Stellar Winds in Massive X-ray Binaries

ISSI Team Meeting 2013+2014

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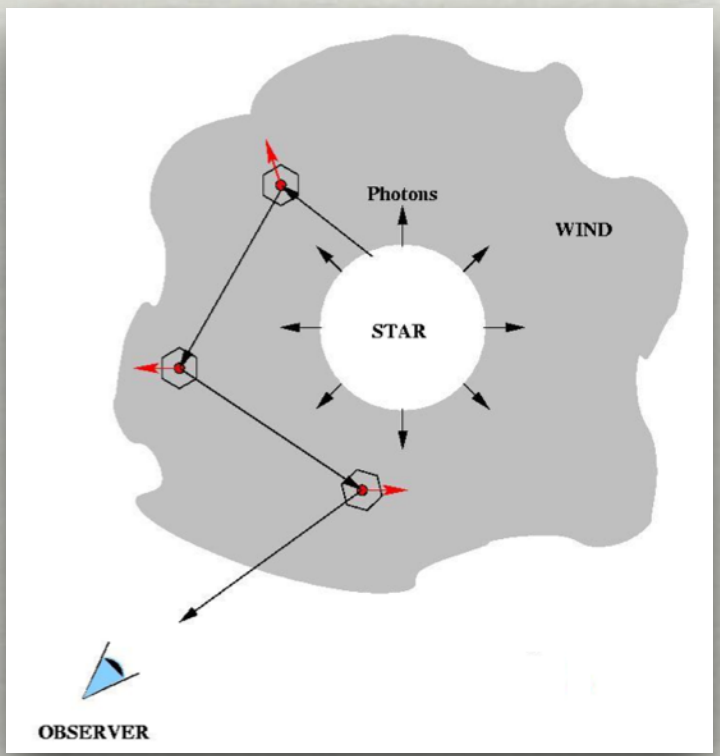
Hot star winds in HMXB

Hot Star Wind Basics

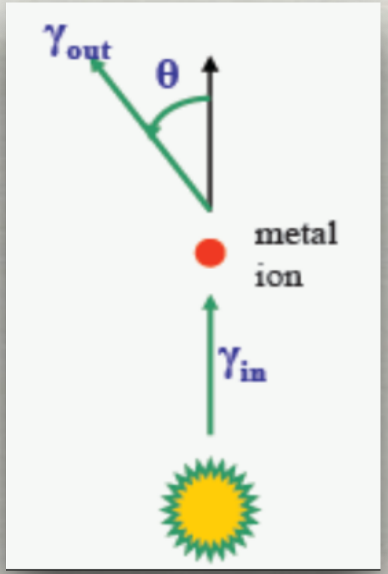


- Wind accelerated by radiation pressure in **metal lines.**
- Requires high luminosity ($L \propto R^2 T_{eff}^4$)

  ➠ **supergiants or hot dwarfs** and many suitable lines close to flux maximum

  ➠ **mass loss depends on metallicity**
- Pioneering work by Lucy & Solomon, 1970 and Castor, Abbott & Klein, 1975.
- Improvements (quantitative description & application) by Friend & Abbott, 1986, Pauldrach, Puls & Kudritzki, 1986.
- Modern review, e.g., by Puls, Vink & Najarro, 2008

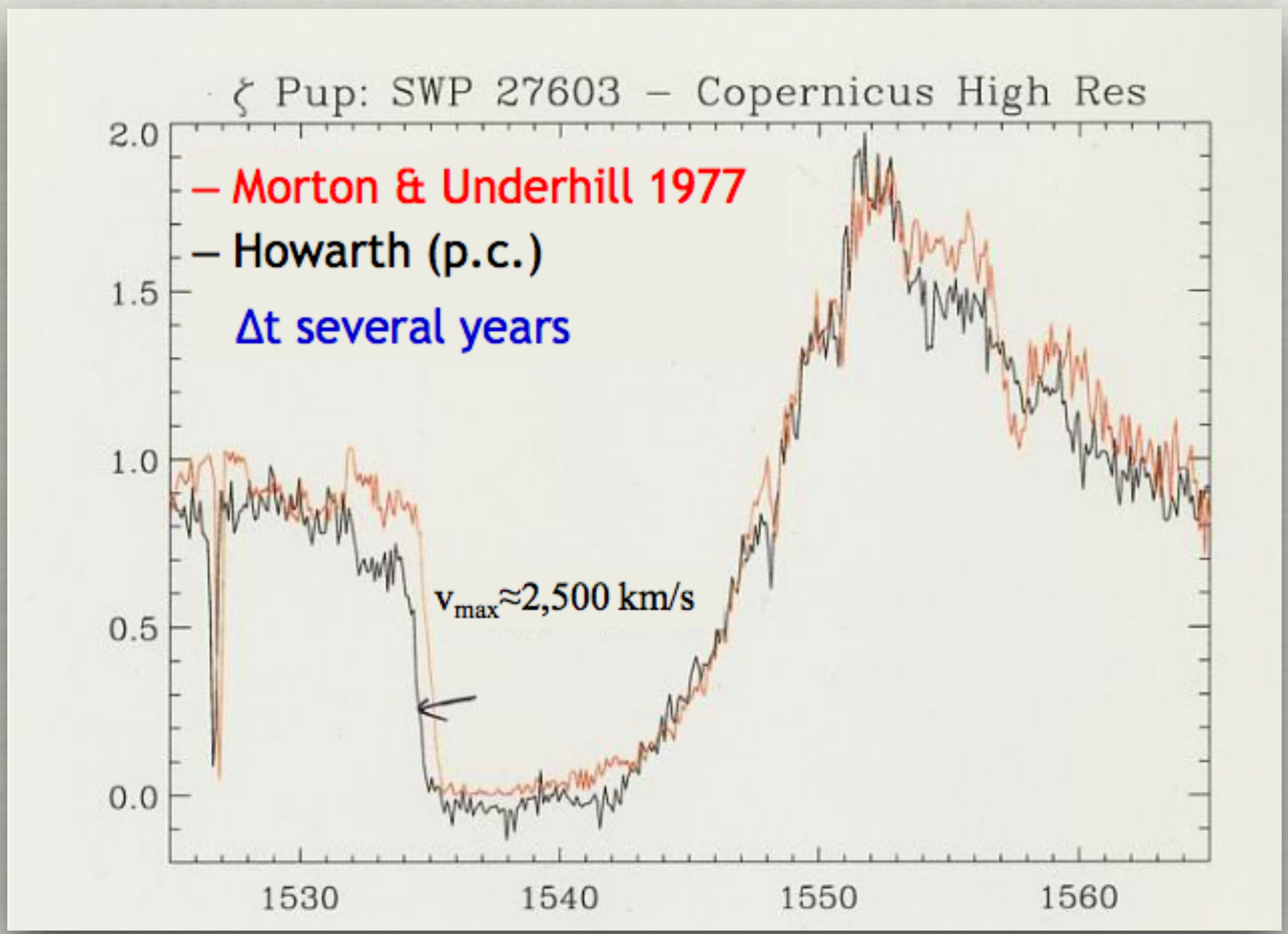
Line acceleration



- Scattering of continuum light in resonance lines of metal ions (fraction ~10^{-3}).
- Momentum transfer from metal ions to bulk plasma (H/He) via Coulomb collisions.
- For OB stars usually assume *single* scattering of photons in wind; not true for Wolf-Rayet stars.
- Assume lines can be treated independently, i.e., total $\Delta P = \sum \Delta P_i$ (ok for OBA stars).
- Realistic models need to treat **millions of lines!**
- Many modelling efforts, mainly still in 1D.

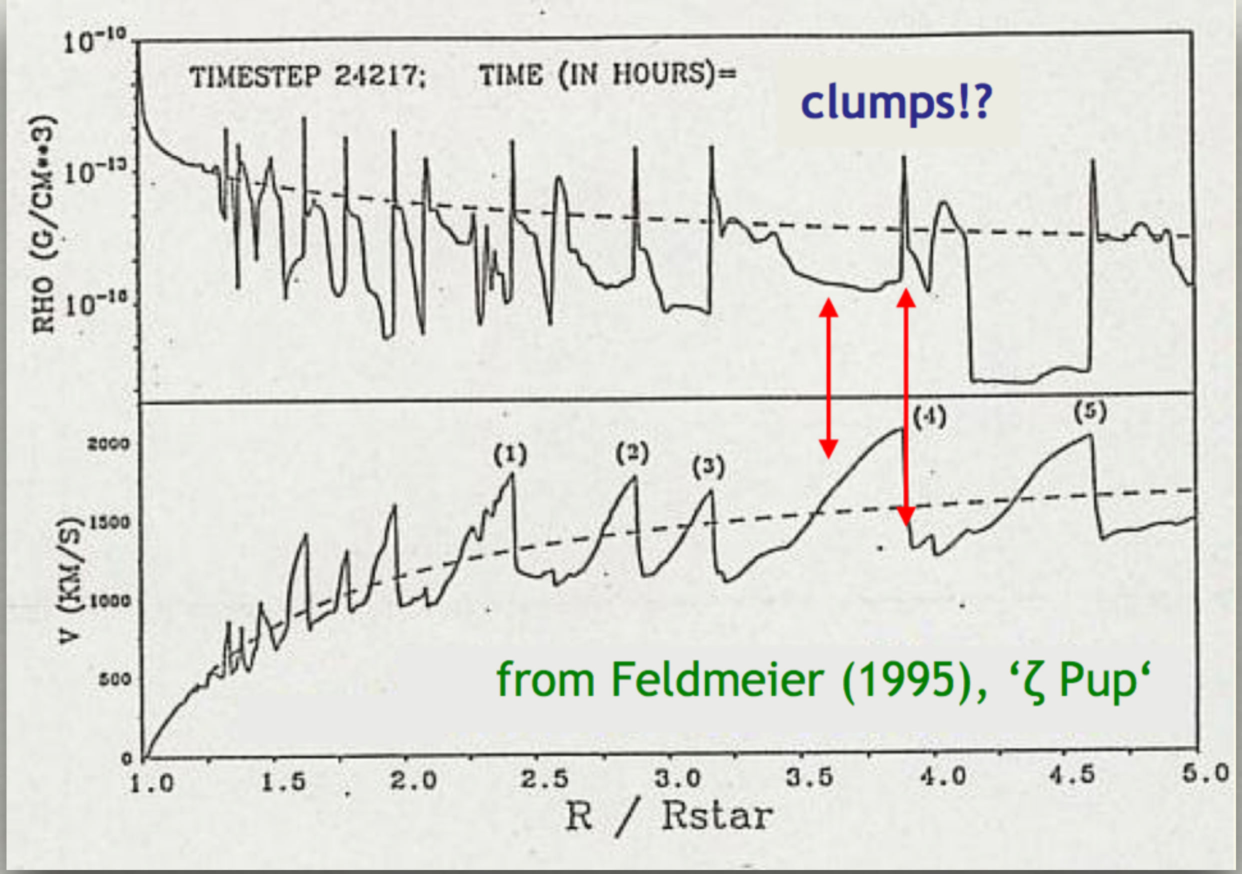
Wind Standard Model

- Observations show: massive star have at least quasi-stationary outflows.
- Only small, in **no way dominant** variability of global quantities ($\dot{M}$, v_∞),
- Standard Model:
  - *stationary, spherically symmetric, homogeneous,*
  - *no rotation, no magnetic fields*
  - $\dot{M} \approx 10^{-7} \ldots 10^{-5}\, M_\odot/yr$, $v_\infty \approx 200 \ldots 3500$ km/s



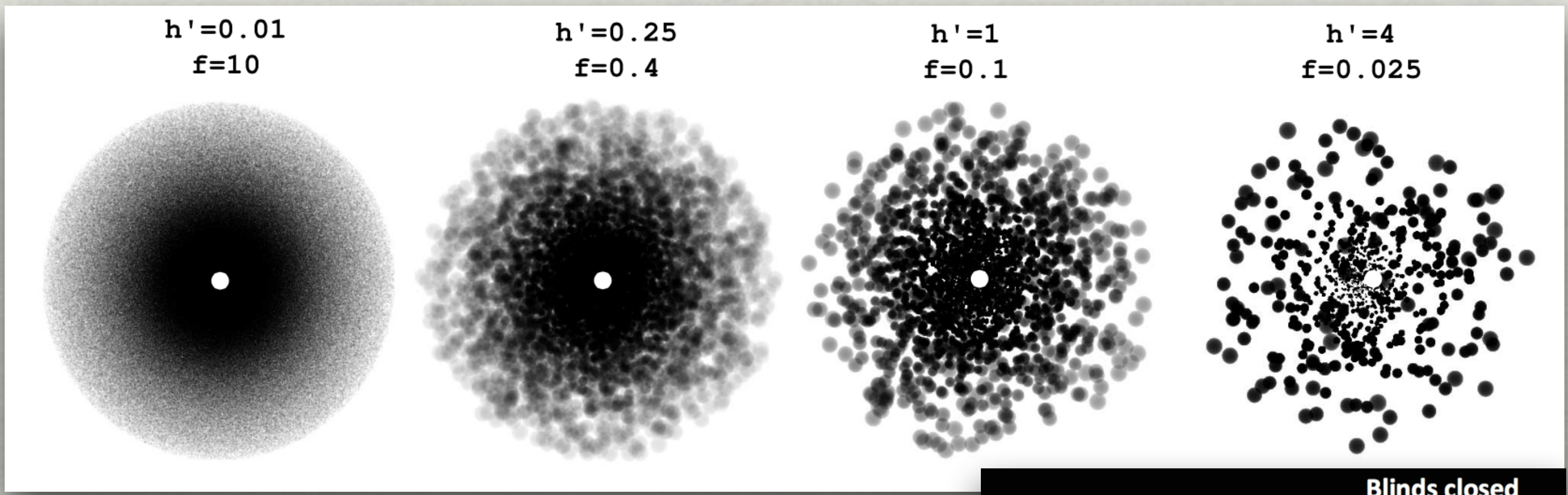
Line Driven Instability

- Hot star winds are intrinsically instable to velocity perturbations (noted already by Lucy & Solomon, 1970)!
- 1D simulations find reverse shocks: density low where velocity high (pre-shock), and vice versa (post-shock).
- Dense zones may be '**clumps**' inferred from observations. Density variation >10.
- Shock heating ➟ X-ray emission (seen by *Einstein, ROSAT, Chandra, XMM-Newton*).

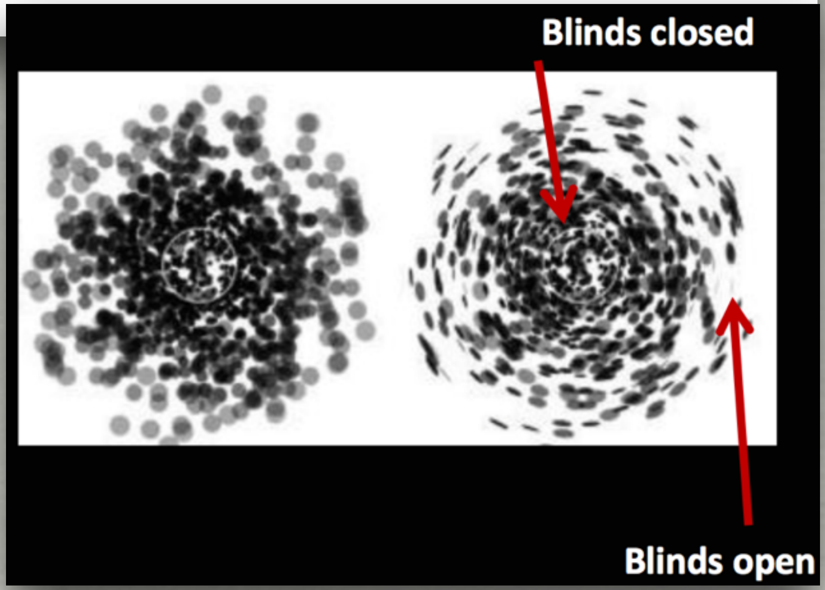


Clump density & shapes

- Simplified description by **porosity length** (clump size/ volume filling factor = mean free path between clumps).



- For higher porosity clump shapes matter ("venetian blinds effect").

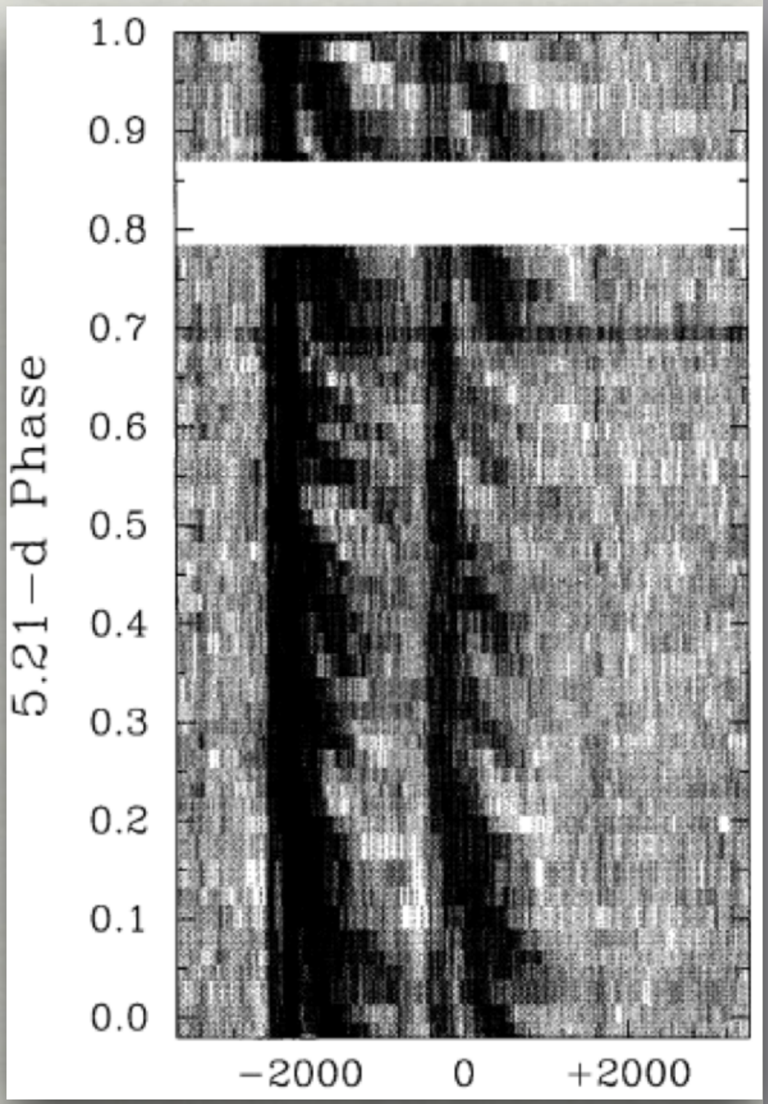


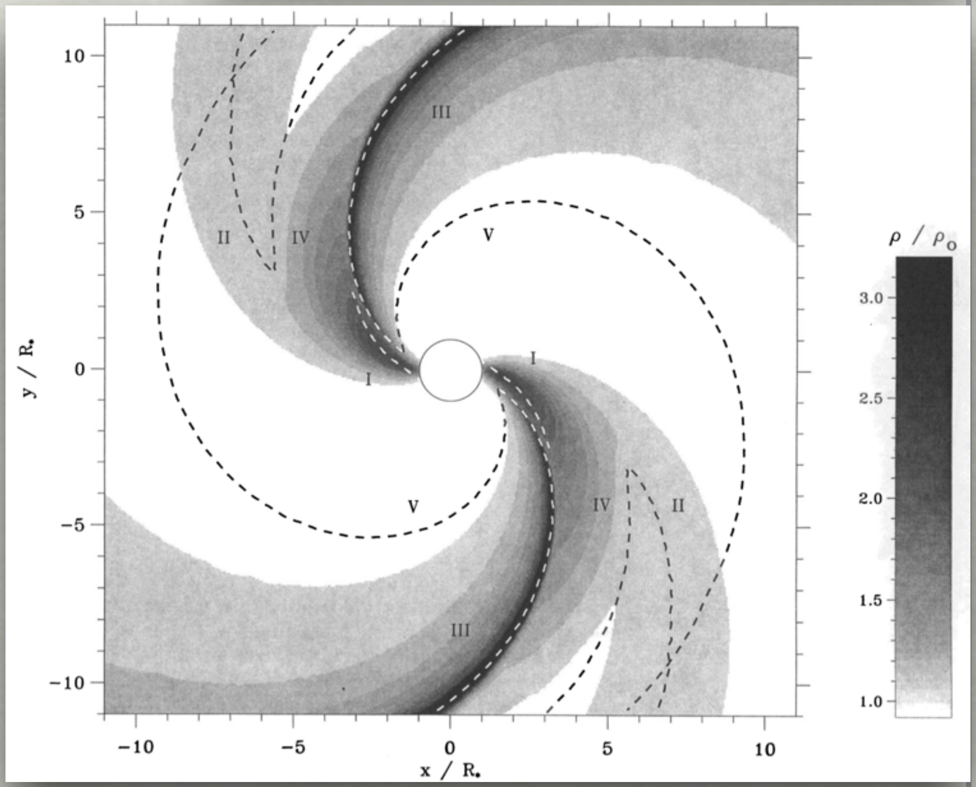
Micro- and macro clumps

- **Micro-clumping**: clumps do *not* affect radiative transfer, i.e., optically thin globally. ➠ Derived mass losses lower by sqrt(density enhancement), relative to smooth wind.
- **Macro-clumping**: clumps optically thick at some frequencies; opacity depends on clump geometry, abundances, and velocity distribution within clump ➠ higher derived mass-loss rates.
- **Many discussions between wind modellers** on role of micro- vs macro-clumping, or limitations of porosity formalism. Different models have different clump distributions for same observed line features.

Large Structures

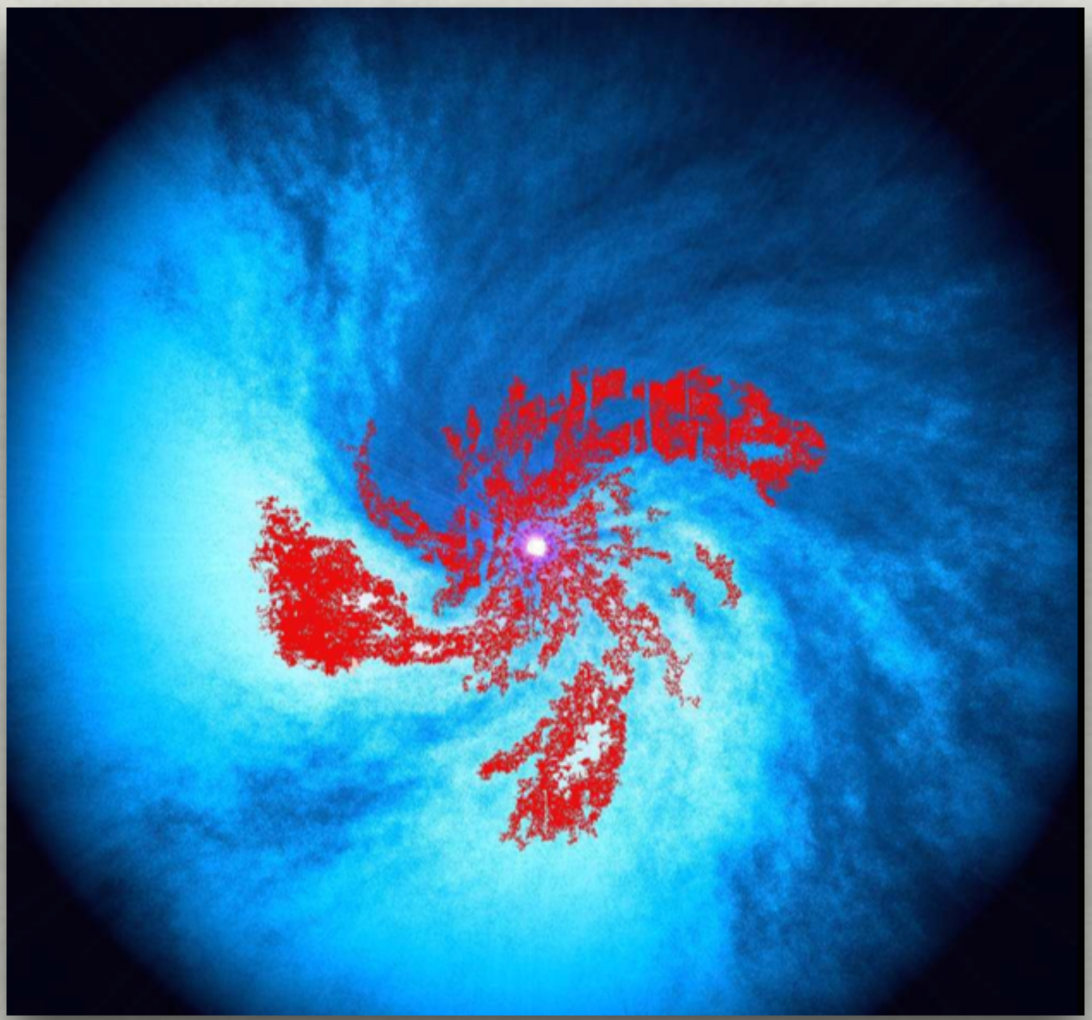
- Discrete Absorption Components (DACs): optical depth enhancements in the absorption troughs of unsaturated UV P Cygni profiles.
- Evolving with stellar rotation phase.
- Interpreted as due to corotating interaction zones (CIRs), known for solar winds, possibly caused by star spots (e.g., Cranmer & Owocki, 1996).
- Density contrast relatively low: from few ten % to factor ~3, but large and massive structures.





Different wind components

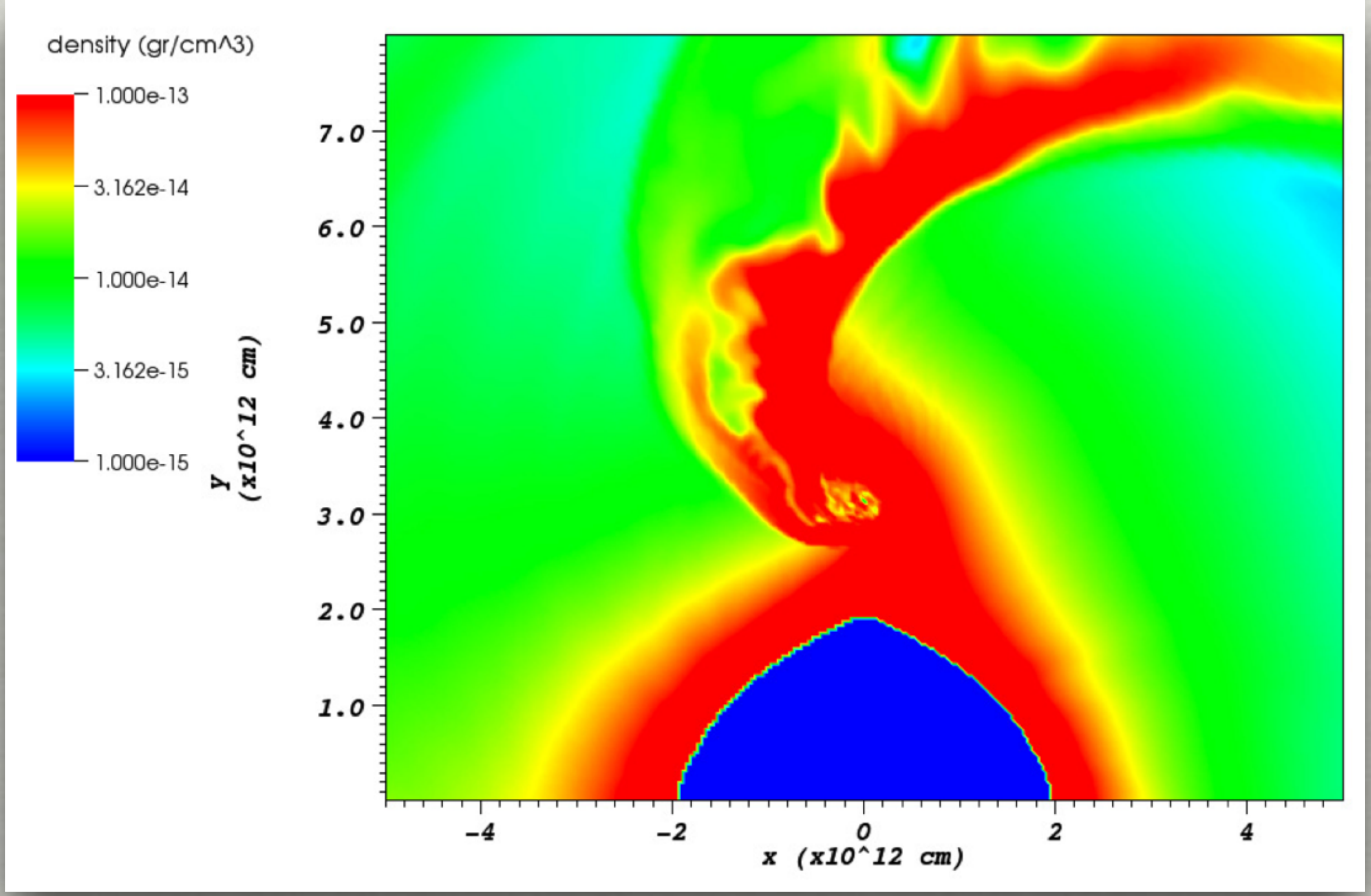
- X-ray studies find different temperature components in stellar winds.
- Sako et al., 1999 (Vela X-1)
  - Inhomogeneous wind: hundreds of cool, dense clumps within hotter, more ionized gas.



- Nazé, Oskinova & Gosset, 2013 (Zeta Puppis)
  - Hot 10^7 K component radiating X-rays.
  - Cool 10^4 K component absorbing X-rays.

Effects of the X-ray source

- Gravitation will focus wind in orbital plane
- Photoionization of the wind by the intense X-ray source within Strömgren sphere ➠ wind acceleration cut off!
- Fluorescent lines from X-ray illumination.
- Bow-shock of compact object moving through dense wind ➠ "accretion wake" following compact object around orbit. (e.g., Manousakis & Walter 2015)

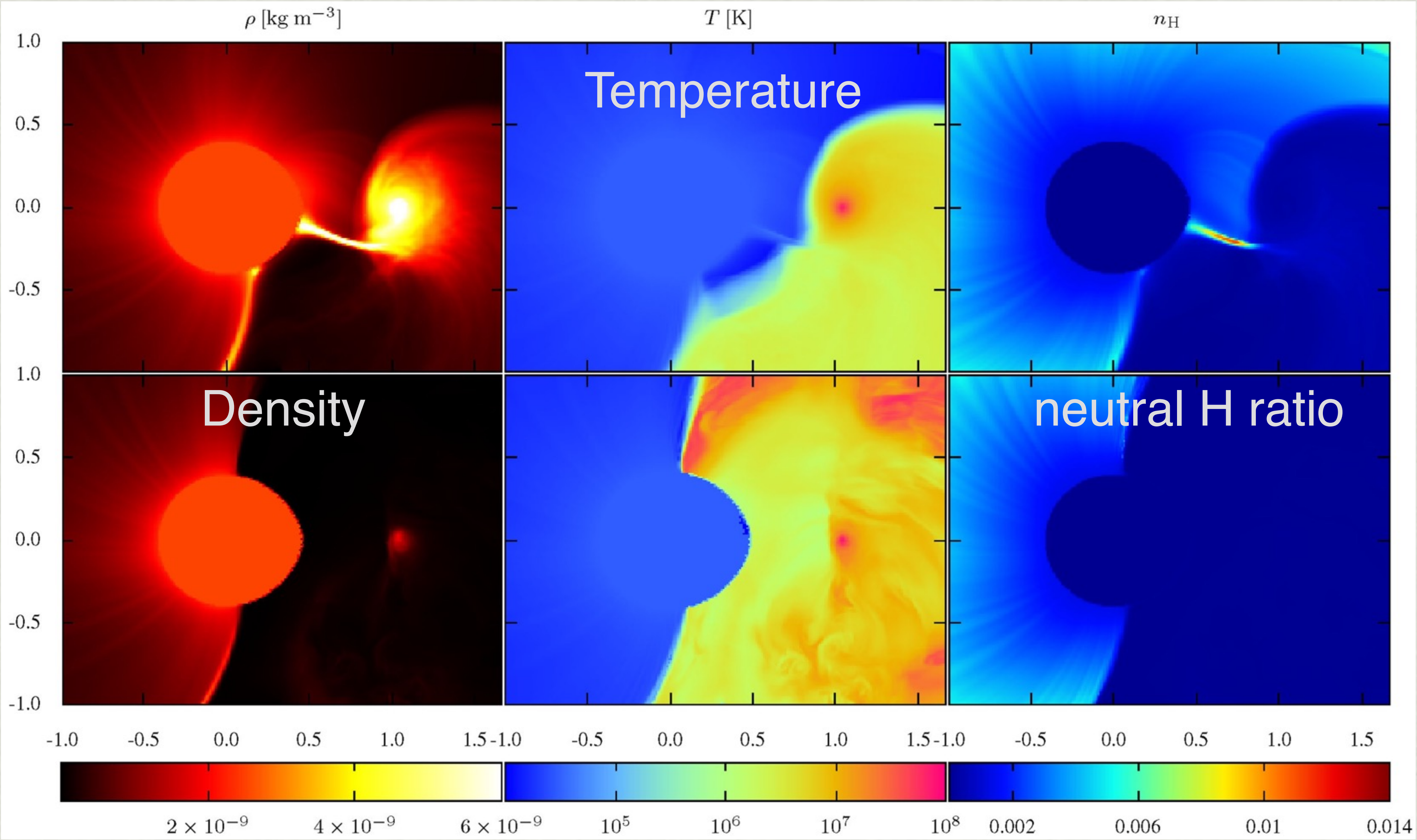


Effects of the X-ray source

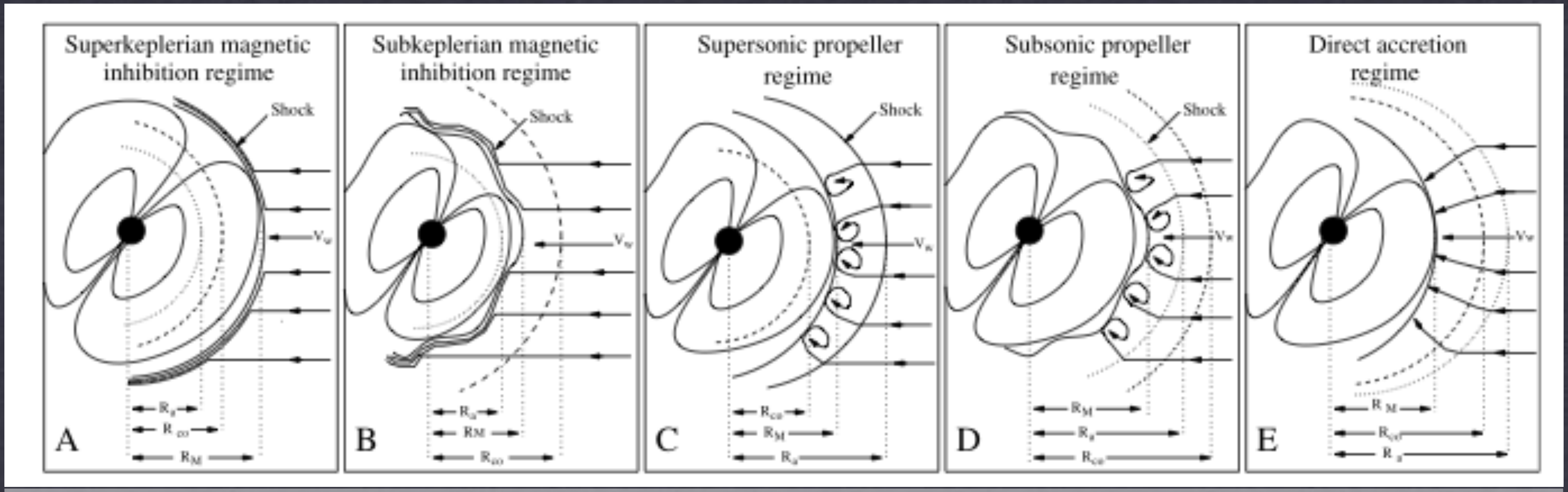
- Model of Cyg X-1 in hard and soft state
  Čechura, Vrtilek & Hadrava, 2015

Low/Hard State

High/Soft State



Wind accretion

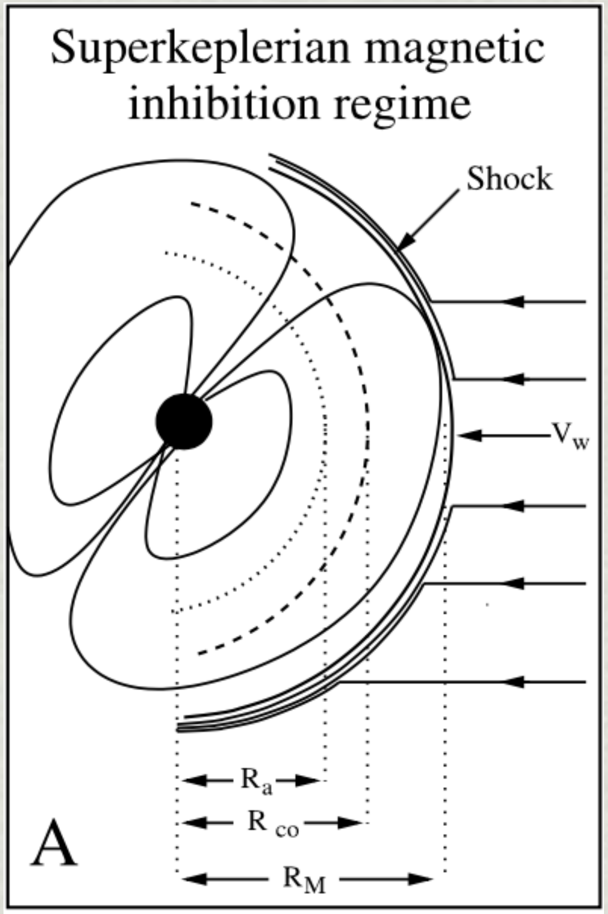


Wind accretion

- Usually assumed no accretion disk is formed ➠ reaction to changes on free-fall timescale (few to ~100 s).
- Bondi-Hoyle-Lyttleton theory (simplification):
  - Accretion radius $R_{acc} = 2GM_{NS} / v_{rel}^2 \approx 10^{10}$ cm, with relative speed v_{rel} usually $\approx v_{wind}$.
  - $\dot{M}_{acc} = \zeta\, \pi R_{acc}^2\, v_{rel}\, \rho \sim \rho / v_{rel}^3 \approx 10^{16}$ g/s ($10^{-7}\, M_\odot$/yr)
  - $L_X = (GM_{NS}/R_{NS}) \times \dot{M}_{acc} \approx$ a few times 10^{36} erg/s
- For magnetised neutron star accretor, also very important:
  - Magnetospheric radius $R_{mag} \sim \rho^{-1/6}\, v_{rel}^{-1/3} \mu^{1/3}$ $\approx 10^9$ cm for typical parameters ($B \approx 10^{12}$ G)
  - Co-rotation radius $R_{co} = 3.7 \times 10^9\, P_{100s}^{2/3}$ cm.

Inhibition of accretion

- **Super-Keplerian magnetic inhibition**:
  $R_{mag} \gtrapprox R_{acc}$ and $R_{mag} \gtrapprox R_{co}$ ➠ no accretion, possibly X-rays from shocks and neutron star rotation power.



- **Sub-Keplerian magnetic inhibition**:
  $R_{mag} \gtrapprox R_{acc}$ but $R_{mag} < R_{co}$
  Weak accretion through Kelvin-Hemholtz instabilities

- **Supersonic propeller**: $R_{mag} < R_{acc}$ but $R_{mag} \gtrapprox R_{co}$
  Matter is captured, but inhibited from accretion. X-rays from dissipation at magnetosphere.

- **Subsonic propeller**: $R_{mag} < R_{acc}$ and $R_{mag} < R_{co}$
  Accretion possible, but matter must be cooled below critical temperature for instabilities to be efficient.

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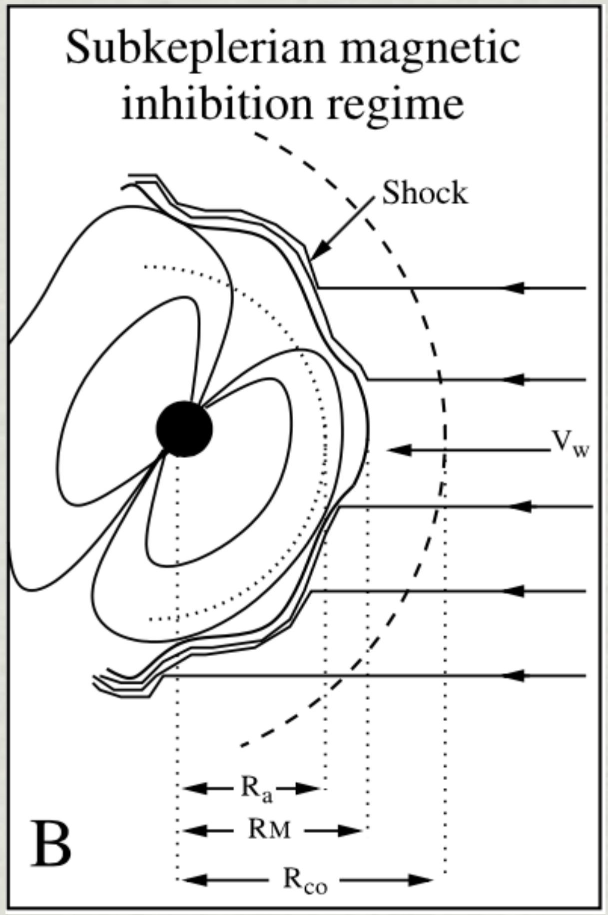

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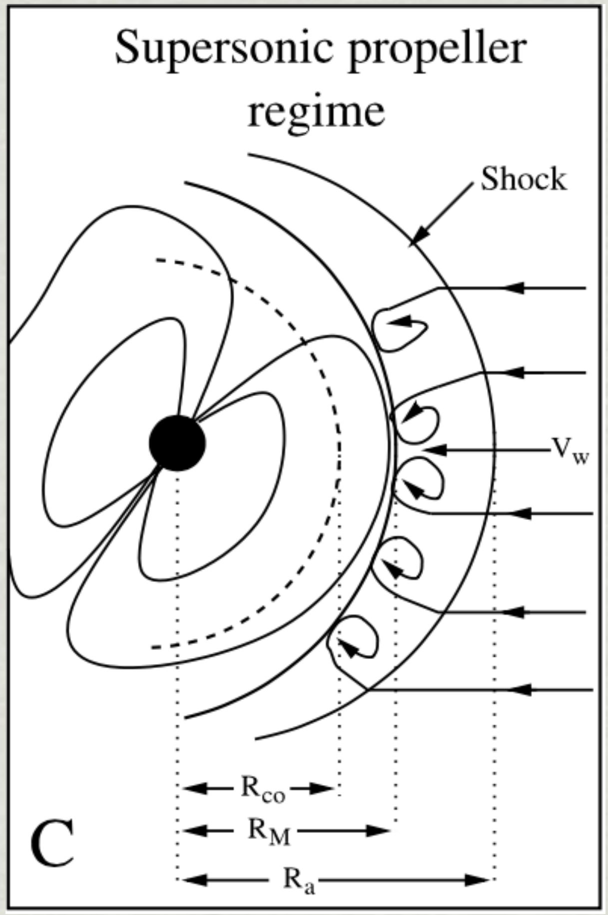

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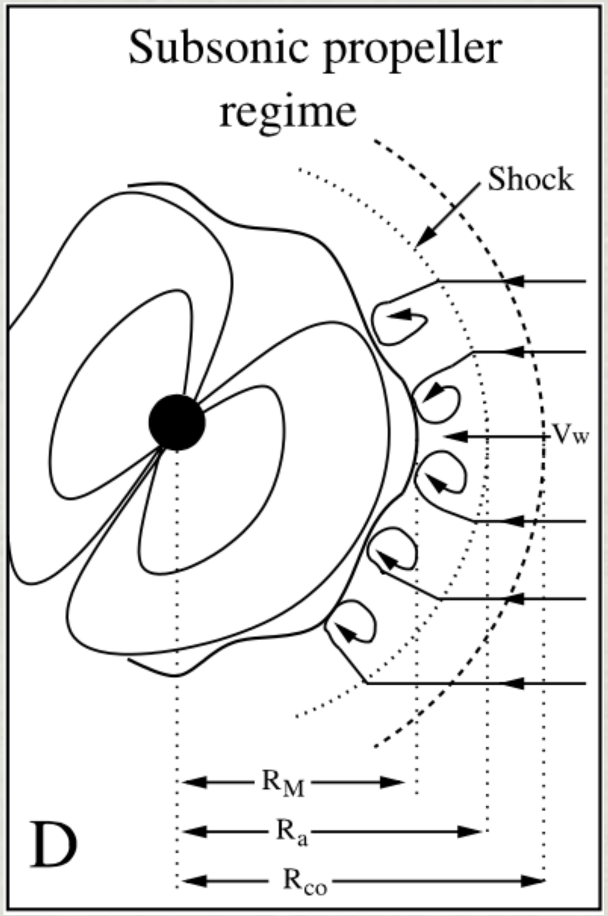
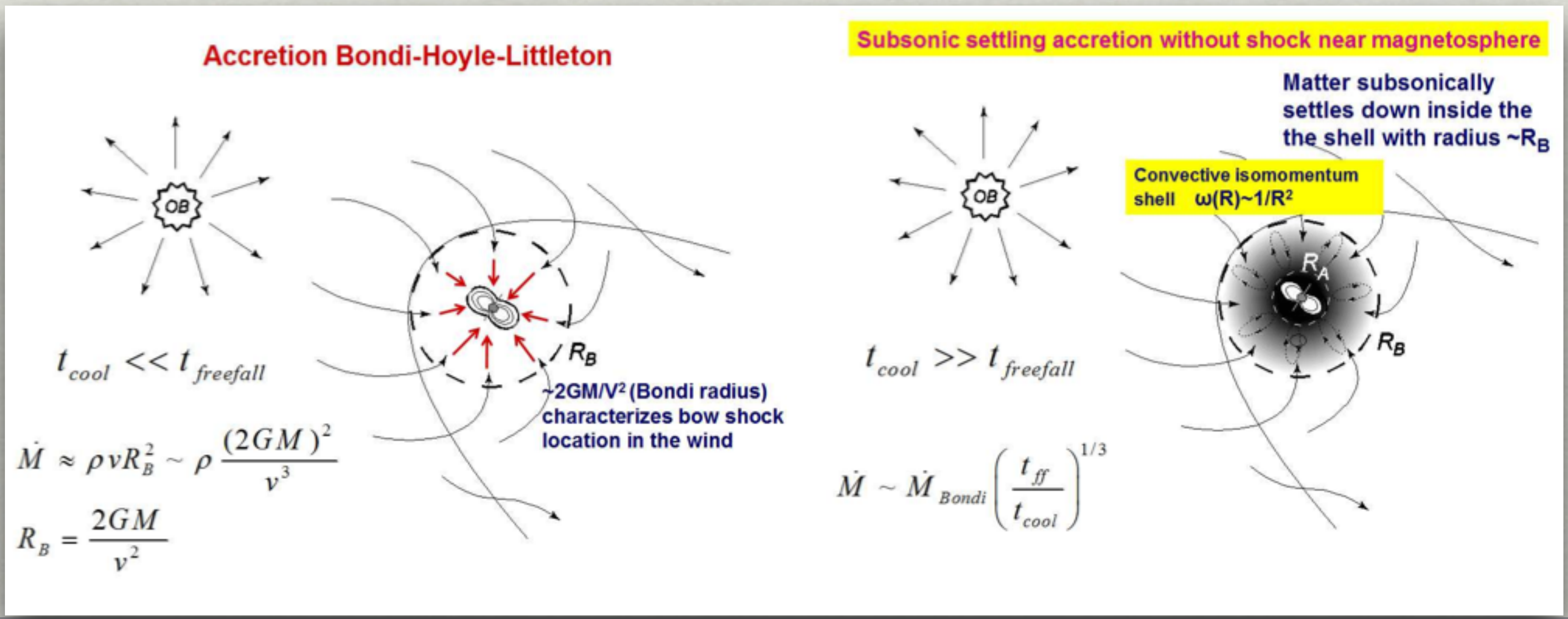
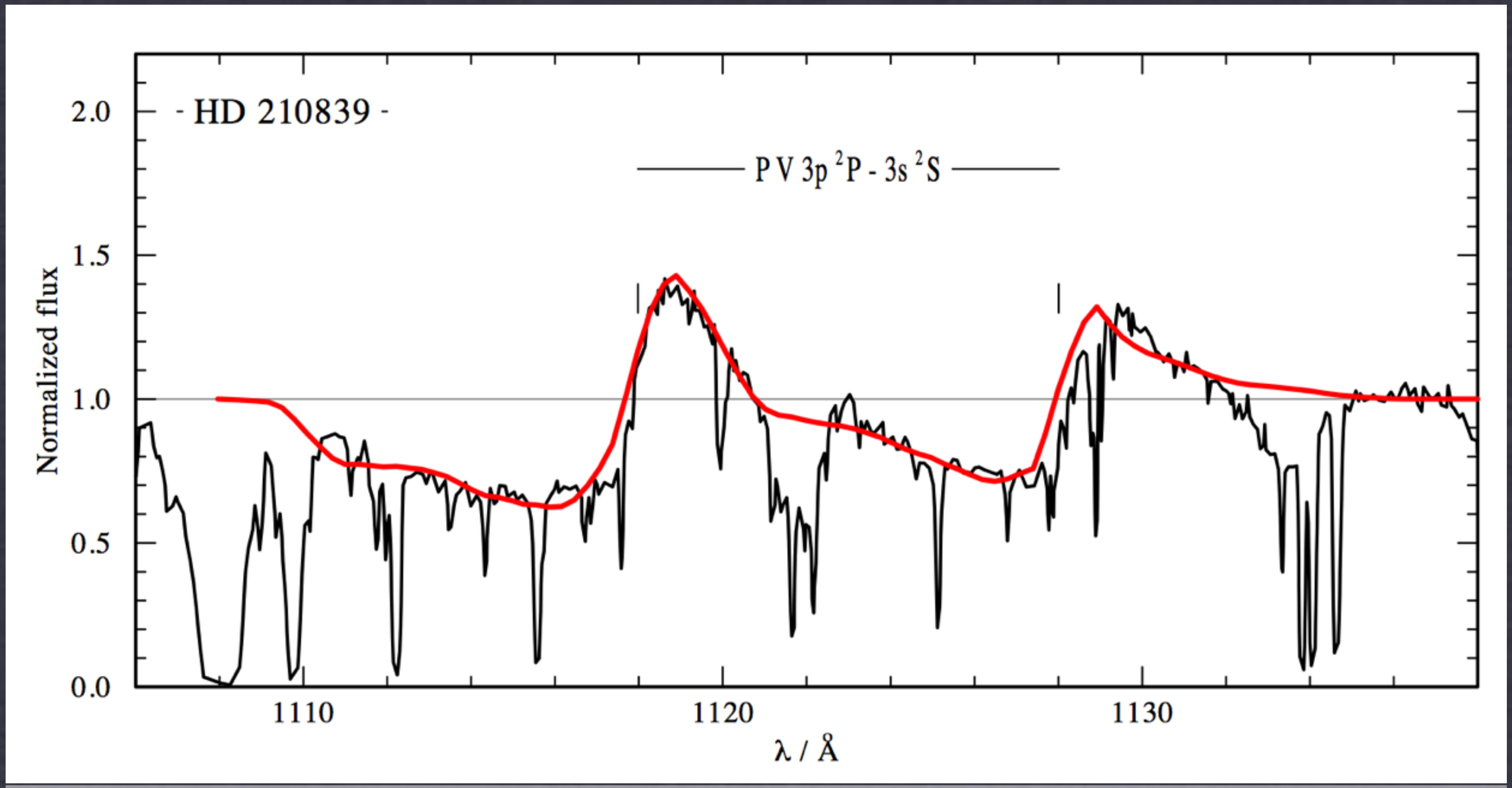


Accretion regimes

- **Direct accretion** (classical BHL): matter falls freely on neutron star ➠ maximum luminosity.
- **Subsonic settling accretion** (newer model by Shakura & Postnov et al.): Compton cooling not fully efficient, shell of material forming and accretion rate reduced by factor 3–10 compared to direct accretion.



Wind diagnostics



Spectroscopy (Opt.+UV)

- Stellar & wind parameters for hot massive stars obtained by **quantitative spectroscopy**, fitting synthetic SEDs and normalised spectra to observations (Optical + UV).
- Various NTLE model codes for photosphere and wind.
- Fit 'by eye', by minimisation or model grid.

Table 1: Comparison of state-of-the-art, NLTE, line-blanketed model atmosphere codes suited for the analysis of hot massive stars

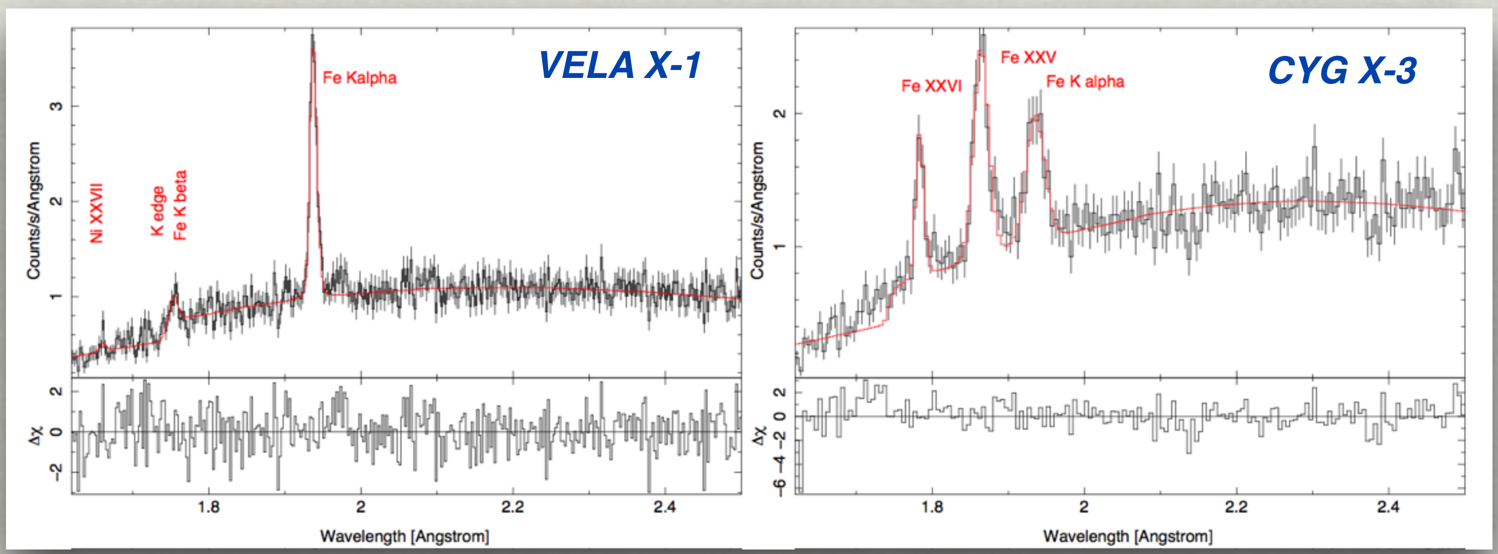
code	Detail/ Surface[1]	TLUSTY[2]	PoWR[3]	PHOENIX[4]	CMFGEN[5]	WM-basic[6]	FASTWIND[7]
geometry	plane-parallel	plane-parallel	spherical	spherical/ pl.-parallel	spherical	spherical	spherical
blanketing	LTE	yes	yes	yes	yes	yes	approx.
diagnostic range	no limitations	no limitations	no limitations	no limitations	no limitations	UV	optical/IR
major application	BA stars with negl. winds	hot stars with negl. winds	WRs, OB-stars	cool stars, SNe	OB(A)-stars, WRs, SNe	hot stars w. dense winds, SNe	OB-stars, early A-sgs
comments	no wind	no wind	-	no clumping no X-rays	-	no clumping	no X-rays (in progress)
execution time	few minutes	hours	hours	hours	hours	1 to 2 h	few min. to 0.5 h

(1) Giddings (1981); Butler and Giddings (1985), (2) Hubeny (1998), (3) Gräfener et al. (2002), (4) Hauschildt (1992), (5) Hillier and Miller (1998), (6) Pauldrach et al. (2001), (7) Puls et al. (2005)

- **Caveat:** *comparisons should be made by as many lines as possible as single line results can often be caused by several mechanisms.*

X-ray spectroscopy

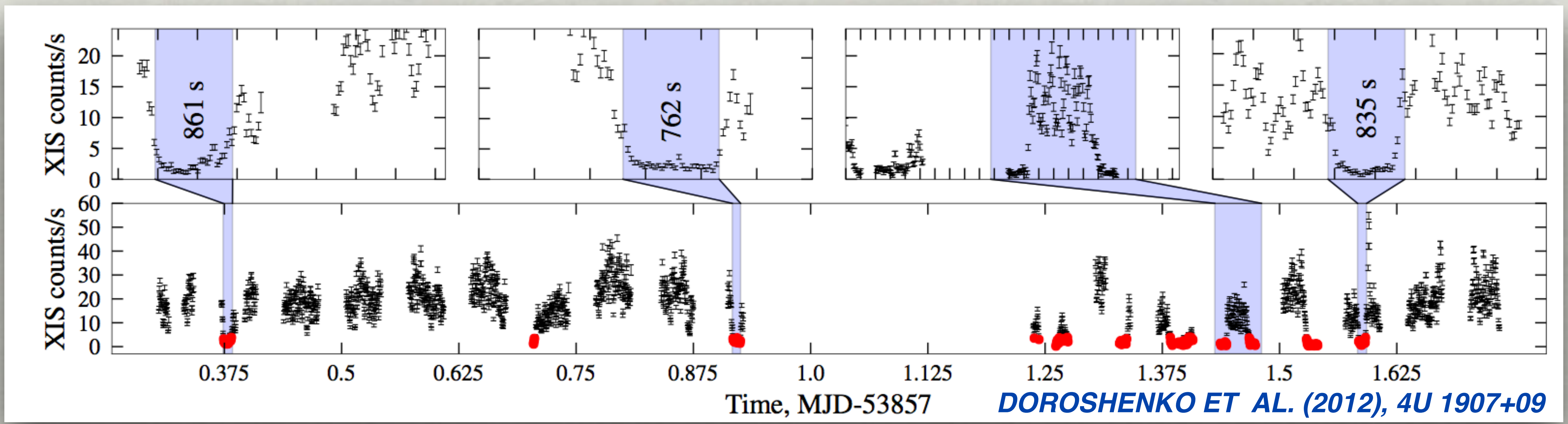
- Fluorescence lines, mostly from emission nearby compact object (few $R_{\odot}$, $\lesssim 0.5\ R_{\star}$).



- Line parameters ➟ distribution, velocities and ionisation of reprocessing material (e.g.Torrejon et al. 2010). **Caveat:** *Disentangling infalling material and wind difficult.*
- Continuum fits yield N_{H} variations (often $10^{22\text{-}24}$!), short term from smaller structures (clumps), long term from system-scale structures (e.g., accretion wakes). **Caveat:** *results depend on spectral continuum, absorption model and abundances used!*

Flares & Off-States

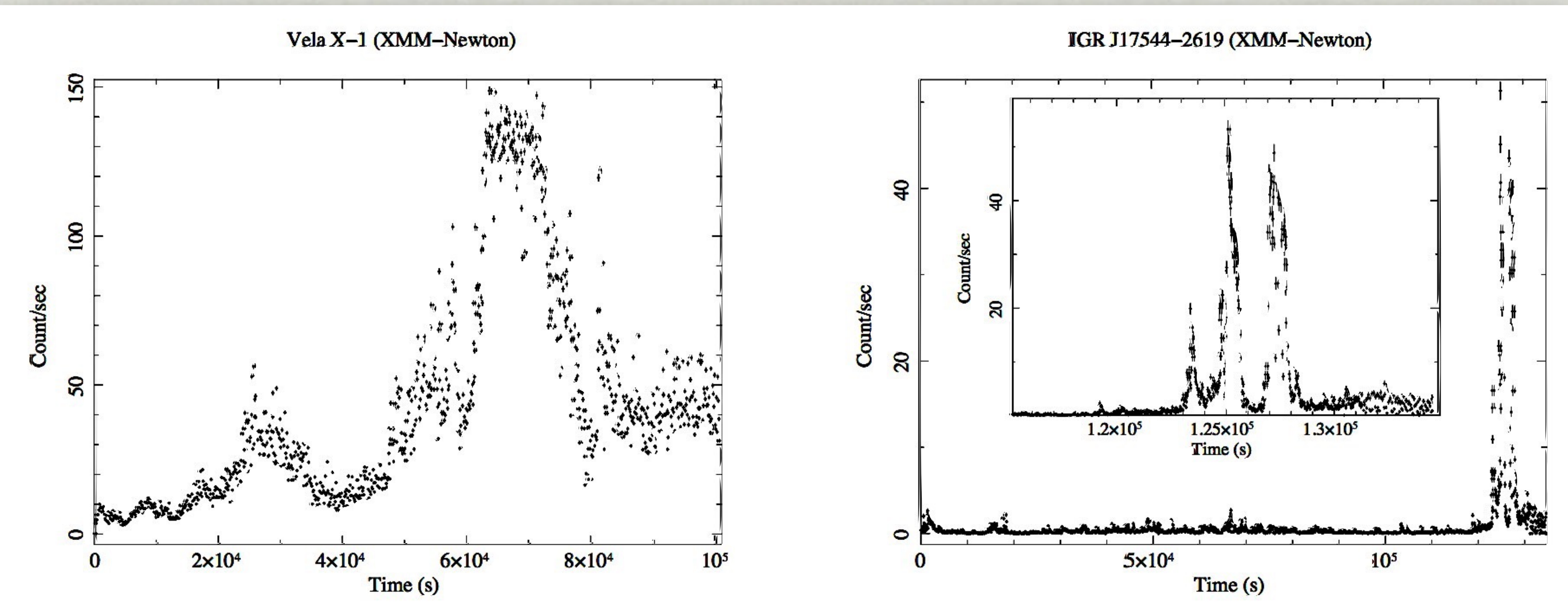
- Occasionally bright flares and more rarely "off-states" are observed in wind accretors.



- Fast reaction in direct accretion ➠ Sampling of wind inhomogenities ➠ caused by clumps and voids?
- **Caveat:** *"Off-state" often just means "source below detection limit". Mix of strong absorption and/or drop in intrinsic brightness in literature.*

The puzzle of the SFXTs

- Supergiant Fast X-ray Transients: wind accretors, similar to SGXB in properties, but mostly at (very) low luminosity, with only infrequent flares.



The puzzle of the SFXTs

- Various ideas in recent years to explain the SFXT behaviour, but none fully convincing:
  - larger distances between accretor and mass donor;
  - winds more clumpy in SFXT;
  - accreting magnetars;
  - magnetic fields of donor stars influencing accretion.
- **No definitive difference between SFXT and SGXB systems identified, but behaviour differs strongly! What drives this? Good question …**

Summary
&
Outlook

Status

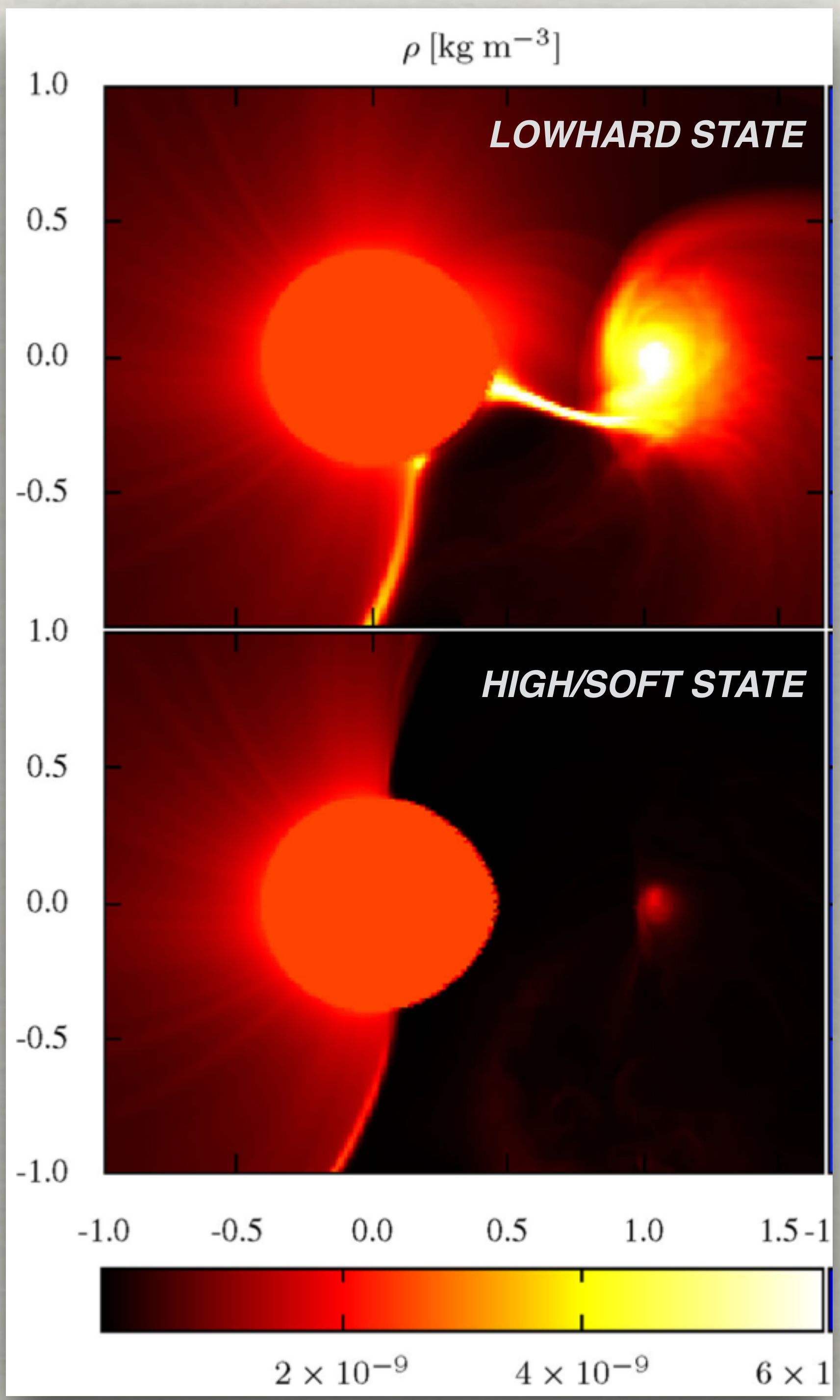
- Many questions still open (see next slide); work ongoing to find answers by this team and others.
- Improvements in models and observational data required.
- Major review (~85 pages draft text) of current knowledge submitted 21 December 2015 to Journal of High Energy Astrophysics.
- Successor team with somewhat different mix of experts, will meet at ISSI in 2016 and 2017.

Some open questions

- Serious discrepancy between clump sizes and density contrasts in simulations (10^{10} cm, 10) vs. observations (up to 10^{12} cm, 10^{4-5}).
- Wind velocities derived in HMXBs are systematically lower (factor of 2-5) than those derived from studies of single stars.
- Large scale structures (CIRs) should be stable over several orbits, but no stable structures seen in HMXB.

Improving the models

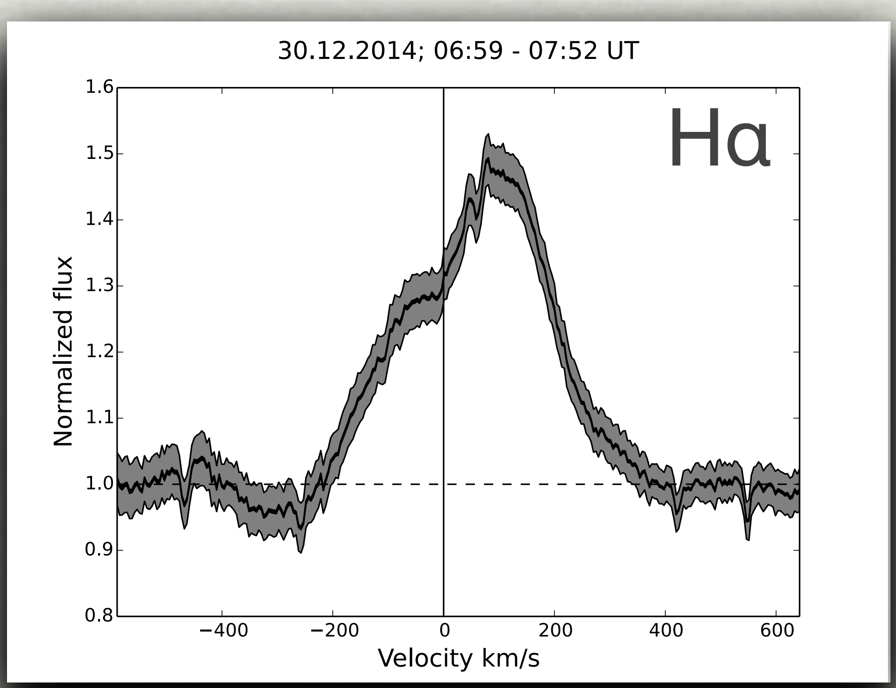
- HMXB models currently start from *smooth & isotropic* wind, wind models tend to ignore the X-ray source and its ionisation.
  ➠ HMXB MHD model with clumps.
  ➠ New code for ionisation prediction.
- Accretion & X-ray emission treated in extremely simplified form (instantaneous conversion, isotropic emission, unrealistic spectra, …)
  ➠ More realistic models of accretion column slowly evolving.



ČECHURA ET AL. 2015, CYG X-1,

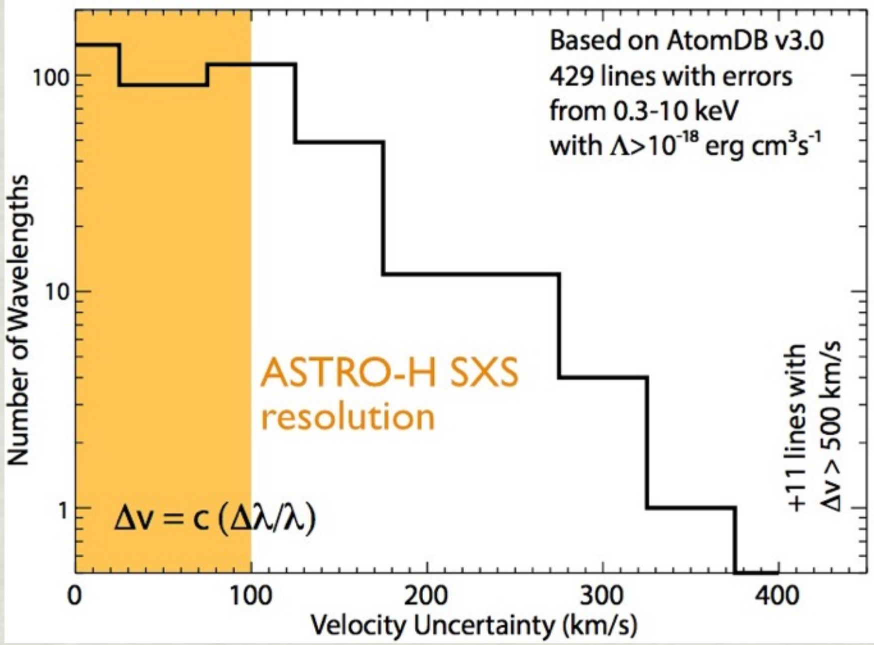
Systematic observations

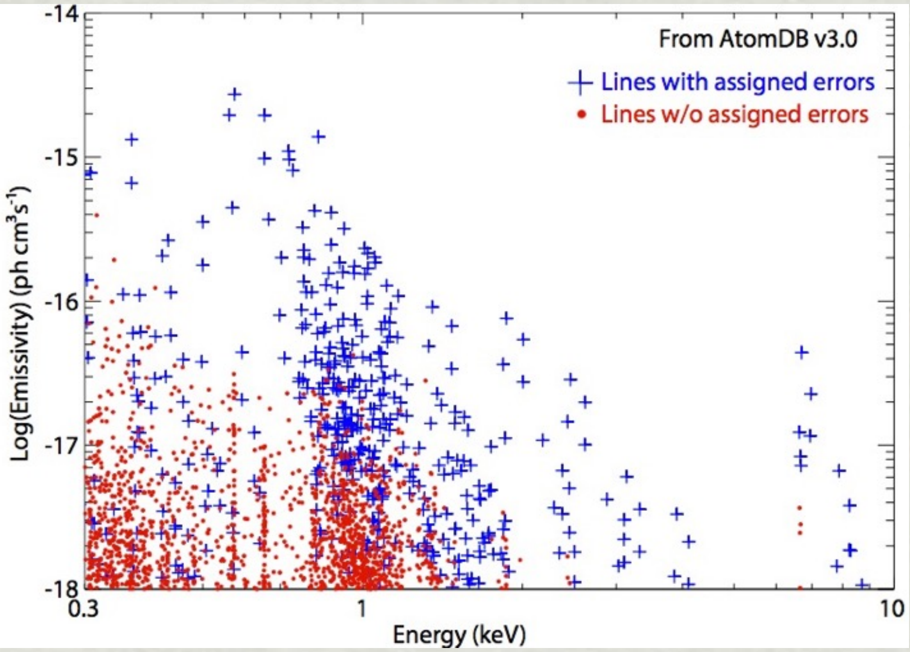
- Observations at all wavelengths, so far mostly sporadic and uncoordinated.
- Promising diagnostics by combining data across wavelengths, especially if close in time. E.g., Doppler tomograms of wind in Cyg X-1 by Čechura, et al. (2015).
- Another example: Coordinated Vela X-1 observations with Chiron (4500 Å – 7500 Å) and Swift/XRT from 28 Dec 2014 to 26 Jan 2015 (J. Kajava). *Analysis in progress, clear variations from day to day, occasional P Cygni profiles in Hα and He I lines.*



Issues with atomic data

- Currently, many line energies are more uncertain than resolution of next generation of X-ray spectrometers!

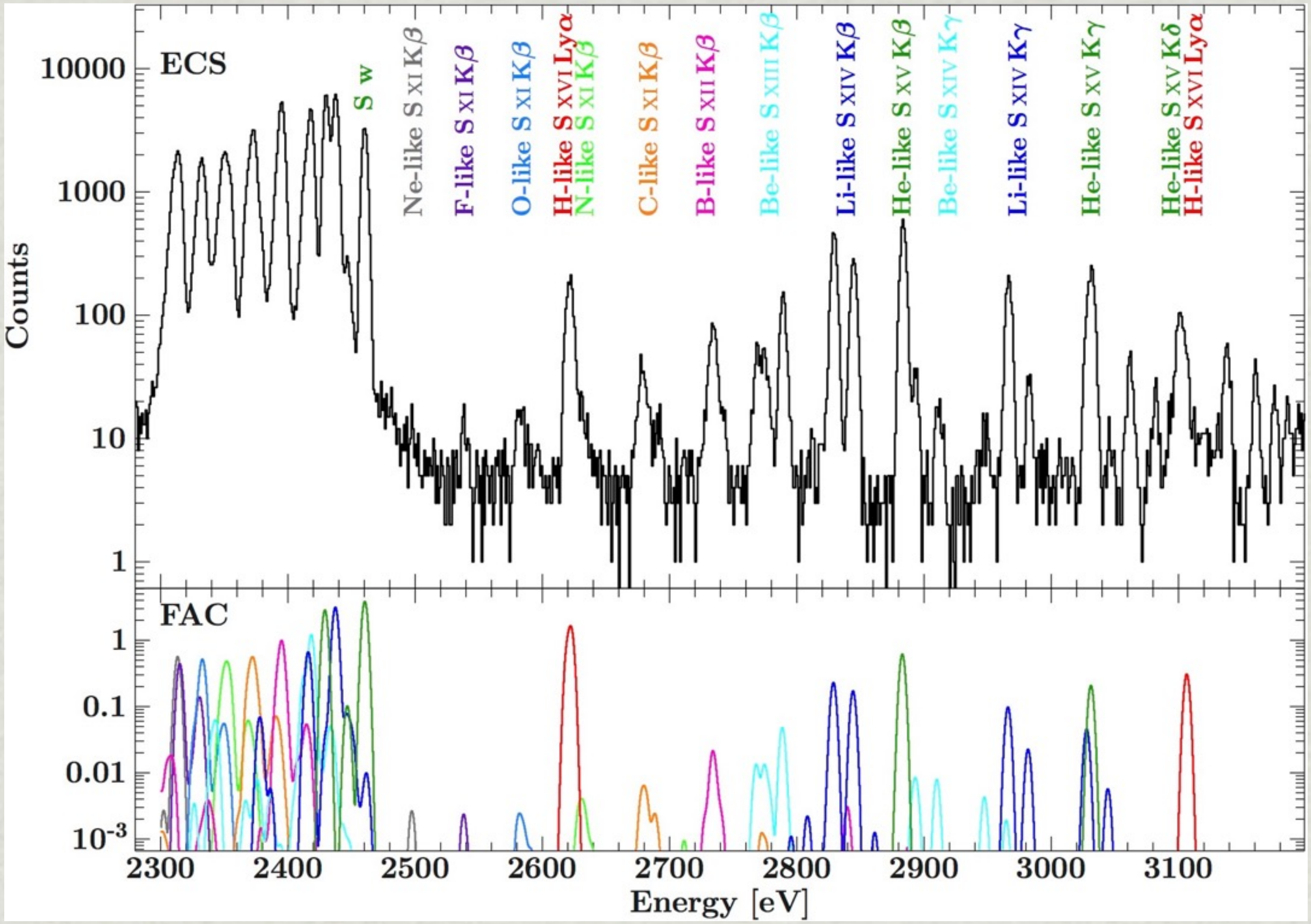




- For various lines, uncertainties not even known.
- Systematic limit on diagnostics (e.g., plasma velocities).

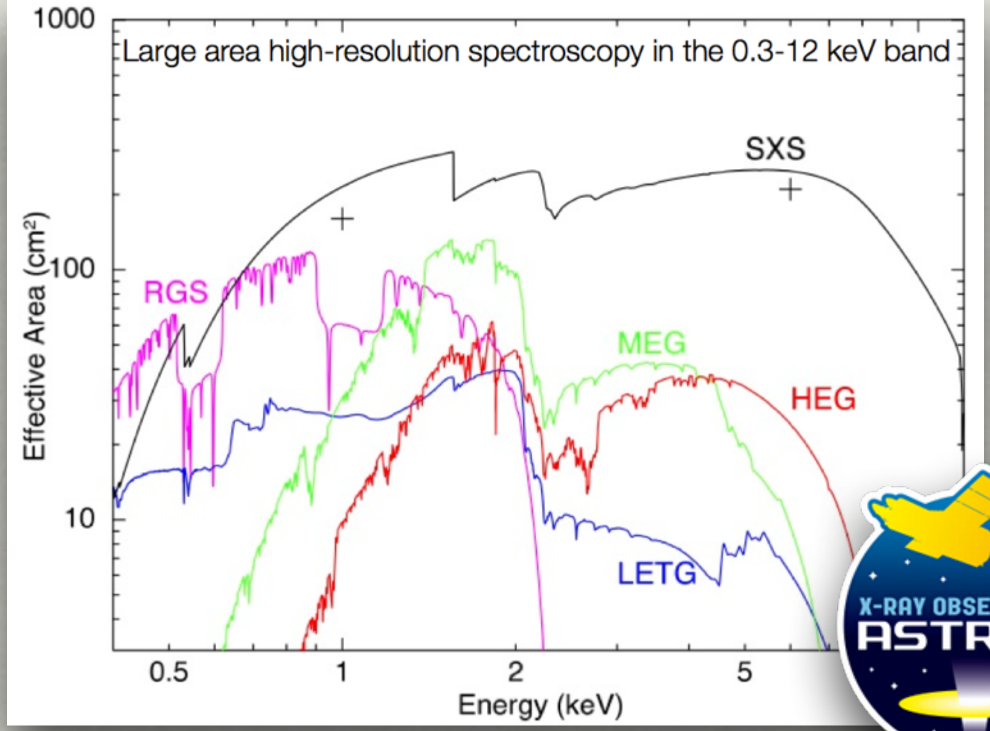
Improved atomic data

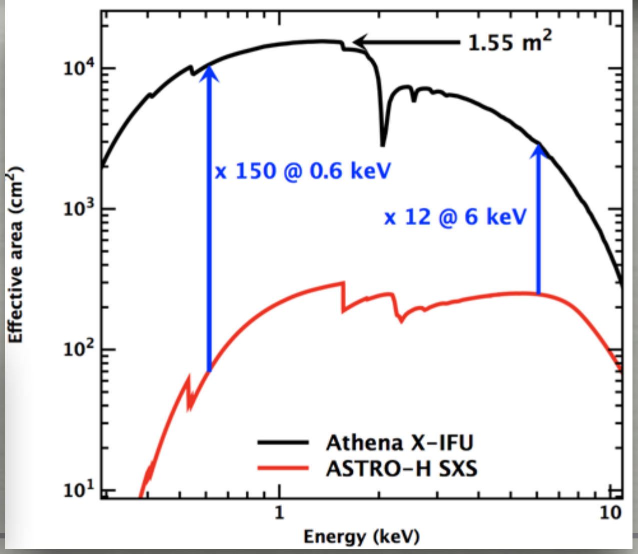
- ESA-funded project by FAU Erlangen-Nürnberg and Harvard Smithsonian CfA to improve data in AtomDB with lab measurements (LLNL, USA) and modelling.
- Measure & calculate line energies, derive uncertainties.
- Update database and provide software interface to common tools.

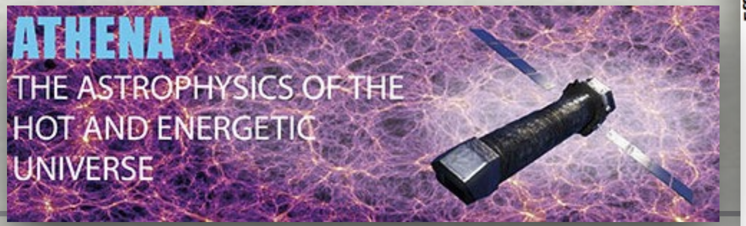


Improved instrumentation

- Fast, sensitive optical spectrographs becoming more generalised ➟ opportunities to study winds on timescales of seconds.
- ***Very soon***: ASTRO-H SXS microcalorimeter: 0.3–12 keV, <7 eV resolution, large effective area ➟ *new era of X-ray line diagnostics!*
- **Late 2020's**: Athena X-ray Integral Field Unit with Transition Edge Sensors (TES), 2.5 eV resolution, much higher effective area.







The Future

Better Wind Models

Better X-ray Source Models

Better spectral models

Fast Opt. / UV / IR spectroscopy

High-resolution X-ray spectra

Some answers; many new questions!

Thank you! Questions?