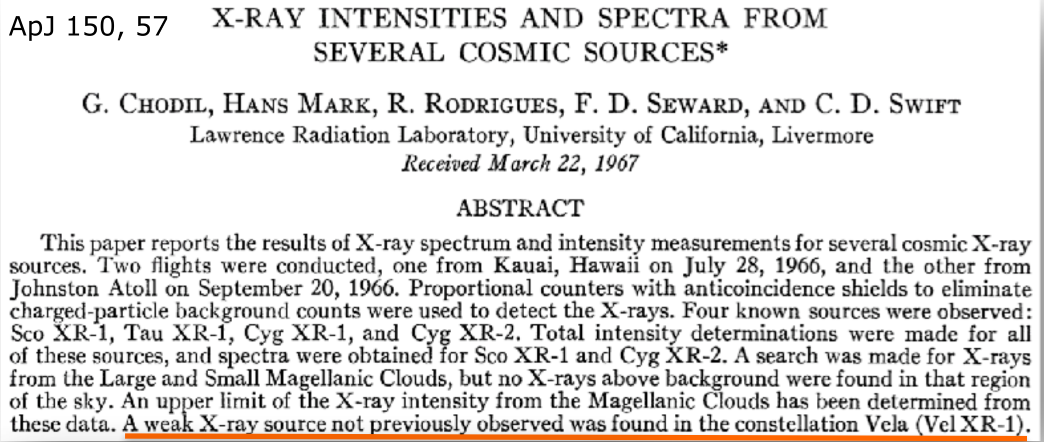
A bit of background

We know this system since 1966 …



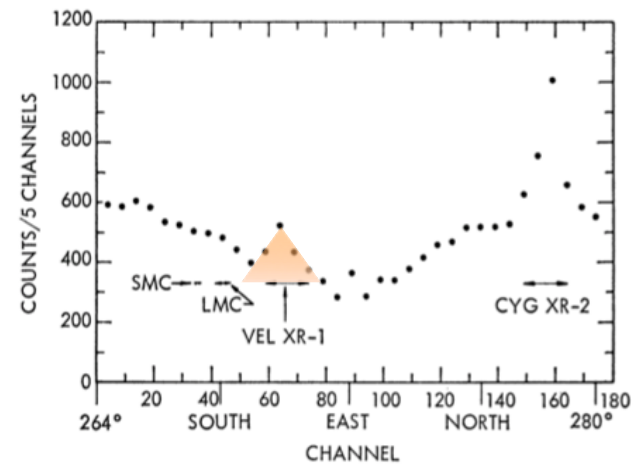
ApJ 150, 57

X-RAY INTENSITIES AND SPECTRA FROM SEVERAL COSMIC SOURCES*

G. CHODIL, HANS MARK, R. RODRIGUES, F. D. SEWARD, AND C. D. SWIFT
Lawrence Radiation Laboratory, University of California, Livermore
Received March 22, 1967

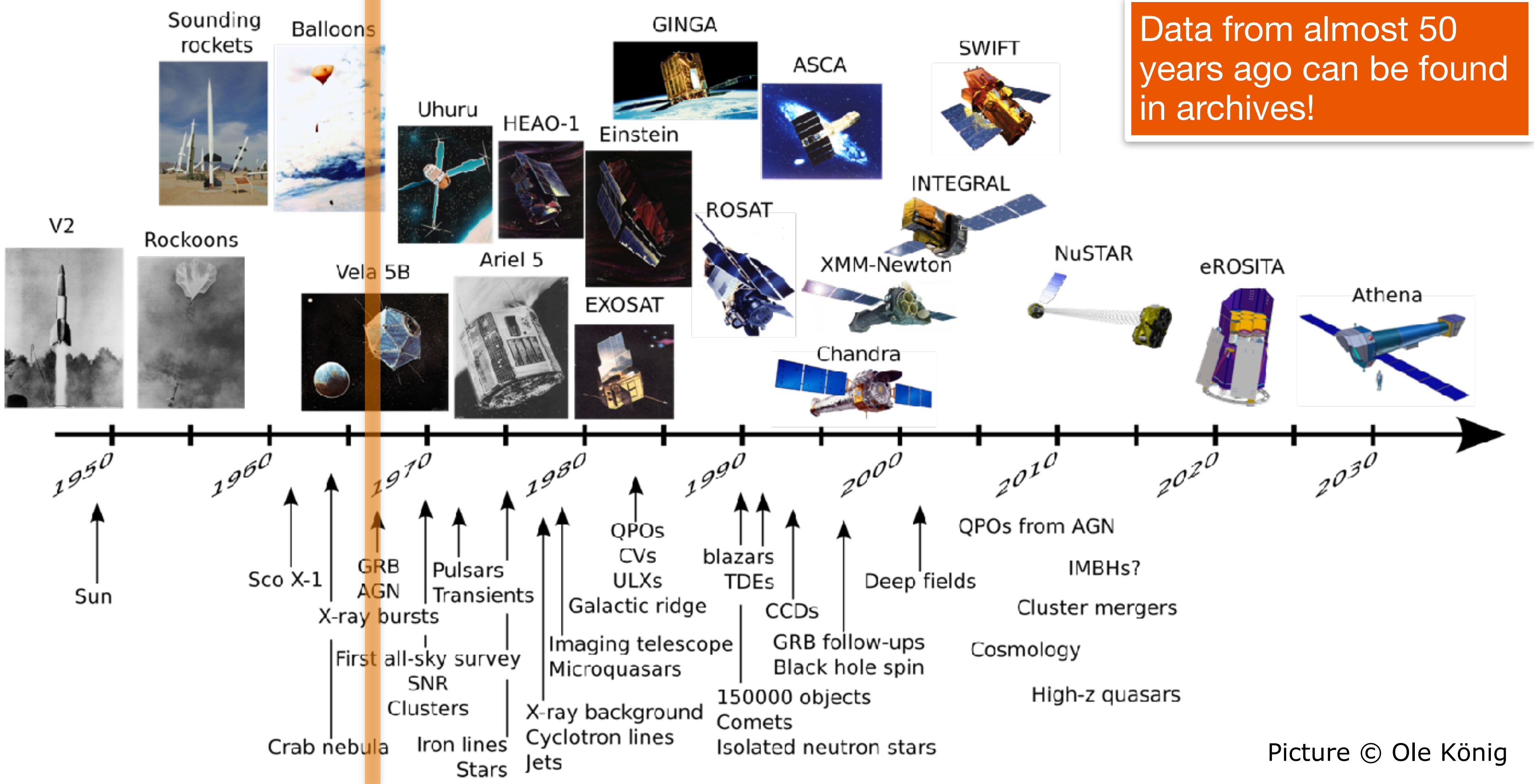
ABSTRACT

This paper reports the results of X-ray spectrum and intensity measurements for several cosmic X-ray sources. Two flights were conducted, one from Kauai, Hawaii on July 28, 1966, and the other from Johnston Atoll on September 20, 1966. Proportional counters with anticoincidence shields to eliminate charged-particle background counts were used to detect the X-rays. Four known sources were observed: Sco XR-1, Tau XR-1, Cyg XR-1, and Cyg XR-2. Total intensity determinations were made for all of these sources, and spectra were obtained for Sco XR-1 and Cyg XR-2. A search was made for X-rays from the Large and Small Magellanic Clouds, but no X-rays above background were found in that region of the sky. An upper limit of the X-ray intensity from the Magellanic Clouds has been determined from these data. A weak X-ray source not previously observed was found in the constellation Vela (Vel XR-1).



… in other words, since the early times of X-ray astronomy

Data from almost 50 years ago can be found in archives!



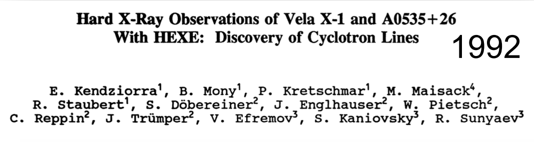
V2
Rockoons
Sounding rockets
Balloons
Vela 5B
Uhuru
Ariel 5
HEAO-1
Einstein
EXOSAT
GINGA
ROSAT
ASCA
Chandra
XMM-Newton
INTEGRAL
SWIFT
NuSTAR
eROSITA
Athena

1950
1960
1970
1980
1990
2000
2010
2020
2030

Sun
Sco X-1
Crab nebula
X-ray bursts
GRB
AGN
First all-sky survey
SNR
Clusters
Pulsars
Transients
Iron lines
Stars
X-ray background
Cyclotron lines
Jets
Imaging telescope
Microquasars
QPOs
CVs
ULXs
Galactic ridge
blazars
TDEs
150000 objects
Comets
Isolated neutron stars
CCDs
GRB follow-ups
Black hole spin
Deep fields
QPOs from AGN
IMBHs?
Cluster mergers
Cosmology
High-z quasars

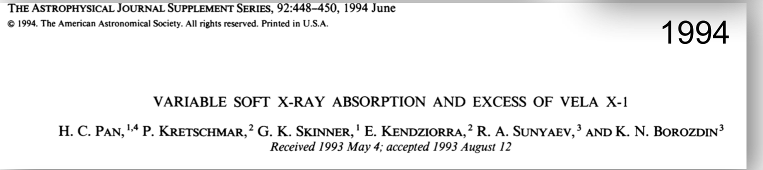
Picture © Ole König

My acquaintance with Vela X-1 is not quote as old, but still …


Hard X-Ray Observations of Vela X-1 and A0535+26
With HEXE: Discovery of Cyclotron Lines

1992

E. Kendziorra[1], B. Mony[1], P. Kretschmar[1], M. Maisack[4], R. Staubert[1], S. Döbereiner[2], J. Englhauser[2], W. Pietsch[2], C. Reppin[2], J. Trümper[2], V. Efremov[3], S. Kaniovsky[3], R. Sunyaev[3]


THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 92:448–450, 1994 June
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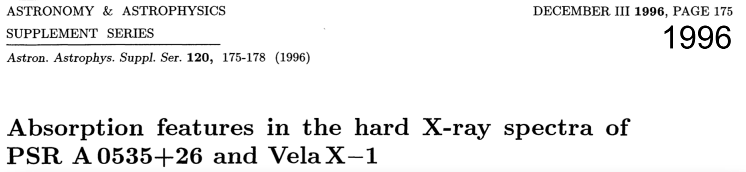
1994

VARIABLE SOFT X-RAY ABSORPTION AND EXCESS OF VELA X-1

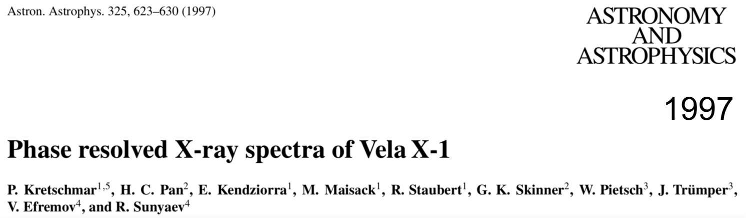
H. C. PAN,[1,4] P. KRETSCHMAR,[2] G. K. SKINNER,[1] E. KENDZIORRA,[2] R. A. SUNYAEV,[3] AND K. N. BOROZDIN[3]
Received 1993 May 4; accepted 1993 August 12


ASTRONOMY & ASTROPHYSICS SUPPLEMENT SERIES — DECEMBER III **1996**, PAGE 175

1996

Astron. Astrophys. Suppl. Ser. **120**, 175-178 (1996)

Absorption features in the hard X-ray spectra of PSR A 0535+26 and Vela X−1

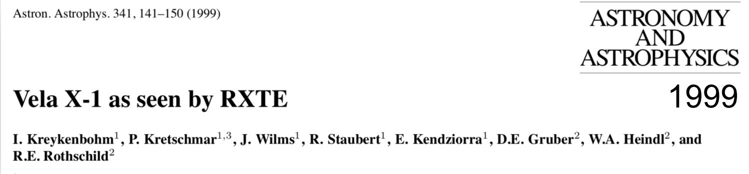

Astron. Astrophys. 325, 623–630 (1997)

ASTRONOMY AND ASTROPHYSICS

1997

Phase resolved X-ray spectra of Vela X-1

P. Kretschmar[1,5], H. C. Pan[2], E. Kendziorra[1], M. Maisack[1], R. Staubert[1], G. K. Skinner[2], W. Pietsch[3], J. Trümper[3], V. Efremov[4], and R. Sunyaev[4]

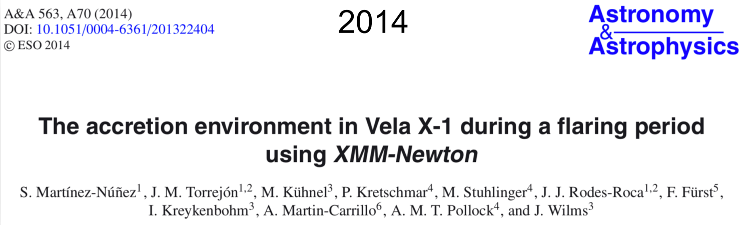

Astron. Astrophys. 341, 141–150 (1999)

ASTRONOMY AND ASTROPHYSICS

1999

Vela X-1 as seen by RXTE

I. Kreykenbohm[1], P. Kretschmar[1,3], J. Wilms[1], R. Staubert[1], E. Kendziorra[1], D.E. Gruber[2], W.A. Heindl[2], and R.E. Rothschild[2]


A&A 563, A70 (2014)
DOI: 10.1051/0004-6361/201322404
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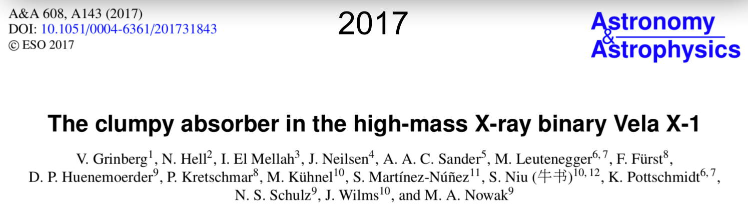
2014

Astronomy & Astrophysics

The accretion environment in Vela X-1 during a flaring period using *XMM-Newton*

S. Martínez-Núñez[1], J. M. Torrejón[1,2], M. Kühnel[3], P. Kretschmar[4], M. Stuhlinger[4], J. J. Rodes-Roca[1,2], F. Fürst[5], I. Kreykenbohm[3], A. Martin-Carrillo[6], A. M. T. Pollock[4], and J. Wilms[3]


A&A 608, A143 (2017)
DOI: 10.1051/0004-6361/201731843
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2017

Astronomy & Astrophysics

The clumpy absorber in the high-mass X-ray binary Vela X-1

V. Grinberg[1], N. Hell[2], I. El Mellah[3], J. Neilsen[4], A. A. C. Sander[5], M. Leutenegger[6,7], F. Fürst[8], D. P. Huenemoerder[9], P. Kretschmar[8], M. Kühnel[10], S. Martínez-Núñez[11], S. Niu (牛书)[10,12], K. Pottschmidt[6,7], N. S. Schulz[9], J. Wilms[10], and M. A. Nowak[9]


Mem. S.A.It. Vol. 90, 221
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2019

Memorie della

Vela X-1 as a laboratory for accretion in high-mass X-ray binaries

P. Kretschmar[1], S. Martínez-Núñez[2], F. Fürst[1], V. Grinberg[3], M. Lomaeva[4], I. El Mellah[5], A. Manousakis[6], A. A. C. Sander[7], N. Degenaar[8], and J. van den Eijnden[8]


A&A 641, A144 (2020)
https://doi.org/10.1051/0004-6361/202037807
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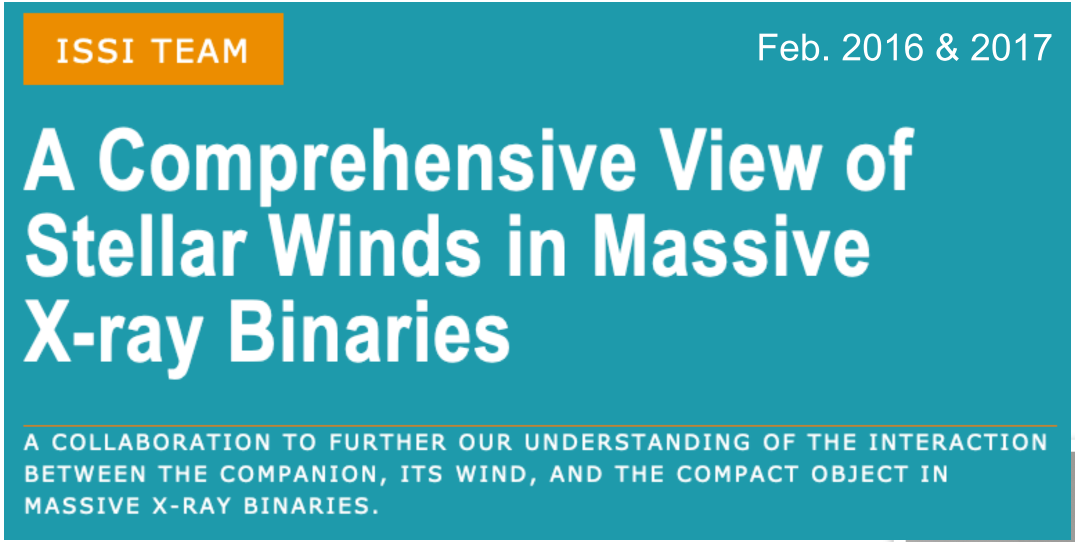
2020

Astronomy & Astrophysics

High-resolution X-ray spectroscopy of the stellar wind in Vela X-1 during a flare

M. Lomaeva[1,2], V. Grinberg[3], M. Guainazzi[2], N. Hell[4], S. Bianchi[5], M. Bissinger né Kühnel[6], F. Fürst[7], P. Kretschmar[7], M. Martínez-Chicharro[8], S. Martínez-Núñez[9], and J. M. Torrejón[8]

It seemed like a straightforward idea – back in February 2017 …



ISSI TEAM

Feb. 2016 & 2017

A Comprehensive View of Stellar Winds in Massive X-ray Binaries

A COLLABORATION TO FURTHER OUR UNDERSTANDING OF THE INTERACTION BETWEEN THE COMPANION, ITS WIND, AND THE COMPACT OBJECT IN MASSIVE X-RAY BINARIES.

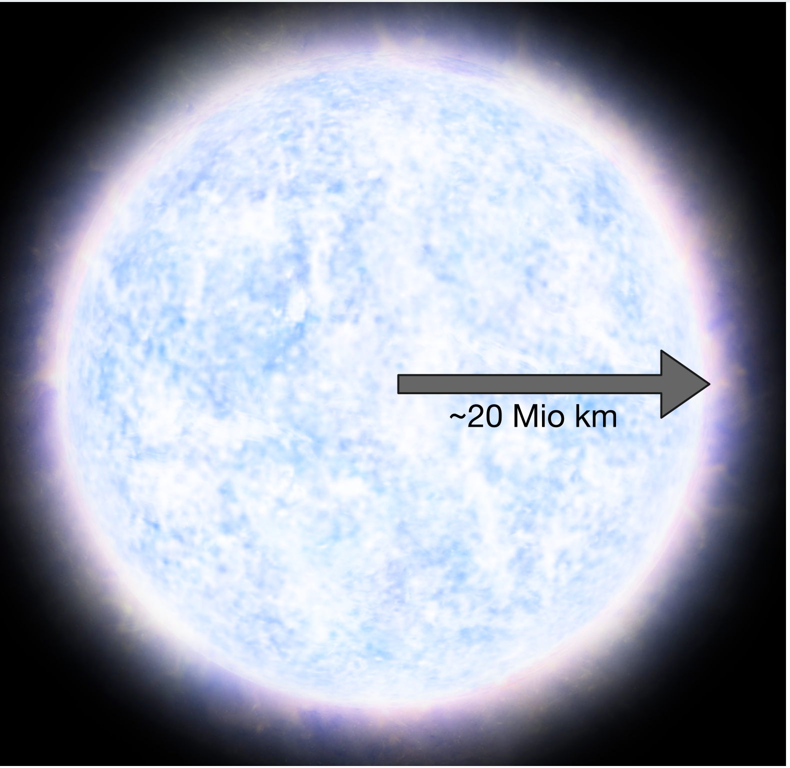
How about summarising the observational knowledge in one paper?

We talked so much about Vela X-1.
But different people use different assumptions based on different published result

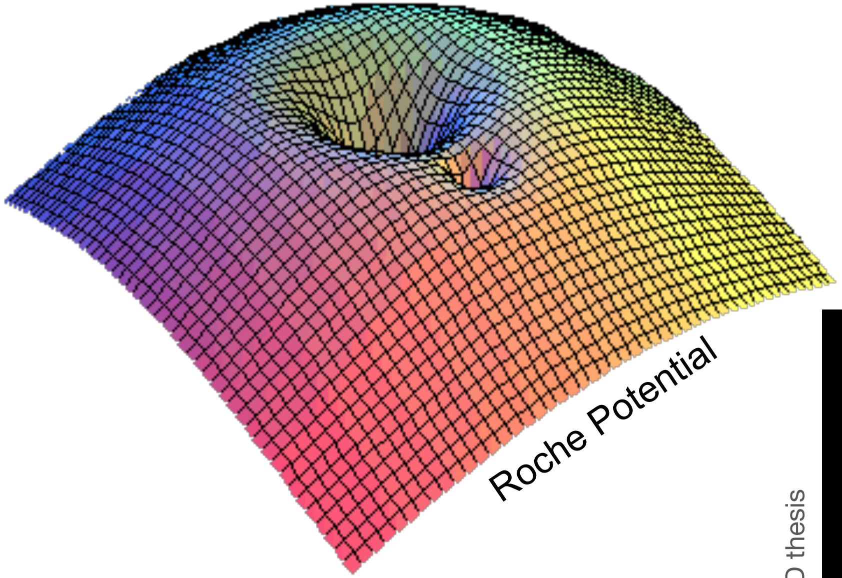
Good idea!
That should not be too hard to do …

3.75 years later …

Two unequal partners – a blue supergiant and a neutron star



Pablo Carlos Budassi, CC BY-SA 4.0, via Wikimedia Commons



West, B.F 2011, PhD thesis

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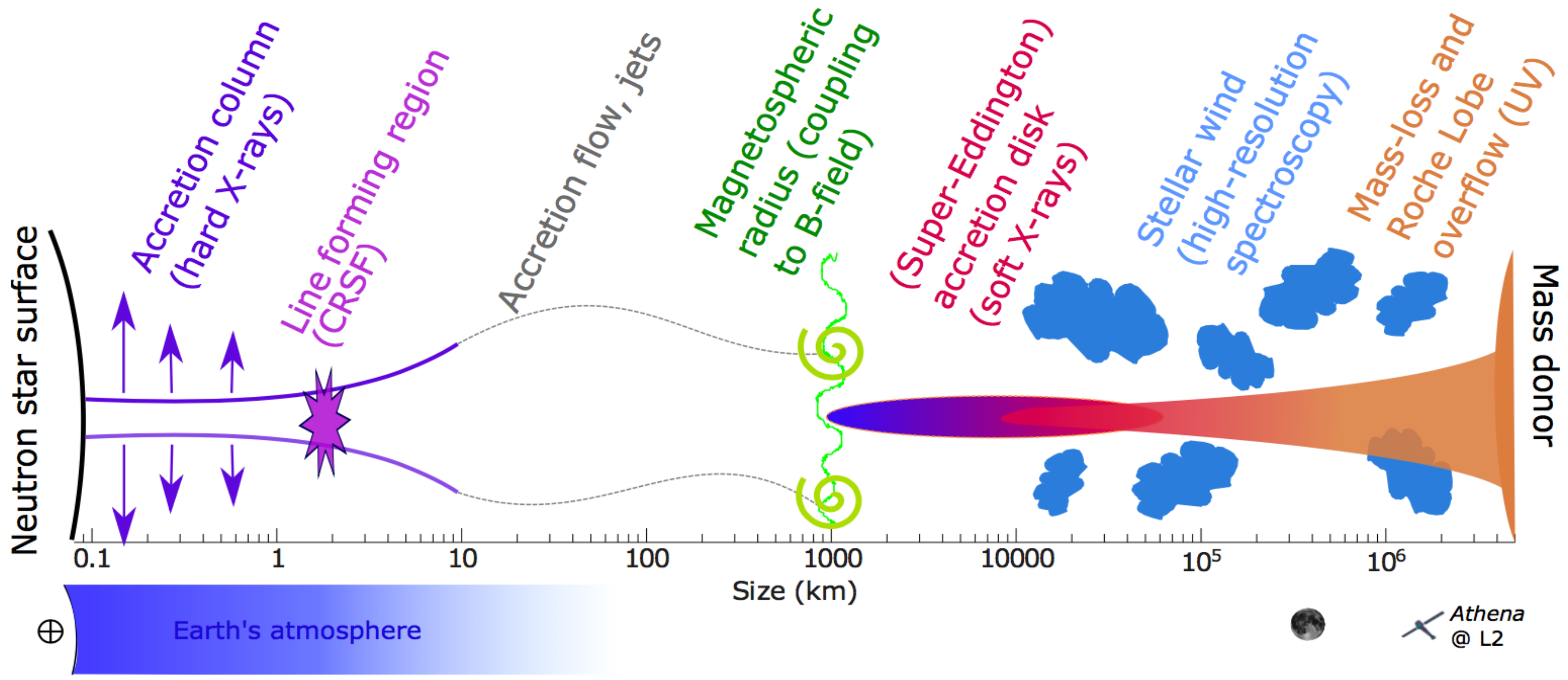
X-ray Binaries: a lot of physics on many different scales



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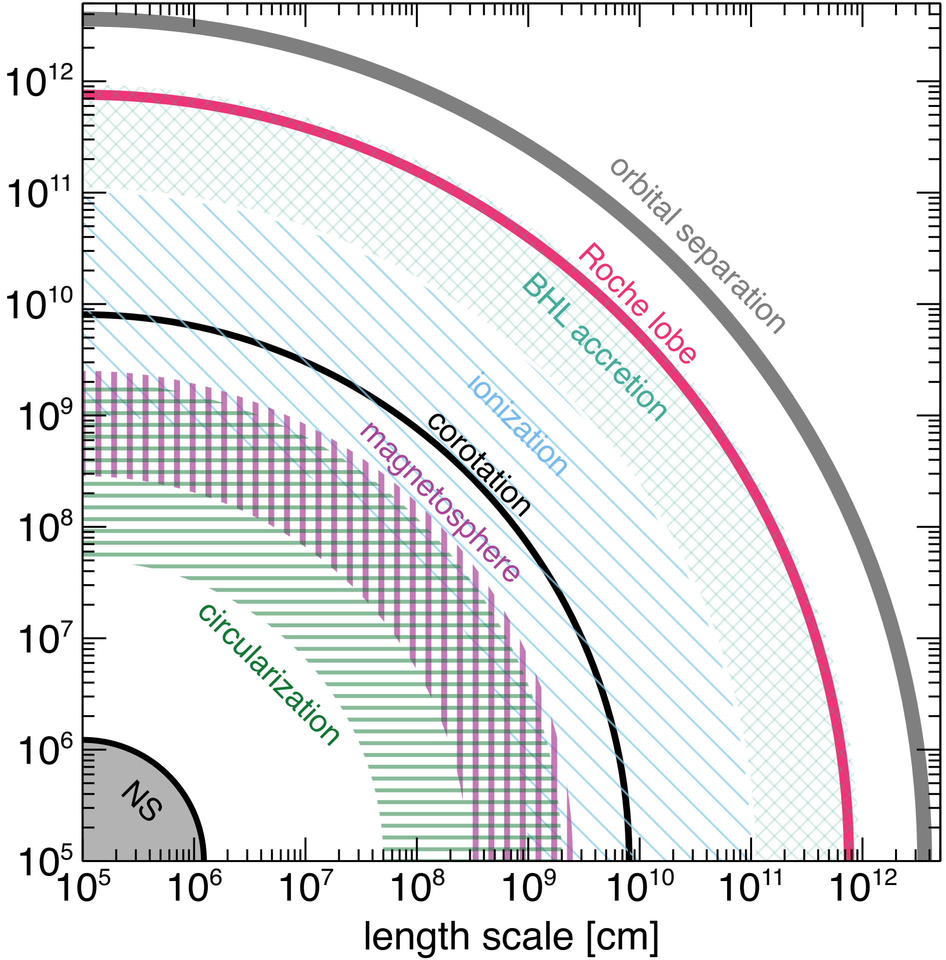
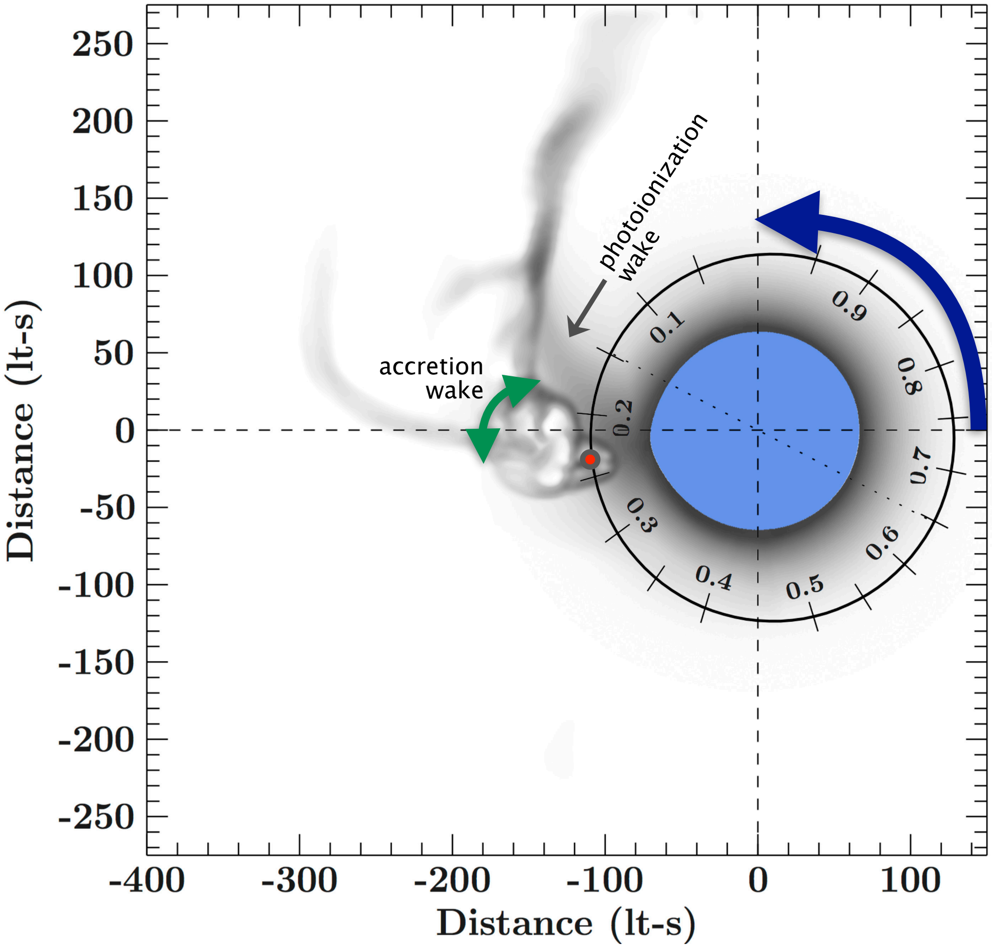
Essential length scales in the Vela X-1 system



- **Roche lobe**: bound to donor star.
- **Bondi-Hoyle-Lyttleton**: gravitational capture from wind.
- **Ionization**: X-rays may ionize inflowing gas.
- **Corotation**: Keplerian orbit at angular speed of neutron star rotation.
- **Magnetosphere**: neutron stars magnetic field dominates.
- **Circularization**: Keplerian orbit with angular momentum of accreted flow.

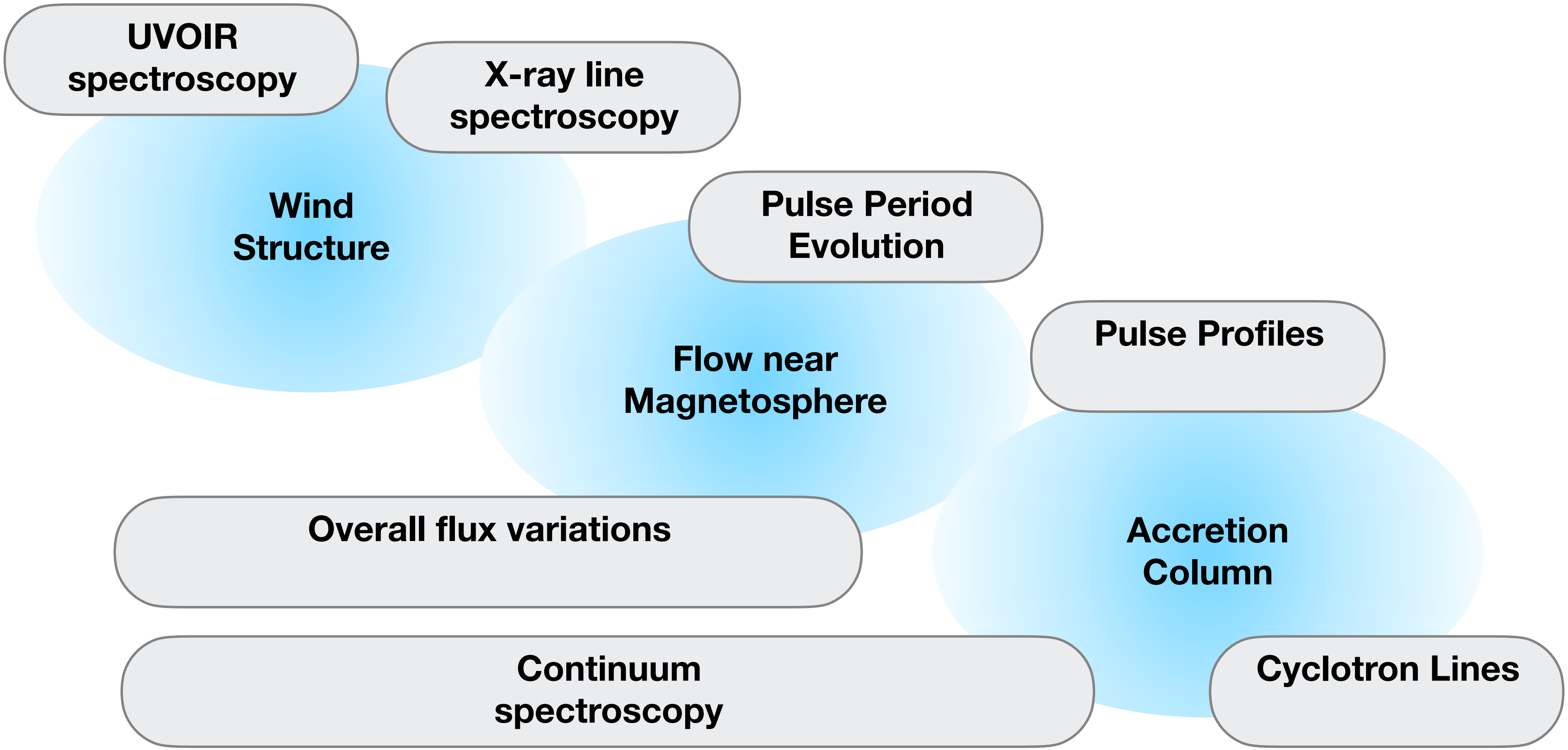
A simplified model picture of the system

- Slightly eccentric, not quite circular orbit.
- Supergiant somewhat distorted towards neutron star ➠ focused wind
- Accretion wake from hydrodynamical interaction.
- Photoionization wake from stalled wind close to neutron star.



Diagnostics

Different diagnostics (obs. & models) covering different scales



UVOIR spectroscopy

X-ray line spectroscopy

Wind Structure

Pulse Period Evolution

Flow near Magnetosphere

Pulse Profiles

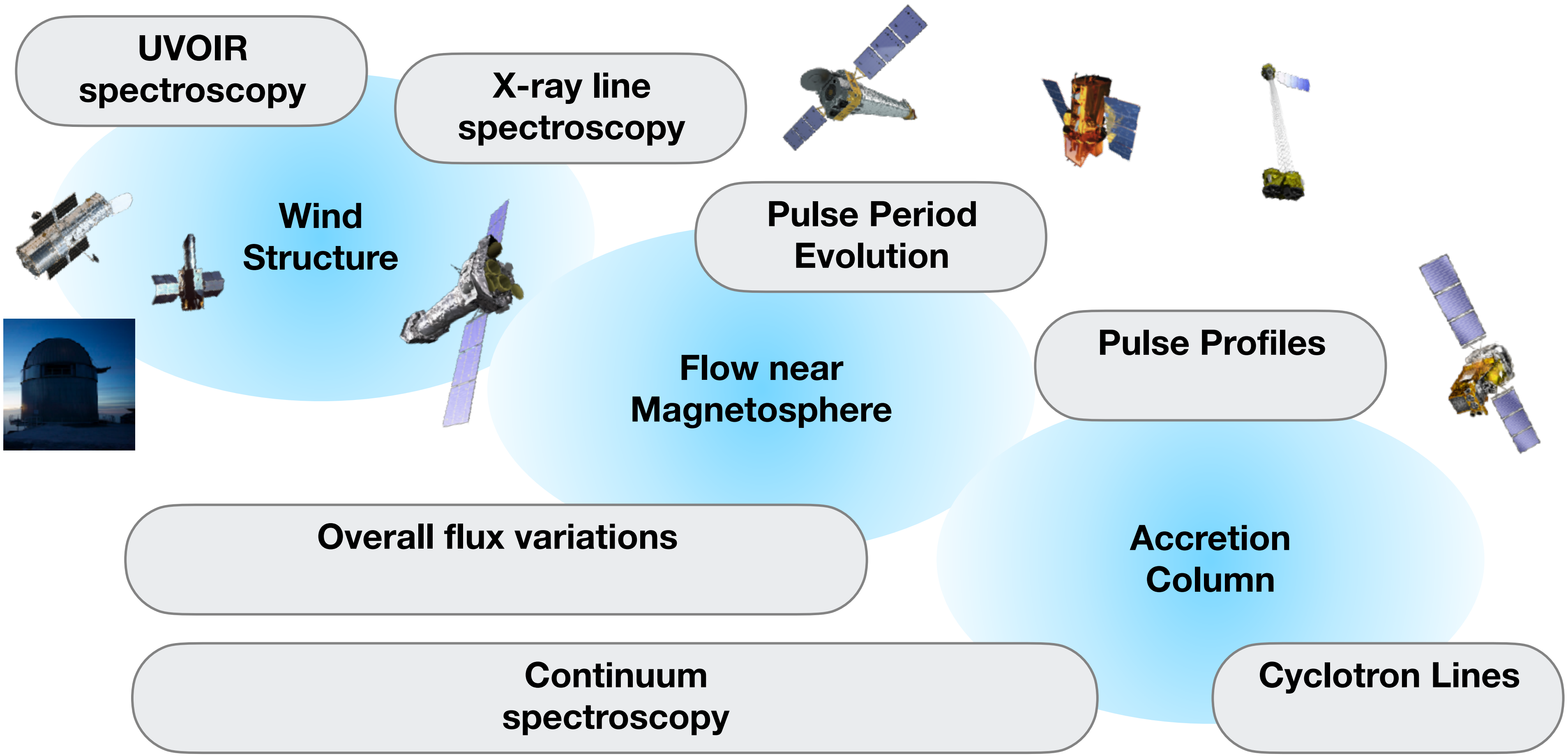
Overall flux variations

Accretion Column

Continuum spectroscopy

Cyclotron Lines

Different diagnostics (obs. & models) covering different scales



UVOIR spectroscopy

X-ray line spectroscopy

Wind Structure

Pulse Period Evolution

Flow near Magnetosphere

Pulse Profiles

Overall flux variations

Accretion Column

Continuum spectroscopy

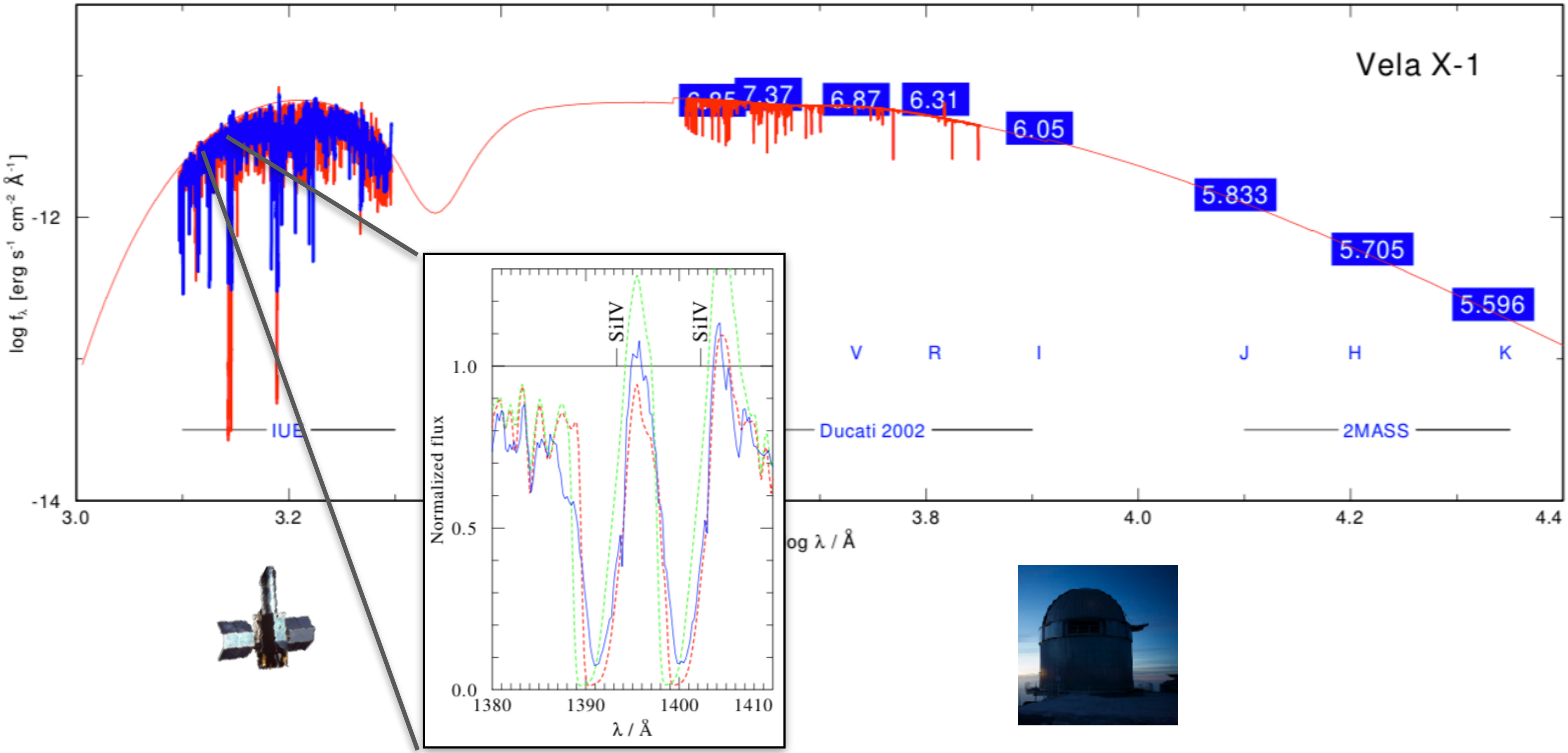
Cyclotron Lines

The Vela X-1 system has been also detected in the radio!

Recent result
(van den Eijnden, et al., *in prep.*):

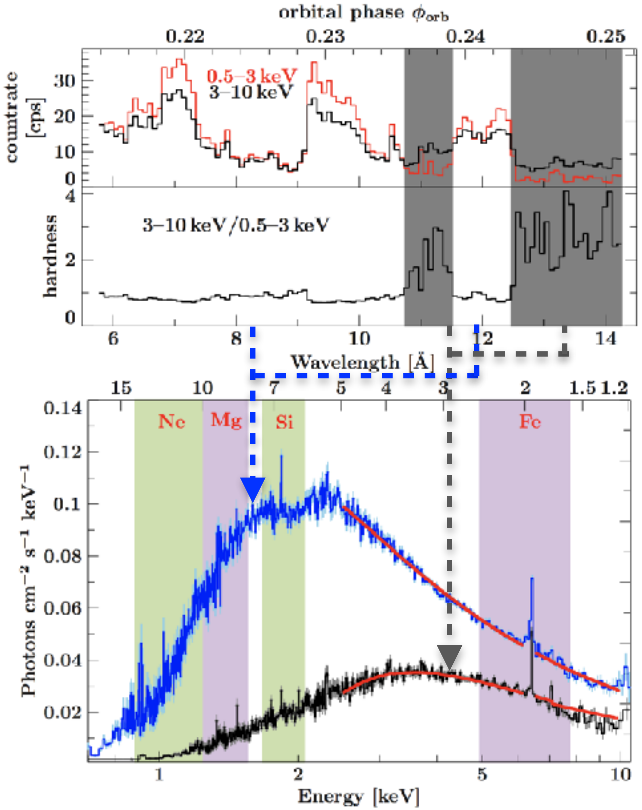
- Highly significant (~100 μJy) radio detection of Vela X-1 with ATCA.
- Observation done by chance at mid eclipse. More observations done recently.
- Flat radio spectrum, like for a compact jet.
- Cannot exclude donor star as radio source yet, but this would also be interesting.

Line spectroscopy to derive wind parameters

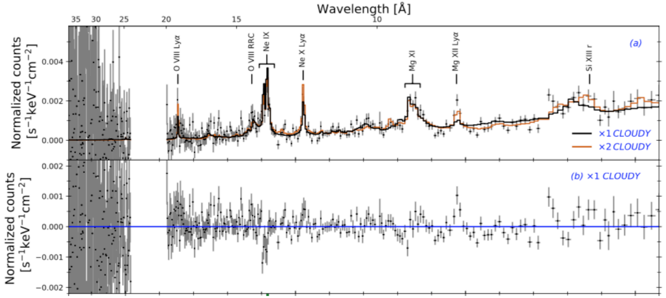


X-ray fluorescence lines can yield information on state of matter

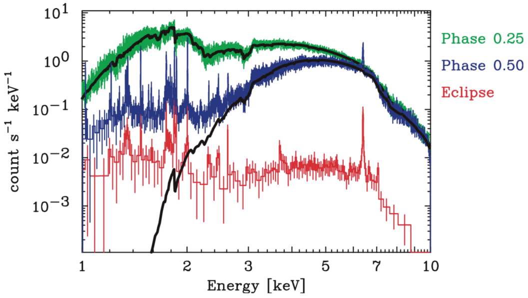
- Plasmas of different densities, temperatures, velocities, and ionization states reprocess the radiation from the neutron star, imprinting characteristic features.
- But interpretation complex and different model codes can yield quite different plasma parameters (Lomaeva et al. 2020).



Grinberg et al. (2017)



Lomaeva et al. (2020)

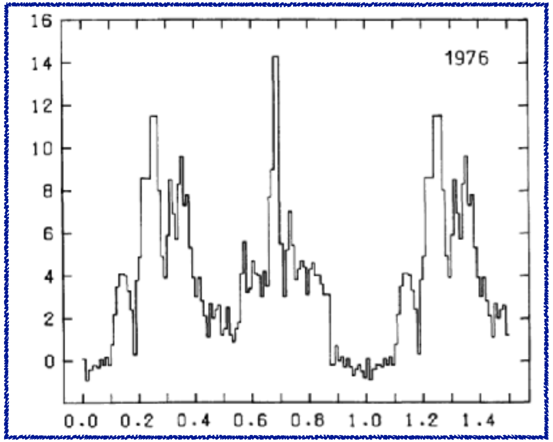


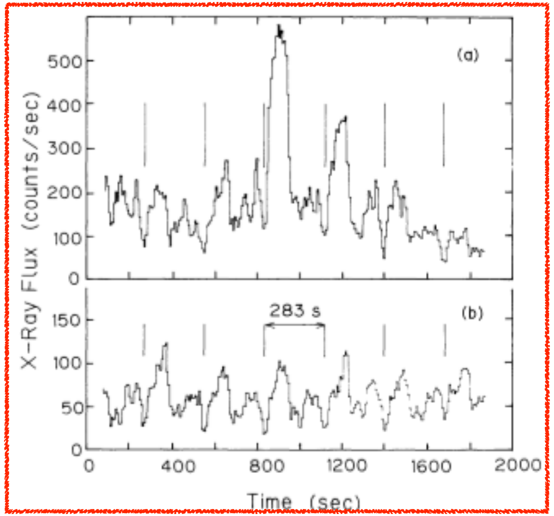
Watanabe et al. (2006)

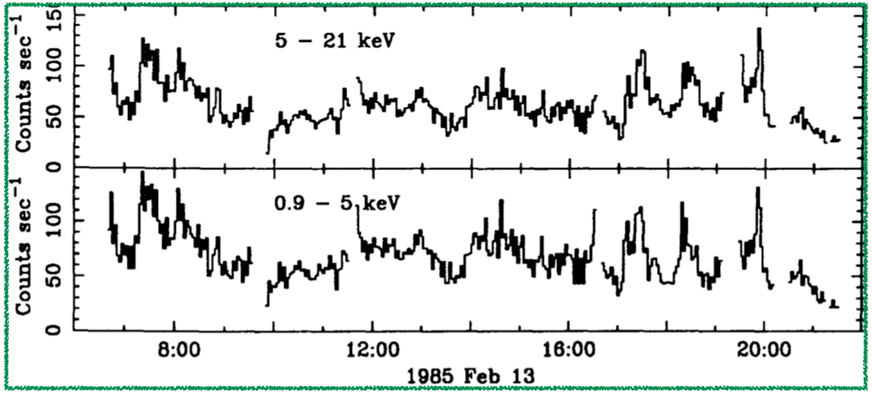
X-ray flux variations are observed on many time scales

- **Orbital:** ~1–10 d
- **Within orbit:** hours – days
- **Pulse period:** minutes

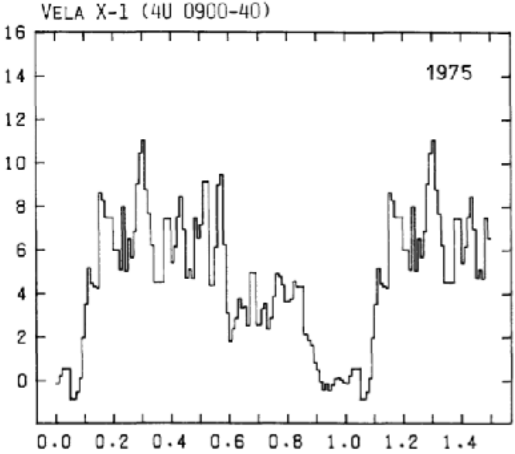
On longer or shorter time scales no evident variation has been reported.



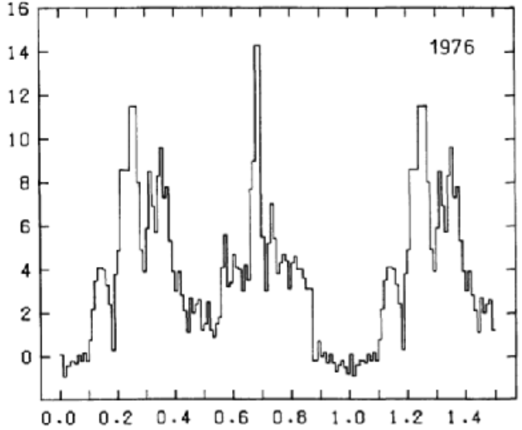


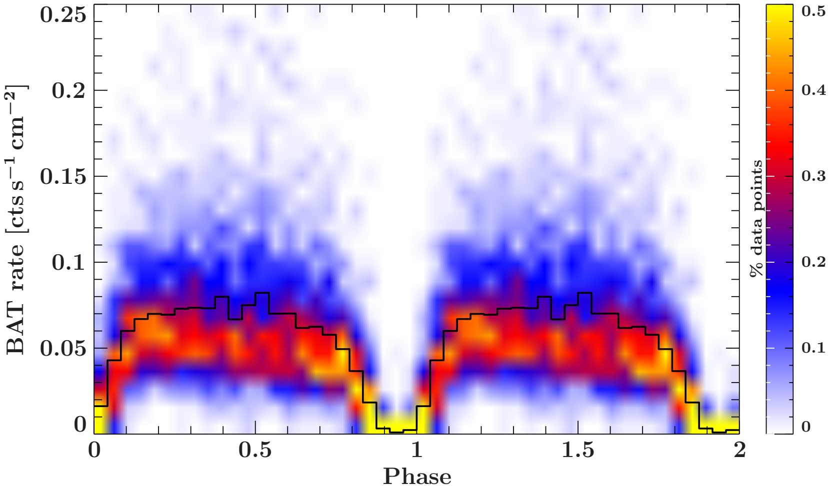


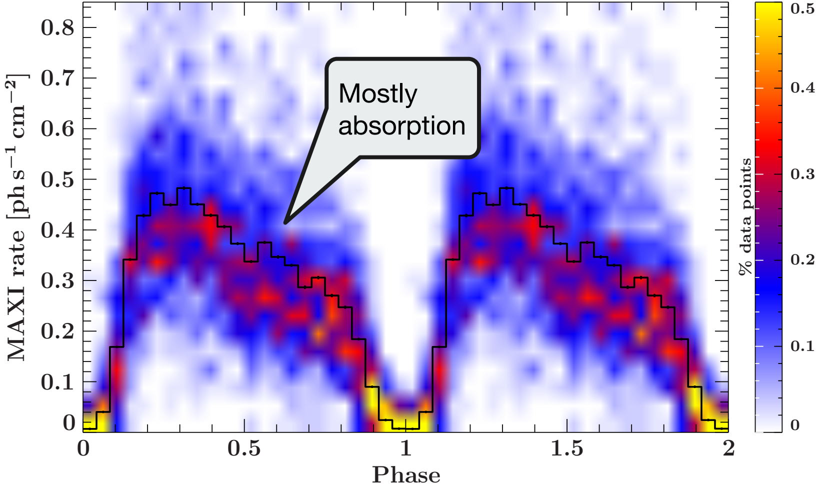
No two orbits are the same, but there are stable mean patterns



Van der Klis & Bonnet-Bideau (1977)
COS-B X-ray detector
1975 & 1976

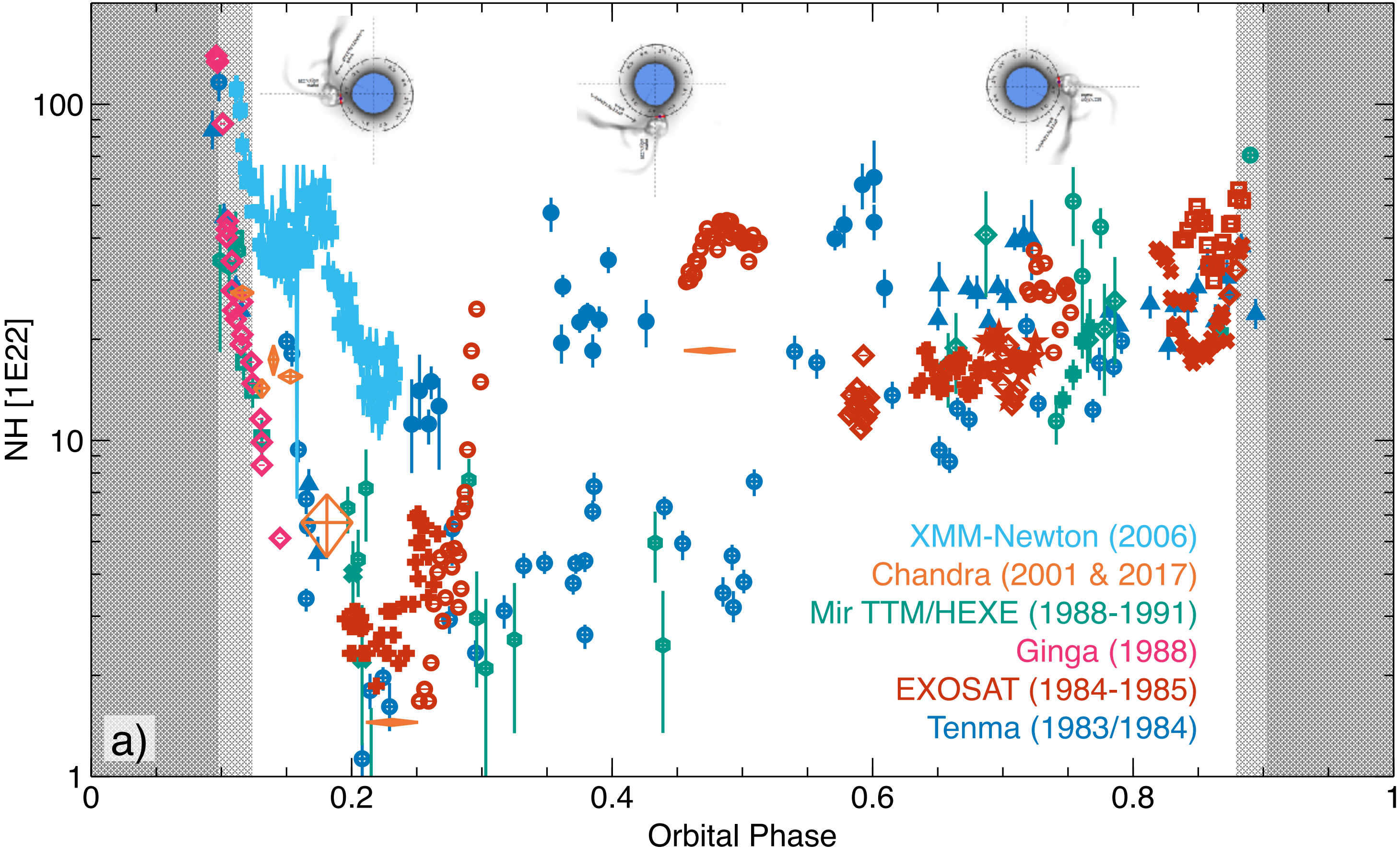






Mostly absorption

Absorption varies strongly along the orbit

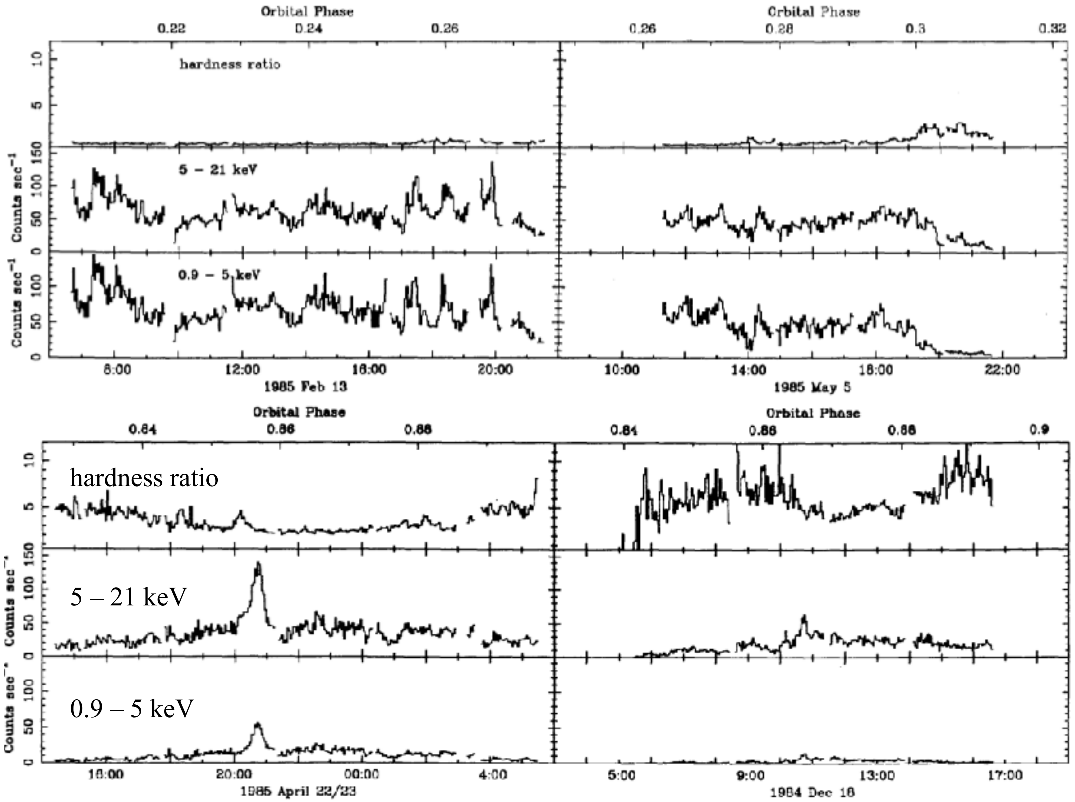


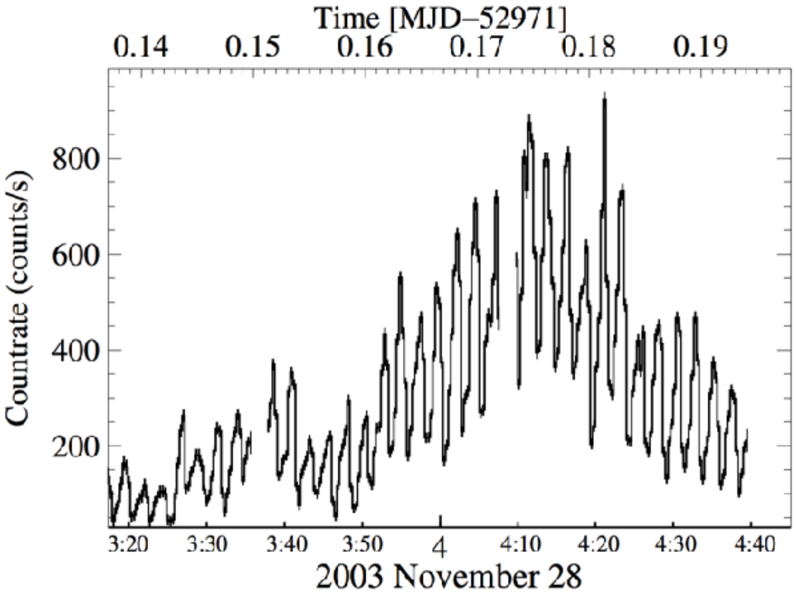
Various satellites find strong N_H variations along orbit as expected from large structures.

But same phases can look very differently at different times!

Caveat: different spectral models and absorption modelling ➟ absolute values not directly comparable.

Apparently chaotic variability at shorter time scales

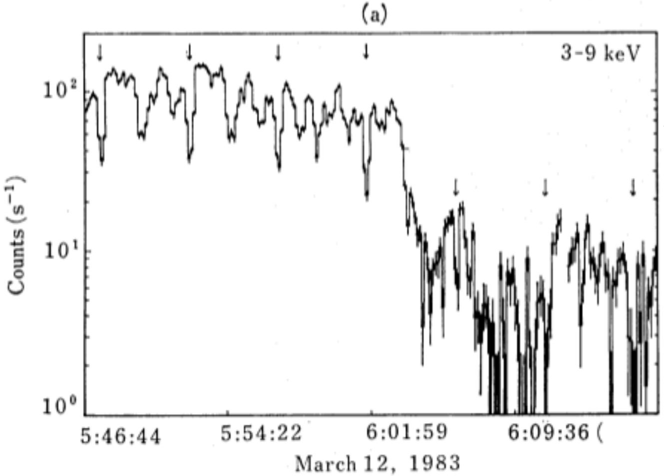




Haberl & White (1990)
EXOSAT
1985

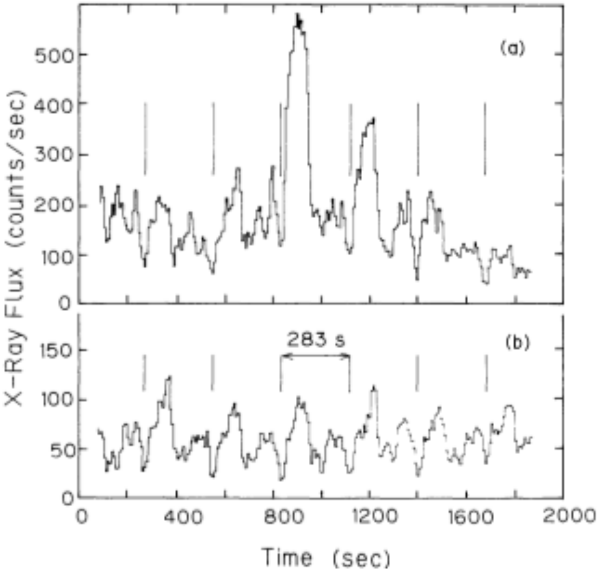
Kreykenbohm et al. (2008)
INTEGRAL ISGRI
2003

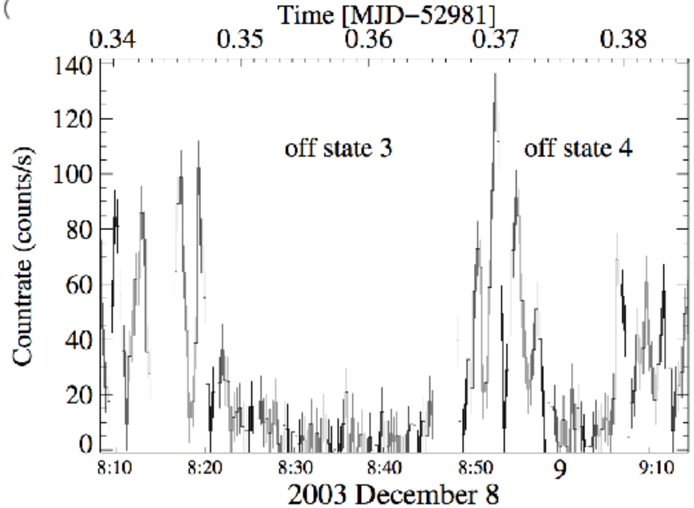
The flux can change from one pulse to next



Inoue et al. (1984)
Tenma
1983

Börner et al. (1984)
Tenma
1983



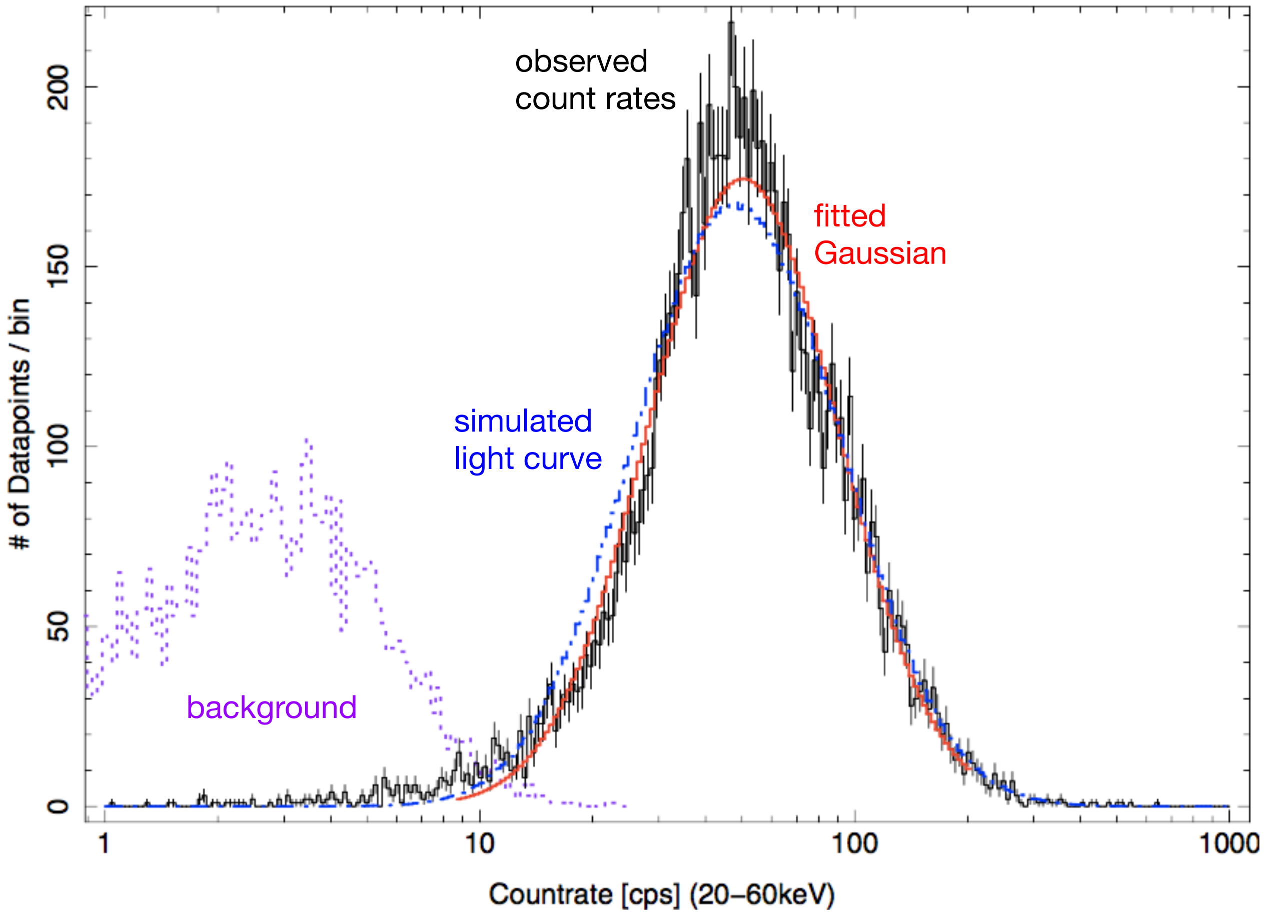


Kreykenbohm et al. (2008)
INTEGRAL ISGRI
2003

Pulse-averaged flux shows log-normal distribution

Fürst et al. (2010):
Bins of 283.5 s (~average over pulse), filtered to avoid eclipse.

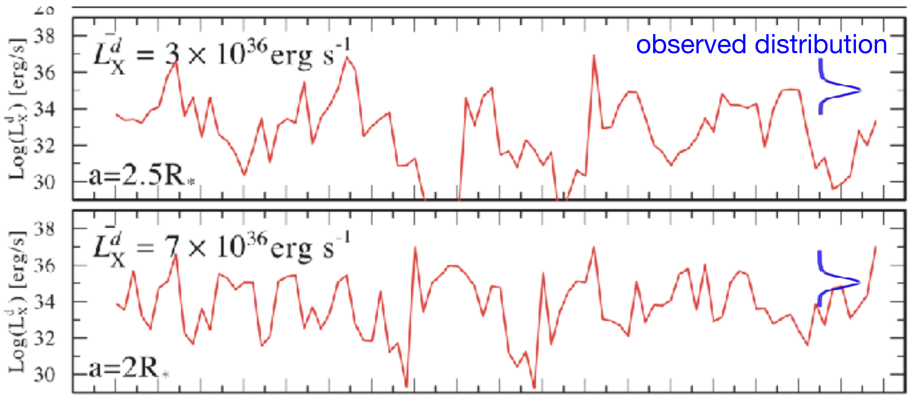
“Shock fronts and turbulence breaking up clumps can transfer any given distribution into a log-normal like distribution.”



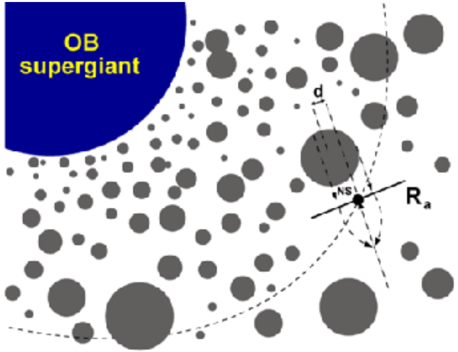
Modelling efforts

Modelling the *right* amount of variation from clumps can be difficult

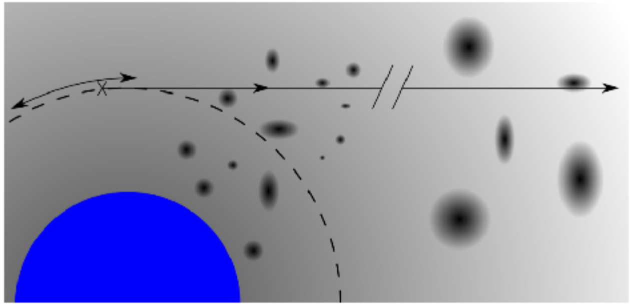
‘Naive’ 1-D modelling of accreting clumps (shells) by BHL accretion over-predicts observed variability strongly.



Simulated clump distribution gives more realistic light curve (Ducci et al. 2009), but clump sizes required uncomfortably large.

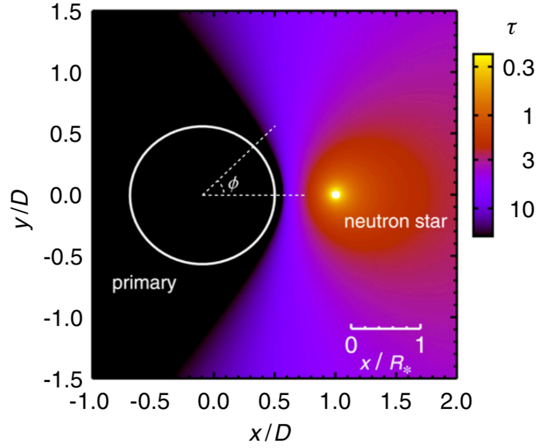


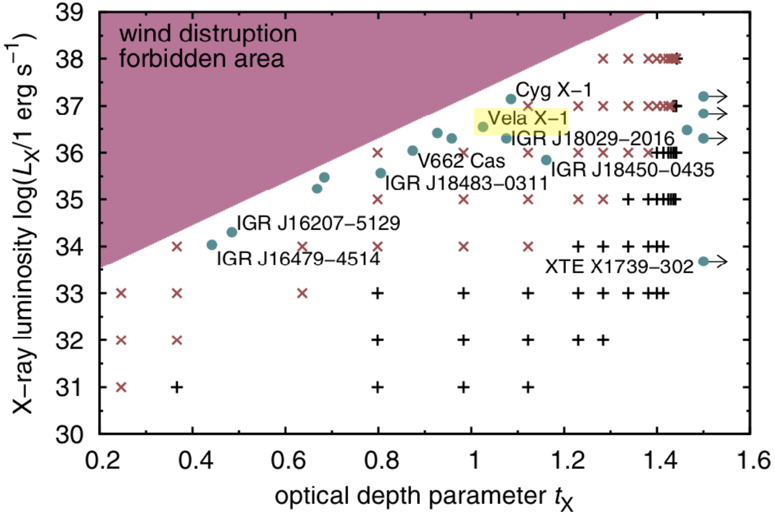
‘Realistic’ clump model for Vela X-1 *under-predicts* observed absorption variations,
if assumed to be caused by clumps (Grinberg et al. 2017)

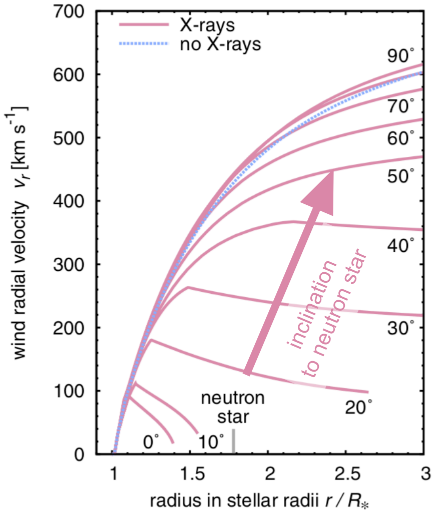


The X-ray radiation may self-regulate the wind

- Photoionization of the wind destroys ions responsible for acceleration
  ➟ bubble of stagnant flow around neutron star
- Krtička et al. (2012, 2015, 2016, 2018): photionization may lead to self regulated winds with HMXB close to forbidden area, where X-rays would fully stop wind.
- Radial solution of wind equation.
- Latest studies include wind clumping (favouring recombination)

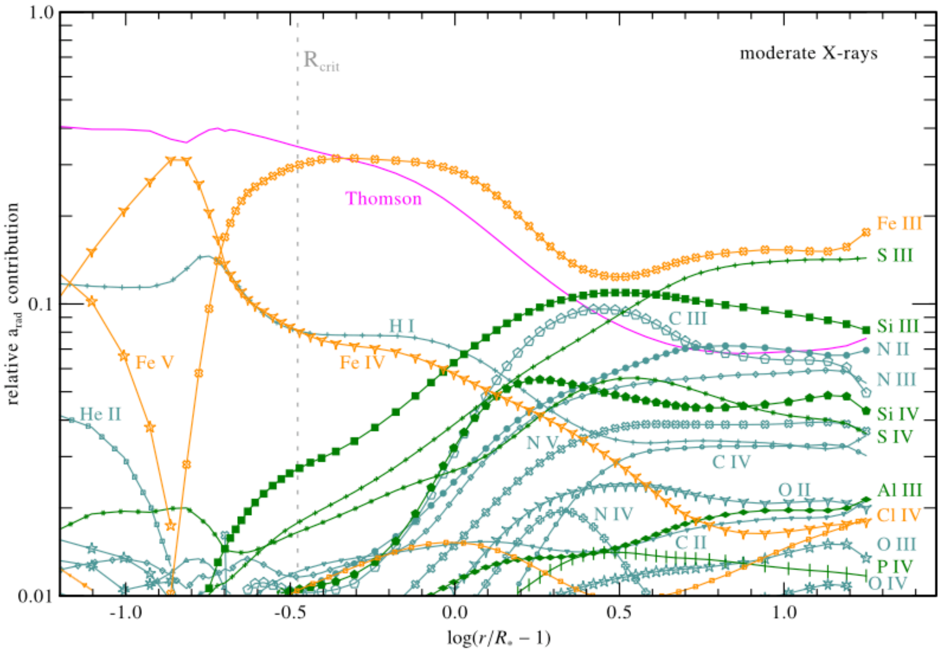






Wind driving can become very complex

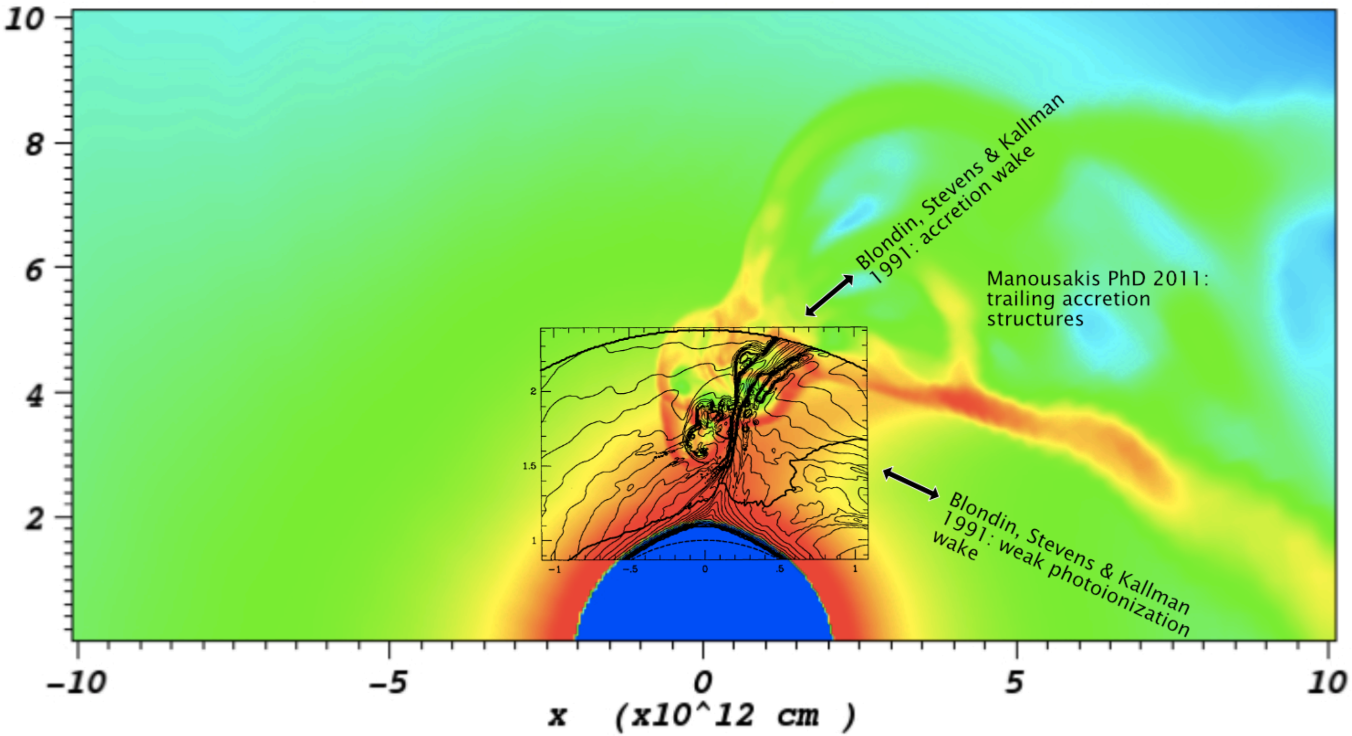
- Sander et al. (2018): Simulations of wind acceleration using updated Potsdam Wolf-Rayet (PoWR) code including impact of X-rays (but in 1D treatment).
- Hydrodynamically self-consistent solution for wind structure, accounting for 16 elements and ~5000 lines in calculations. Different ions dominate acceleration at different distances.
- Wind velocity profile differs strongly from a “beta law”.
- Wind speed very low in inner zone ➟ impact on accretion (see later slides).
- Weak X-rays can *increase* wind driving in outer zone and terminal velocity. Strong X-rays disrupt wind.



$$\xcancel{v(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta}$$

Hydrodynamic models also predict variations

- 2D hydrodynamic models by Blondin et al. (1990, 1991, 1994) later picked up and enhanced by Manousakis et al. (2011, 2012, 2013, 2014) also yield clear variations.
- Radiative transfer not handled in detail, relying on critical ionization parameter as “on-off” switch.
- Wind clumping not (yet) included.
- Orbit approximated as circular.
- See also Čechura & Hadrava (2015) for Cyg X-1.



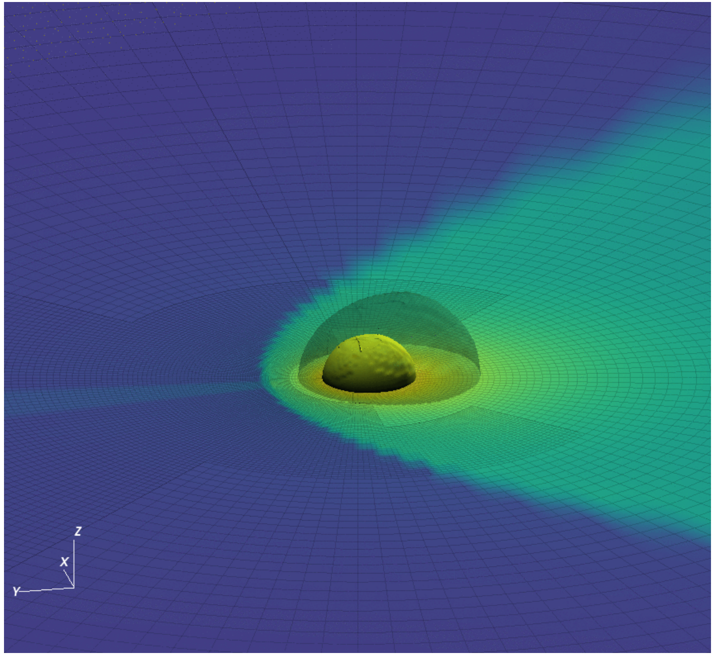
Blondin, Stevens & Kallman 1991: accretion wake

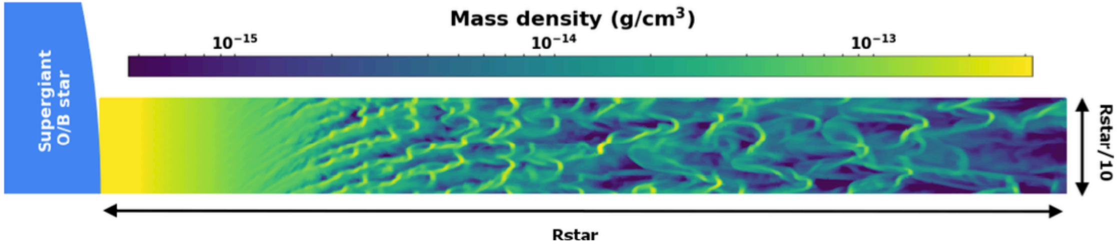
Manousakis PhD 2011: trailing accretion structures

Blondin, Stevens & Kallman 1991: weak photoionization wake

2D/3D Models of local accretion remain a challenge

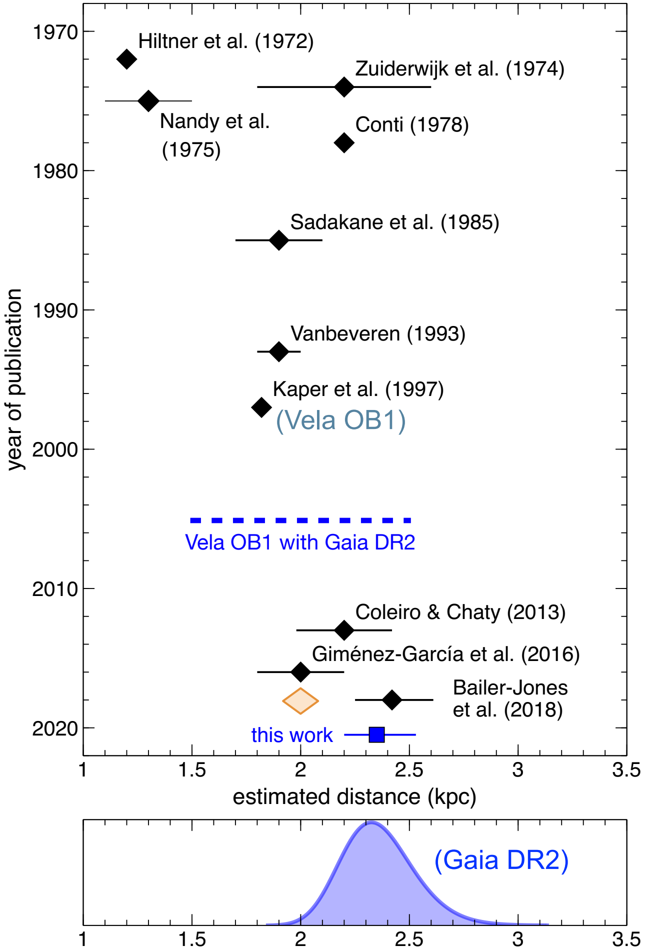
- El Mellah et al. (2018): 3D hydrodynamic simulations of the wind in the vicinity of the accretor. Several spatial orders of magnitude, down to the NS magnetosphere within spherical stretched adaptive mesh.
- Inflow ‘extruded’ from realistic 2D simulation of clump formation close to star (Sundqvist et al. 2017).



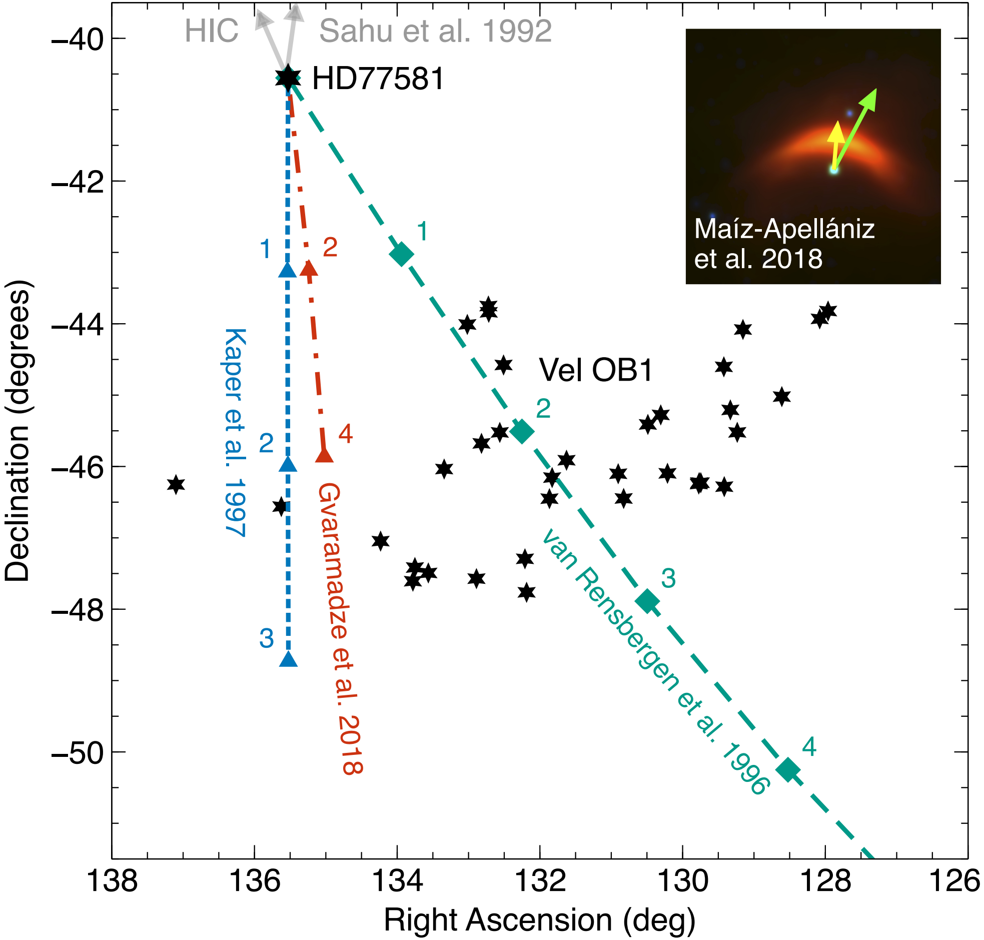


The knowns and unknowns of the Vela X-1 system

Distance and origin of this runaway HMXB system

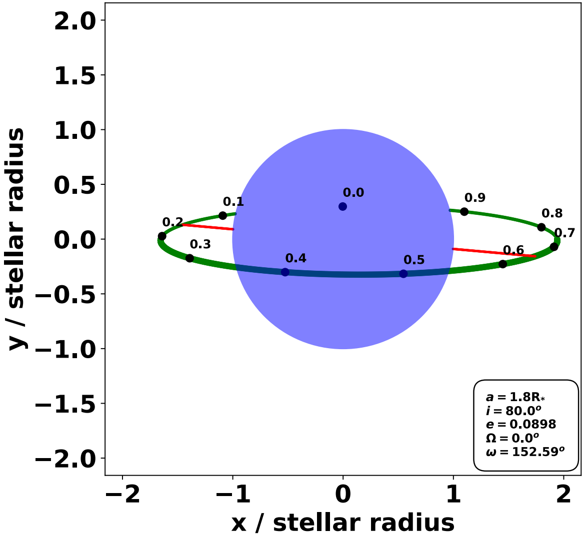


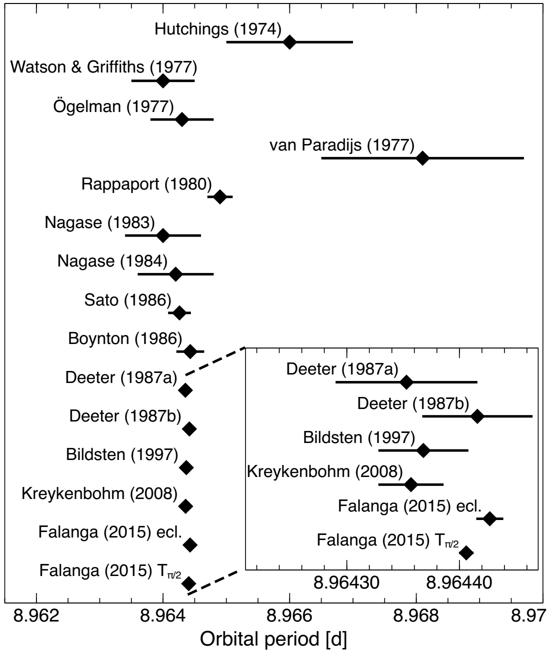
Update with Gaia EDR3 results!

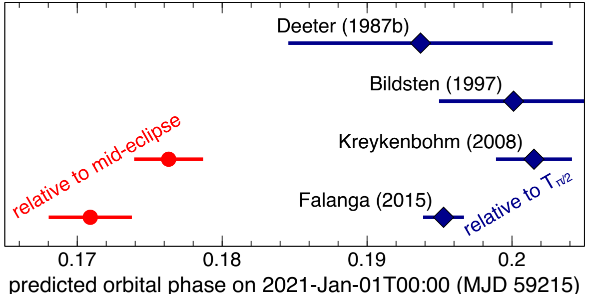


Orbital parameters

- The orbital period is extremely well known (8.964357±0.000029 d), due to eclipses, but slight tension between last two determinations.
- Small but *significant* difference between zero points of orbital phase.
- Eccentricity very well determined from X-ray pulse timing (0.0898±0.0012).
- Inclination (73-90 deg) is major unknown factor for orbit scale ➟ impacts mass & radius determination!

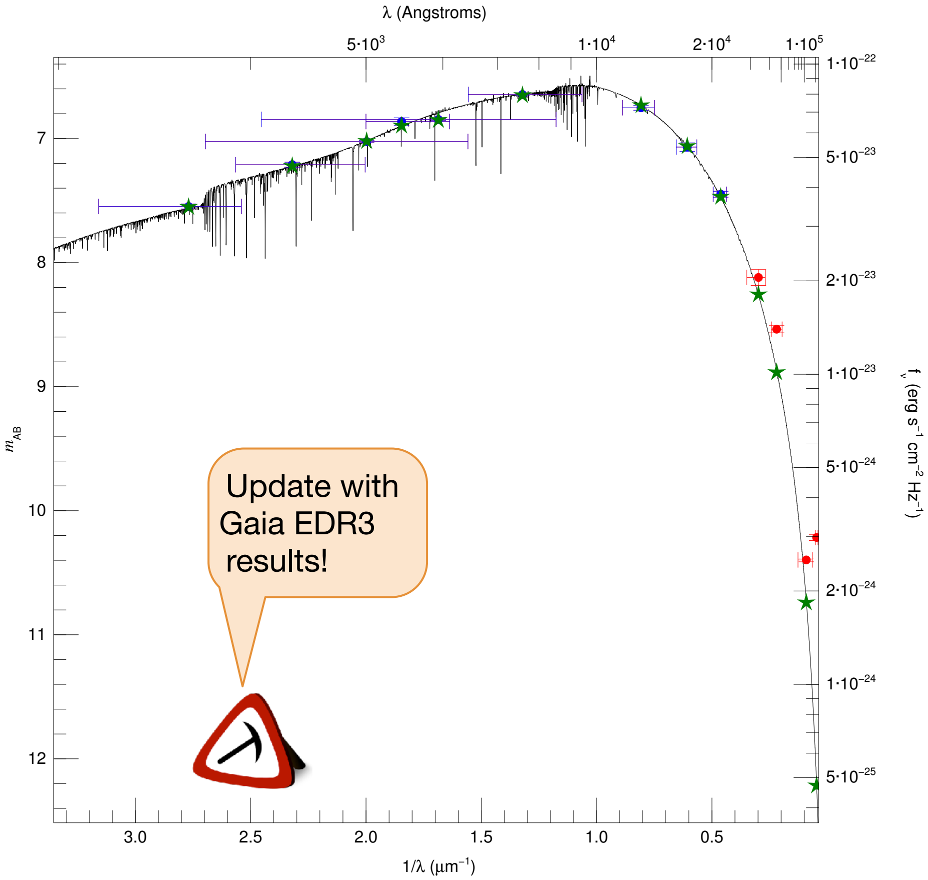






New spectral classification of mass donor

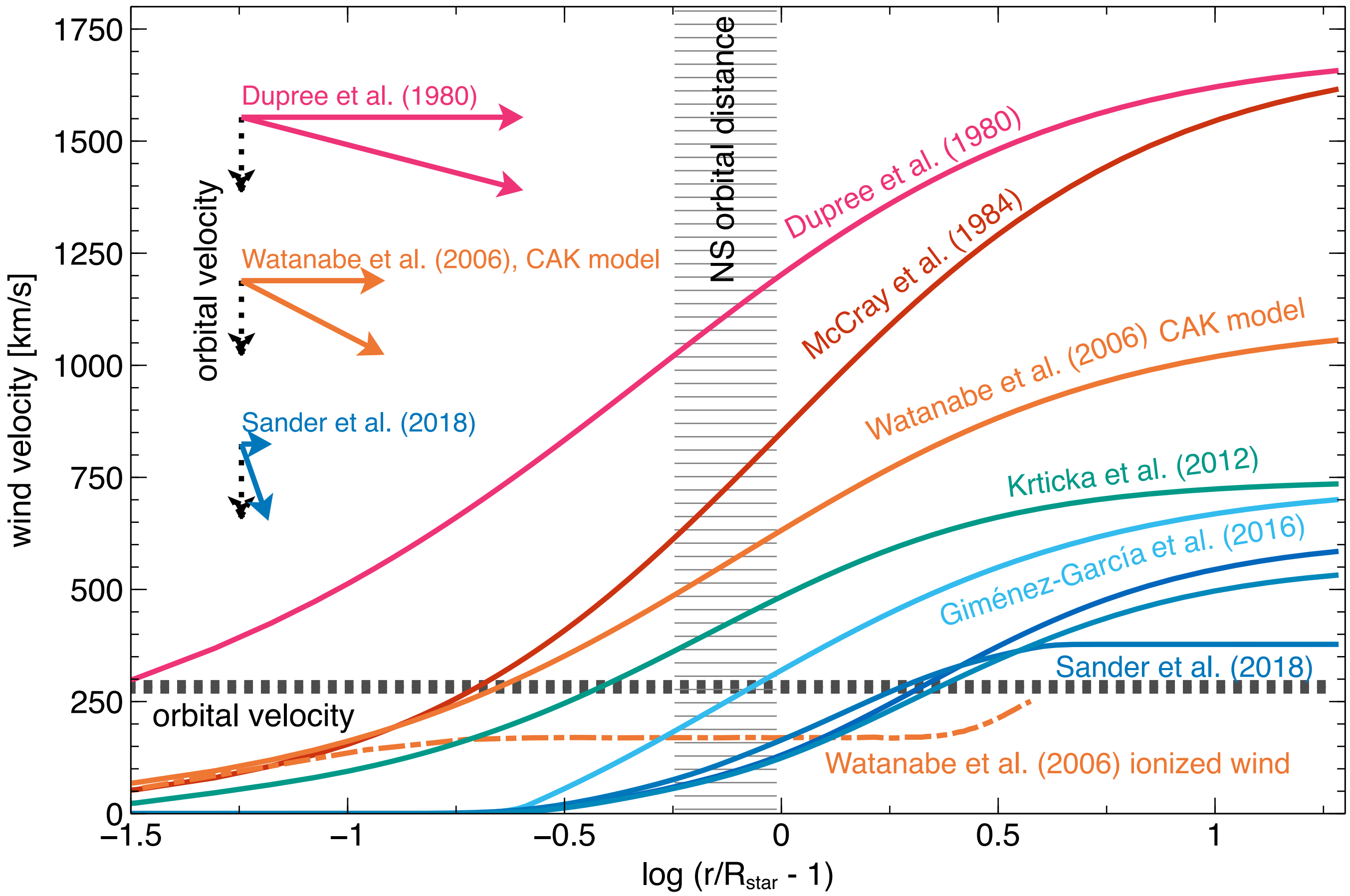
- Different spectral classifications listed in SIMBAD: B0 to B0.5 and in luminosity class from Ib to Ia.
- New spectral classification based on Galactic O-Star Spectroscopic Survey (GOSSS) and Gaia DR2 distance: spectral type & class: **B0.2 Ia**
- Stellar parameters to be redone with Gaia EDR3 distances. *Ongoing, results maybe this Friday.*



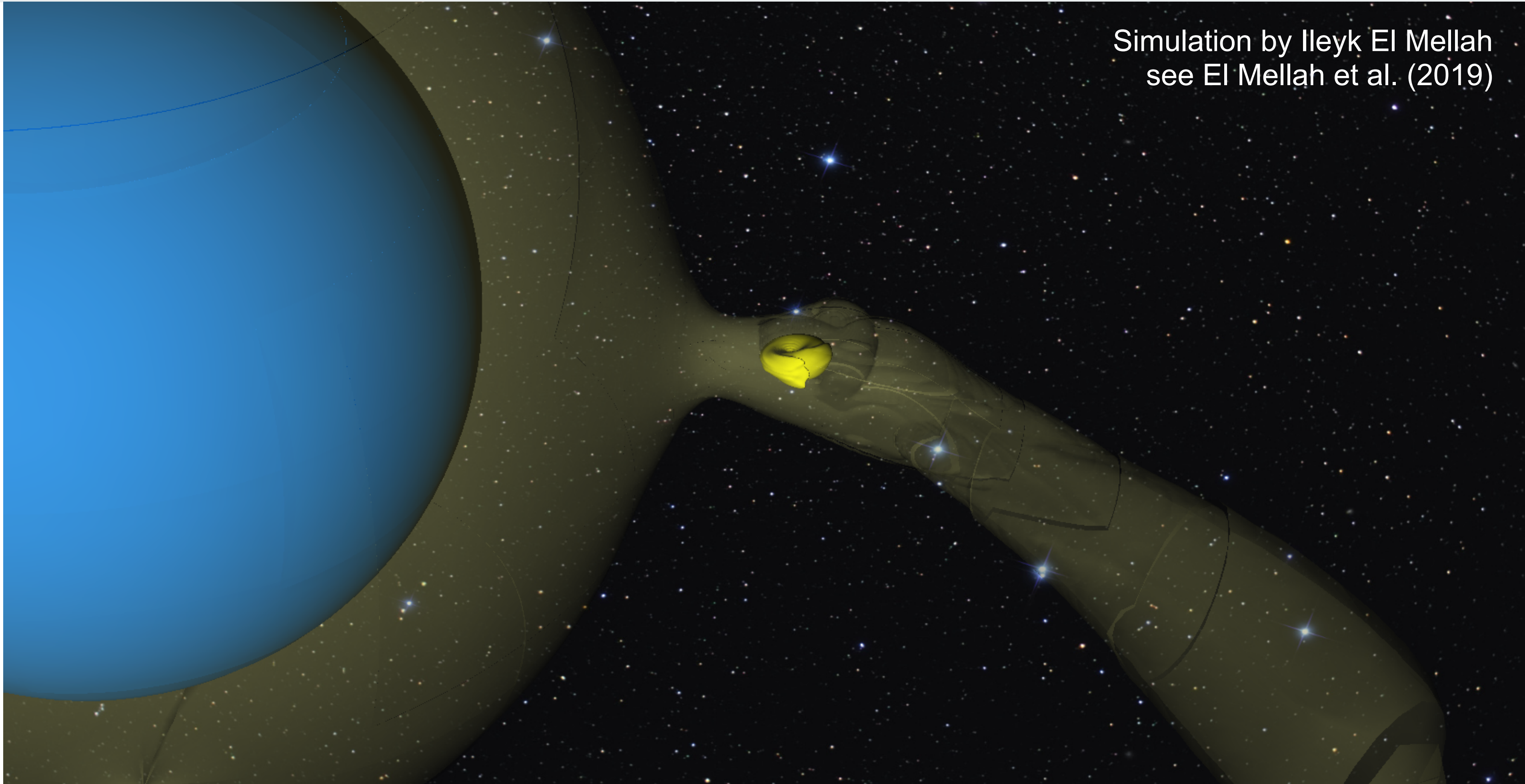
Update with Gaia EDR3 results!

Blowing in the wind – at very different velocities

- Terminal wind speeds and velocity profiles derived very differently over the years.
- Major impact on accretion flow close to neutron star!



Between wind and disk accretion?



Simulation by Ileyk El Mellah
see El Mellah et al. (2019)

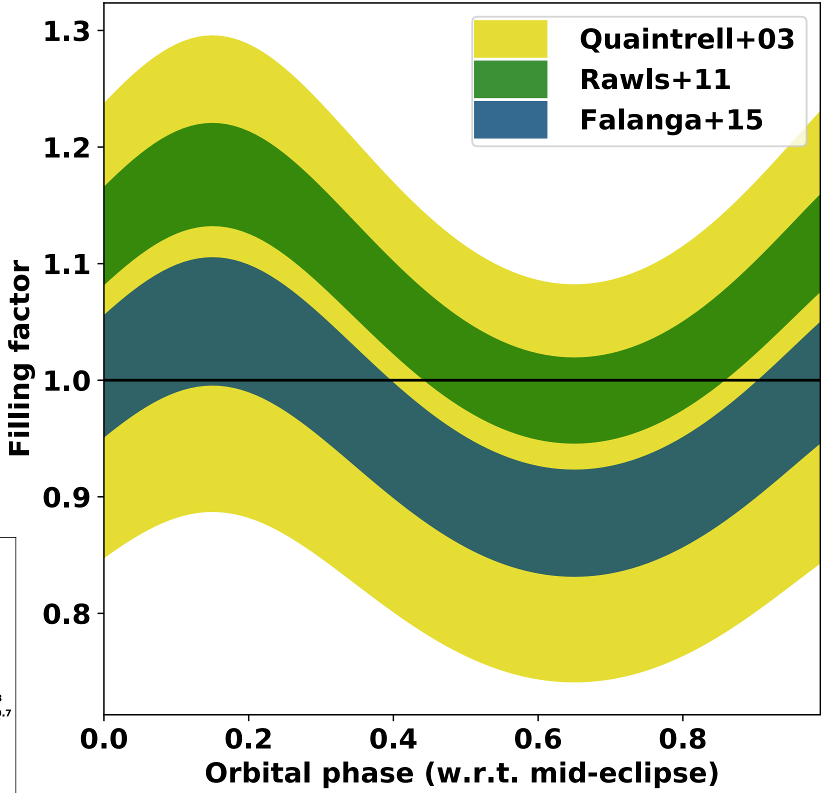
A variable mass transfer?

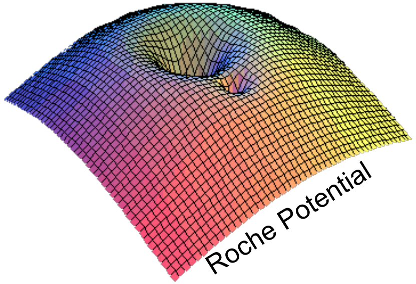
- **Filling factor** (ratio between stellar and Roche Lobe radius) varying along orbit due to eccentricity and often >1.

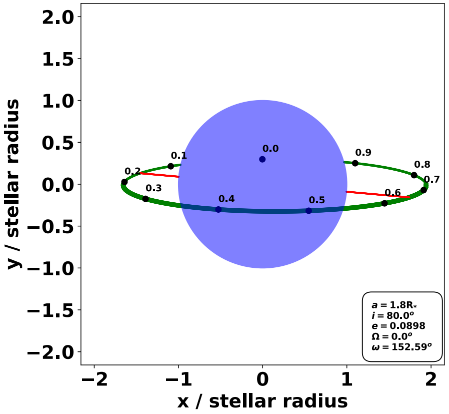
➡ Either the inclination, and thus mass ratio between giant star and neutron star is on upper end of assumed distribution.

➡ Or have intermittent Roche-Lobe overflow at some orbital phases.

➡ Mass transfer may be more complicated than basic wind acceleration.

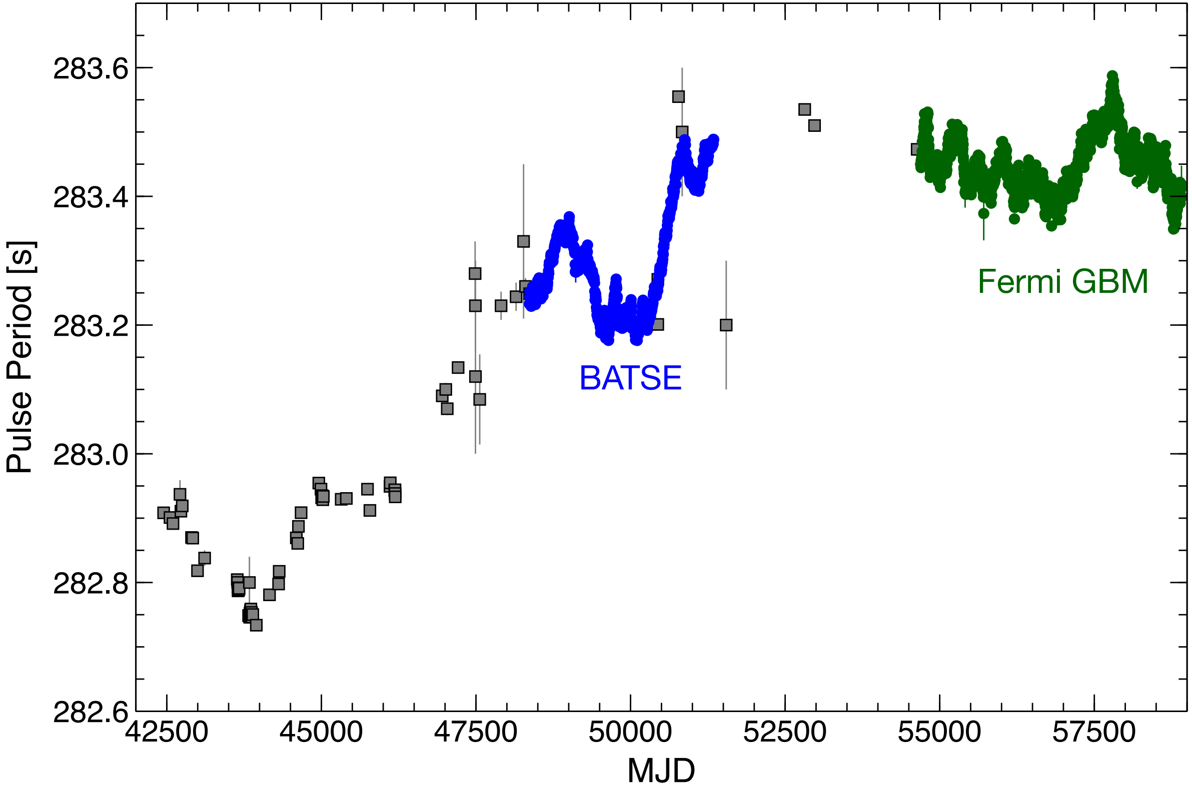






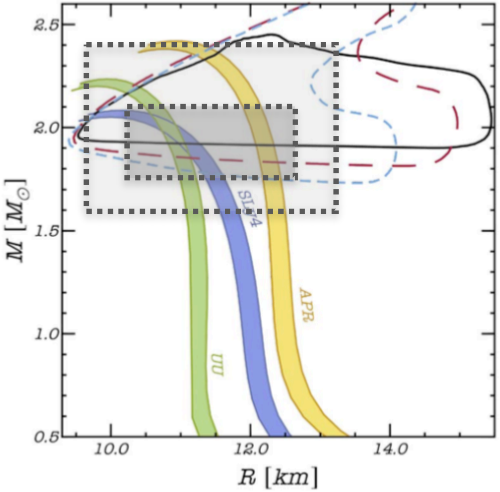
How random are the torques on the neutron star?

- Long-term pulse period evolution usually described as random walk.
- **Caveat:** period changes are ‘measured’ between data points at least days apart, much longer time scales than flux variations.
- A convincing theory for wind-accreting systems is lacking.
- Some spectral evidence for temporary accretion disk formation (Liao et al. 2020).
- Vela X-1 is **not** in spin equilibrium. The corotation radius is much larger than the magnetospheric radius!

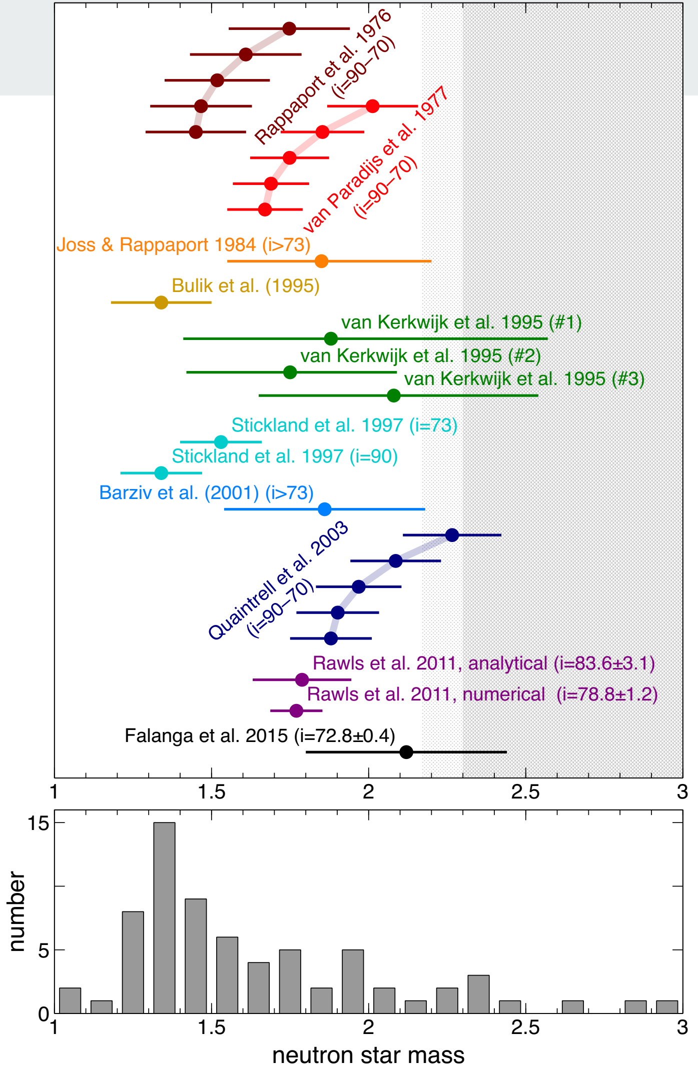


Probably a massive neutron star

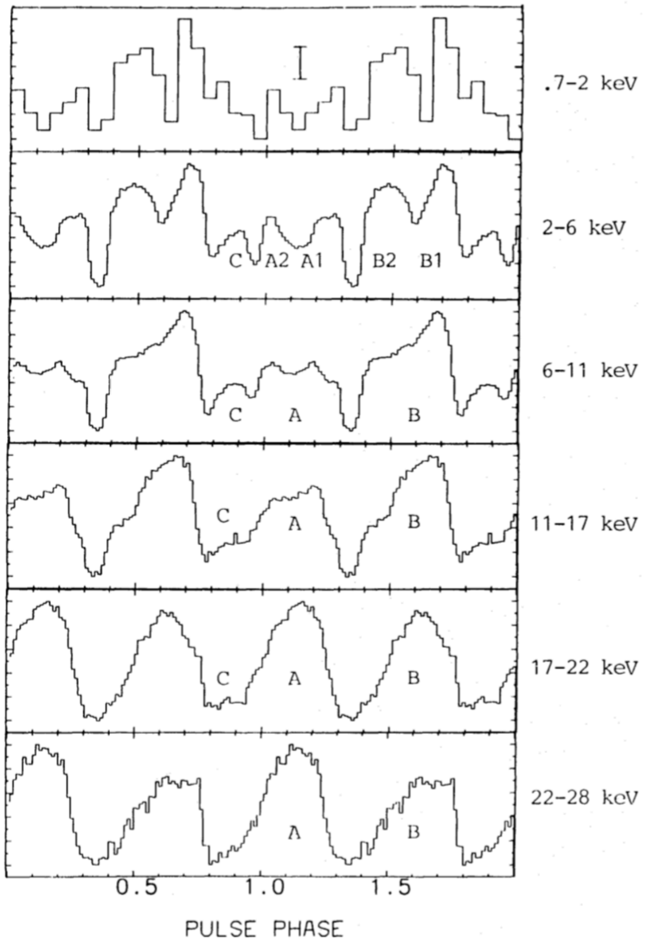
- Vela X-1 is often quoted as example of massive (clearly > 1.4 M☉, maybe > 2 M☉) neutron star.
- Full picture, taking into account inclination uncertainty is less clear, but leaning towards heavy solutions.
- Mostly in mass range where radius is almost stable according to theoretical equations of state (EOS)
  ➟ probable radius 11–12.5 km.
- For highest possible masses interesting area of EOS would be sampled.



Maselli et al. (2020)



Pulse profiles *should* allow to disentangle the emission geometry



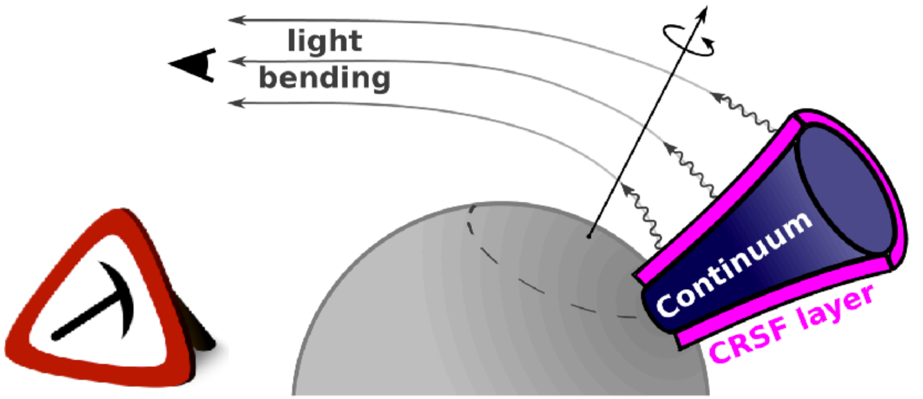
Raubenheimer (1990)

- The pulse profile is complex at lower energies and overall *usually* rather stable.
- Doroshenko et al. (2011) found changed pulse pattern in “off-state”.

➡ *In principle* able to derive information on emission geometry.

- But complicated analysis if general relativity and realistic emission geometries are taken into account! Still quite a bit of work on models and comparison.

Falkner at al. (2016)

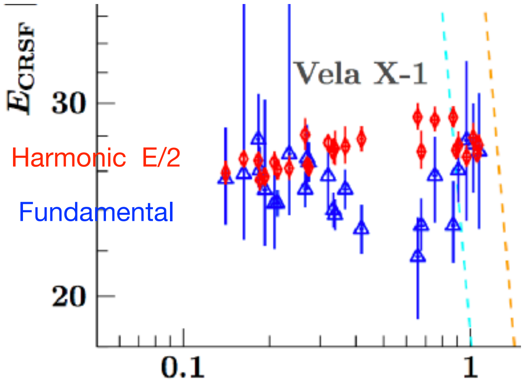


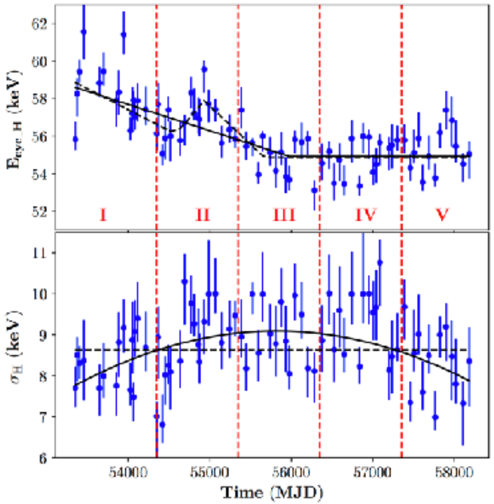
Cyclotron lines maybe more puzzling than enlightening

- Cyclotron Resonant Scattering Features found in 36 sources so far (Staubert et al. 2019).
- Most direct measure of magnetic field strength. Variations in observed centre energy ➟ changes in (height of) emission region.

- Fürst et al. (2014): *harmonic* line varies with luminosity. No clear picture for fundamental.
- Ji et al. (2019, submitted): possible long-term trend in energy (Swift BAT).

➡ Will need improved accretion column models to better interpret the data.

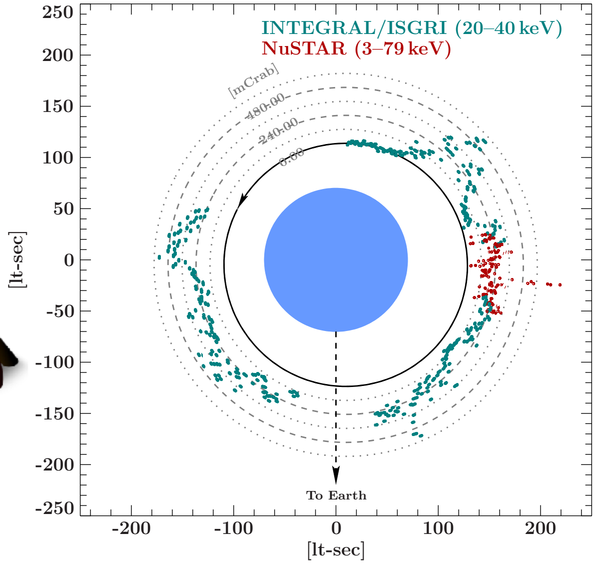




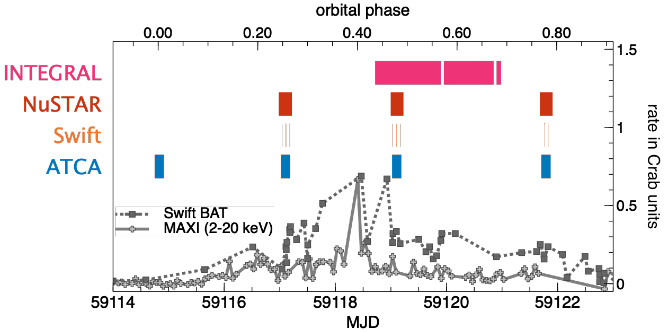
Further progress

More observational data is available and being studied

- Major observational X-ray campaign in January 2019 motivated by planned X-Calibur balloon observations (polarisation). The balloon failed early, but the X-ray data is being analysed.
- Radio observations at 4 orbital phases end Sep 2020.

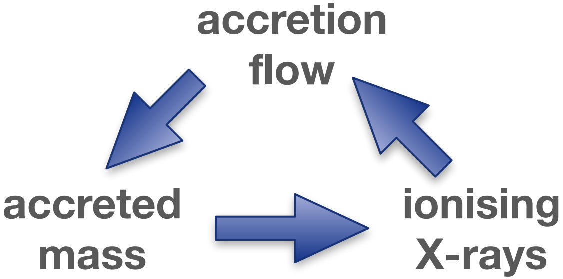


- Could still use:
  - More multiple high-resolution spectra in optical and near bands.
  - Newer UV spectra – we still rely on IUE (1978-1996).
  - High-resolution X-ray spectra on shorter time scales (XRISM, Athena).
  - X-ray polarization data (IXPE).



Some ideas for further improvements

- Find more ways for interacting detailed models, as single approach with all features would be intractable.
- Include effects of eccentric orbit in model calculations.
- Model emission from accretion column based on available pulse profiles.
- Realistic calculations of absorbing structures (N_H).
- Interferometric observations in the future (GRAVITY+) *might* be able to resolve the scale of the accretion radius and allow for independent constraints on stellar radius.
- Determine evolutionary stage of the donor star (on the way to red supergiant or back to blue and maybe to WR?).
- Retrace system history in Galactic potential – requires more high-resolution spectra for absolute radial velocity.
- Make right old data in archives accessible again (software issue).



accretion flow

accreted mass

ionising X-rays

Work continues to solve a complex, multi-scale puzzle

X-rays

accretion column processes

magneto-spheric coupling

disk? shell? outflows?

mass capture $f(\rho, v_{rel})$

structures & clumps

wind driving

emission pattern & spectrum

relativist. light bending

radiation transport

absorption scattering fluorescence

ionisation wind feedback

stellar surface heating

Thank you! Questions?