Probing the clumpy winds of giant stars with high mass X-ray binaries

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December 10, 2015

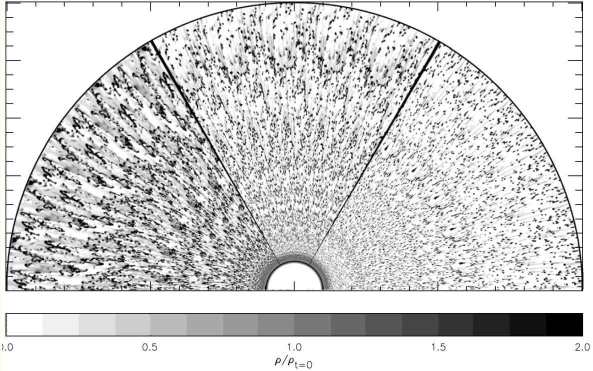
1. Clumpy winds of O/B stars
2. Three challenges of HMXBs as probes of clumpy winds
3. Probing the clumpy winds of giant stars
   - Cygnus X-1: orbital variability of absorption
   - Cygnus X-1: X-raying the clumps
   - Vela X-1: deciphering accretion structure
4. Outlook: Astro-H and Athena

Winds of O/B stars

LH 72 in LMC; ESA/Hubble, NASA and D. A. Gouliermis

- line-driven (scattering of the star's UV radiation; CAK-winds after Castor, Abbott & Klein, 1975)
- mass loss $\gtrsim 10^{-7} M_{\odot}/\mathrm{yr}$
- terminal velocities $> 2000\,\mathrm{km/s}$
- trigger or inhibit star formation
- impact chemical evolution of galaxies through enrichment

Clumpy winds



Dessart & Owocki, 2005; 2D simulations

line-driving unstable to velocity perturbations

line-deshadowing instability (LDI)

$\Rightarrow$ perturbations grow rapidly

$\Rightarrow$ strong shocks

$\Rightarrow$ formation of dense gas-shells

$\Rightarrow$ wind clumping

Multiple observational lines of evidence structure of optical emission lines *(Hillier 1991, Eversberg et al. 1998, Markova et al. 2005)*; wind-shocks as explanation for strong X-ray emission from single O-stars *(Feldmeier 1997)*, etc.

but: clump properties inferred indirectly, probes only clump ensamble

High mass X-ray binaries:

Material flows from O/B star onto neutron star or black hole

- ► accretion and ejection processes
- ► bulk of radiation in X-ray range

High mass X-ray binaries:

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winds influence the accretion rate and thus X-ray production

- flares
- long-term variability?
- superfast X-ray transients

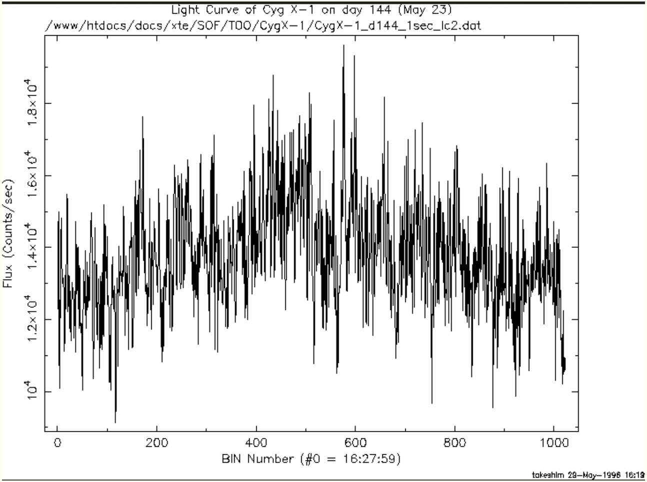
⇔

radiation from close to BH/NS effectively X-rays the wind

- in situ probes close to stellar surface
- different parts of the wind at different orbital phases

Challenge I: intrinsic variability

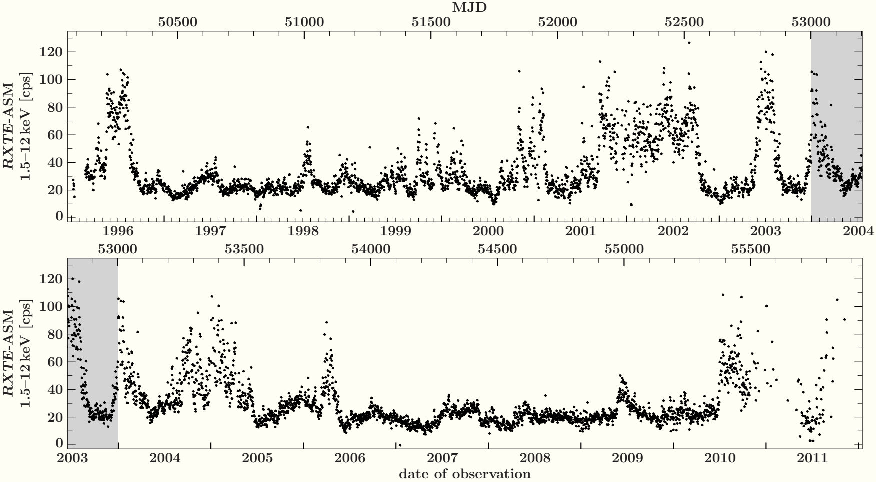
X-ray binary intrinsic variability on timescales from seconds to years:



solution: talk to X-ray binary experts!

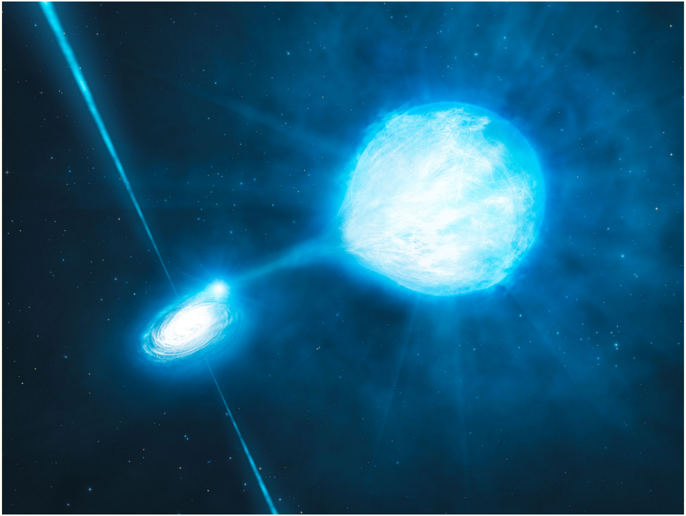
Challenge I: intrinsic variability

X-ray binary intrinsic variability on timescales from seconds to years:



solution: talk to X-ray binary experts!

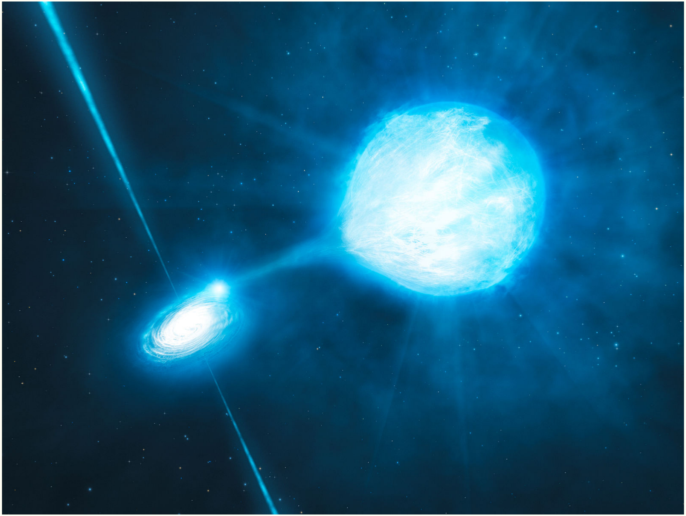
Challenge II: accretion structure



NS/BH disturbs the wind, resulting in accretion & photoionization wakes and focused winds

analytical and numerical models of compact object/wind interaction so far for smooth winds only

Chance: accretion structure



NS/BH disturbs the wind, resulting in accretion & photoionization wakes and focused winds

analytical and numerical models of compact object/wind interaction so far for smooth winds only

solution: learn more about accretion structure of HMXBs

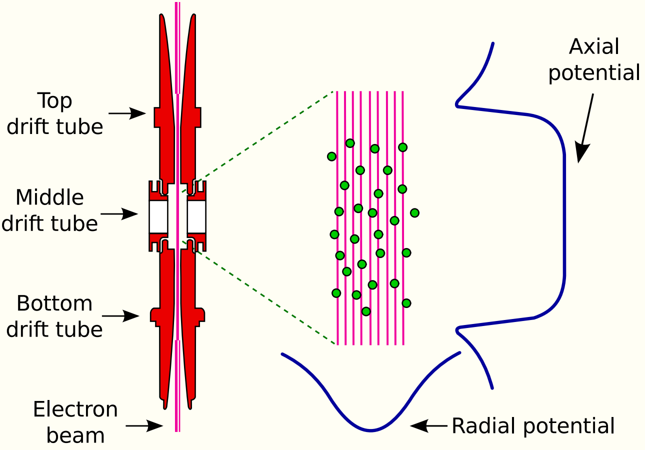
Challenge III: reference line energies

cold(er) clumps
⇒ low ionization lines

$E_{\rm obs} \neq E_{\rm lit}$
Doppler shifts or lack of knowledge of atomic physics?

solution: lab measurements!

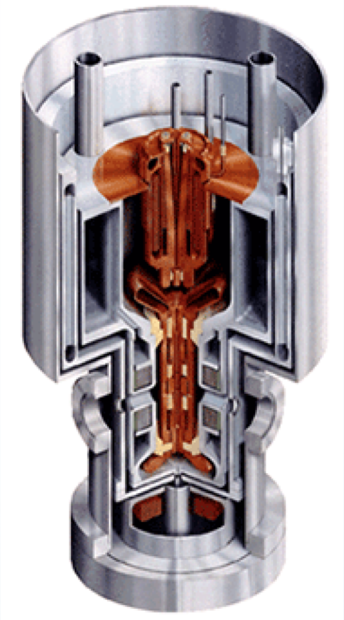
crucial for microcalorimeters! (*Astro-H*, *Athena*)

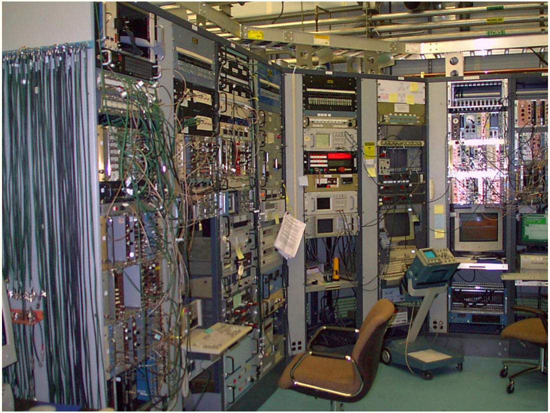


https://ebit.llnl.gov/overviewEBIT.html

EBIT: Electron Beam Ion Trap

Challenge III: reference line energies

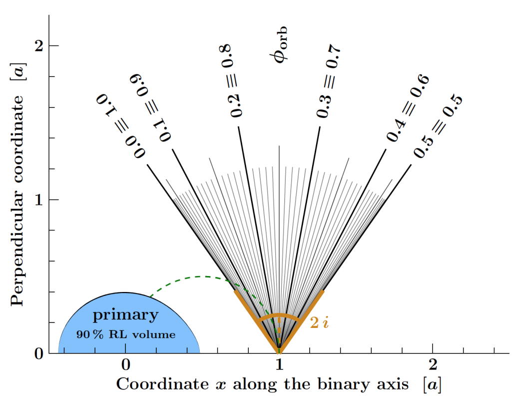




Use EBIT-I @ LLNL

N. Hell, G. Brown; Si, S, Mg, Al, Cl, Ar, and Mn data exist, publications in prep.

Cyg X-1 / HDE 226868 system



Hanke 2011

companion:
O-type supergiant

mass loss rate: $\sim 2 \times 10^{-6} M_{\odot}\, yr^{-1}$

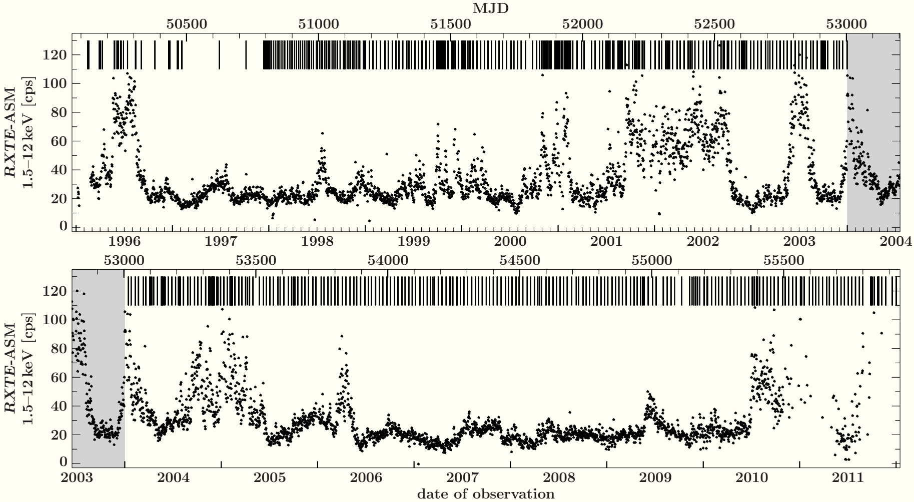
orbital period: 5.6 days

inclination: $i \approx 27^{\circ}$ *(Orosz et al., 2011)*

ISM equivalent hydrogen density: $\sim 0.5 \times 10^{22}\,\mathrm{cm}^{-2}$ *(Xiang et al., 2011)*

- orbital variability of overall absorption ⇒ focussed wind
- orbital variability of 'dip'-occurence ⇒ individual clumps in the wind

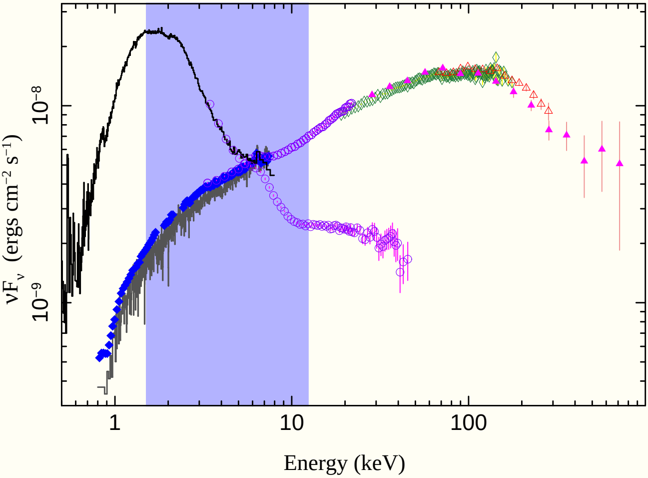
RXTE campaign



Grinberg et al., 2013, 2014

typical exposure: $\sim$2 ks

X-ray states



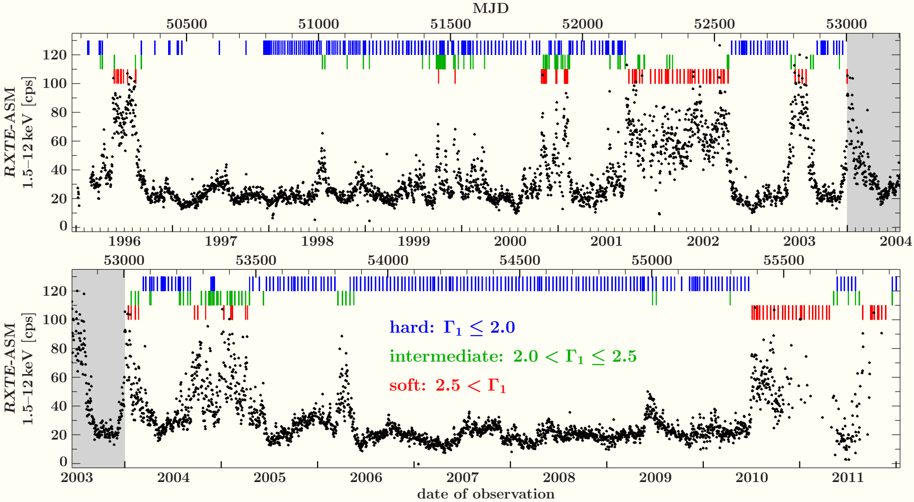
distinct radiation regimes
≙ states

only hard state useable for absorption studies

Cygnus X-1; *Nowak et al., 2011*

Chandra • *Suzaku*-XIS • *Suzaku*-GSO • *RXTE*-PCA • *RXTE*-HEXTE • *INTEGRAL*

RXTE campaign

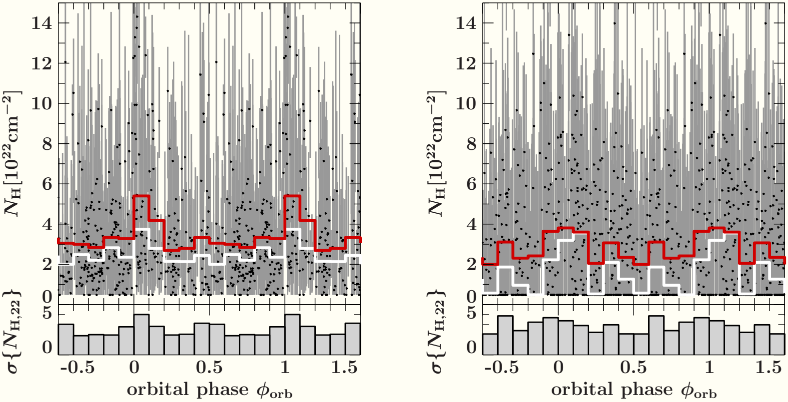


Grinberg et al., 2013, 2014

typical exposure: ∼2 ks

Orbital variability of absorption: soft and intermediate states

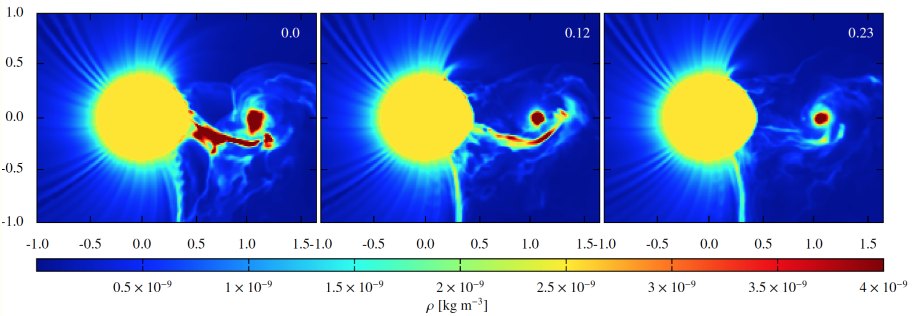
disk component ⇒ large uncertainties in N_H



wind strongly ionized ⇒ mainly transparent to X-rays

Orbital variability of absorption: soft and intermediate states

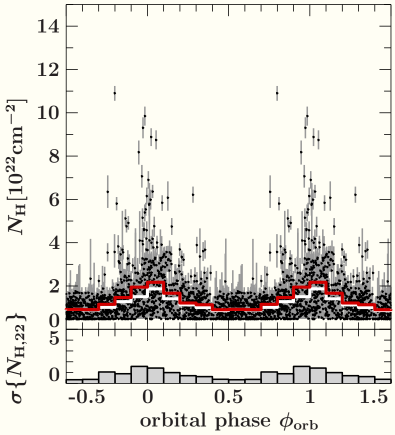
ionized material ⇒ line-driving mechanism breaks down ⇒ changes in the geometry of the system



Čechura & Hadrava, 2015

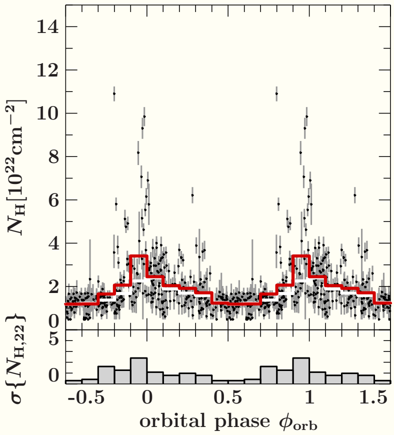
Orbital variability of absorption: hard state

all hard state data



$\Rightarrow$

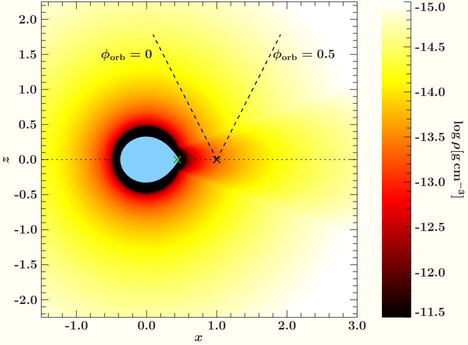
one long, stable hard state

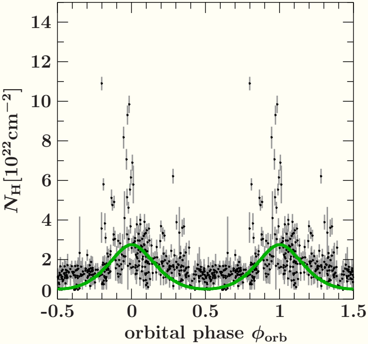


Grinberg et al., 2015

Hard state: a focussed wind model

- toy model for a focussed CAK wind *(Gies & Bolton, 1986; Friend & Castor, 1982)*



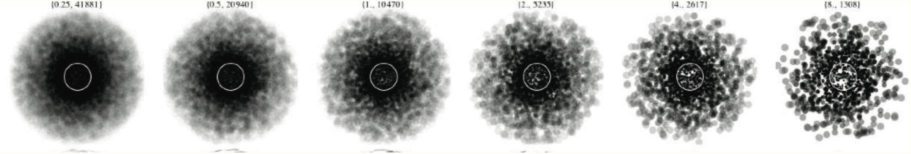


Grinberg et al., 2015

- fails to describe the variability due to lack of clumps

Hard state: a clumpy wind model

(Owocki&Cohen 2006, Sundqvist et al. 2012, but see also Oskinova et al. 2012)



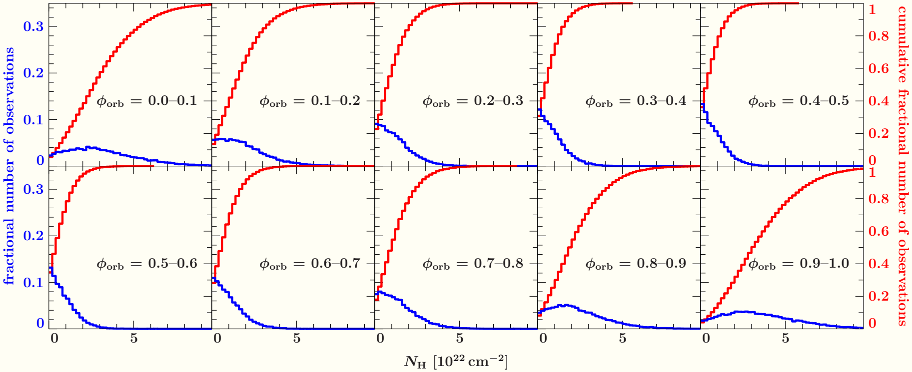
(Fig. from Sundqvist et al. 2012)

- discrete, spherical clumps
- β velocity law
- no focussed wind component (yet)

- known: stellar parameters, terminal velocity, mass loss rate
- variable: number of clumps N and terminal porosity length h_∞

Hard state: a clumpy wind model

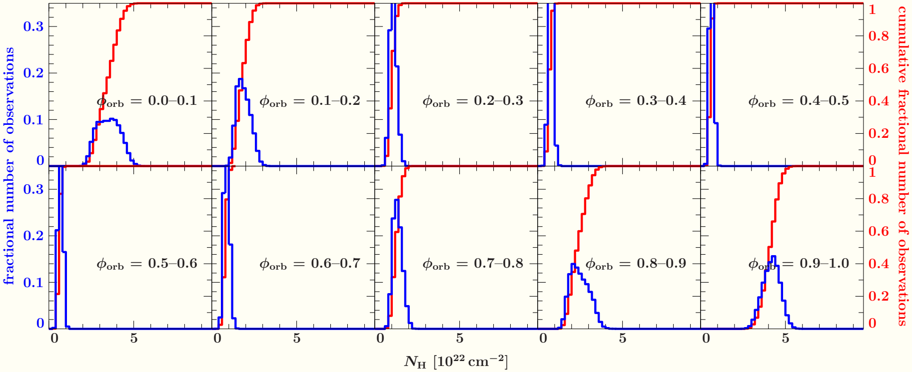
terminal porosity length $h_\infty = 0.1\, R_*$ stellar radii



Grinberg et al., 2015

Hard state: a clumpy wind model

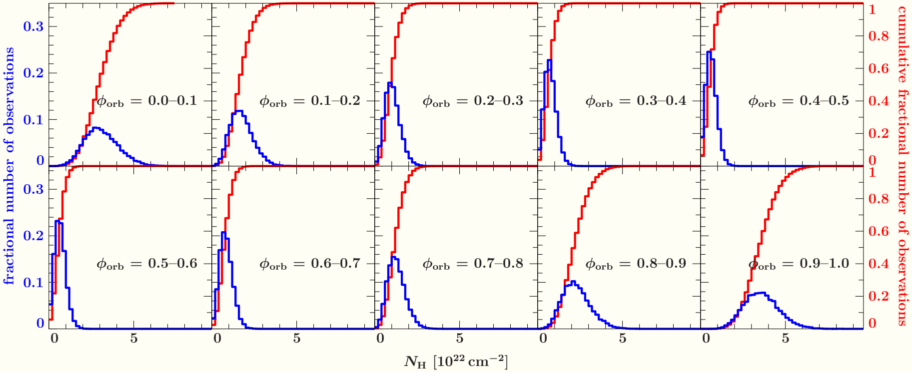
terminal porosity length $h_\infty = 10\, R_*$ stellar radii



Grinberg et al., 2015

Hard state: a clumpy wind model

terminal porosity length $h_\infty = R_*$ stellar radius

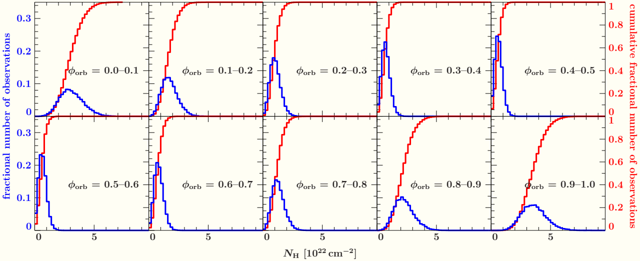


Grinberg et al., 2015

Hard state: a clumpy wind model

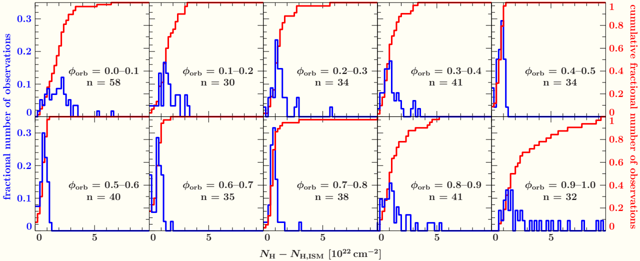
model

$h_\infty = R_*$

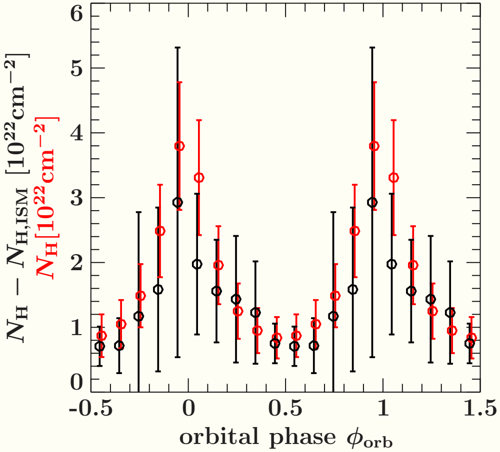


observations

✓



Hard state: a clumpy wind model



Grinberg et al., 2015

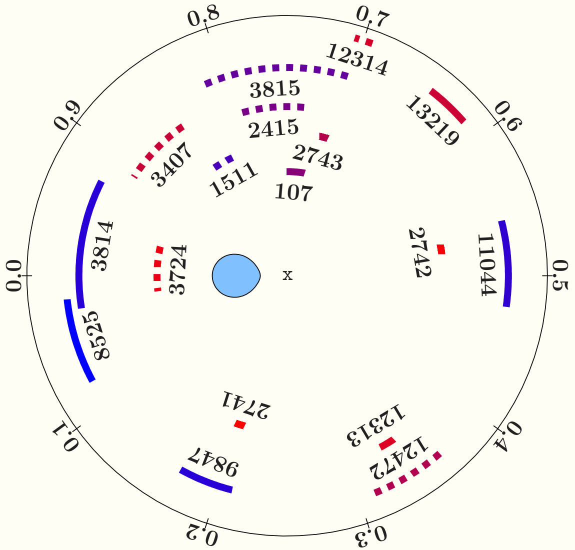
agreement between data (black) and model (red)

$h_{\infty} \approx R_{*}$ agrees with values for single O stars

non-Gaussian tail for $\phi_{\mathrm{orb}} \approx 0$ in data
$\Rightarrow$ structure in wind $\Rightarrow$ focussed wind? non-spherical clumps?

average values (circles) and standard deviations (error bars on the average values)

Chandra campaign

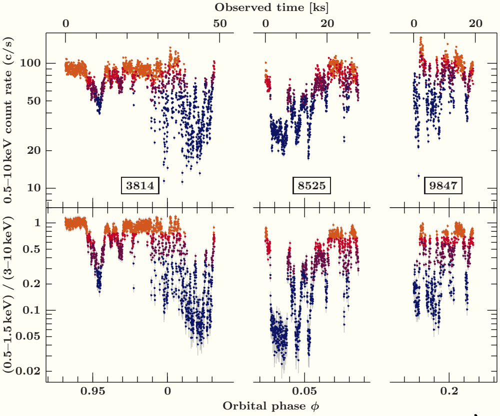


four observations in hard state: ObsIDs 3814, 8525, 9847, 11044

three observations show dipping: ObsIDs 3814, 8525, 9847

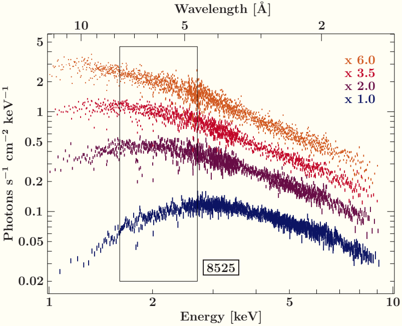
Miškovičová et al., A&A subm.

Dipping states



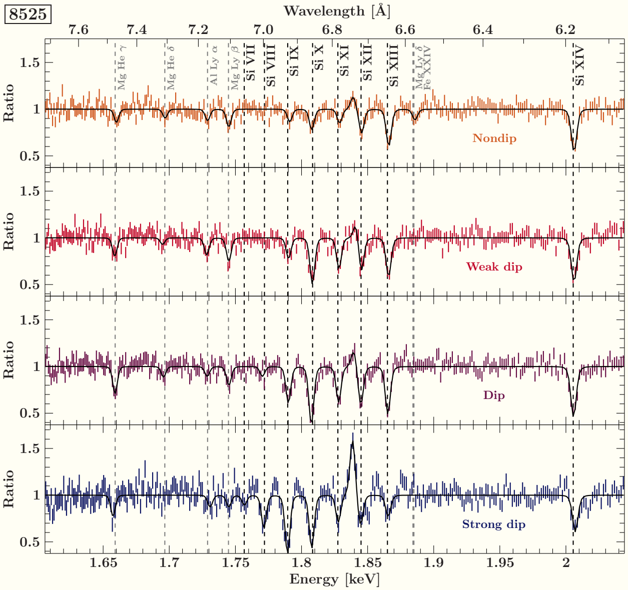
divide each observation in four dipping stages with similar SNR

$\Longrightarrow$



Hirsch et al., in prep.

Clump structure



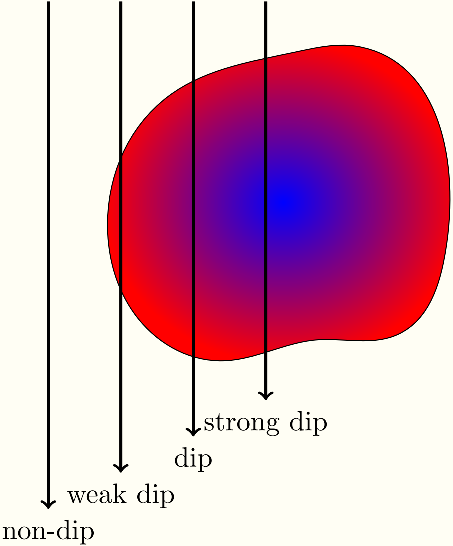
lower ionization stages of Si and S appear when absorption stronger

same Doppler-shift for lines in the same ObsID

⇒ onion-like clump structure

Hirsch et al., in prep.

Clump structure



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Hirsch et al., in prep.

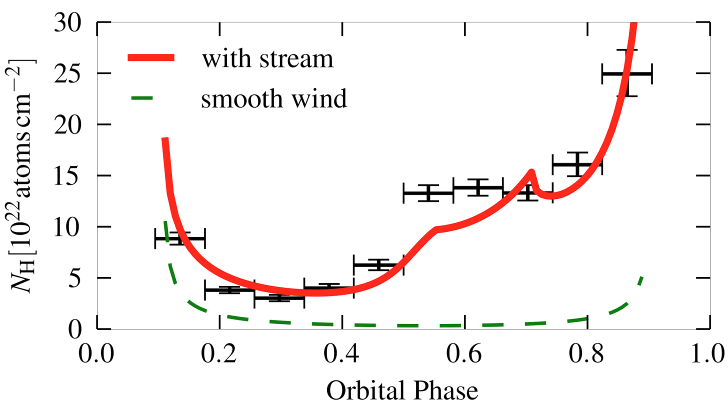
Vela X-1

- B0.5 Iab supergiant
- 283 s pulsar
- eclipsing 9 d orbit

- binary separation: 53.4 $R_\odot$
  $\Rightarrow$ neutron star embedded in companion wind

Variability along the orbit

changing baseline absorption best accessed with all sky monitors, e.g., MAXI, averaging over many orbits:



Doroshenko et al. 2013

Wind and accretion structure

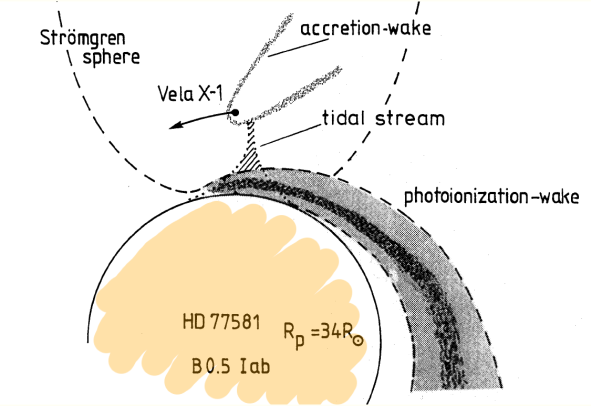


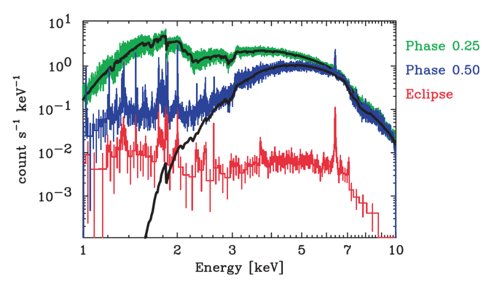
Fig. from Kaper et all, 1994

accretion wake
focussing of the wind through gravity

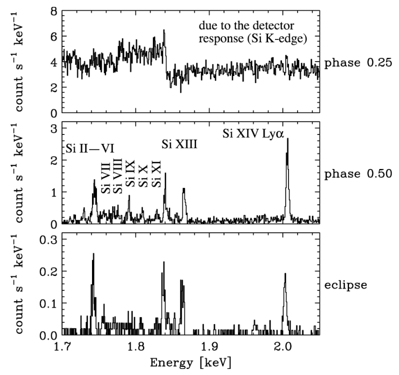
photoionization wake
shocks on interface between CAK-wind and ionized plasma around neutron star

$\Rightarrow$ absorption highly variable with orbital phase $\phi_{\rm orb}$

High resolution spectra along the orbit



Watanabe et al. 2006

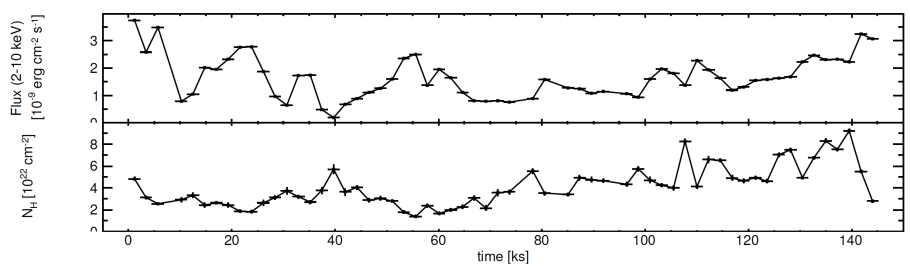


Watanabe et al. 2006

high & low ionization stages seen at $\phi_{\mathrm{orb}} \approx 0.5 \Rightarrow$ simultaneous presence of hot and cold gas

Short-term variability

Suzaku at $\phi_{\rm orb} = 0.17$–36:



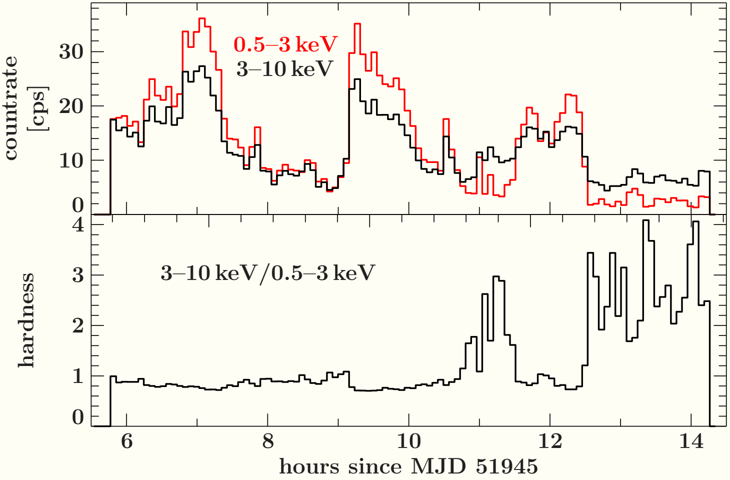
Odaka et al. 2013

$\Rightarrow$ highly variable absorption atop orbital variability at $\phi_{\rm orb} \lesssim 0.5$

- time scales as short as 1–2 ks
- also seen in *XMM* (Martinez-Nunez et al. 2014) and *EXOSAT* (Haberl et al. 1990)

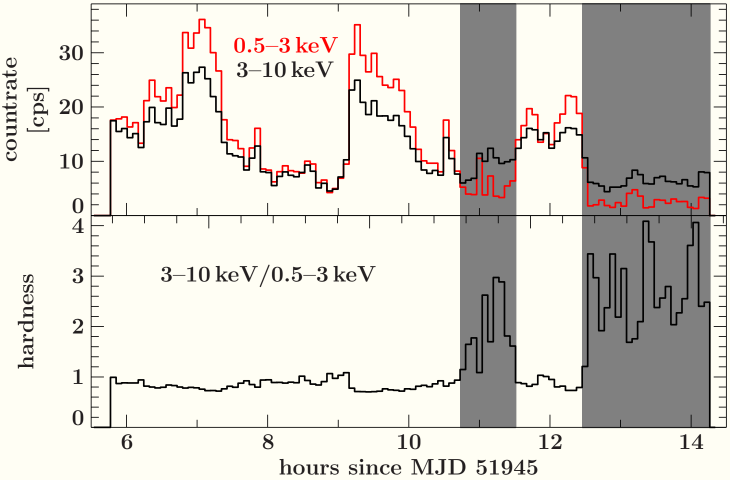
BUT: *Chandra*-HETG observations always been analyzed as a whole!

Short term variability in *Chandra* observations



ObsID 1928, Feb 11 2001

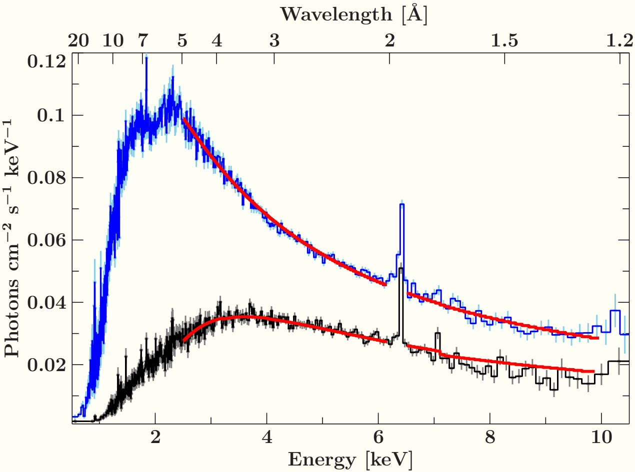
Short term variability in *Chandra* observations



ObsID 1928, Feb 11 2001

⇒ clearly defined periods of enhanced hardness

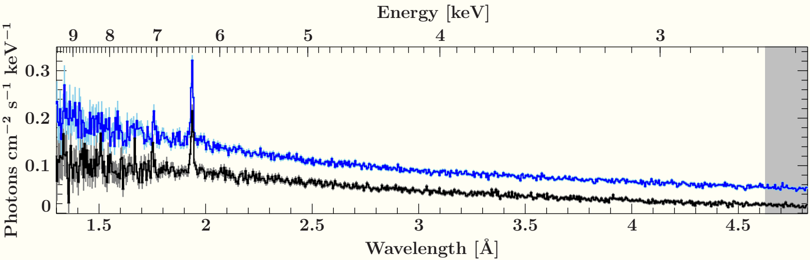
Hardness-resolved spectra

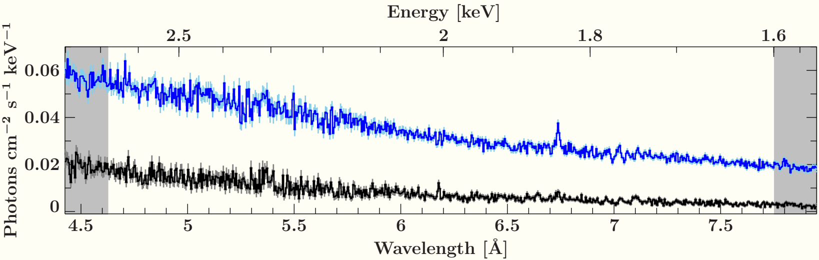


the 2.5–10 keV continuum:

- cannot be described with same N_h, but different power laws
- can be described with same power law, but different N_h

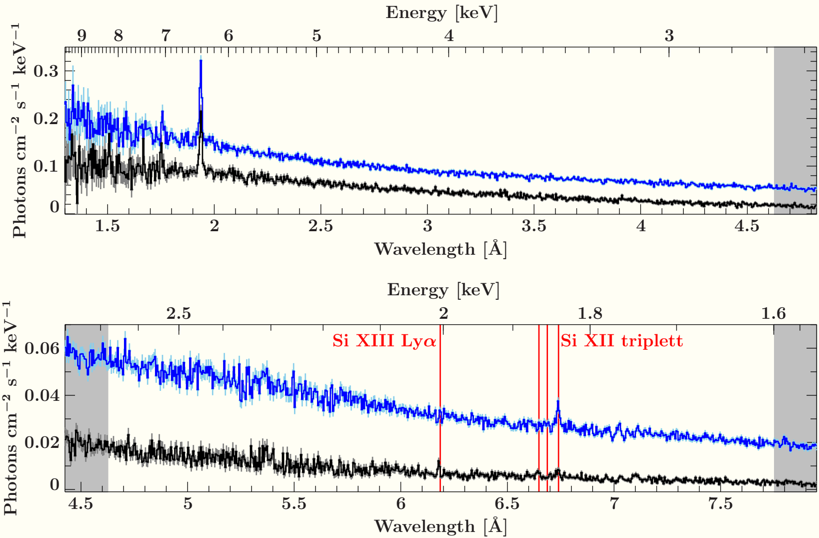
Hardness-resolved spectra





Marked: detection in composite spectrum (Goldstein et al. 2004)

Hardness-resolved spectra



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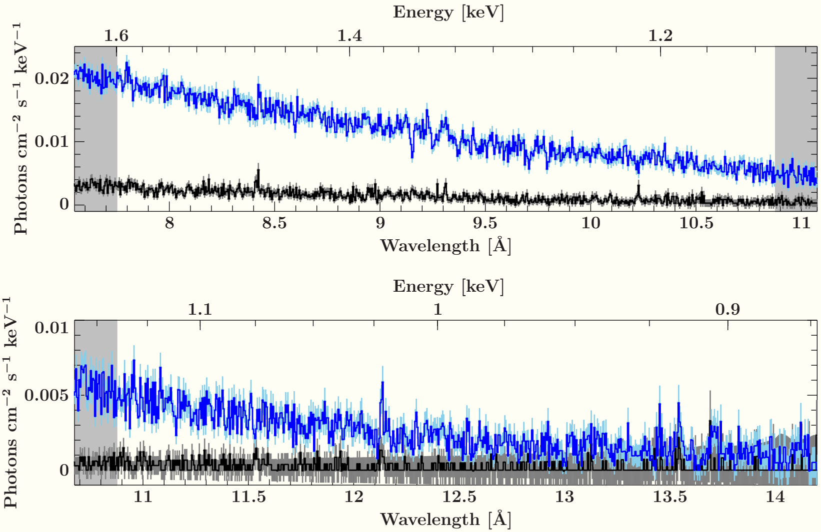

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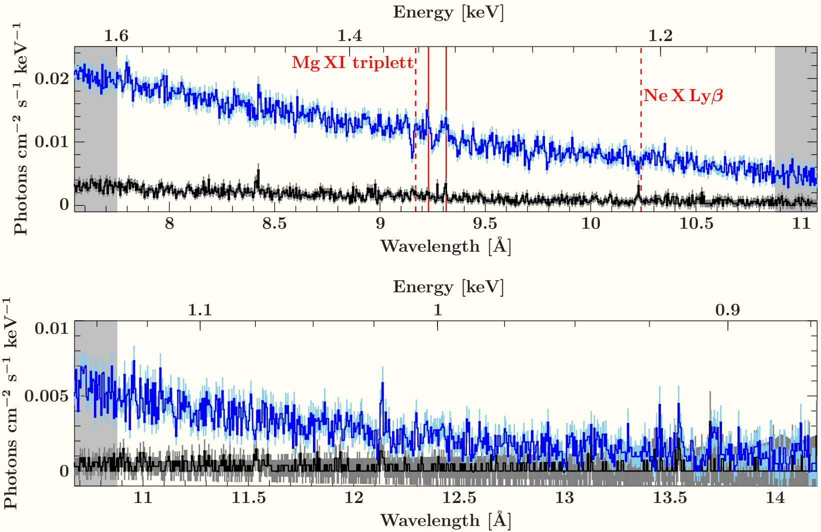
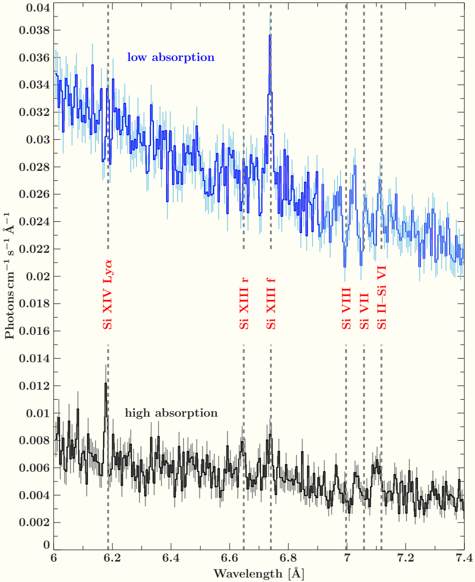


Marked: detection in composite spectrum (Goldstein et al. 2004)

Si region



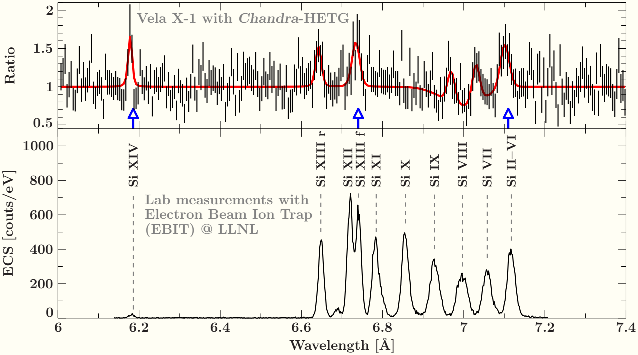
no Si lines except of Si XIII triplett have been previously detected in the composite spectra (Goldstein et al. 2004)

lines in the high hardness/high absorption spectrum

complex structure in low absorption spectrum

Si region during dips

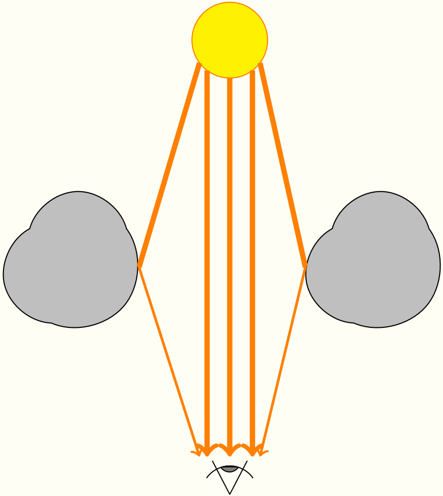
- use newest lab reference values for line energies
- tie lines with similar blueshifts



high ionization lines: ionized part of the wind
$v \approx -300$ km/s

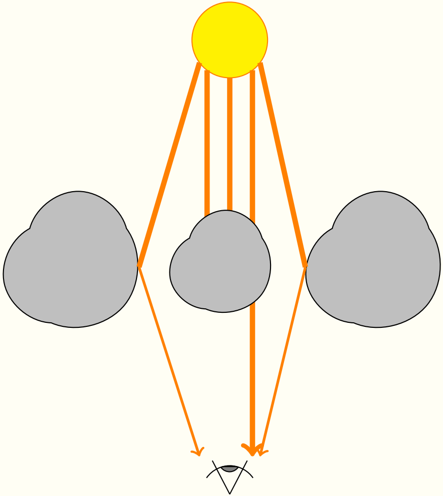
low ionization lines: reflection from clumps
$v \approx -1000$ km/s

Toy geometry



low hardness/absorption

Toy geometry

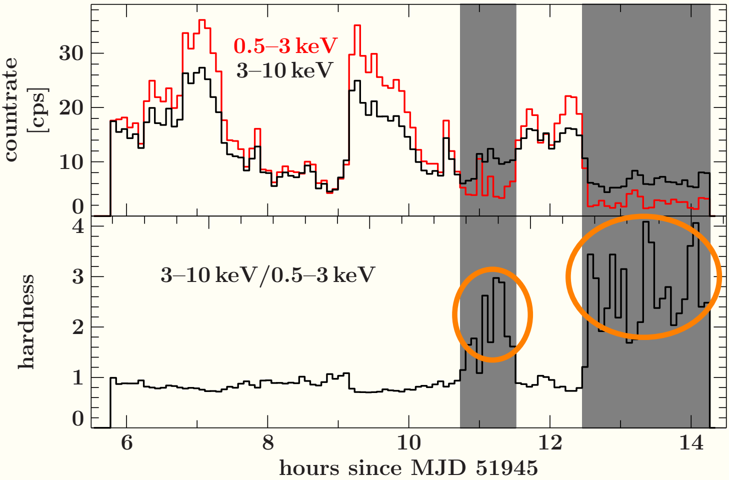


high hardness/absorption ⇒ *dips*

- clumps coming into the line of sight
- reduced continuum, makes fluorescent lines visible
- different velocities for hot (ionized) and cold (not yet ionized) medium

⇒ wind clumps or a patchy accretion wake?

Even shorter timescales?

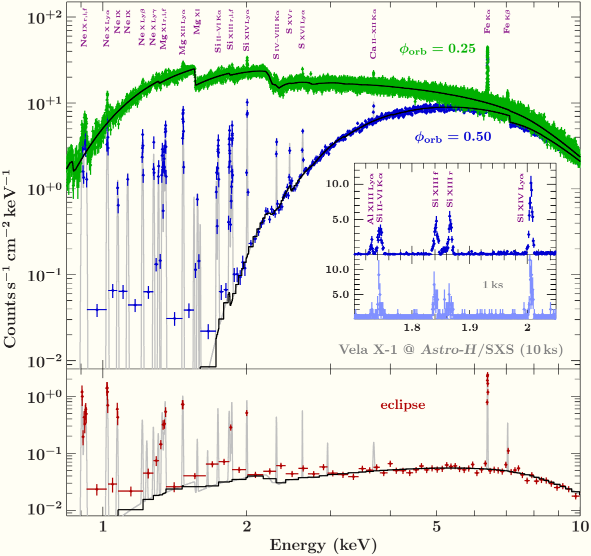


⇒ shorter-term variability not yet accessible, but possibly crucial, also to test simulations *(e.g., Blondin et al. 1990)*

Outlook: *Chandra* & *Astro-H*

***Chandra*-HETGS**
∼180 ks at
$\phi_{orb} = 0.15$–0.45
forthcoming

Astro-H
higher effective area,
but lower energy resolution in Si-region



Kitamoto et al. 2014; plot by M. Kühnel & N. Hell

SWG3.3: End Points of Stellar Evolution

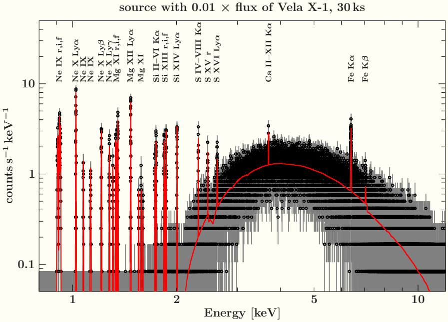
science goal R-SCIOBJ-332

Athena shall determine the geometry, porosity and mass loss-rate of stellar wind structures of isolated massive stars, especially in the presence of magnetic fields, through phase spectroscopy for a sample of objects. *Time resolved spectral analysis of X-ray emission from a sample of high mass X-ray binaries hosting supergiant and hypergiant companions shall be carried out to seek independent estimates of massive star wind properties.*

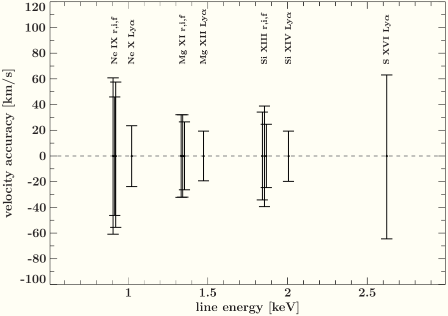
`http://athena2.irap.omp.eu/IMG/pdf/ASIE_final_public.pdf`

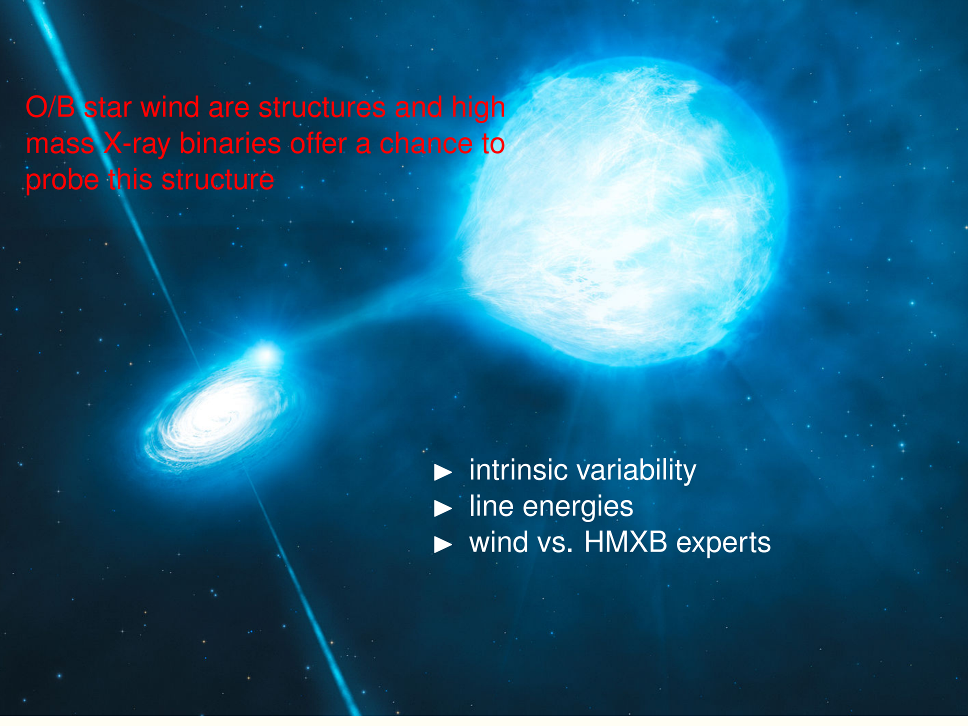
Outlook: *Athena*

- potential to resolve down to timescales of ∼10–100 s, but unclear whether bright sources (10–100 mCrab) can be observed
- fainter analogues can be observed ⇒ increase in sample!



⇒




O/B star wind are structures and high mass X-ray binaries offer a chance to probe this structure
► intrinsic variability
► line energies
► wind vs. HMXB experts