Revealing the physics of accretion disk winds with Hercules X-1

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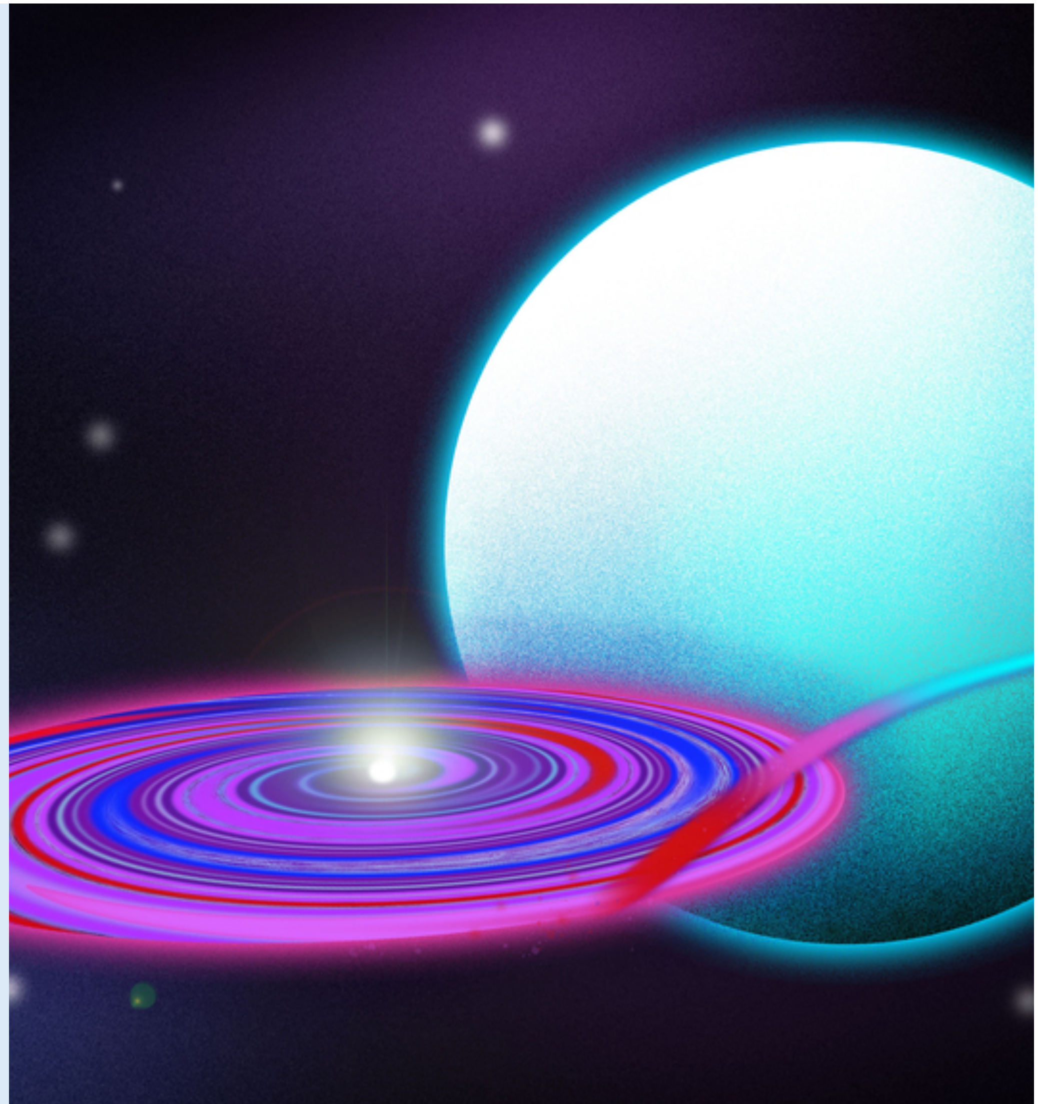
HARVARD & SMITHSONIAN


Credit: Jose-Luis Olivares, MIT

Accretion disk winds

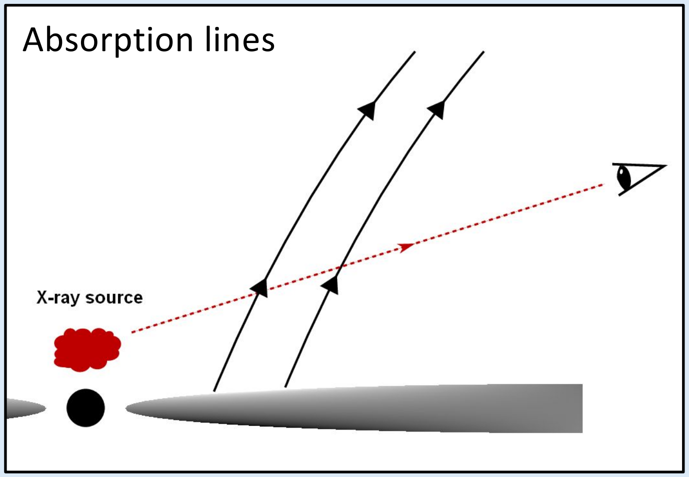
- Observationally confirmed in many types of accreting systems:
  - Active galactic nuclei and tidal disruption events (supermassive black holes)
  - **X-ray binaries** (stellar-mass black holes and neutron stars)
  - Accreting white dwarfs

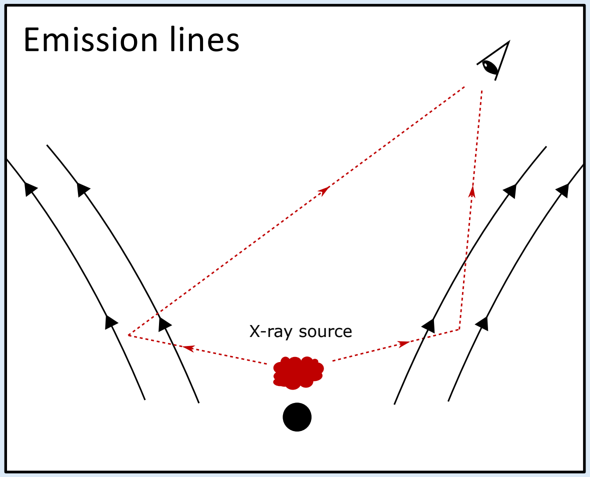
- A number of possible launching mechanisms
  - Radiation pressure, line driving, magnetic forces, thermal driving

Outflows from accreting systems – why do we care?

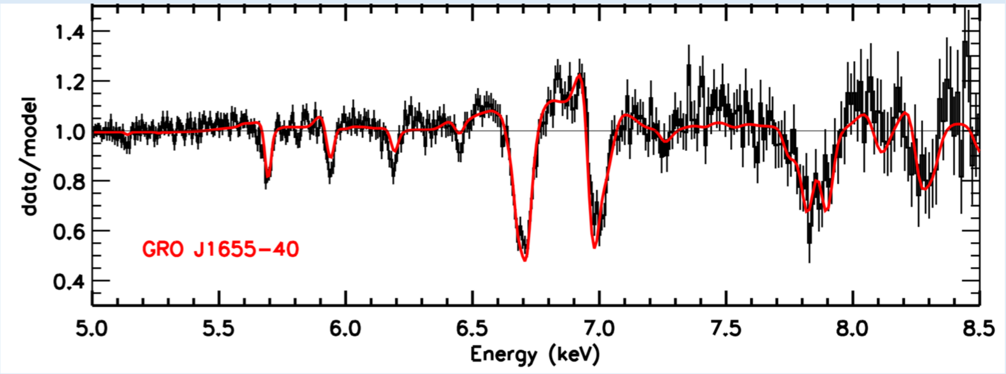
- Can carry away large fraction of originally infalling mass
- Winds from inner accretion flow may reach relativistic velocities (~0.1c) -> huge kinetic power
- We can measure outflow elemental abundances
- Current status:
  - Launching mechanism unknown in most systems
  - Wind energetics (and impact on surroundings!) poorly constrained

Studying ionized outflows with X-ray spectroscopy





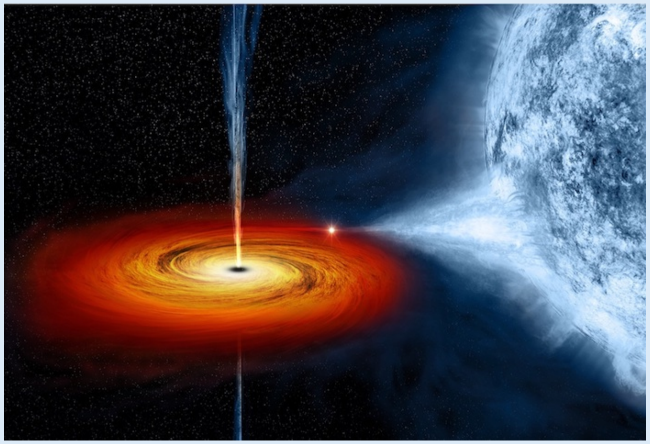
- Absorption spectra particularly useful
  - But only sample wind at a single point!
- Can model wind re-emission to study 3D wind structure
  - Emission often weak, modelling can be degenerate
- Second major issue: almost never measure the wind number density

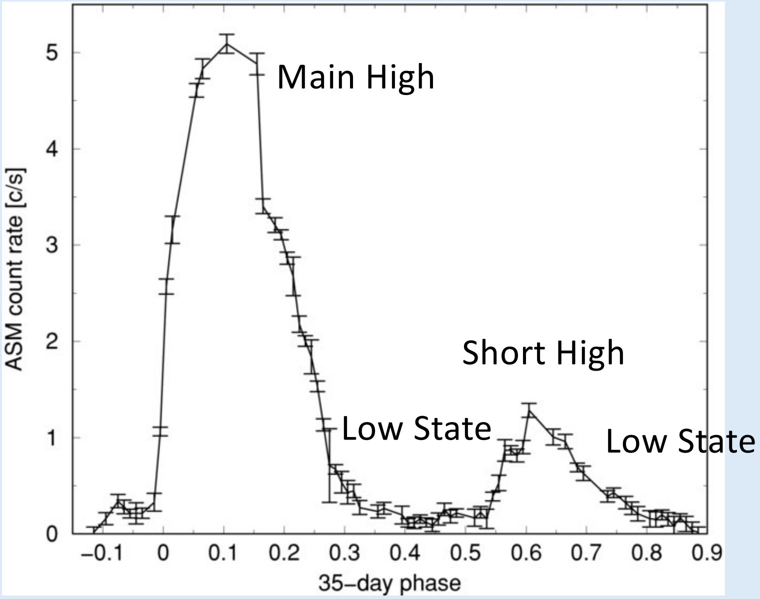


Miller et al. 2015

Hercules X-1: an X-ray binary with a warped disk

- A bright neutron star X-ray binary discovered in early 1970s
- Observed nearly edge-on
- 35-day cycle of high and low flux states





Leahy&Igna 2010

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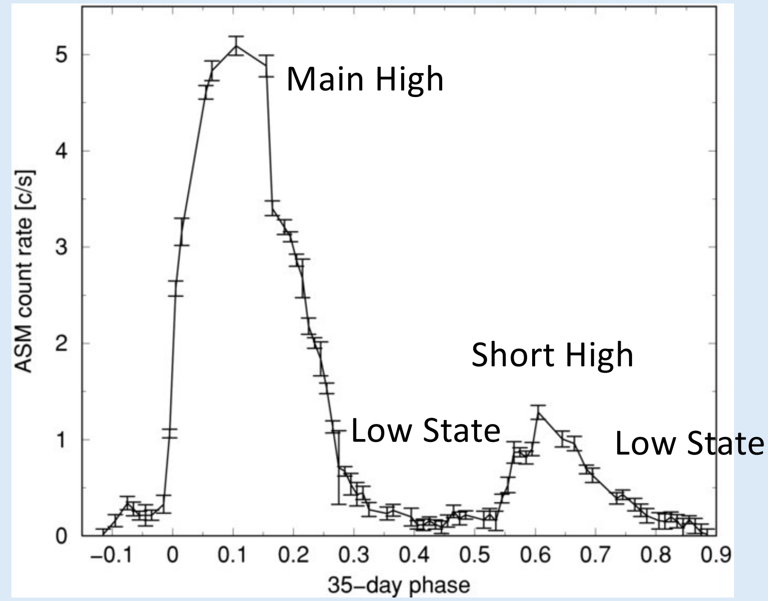

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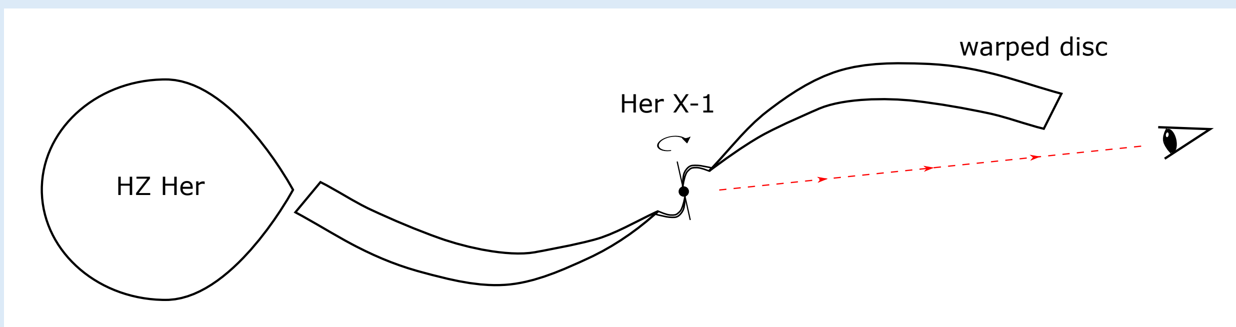

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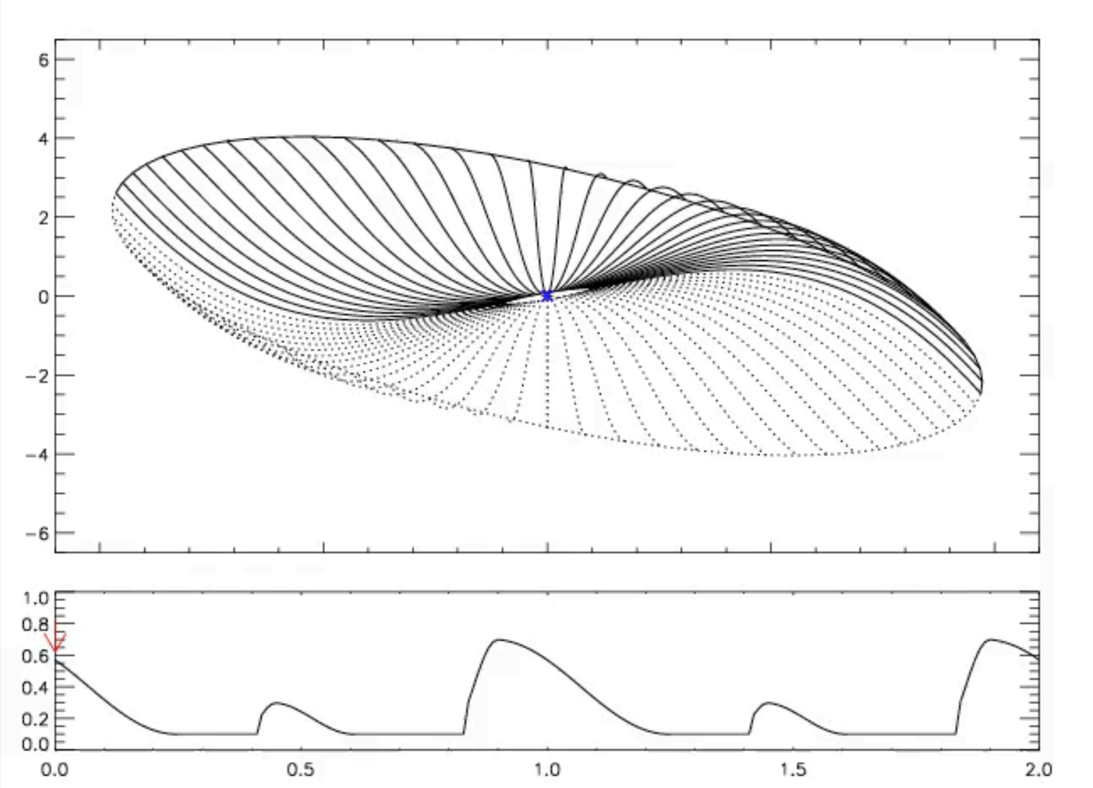

Precession phase

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

Hercules X-1: an X-ray binary with a varying sightline

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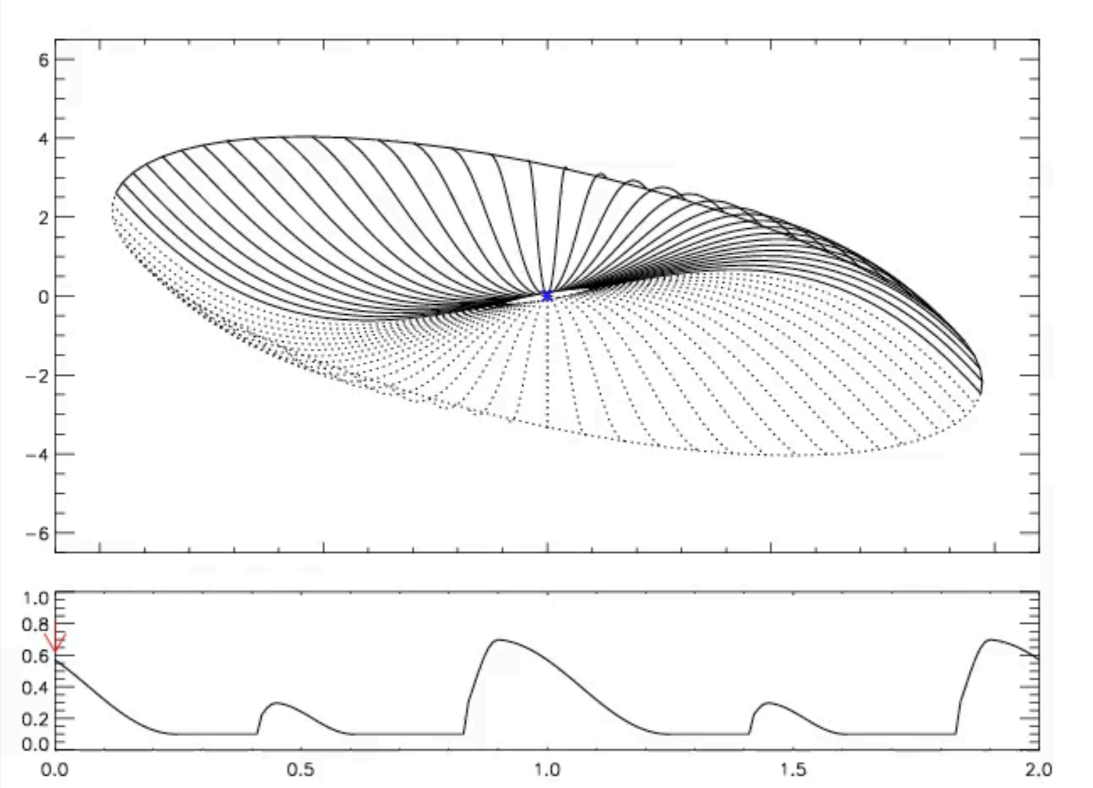

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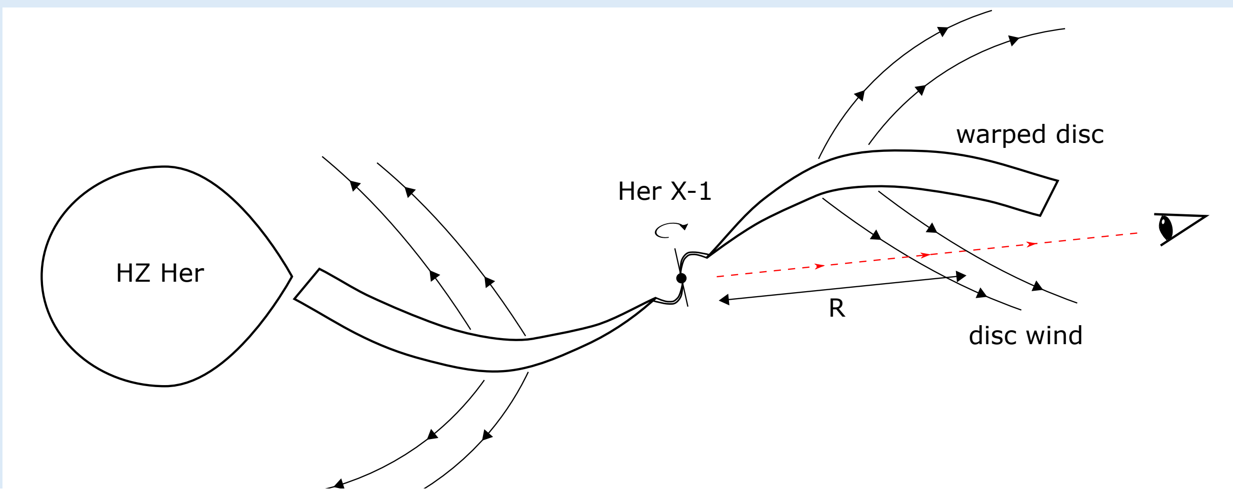

Kosec et al. (2020)

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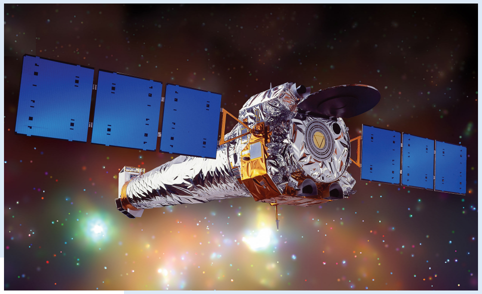
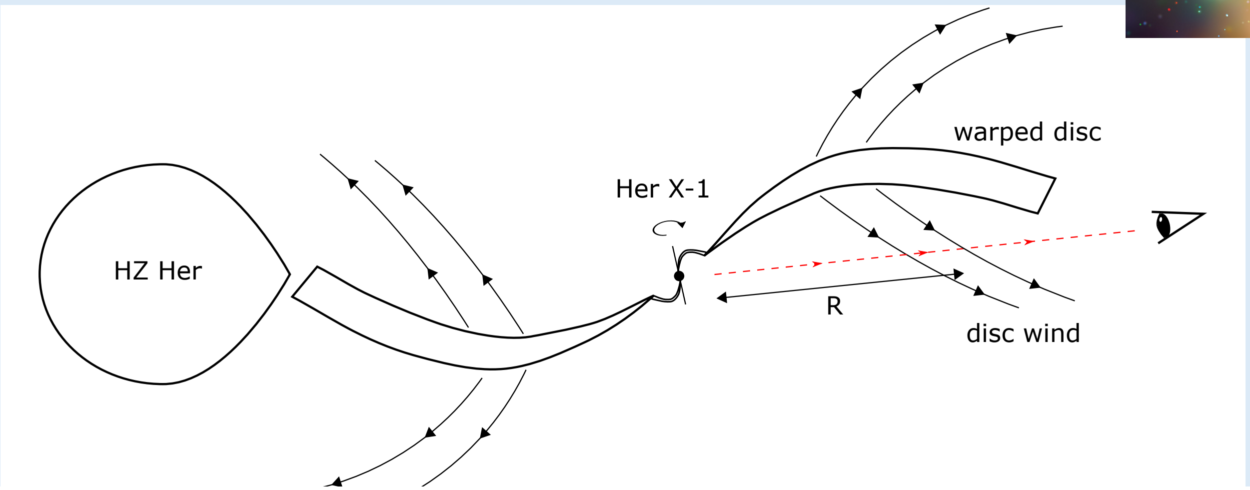


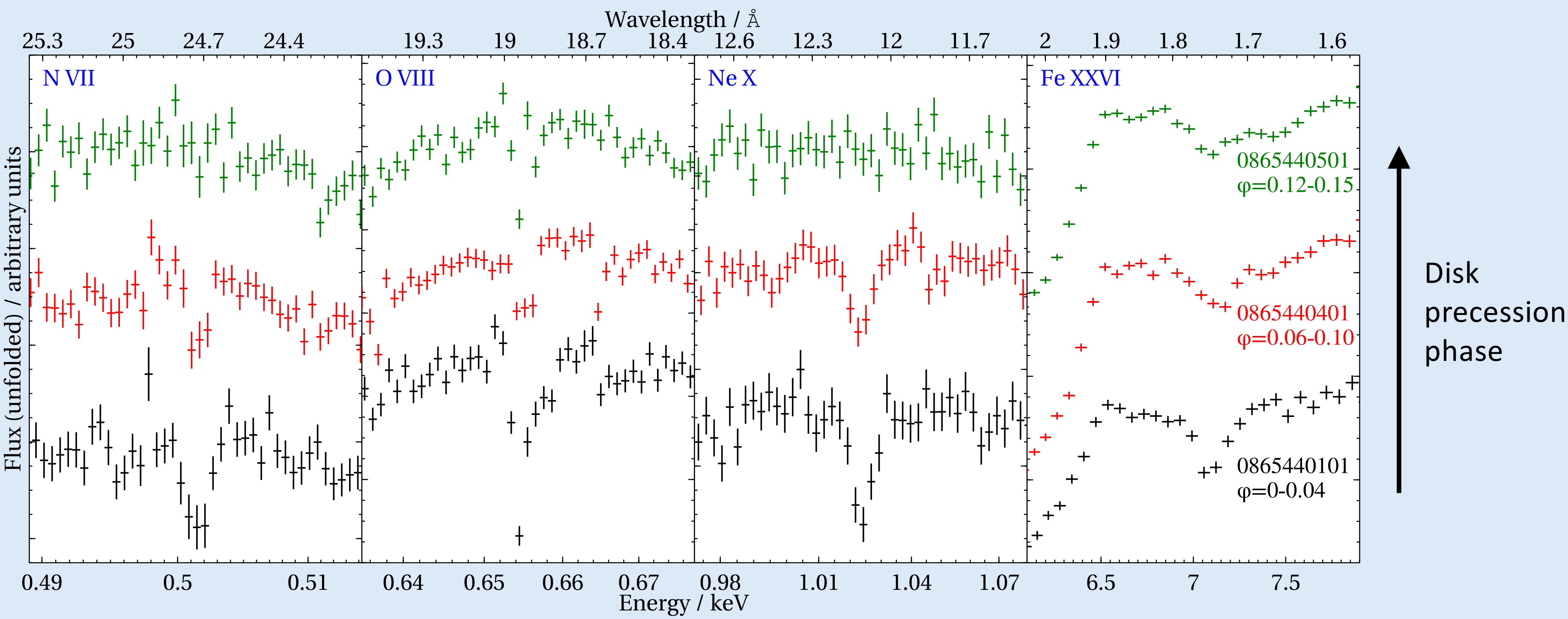
- Execute a large observational campaign with XMM-Newton (400 ks) and Chandra (50 ks)
- Study the evolution of wind properties with precession phase -> height above accretion disk



Kosec et al. (2020)

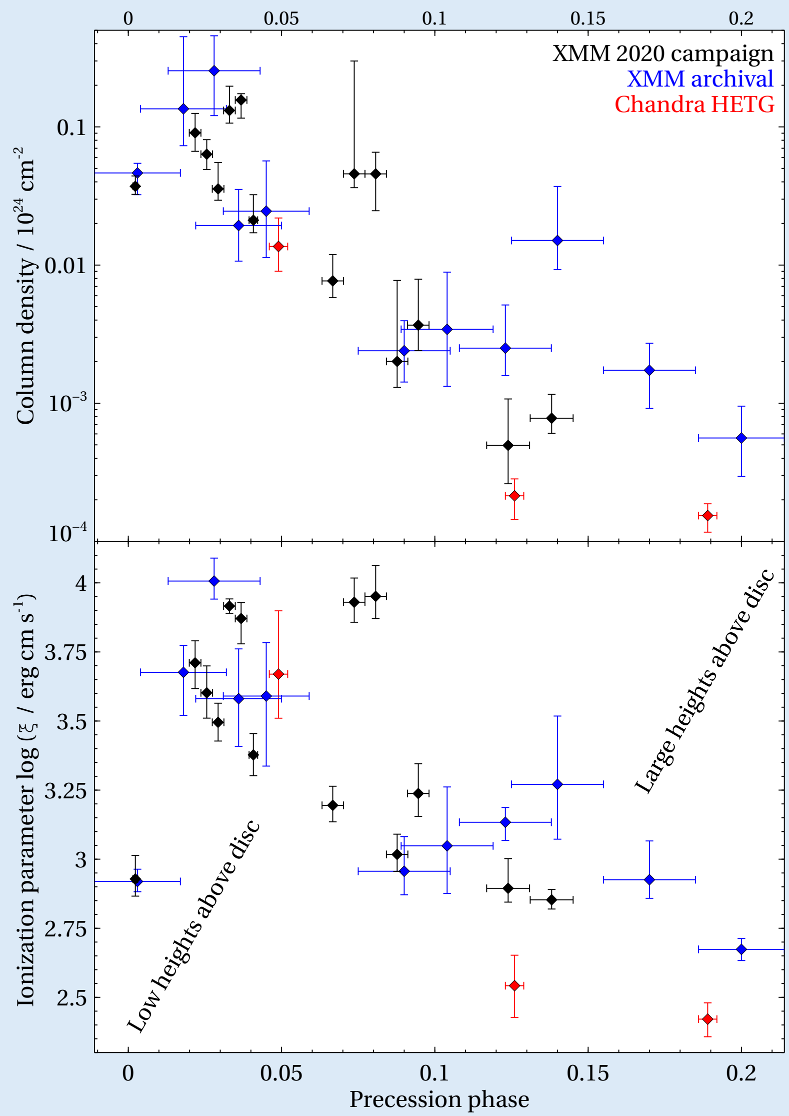
Wind evolution with disk precession phase

- Line optical depth decreases with disk precession phase



Disk wind properties

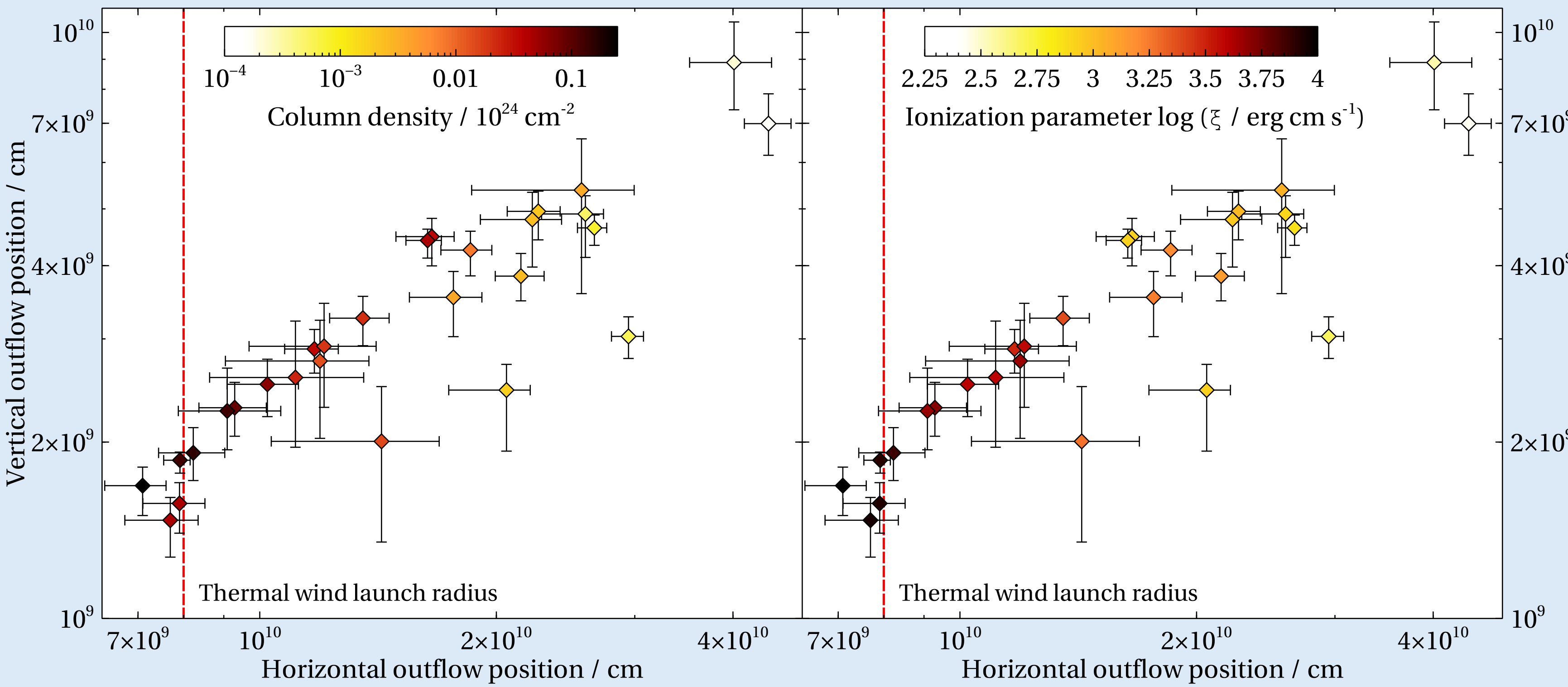
- Measure disk wind properties using photo-ionization model PION at 28 epochs:
  - Column density N_H
  - Ionization parameter $\xi = \frac{L}{nR^2}$
- Column density strongly decreases with precession phase, from 10^{23} to 10^{20} cm^{-2} -> wind weakens at greater heights
- Ionization parameter: similar evolution, but less variable



Kosec et al. (2023)

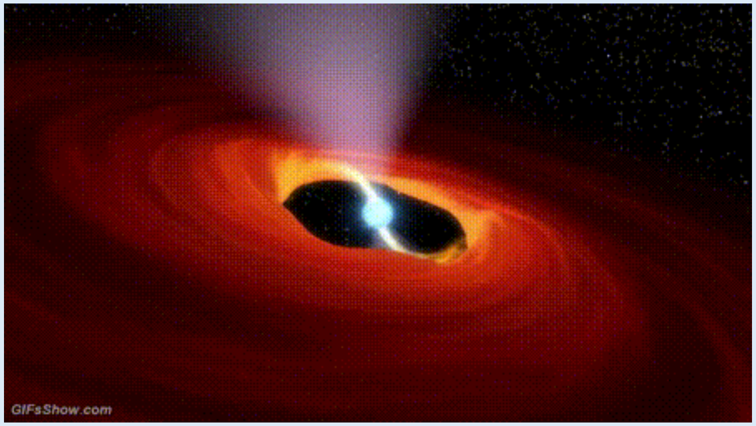
A 2D map of the disk wind

- Model the warped disk shape, using measured absorber distances from the X-ray source -> obtain the first 2D map of an accretion disk wind



Hercules X-1: an X-ray ***pulsar***

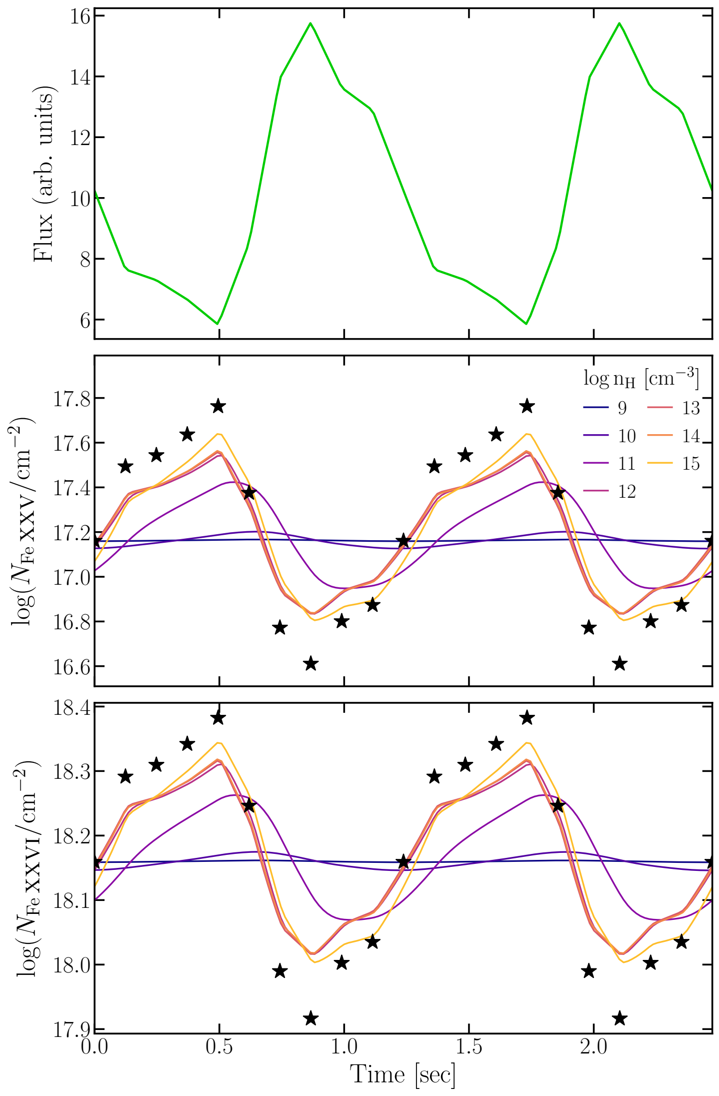
- Powered by a highly magnetized (10^{12} G) neutron star rotating every 1.24 sec
- Matter channeled onto magnetic poles -> anisotropic X-ray emission -> X-ray pulsations
- Time-dependent irradiation of disk wind -> wind ionization periodically responds to time-variable radiation field
- Ion recombination timescale depends on number density: $t_{rec} = (\alpha_{rec} n_e)^{-1}$



Simulating the ionization response of the wind

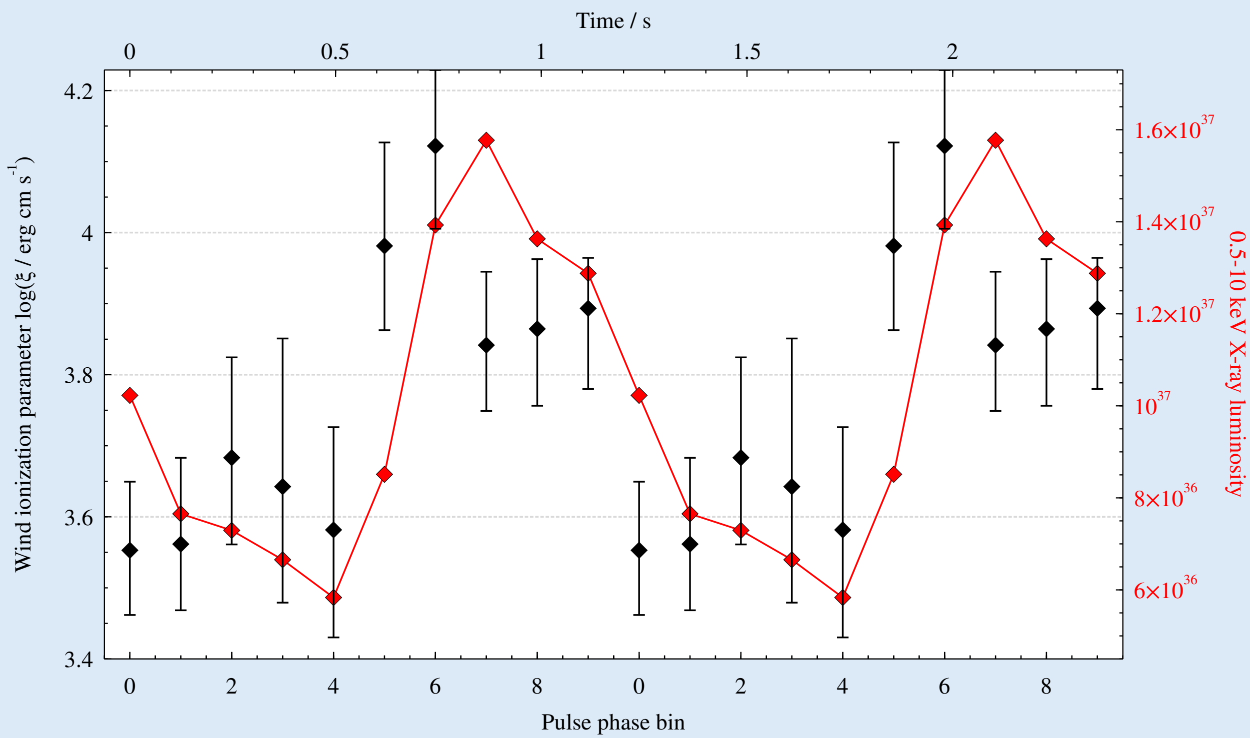
- Use time-dependent photoionization code TPHO (Rogantini et al. 2022)

- Simulate response of wind ionization to realistic Her X-1 pulsations, observe changes in line column densities
  - Low number density -> no variation
  - Intermediate density -> ionization response delay
  - High density -> immediate response



Ionization response of the wind: XMM-Newton data

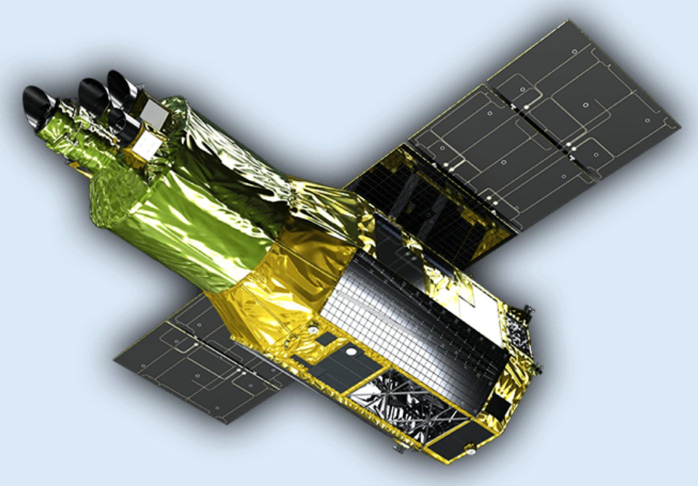
- Analysis of highest-quality XMM-Newton observation of Her X-1
- Split data by pulse phase into 10 bins
- Model wind absorption lines with PION photoionization model
- Conclusion: wind responds immediately to flux variations
    - Wind number density is at least 10^{12} cm^{-3}

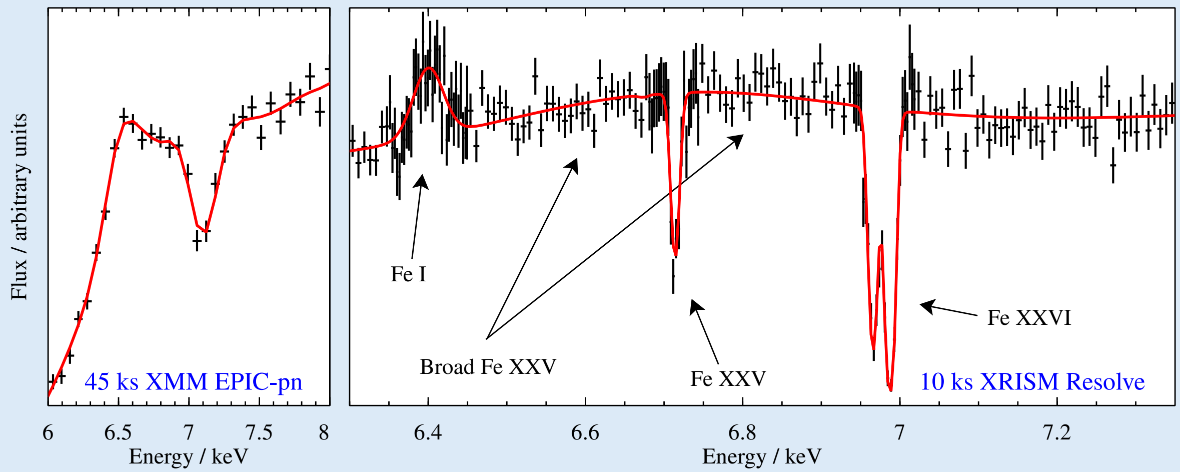


Kosec et al. (2024)

Future: precision wind mapping with ***XRISM***

- Current XMM data pushed to the limit. XRISM will offer much better spectral resolution
- XRISM -> precision measurements of wind ionization response to X-ray pulsations in Her X-1





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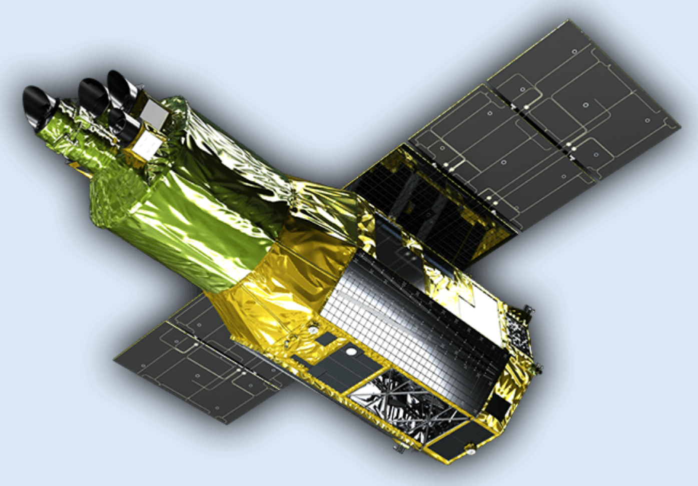
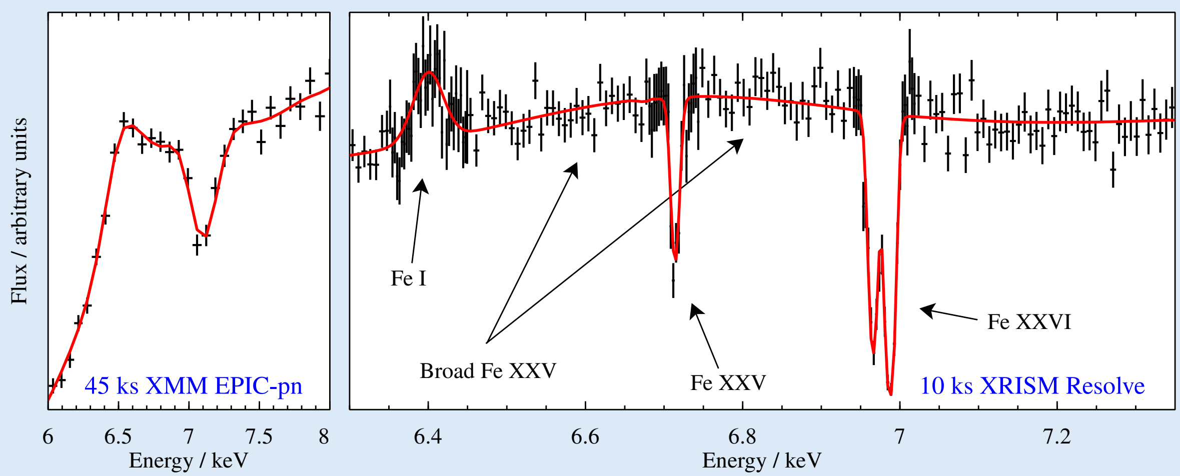


- Current XMM data pushed to the limit. XRISM will offer much better spectral resolution
- XRISM -> precision measurements of wind ionization response to X-ray pulsations in Her X-1
- Large campaign on Her X-1 with XRISM (180 ks), XMM-Newton (80 ks), Chandra (50 ks), NuSTAR (50 ks) executed on **September 10-14 2024**: stay tuned for new exciting results!!



Conclusions

- Thanks to its warped, precessing accretion disk and pulsating X-ray source, Hercules X-1 offers unique insights into the physics of accretion disk winds in X-ray binaries

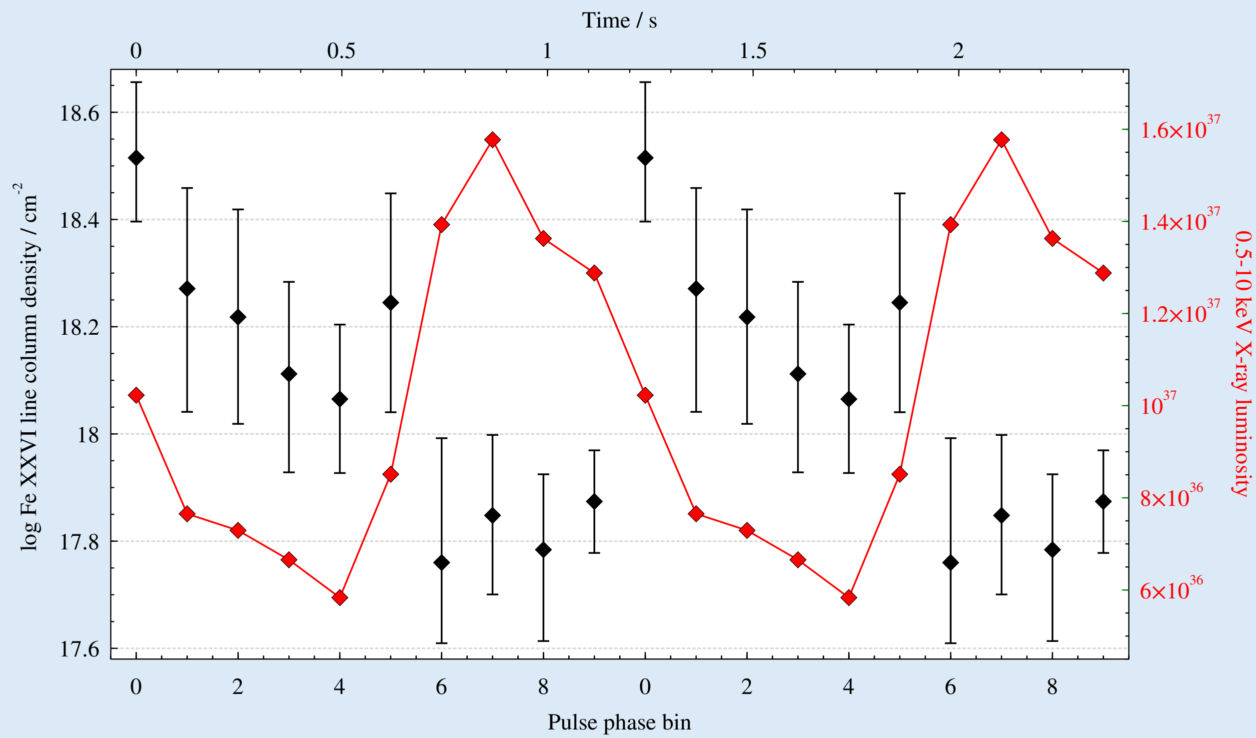
- We leveraged the disk precession to study the wind vertical structure, and produce the first 2D map of a disk wind

- Leveraging the X-ray pulsations of Her X-1, we obtained first constraints on the wind number density

- A combined X-ray campaign led by ***XRISM*** (carried out last week!) will allow us to measure the wind density over a range of heights, constraining the wind launching mechanism

Analysis of XMM-Newton EPIC pn data: Phenomenological method

- Analysis of highest-quality XMM-Newton observation of Her X-1
- Split EPIC data by pulse phase into 10 bins
- Analyze wind absorption lines with Gaussian models: line column density anti-correlates with X-ray flux



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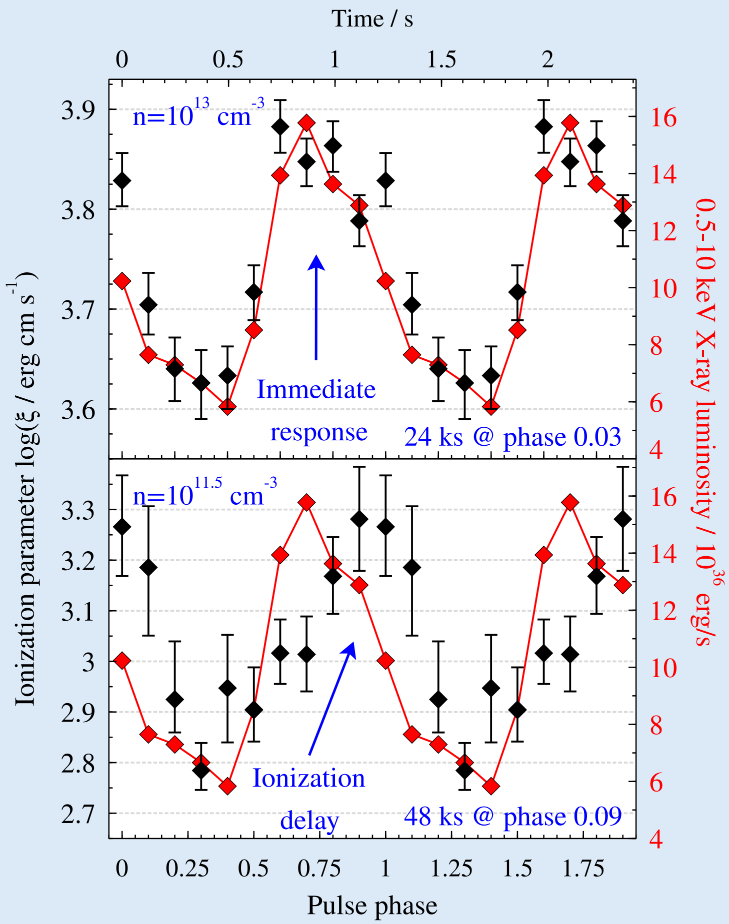

Her X-1: A large observational campaign

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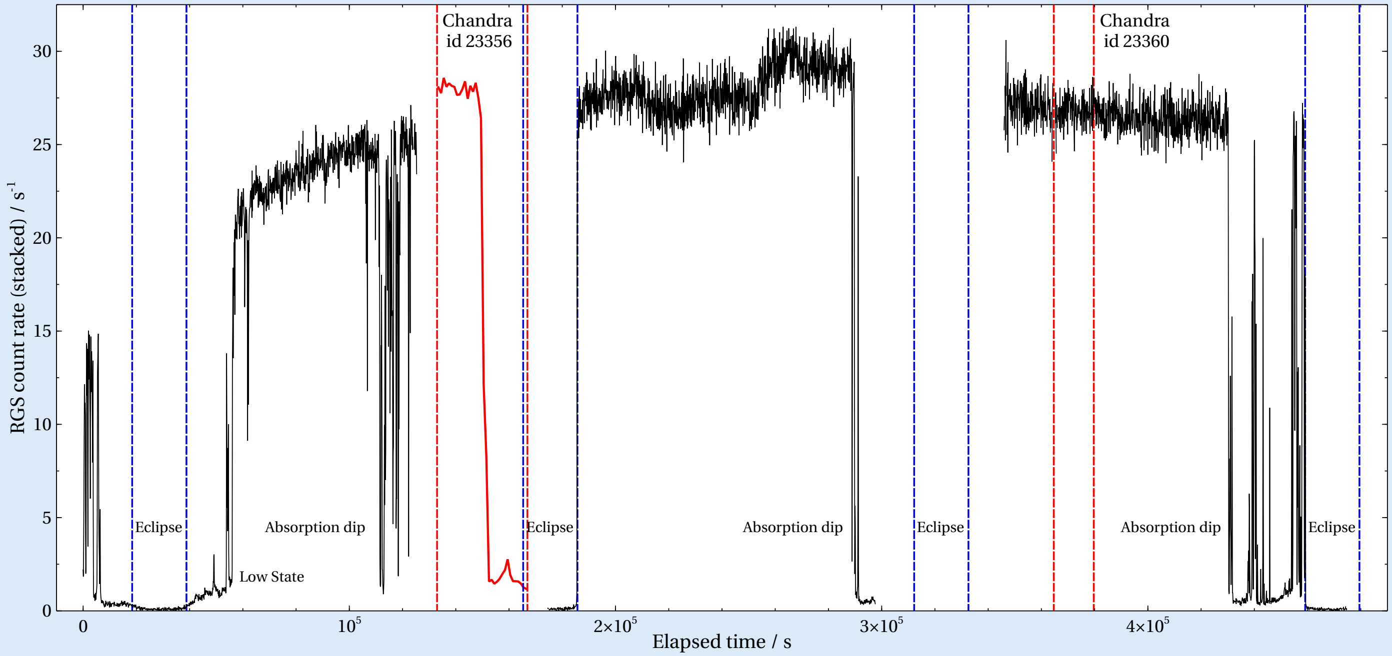
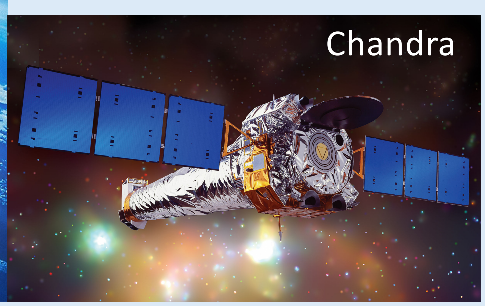
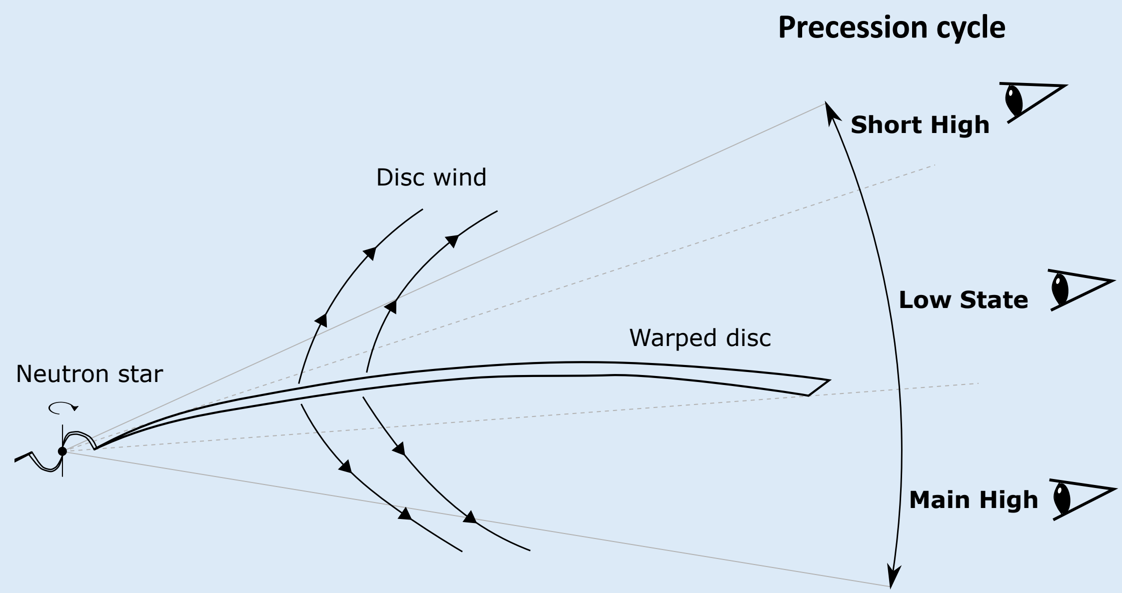


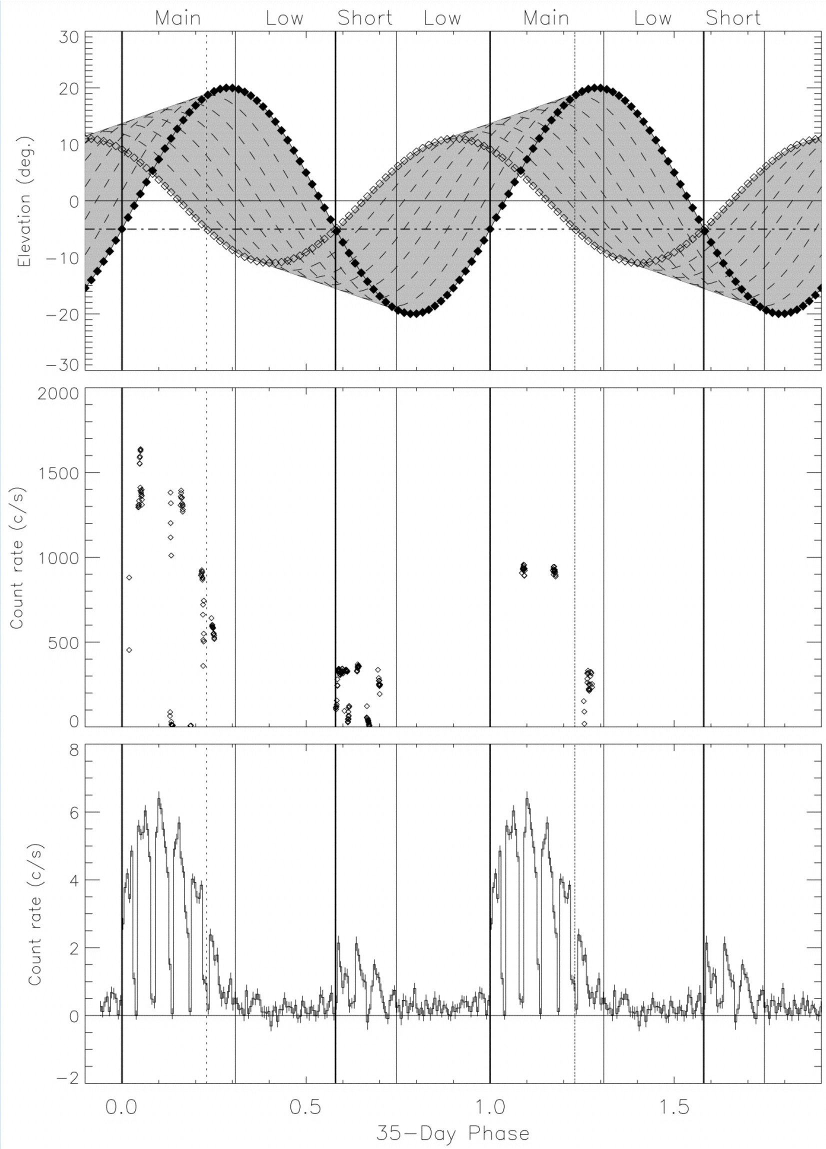


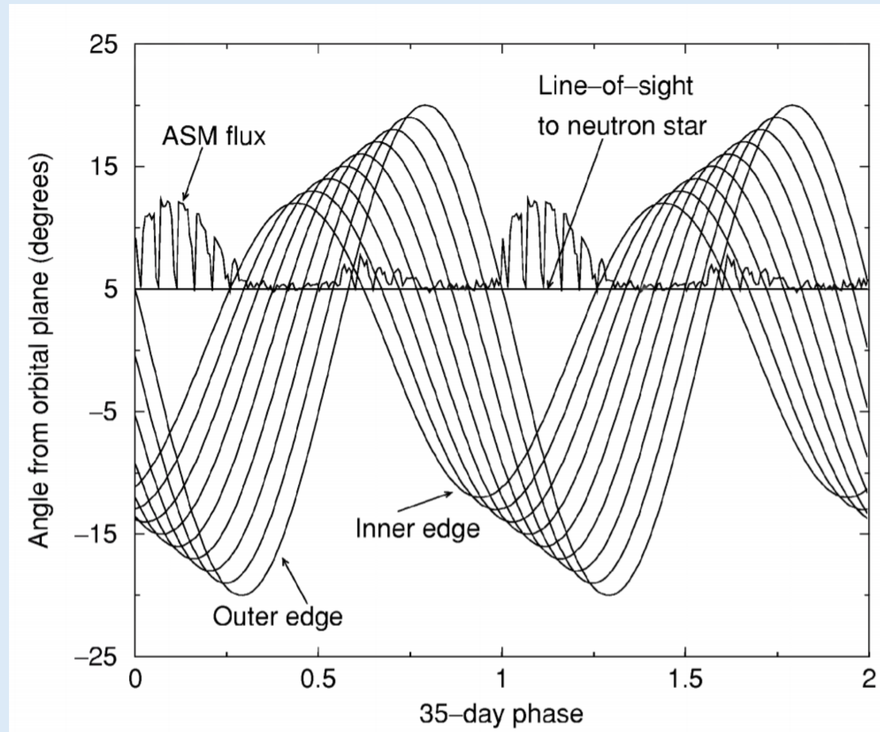
Kosec et al. (2022)

Accretion disk wind in Hercules X-1

- Detected in 8 out of 9 archival High State XMM-Newton observations
- A strong wind parameter variation: may be explained by a varying line of sight
  - Different observations sampling different parts of the vertical wind structure
  - A unique system to study the physics of disk winds!!
- To follow up this opportunity: a Large XMM (380 ks) + Chandra (50 ks) campaign during a single precession cycle





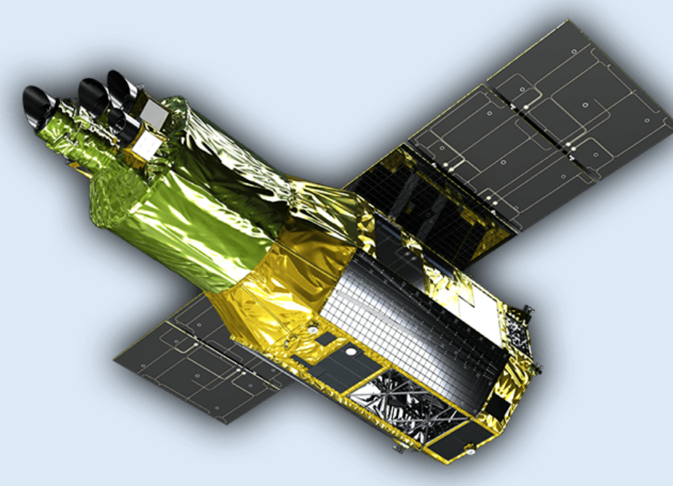


Scott+00, Leahy+02

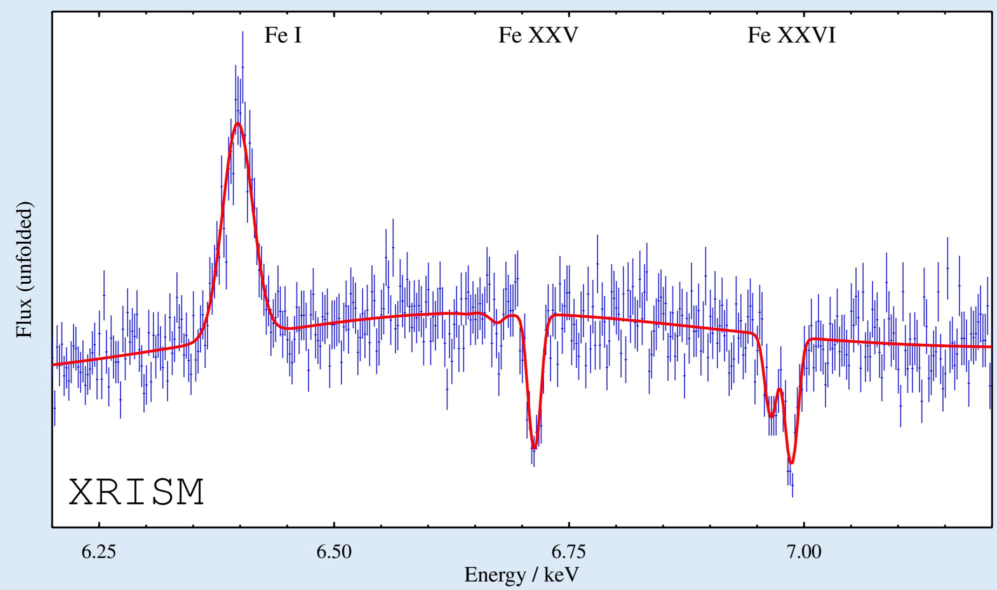
This talk: accretion disk winds in X-ray binaries

- But I am interested also in
  - Active galactic nuclei
  - Tidal disruption events
  - Quasiperiodic erupting systems
  - Ultraluminous X-ray sources

Future: precision wind mapping with ***XRISM***



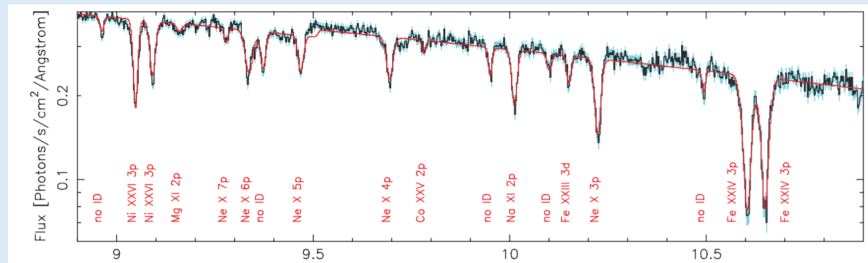
- Current XMM data pushed to the limit. XRISM will greatly improve data quality
- 10 ks XRISM simulation of Her X-1 (Kosec et al. 2023c): excellent spectral quality
- XRISM -> precision measurements of wind ionization response to X-ray pulsations in Her X-1

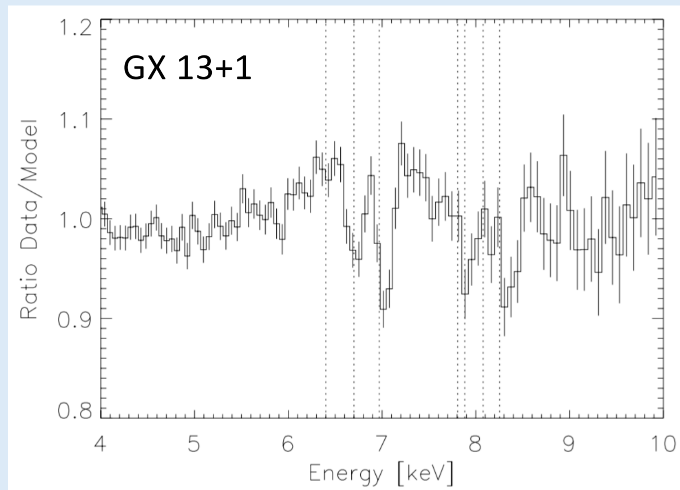


Accretion disk winds in X-ray binaries

- Blueshifted (~1000 km/s) absorption lines ubiquitous in high inclination soft state black hole XRBs, also in neutron star systems
- Launch solid angle
  - Could be as small as 5-10° from the disk
  - Still can carry away significant fraction originally infalling mass
- Launching mechanism
  - Radiation pressure on electrons insufficient, wind too ionised for line-driving
  - Compton heating and magnetic fields strong candidates for wind driving

GRO J1655-40

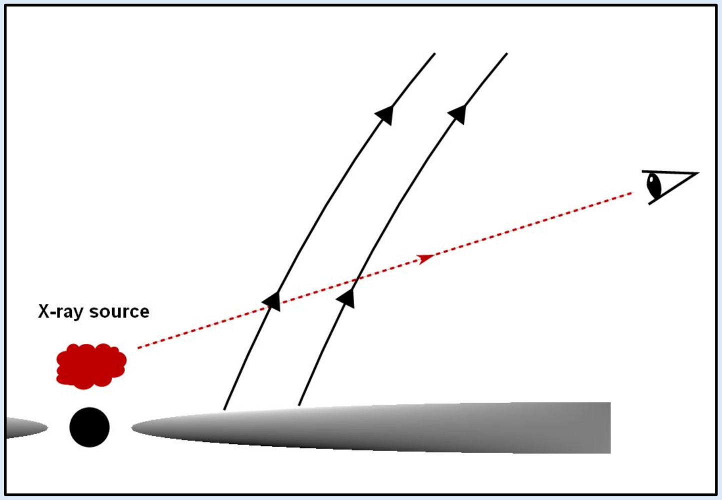




Miller et al. (2008), Ponti et al. (2012), Diaz Trigo et al. (2012)

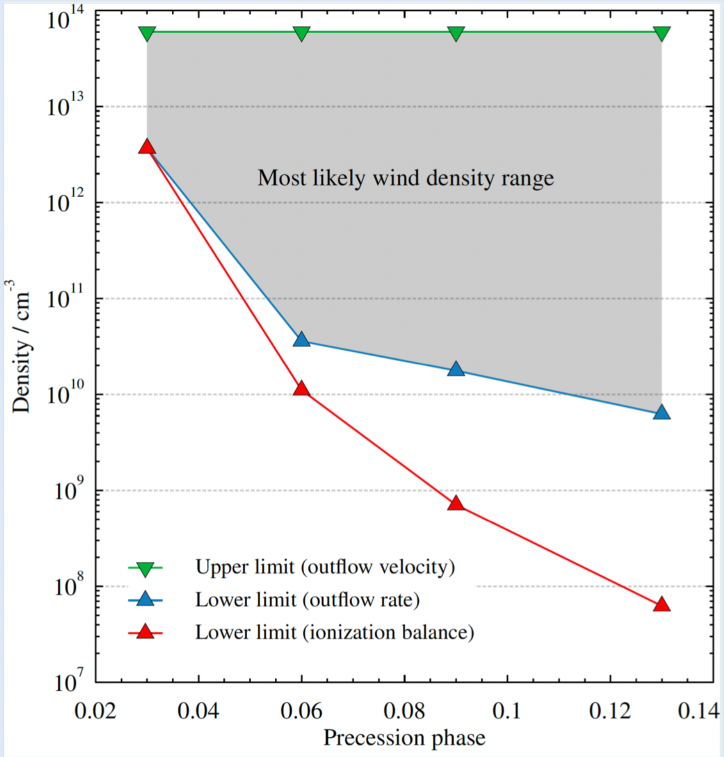
Understanding the properties of disk winds

- Wind ionized as it lifts from the disk -> study X-ray spectral transitions
- Photoionization wind modeling:
  - Measure wind velocity v, column density N_H, ionization parameter ξ, but usually NOT number density n
- Number density: crucial parameter to determine wind location and energetics
- $\xi = \frac{L_{ion}}{nR^2}$ $\qquad$ $\dot{M}_{out} = \Omega C_V \mu m_p n R^2 v$



Her X-1 and its disk wind

- Known to host a warped disk precessing every 35 days
- Our line of sight varies over the 35-day period: we can sample vertical disk wind structure
- Even with deep observations (500+ ks XMM-Newton), constraints on wind number density are weak (3-4 dex of parameter space)



Time-dependent ionization with XRISM

- Simulate a 25 ks pulse-resolved XRISM observation of Her X-1 with TPHO model
- Assume a range of wind densities from 10^{10} to 10^{13} cm^{-3}
- Wind response easily detectable, and density measurable from any time delays