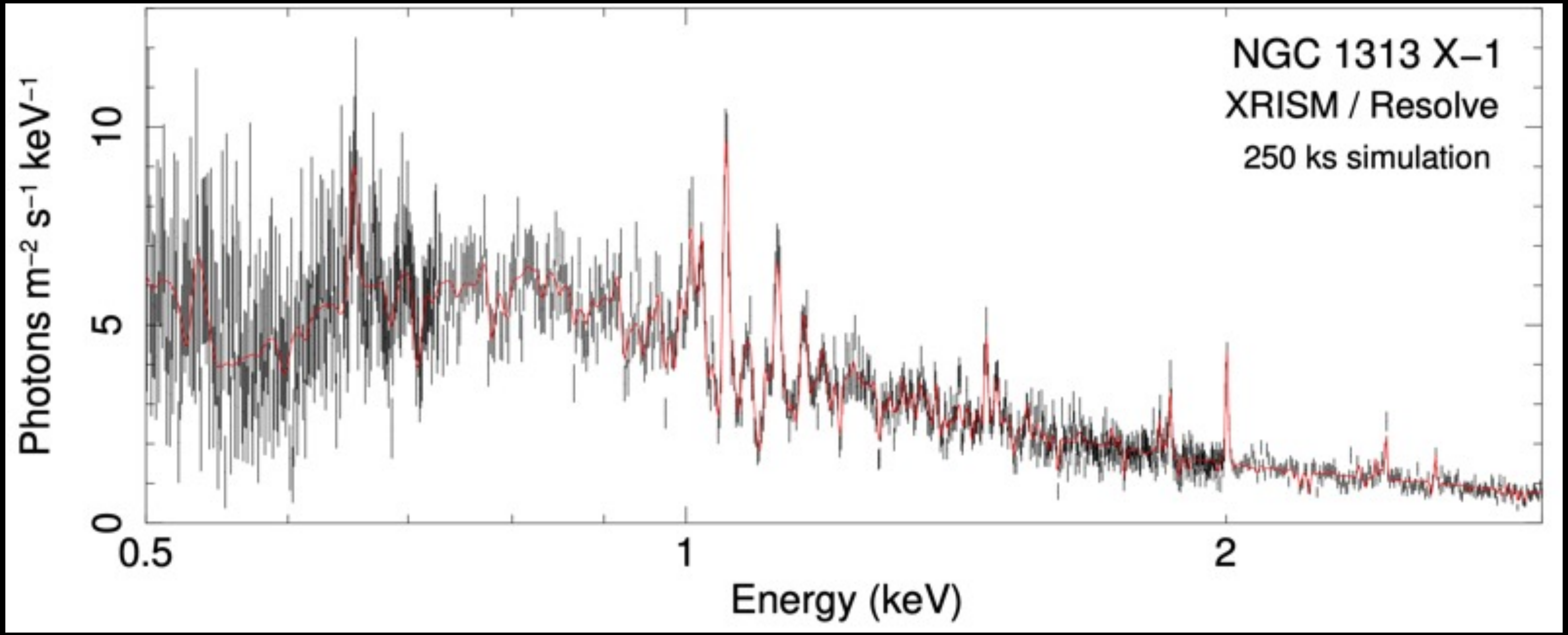


30 ks simulation of GRO J1655-40

Fukumura+22, Tomaru+23

Future: ULX outflows with XRISM

- XRISM can resolve individual outflow lines in the important 0.75-4 keV region (Ne, Fe, Mg, Si, S transitions)
- Limited effective area: 100s ks exposures still needed for sufficient statistics
- Non-dispersive spectrometer: less source contamination!



Pinto+19, Pinto+23

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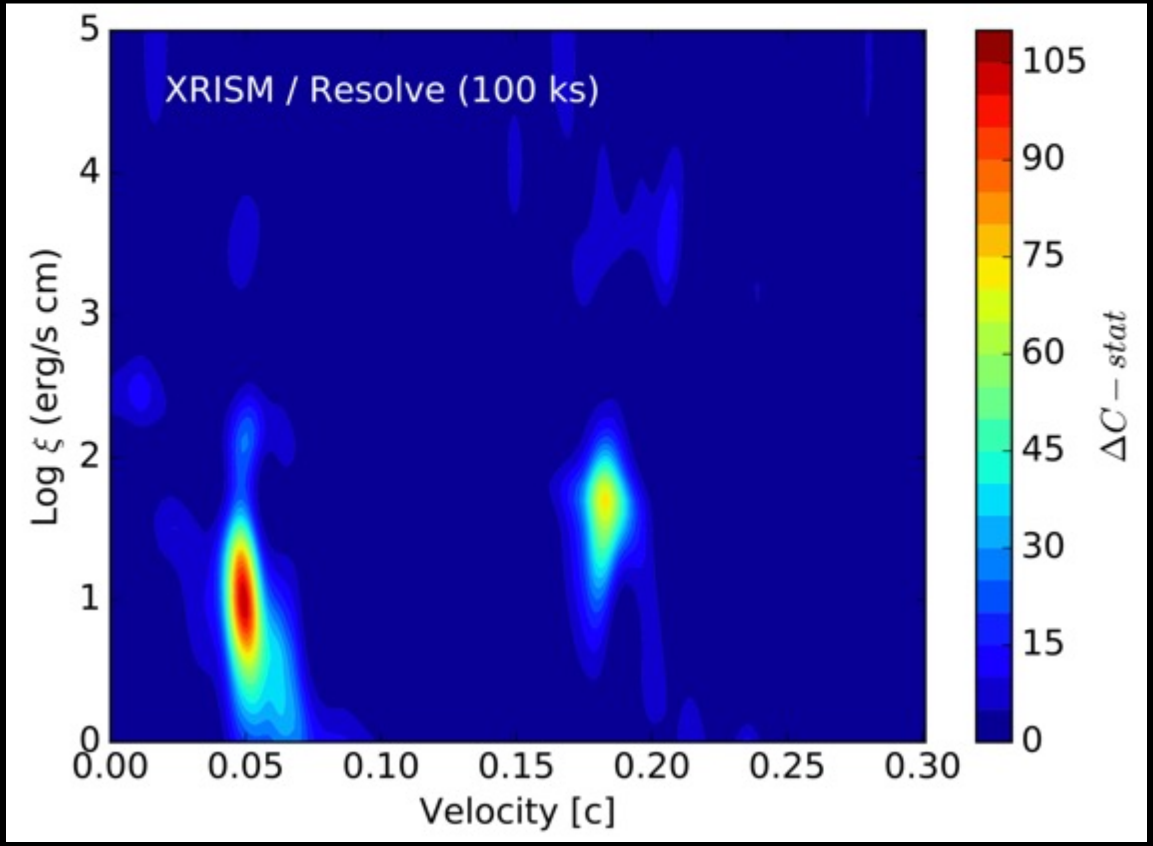


ULX wind detection in 100 ks XRISM exposure

Pinto+19, Pinto+23

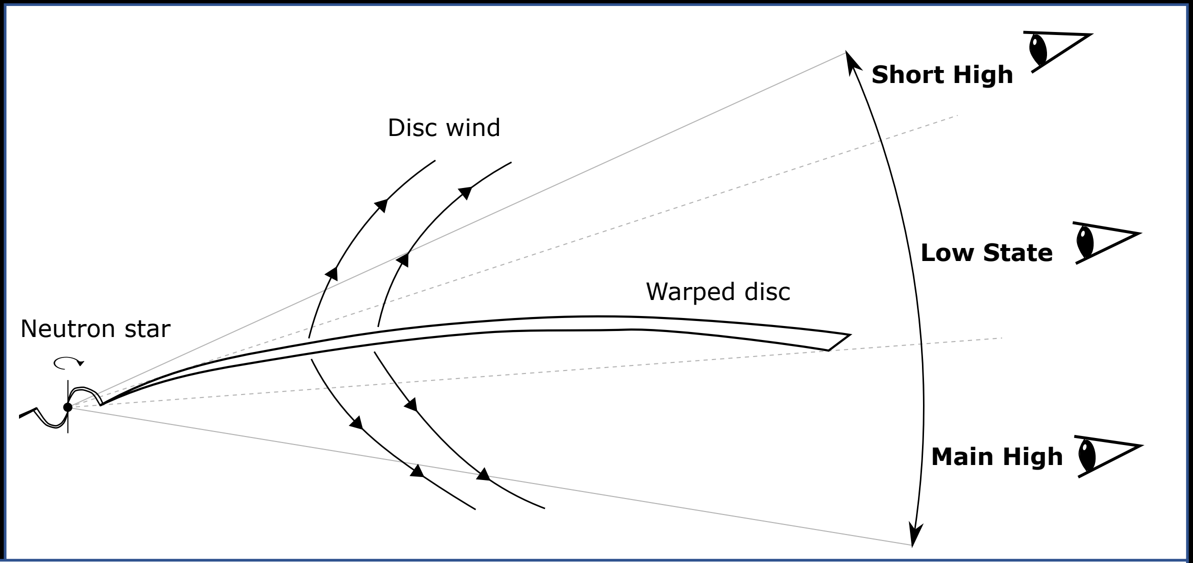
High-resolution X-rays spectroscopy of X-ray binaries:
A biased review

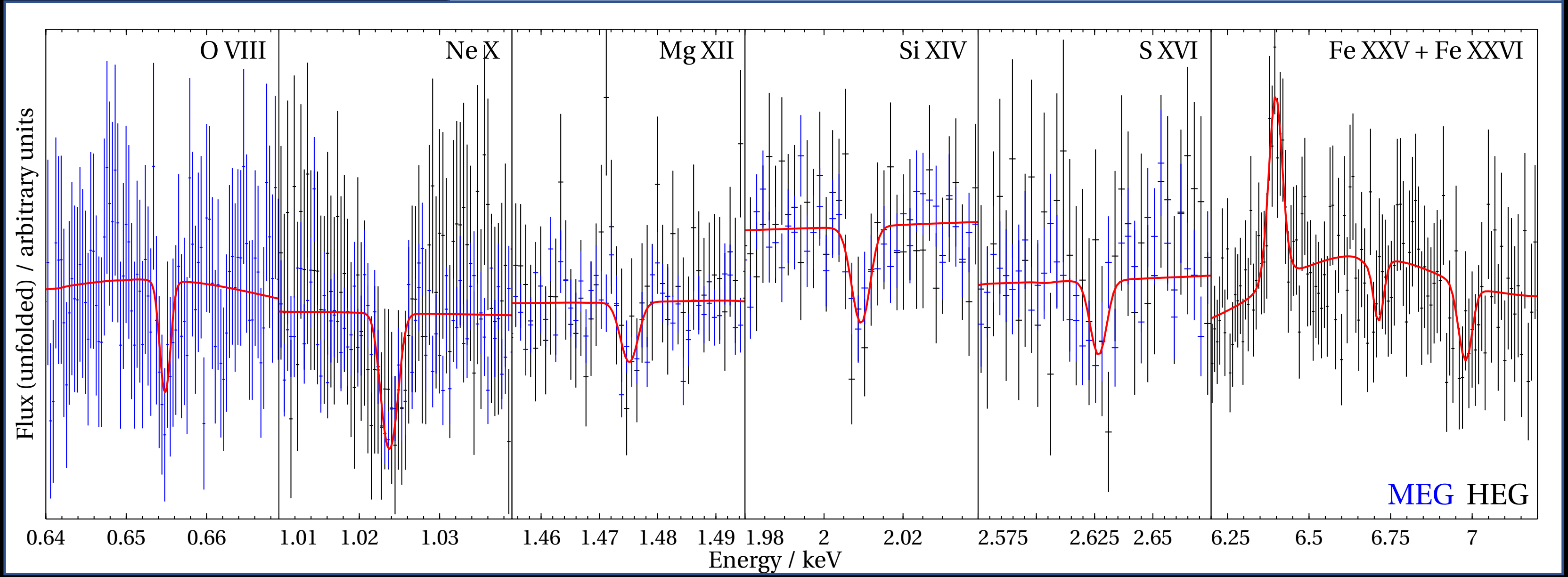
- This talk: accretion disk winds in X-ray binaries (standard and ultraluminous)
- X-ray binary disks and atmospheres
- ISM dust and scattering haloes – talk on Tuesday by I. Psaradaki
- Stellar winds in high-mass binaries: Cyg X-1, Vela X-1, Cen X-3
- Jets: SS 433

Her X-1: disk wind in the Short High state

- X-ray source uncovered in the Short High state
  - Is any wind absorption present?
- The only Chandra obs. of Short High state (from 2002!)
  - Same absorption lines as in Main High state

Precession cycle





Kosec+23 (subm.)

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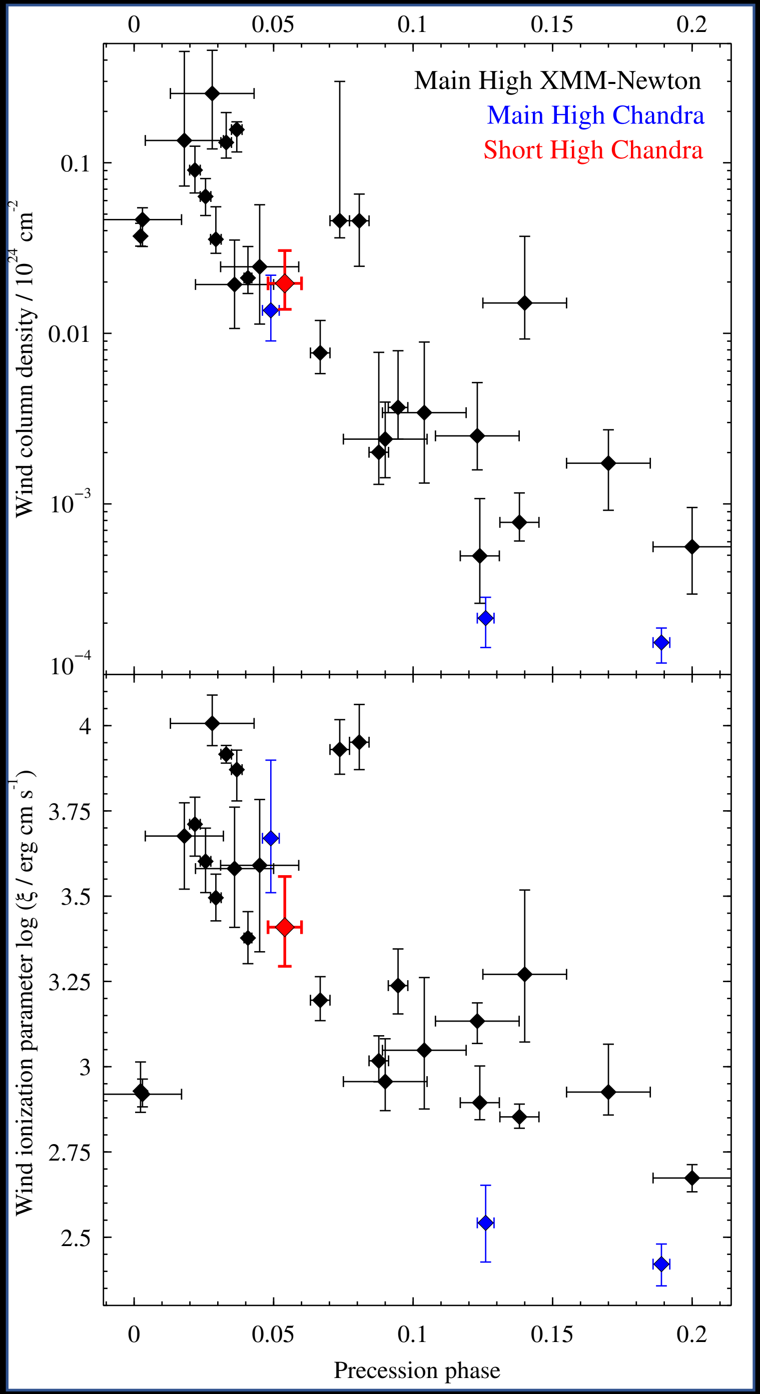
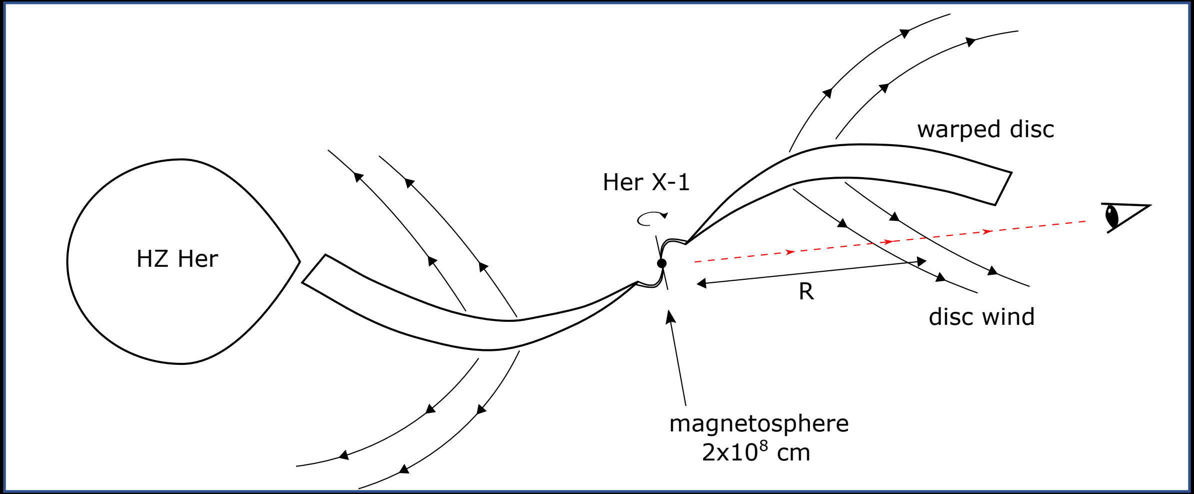
- X-ray source uncovered in the Short High state
  - Is any wind absorption present?
- The only Chandra obs. of Short High state (from 2002!)
  - Same absorption lines as in Main High state
  - Wind properties consistent with those during Main High state



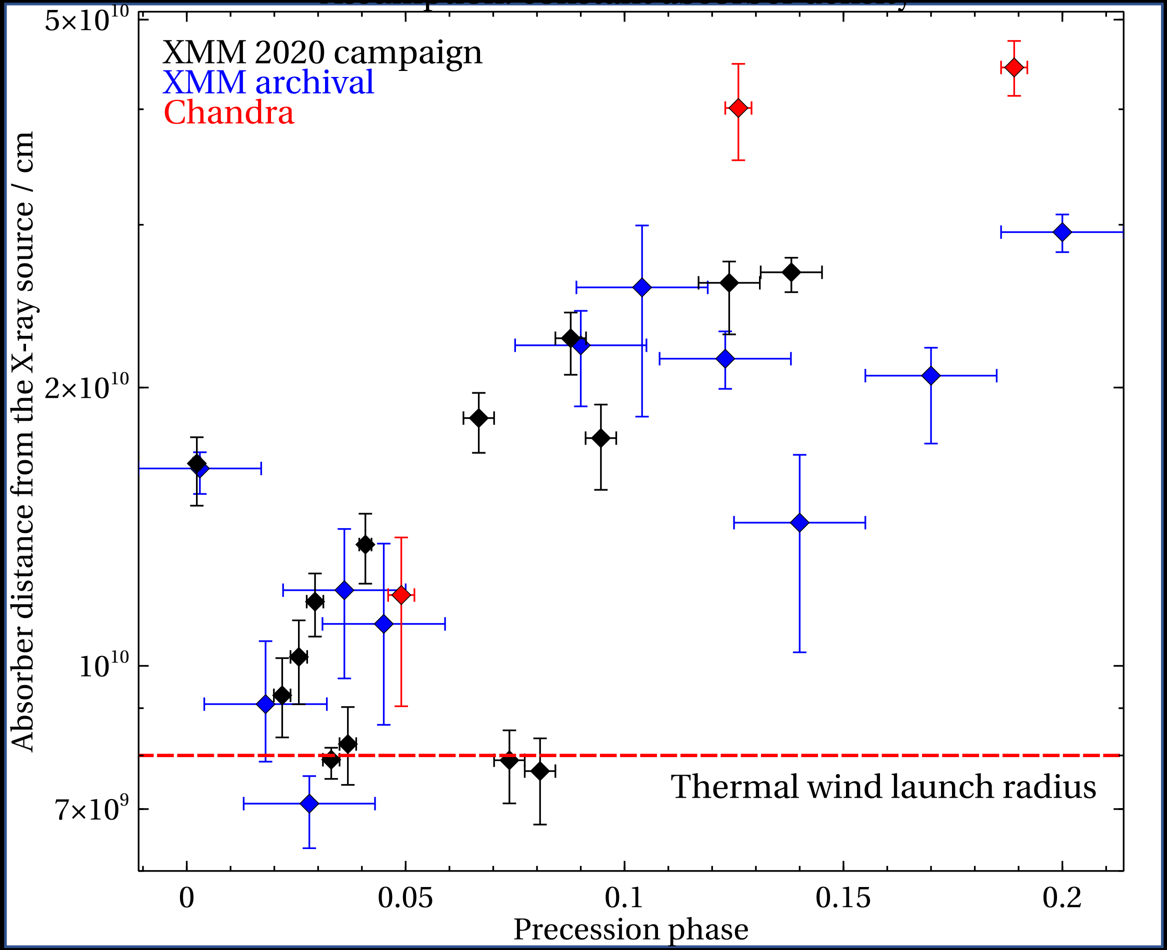
Kosec+23 (subm.)

Location of the absorber

- From the outflow properties, can estimate its location
  - $\xi = \frac{L_{ion}}{nR^2}$ L_{ion} – ionizing luminosity
  - $N_H = n\Delta R$ ΔR – thickness of the absorber
  - $R = \frac{L_{ion}}{N_H \xi} \frac{\Delta R}{R}$

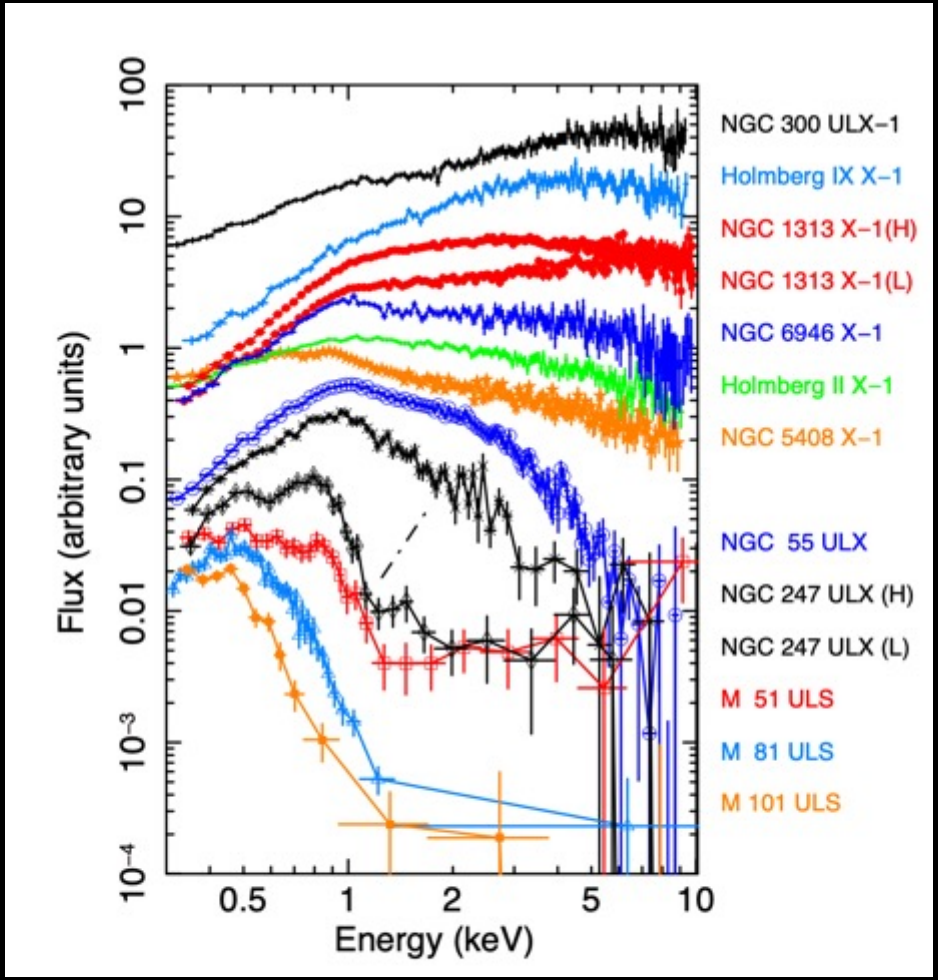


Begelman+1983



Radiation-driven outflows

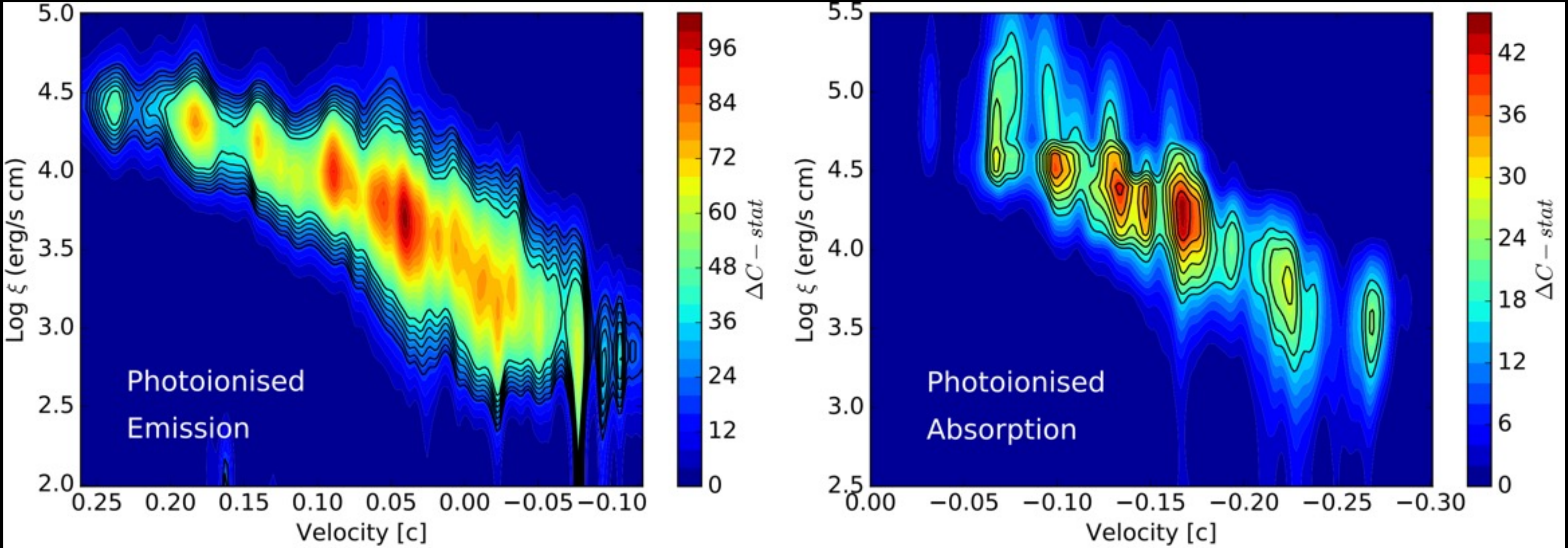
- Eddington limit: limit of maximum theoretical mass accretion rate onto a body:
  - $L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M \cong 1.3\times10^{38} \left(\frac{M}{M_S}\right) \frac{erg}{s}$
- Naturally expect radiation-driven winds in systems accreting around or above the Eddington limit
- Radiation pressure highest in the inner flow regions -> the outflow very fast and energetic



Pinto+20

UFOs in super-soft ULXs?

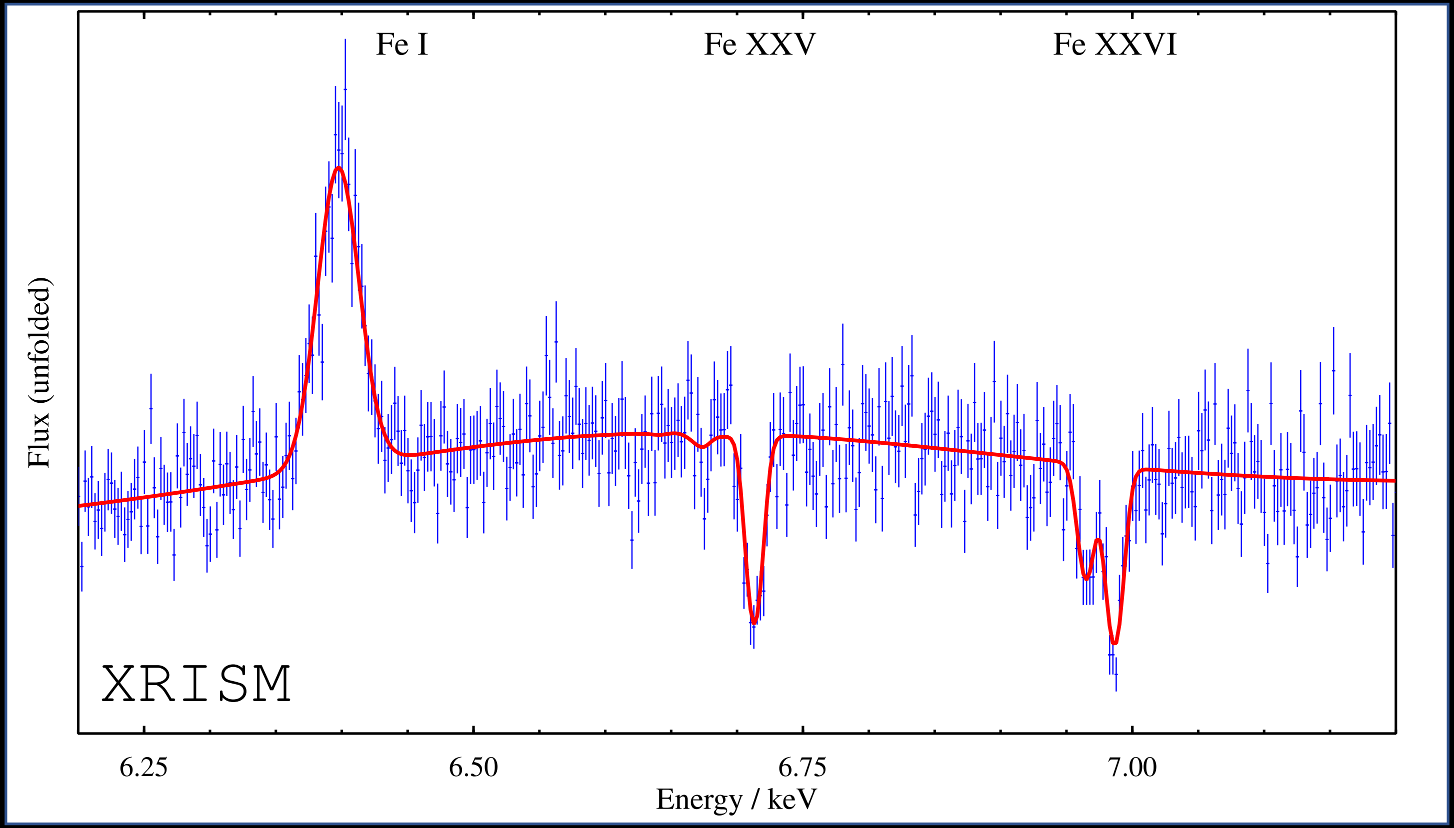
- Spectrally very soft ULX showing both emission and absorption lines in the spectrum: none completely rest-frame: absorber blueshifted by 0.17c, emission redshifted by 0.04c



Pinto+17,+21

Future: Her X-1 and other X-ray binaries

- 10 ks XRISM simulation: excellent spectral quality in the hard X-ray band
- Fast timing of X-ray binaries with XRISM: down to 1ks, or even lower time-resolved bins



10ks simulation of Her X-1 disk wind with XRISM

Kosec+23 (subm.)