Chandra high-resolution X-ray spectroscopy: shocking view on massive stars

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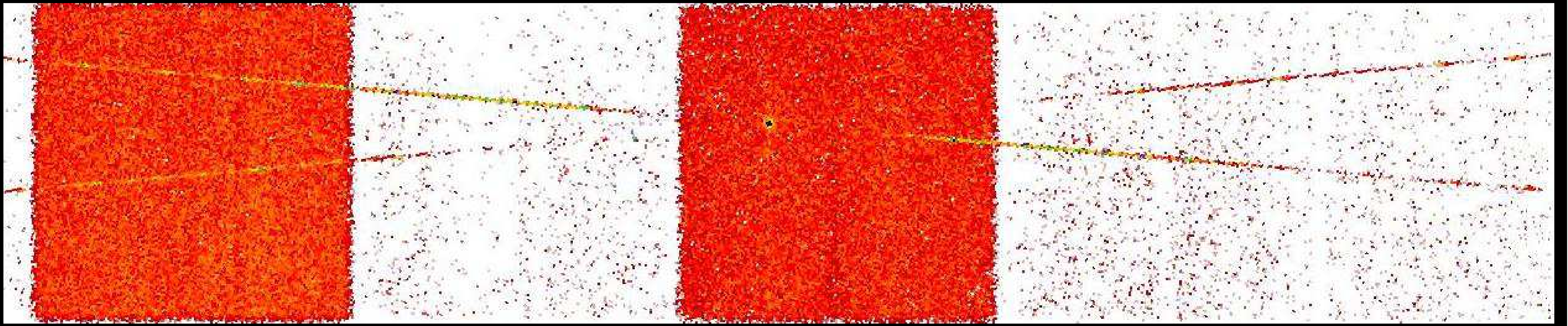
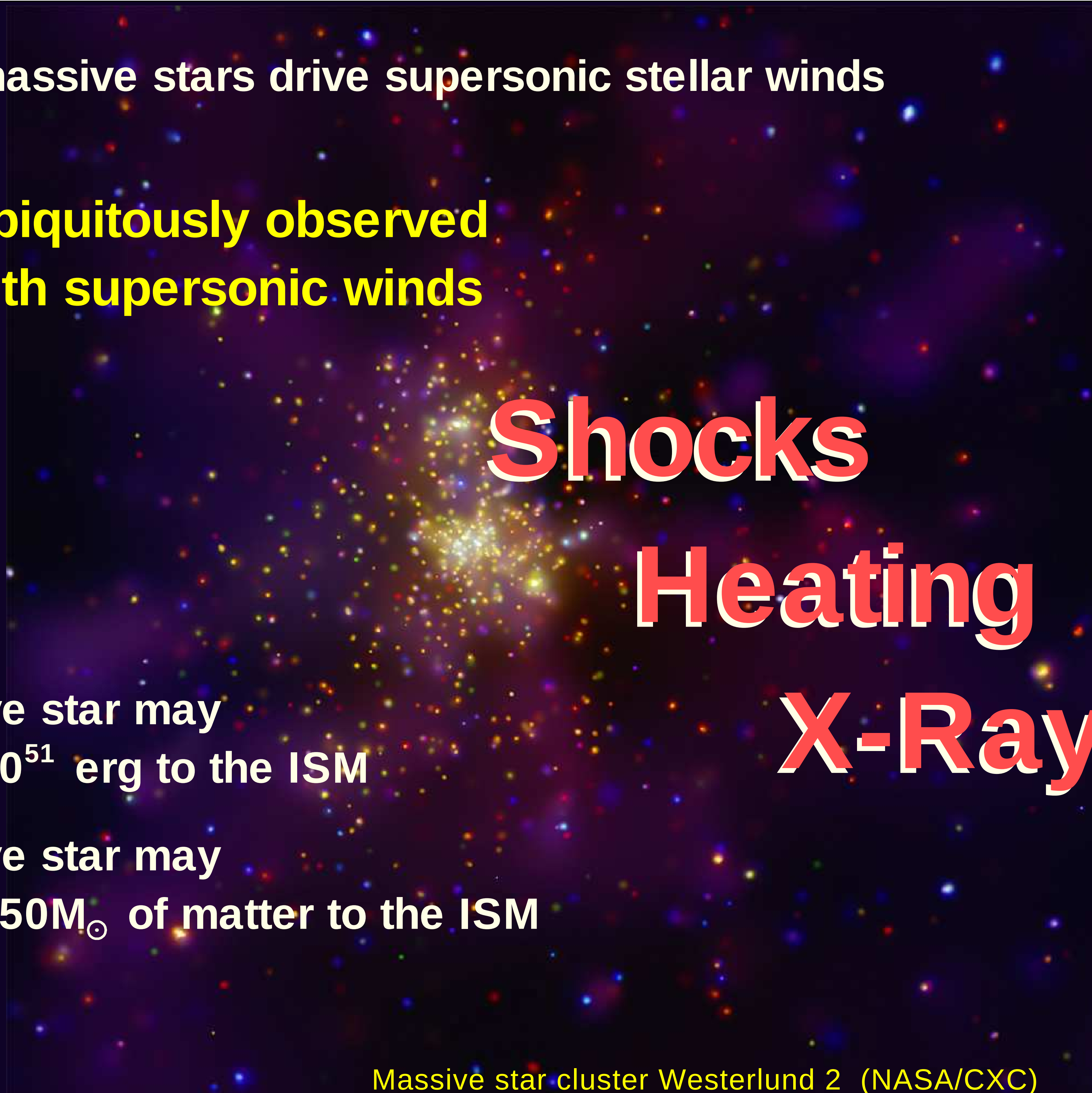


ACIS Raw Detector Image of O-type supergiant ζ Puppis

Chandra Science for the Next Decade
Chandra Workshop 2016

Hot massive stars drive supersonic stellar winds

X-rays are ubiquitously observed from stars with supersonic winds



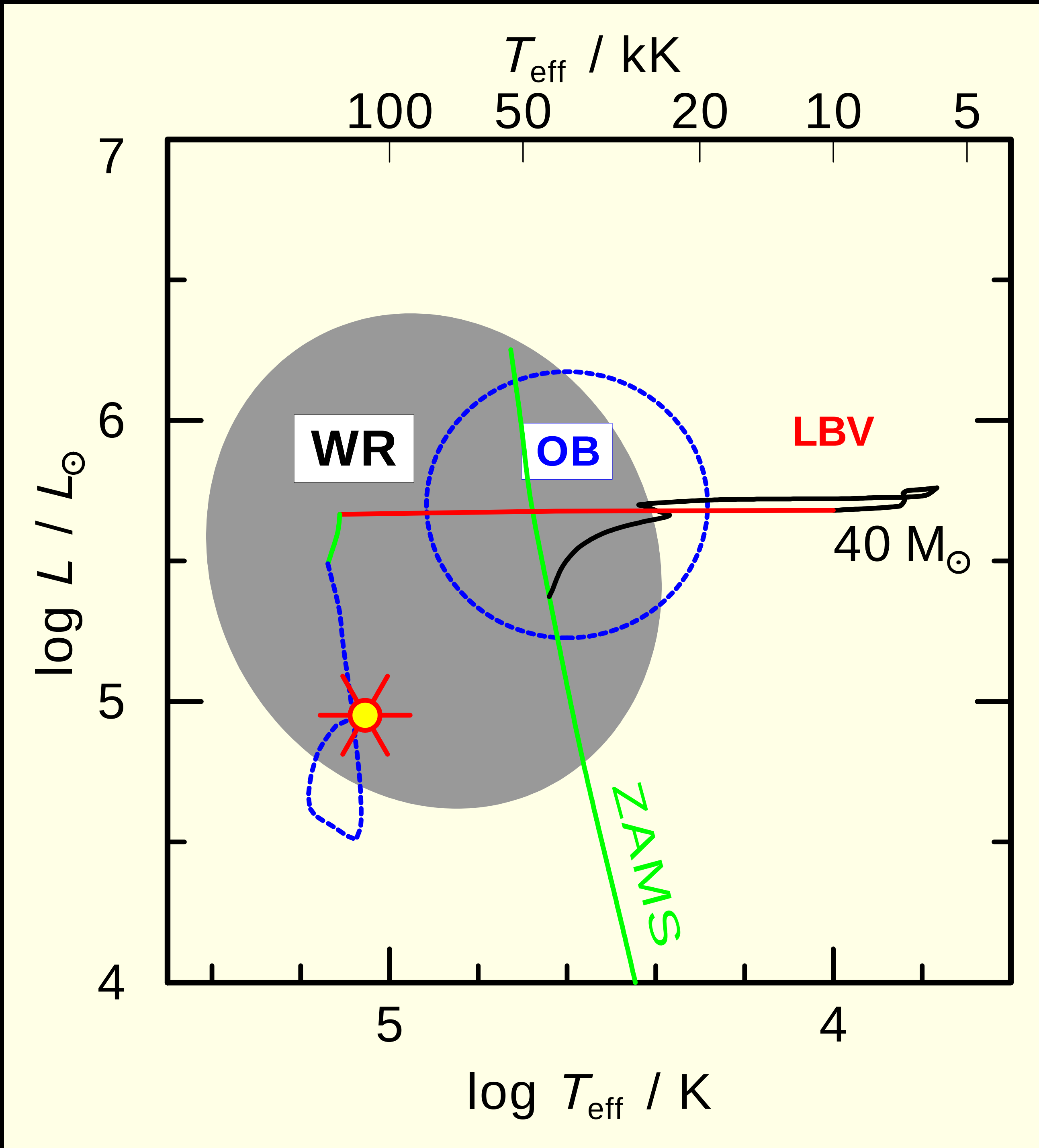
Shocks

Heating

X-Ray

- **a massive star may deposit up to 10^{51} erg to the ISM**
- **a massive star may deposit up to $150 M_{\odot}$ of matter to the ISM**

Massive star cluster Westerlund 2 (NASA/CXC)



Mass removal by wind drives the evolution

- OB → (LBV, RGS) → WN → WC → WO
- Winds are getting denser and more enriched

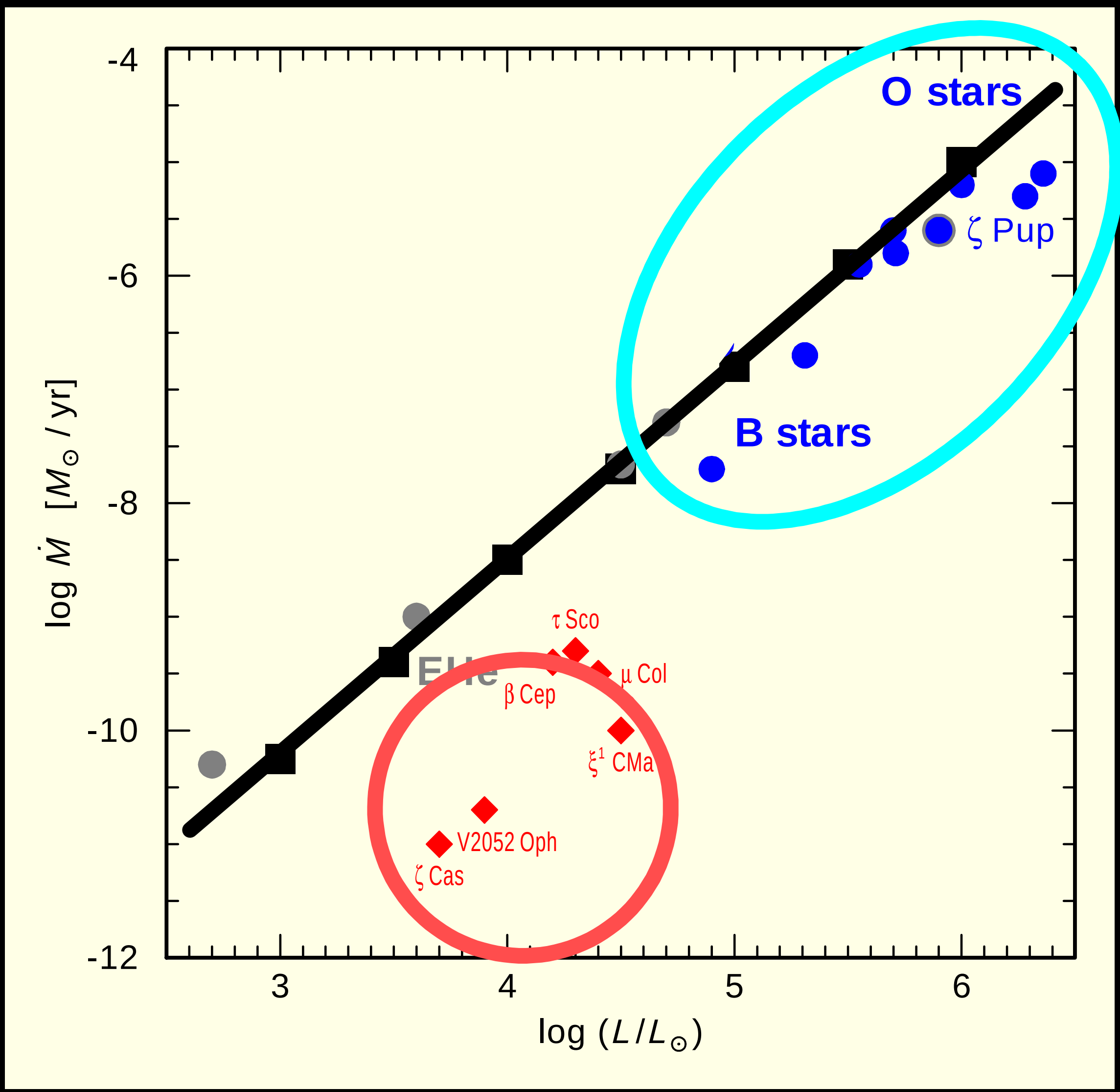
X-rays: elucidate all stages of massive star lives

Chandra's guided tour through the upper part of the HRD

OB2 NASA/CXC/SAO/J.Drake et al,

Stop I. Main sequence OB stars & the Weak Wind Problem

OB-dwarfs - the most common type of massive stars!



$\dot{M}_{obs}$ derived from optical/UV is 100 lower than predicted $\dot{M}_{theory}$

Rosat observations of B stars
EM(X-ray) > EM(optical/UV)
(Drew+ 94, Cassinelli+ 94)

- **Do X-rays quench stellar winds?**
- **Is the major part of the wind very hot T> 10MK?**

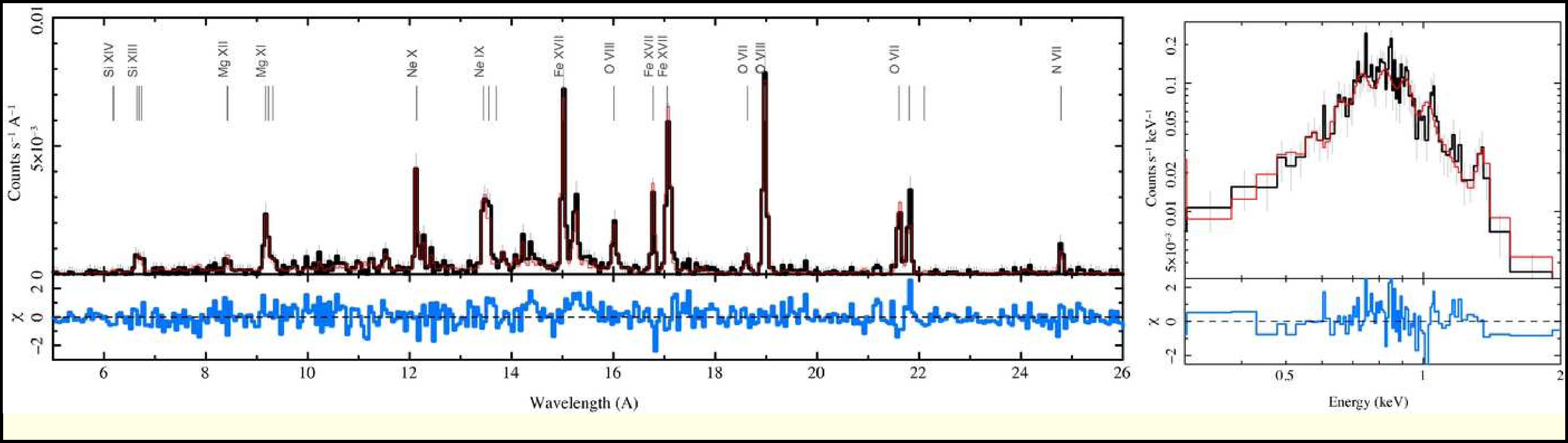
Chandra grating spectra can help to answer these fundamental questions about stellar winds

Chandra grating spectra of main sequence O stars

ζ Oph (O9.2IV), μ Col (O9.5 V), AE Aur (O9.5 V), σ Ori AB (O9.5 V + B0.5 V): similar X-ray grating spectra

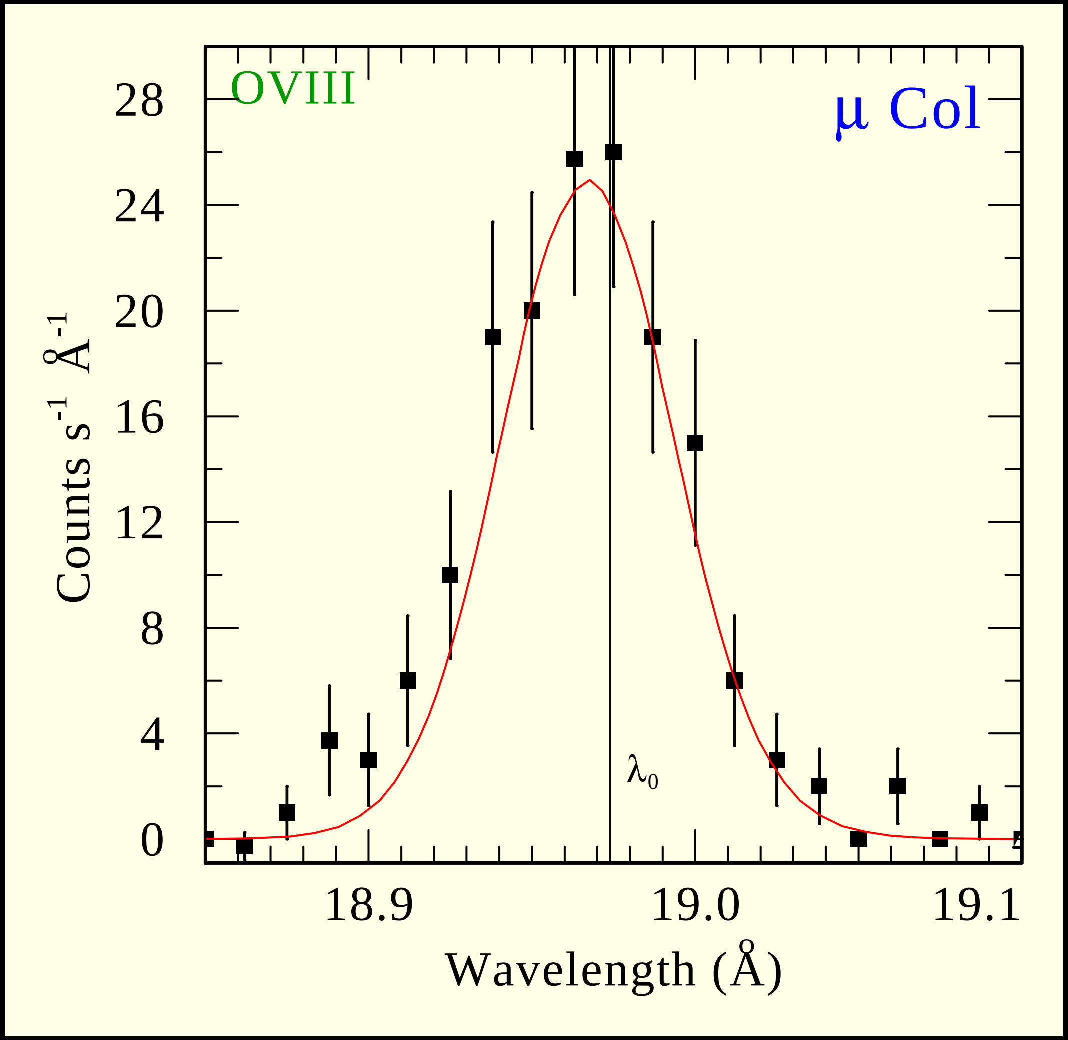
Spectral diagnostics: line ratios in He-like ions, line shapes, evidence of wind absorption:

- X-rays are generated very close to the photosphere
- Hot plasma occupies large volume
- Hot plasma expands supersonically



μ Col (O9.5V) Chandra & Suzaku (Huenemoerder+ 12)

Lines profiles from high resolution LETGS spectrum of μ Col and our 3-D wind model fit (Huenemoerder+ 12)



$\dot{M}_{\text{X-ray}}$ from X-ray spectra

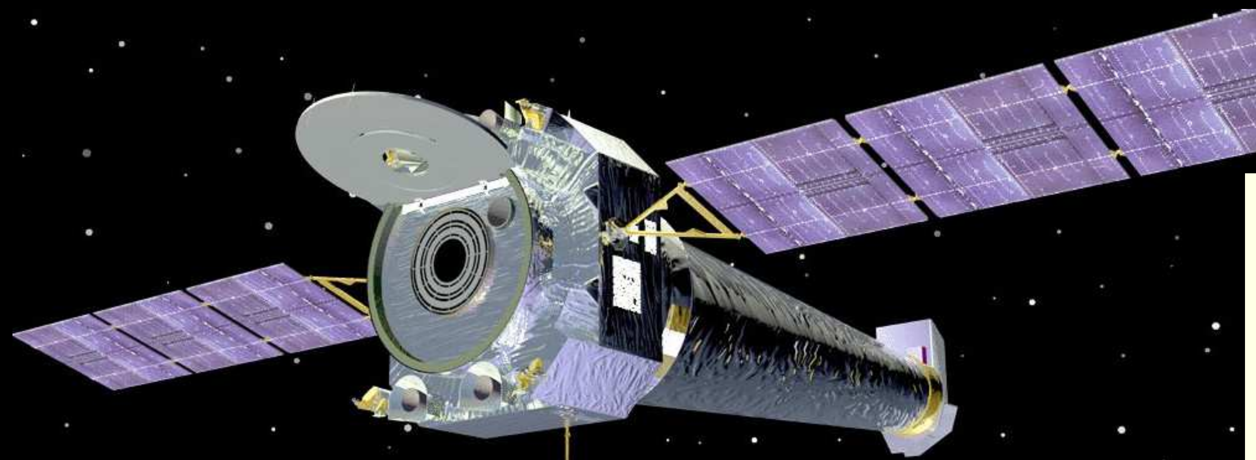
$$\log \dot{M}_{\text{X-ray}} = -8.7\,[M_\odot/\text{yr}]$$
$$\log \dot{M}_{\text{UV}} = -9.5\,[M_\odot/\text{yr}]$$

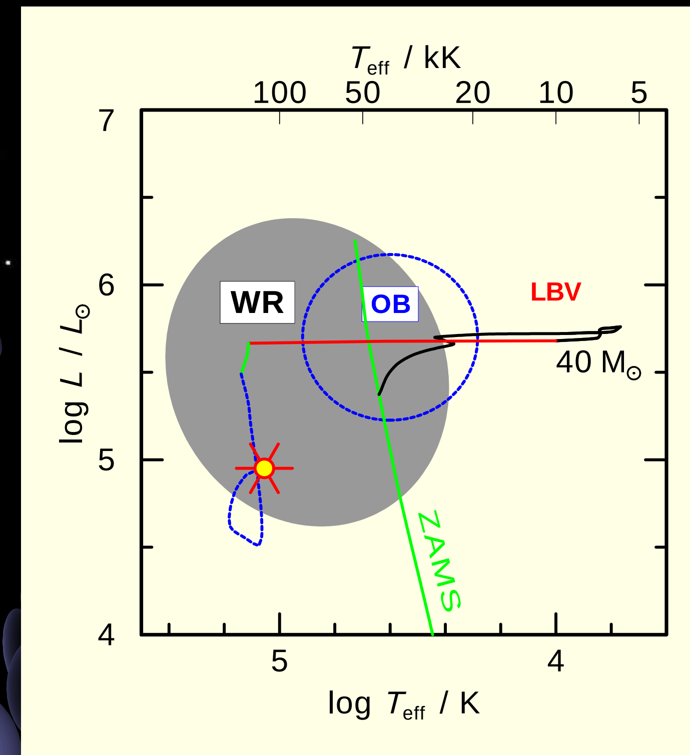
Most of the wind matter is hot!

velocity $_{\text{hot gas}}$ > velocity $_{\text{cool gas}}$
(1600 km/s > 1200 km/s)

Chandra chandges stellar wind paradigm: winds of OB dwarfs are predominantly hot (e.g. Lucy'12).

Stop II. OB (super)giants and their X-ray lines



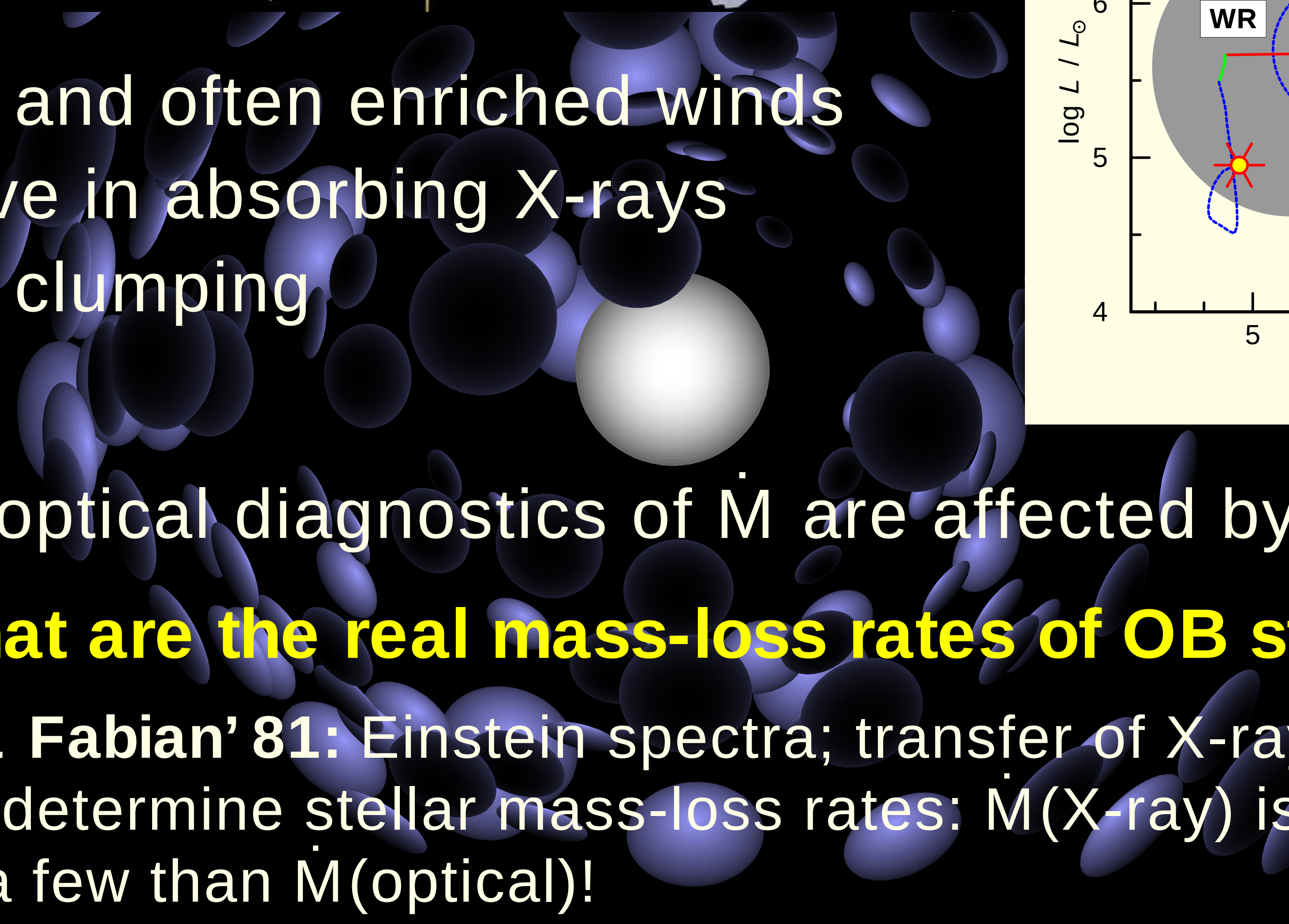


- Strong and often enriched winds
- Effective in absorbing X-rays
- Strong clumping

UV and optical diagnostics of $\dot{M}$ are affected by clumping.

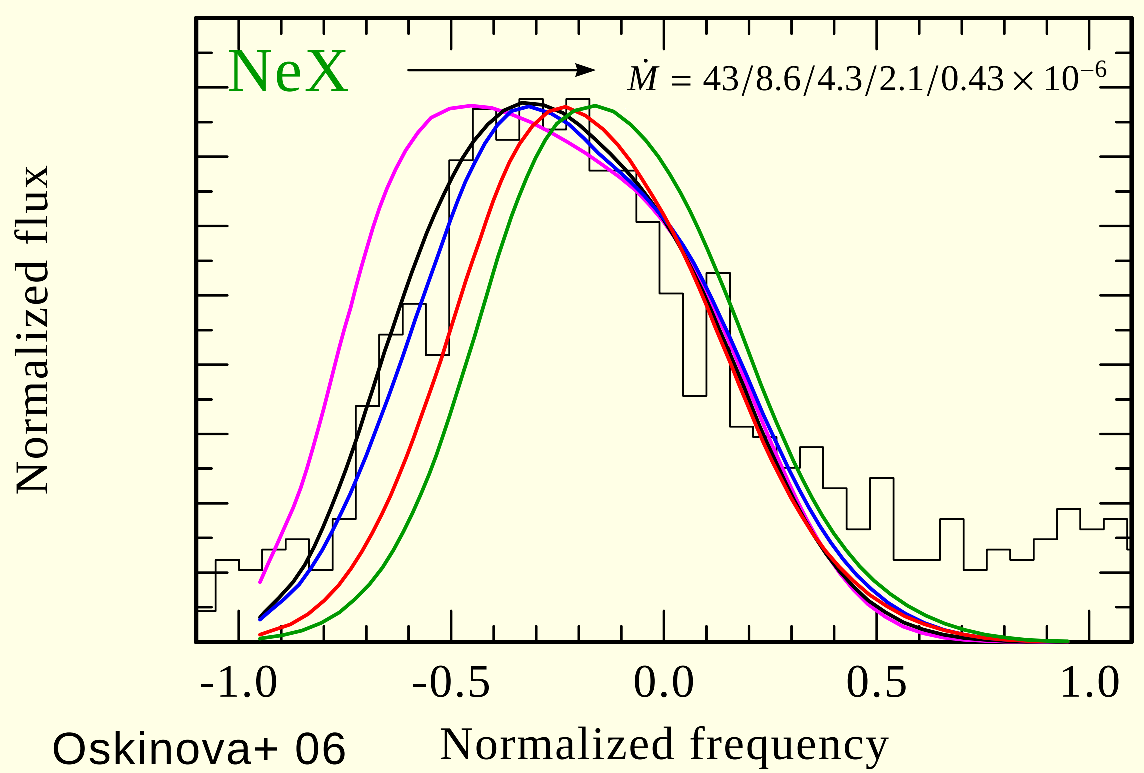
What are the real mass-loss rates of OB stars?

Stewart & Fabian' 81: Einstein spectra; transfer of X-rays through a wind to determine stellar mass-loss rates: $\dot{M}$(X-ray) is lower by a factor of a few than $\dot{M}$(optical)!



our 3-D model of clumped stellar wind

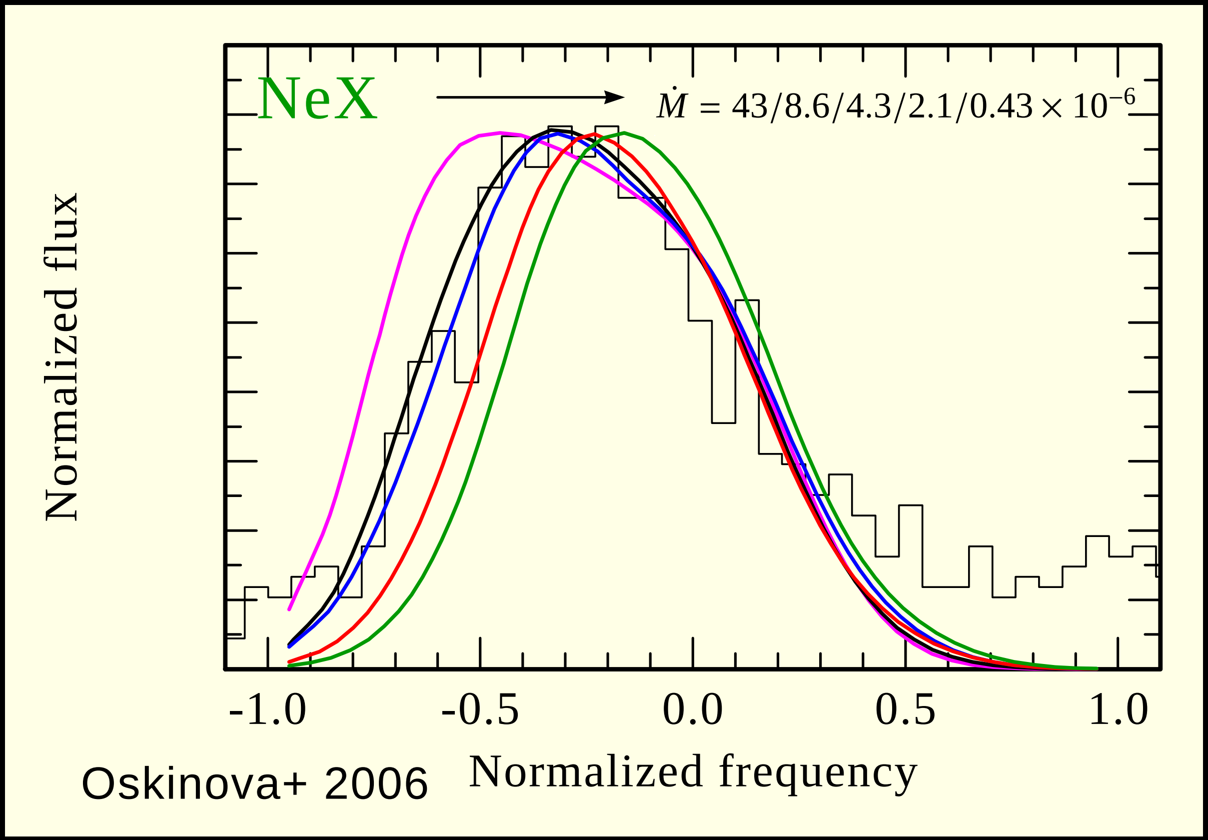
X-ray emission line shapes probe wind density



Oskinova+ 06

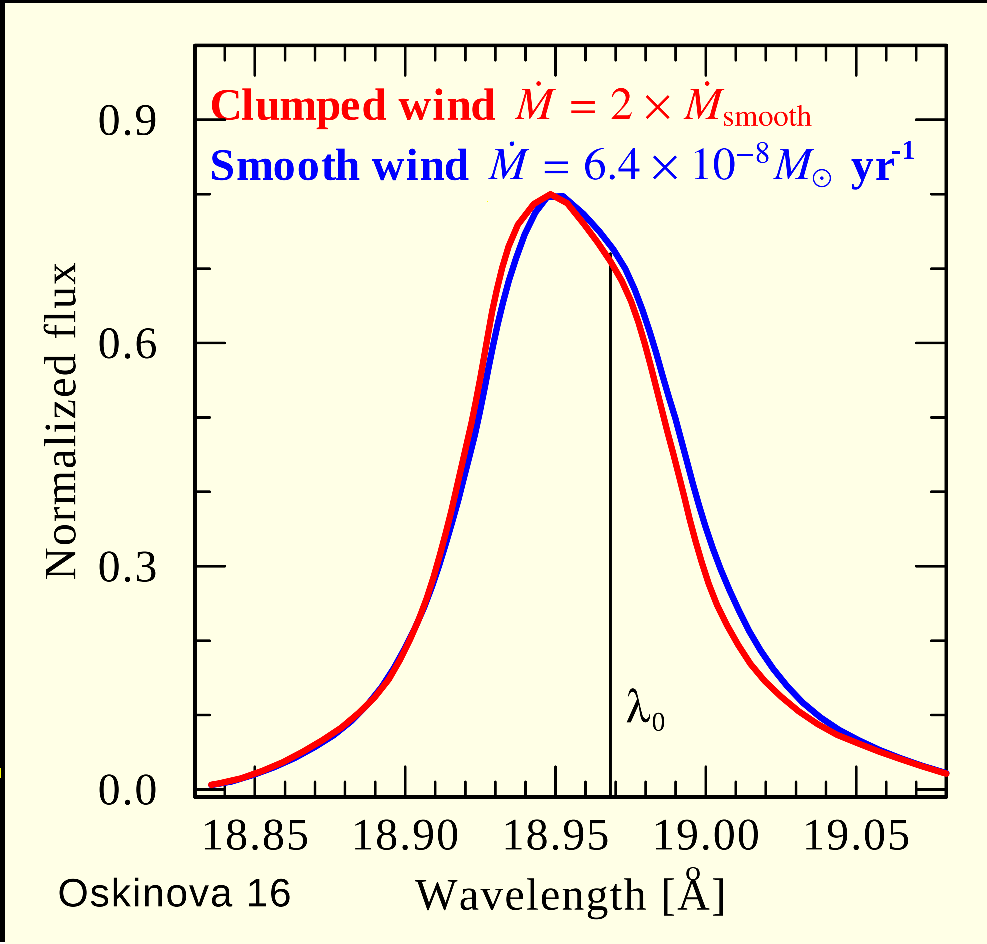
Comparison of observed NeX line in spectrum of ζ Pup with model lines -> **X-ray line shape and flux are sensitive to mass-loss rate $\dot{M}$** (Macfarlane+ 91, Oskinova+ 06)

HETGS spectra of OB-supergiants



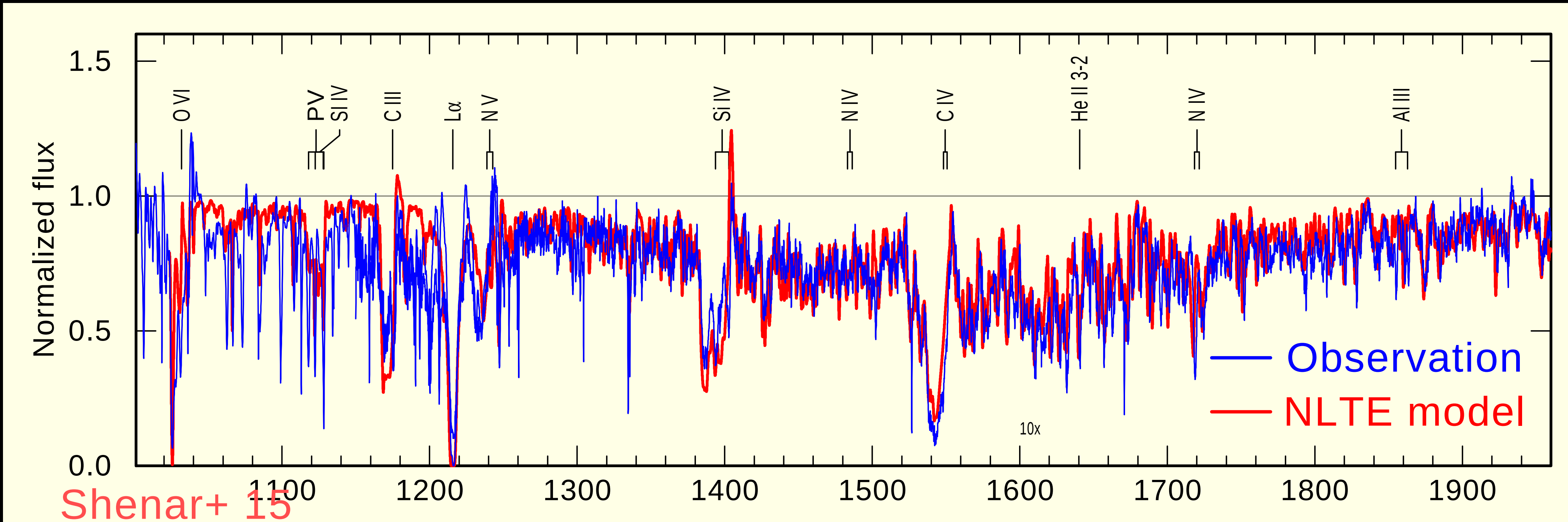
Comparison of observed NeX line in spectrum of ζ Pup with model lines -> **X-ray line shape and flux are sensitive to Ṁ** (Oskinova+ 06, Cohen+ 09)

But! line shape and flux are also sensitive to: **clumping, velocity field, abundnaces, wind geometry, hot plasma distribution, resonant scattering, cool wind ionization, etc…**



Model OVII lines assuming different Ṁ

Breaking degeneracy: non-LTE models with X-rays

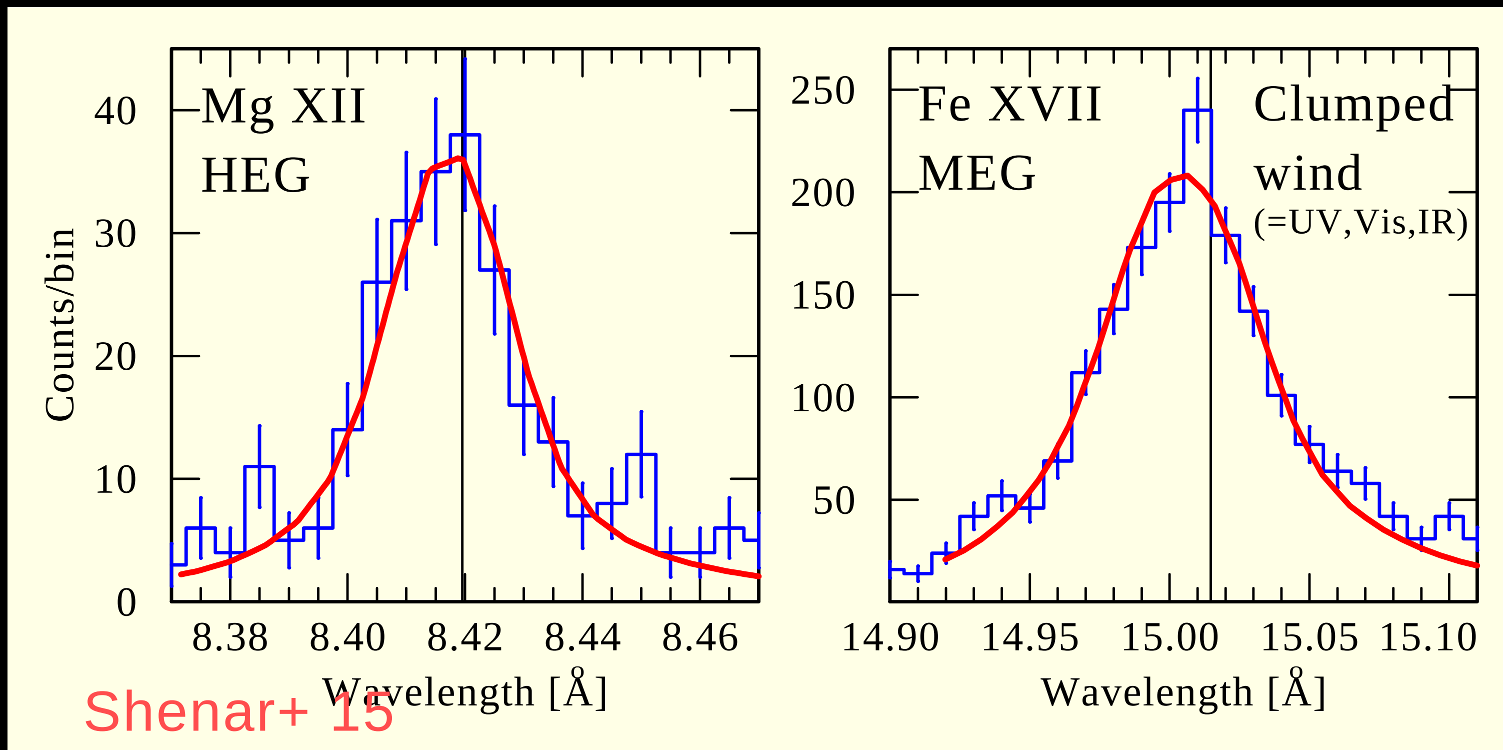


Shenar+ 15

Analysis of UV, optical, IR spectra with non-LTE wind model **PoWR: Teff, R, M, abundances, cool wind velocity and $\dot{M}$**

- **PoWR model** includes effect of X-rays on cool wind: Auger ionization
- The cool wind attentuates X-rays - only multiwavelength analysis delivers realistic wind paramters (v_W, $\dot{M}$).

Derived $\dot{M}$ well agree with theoretical predictions



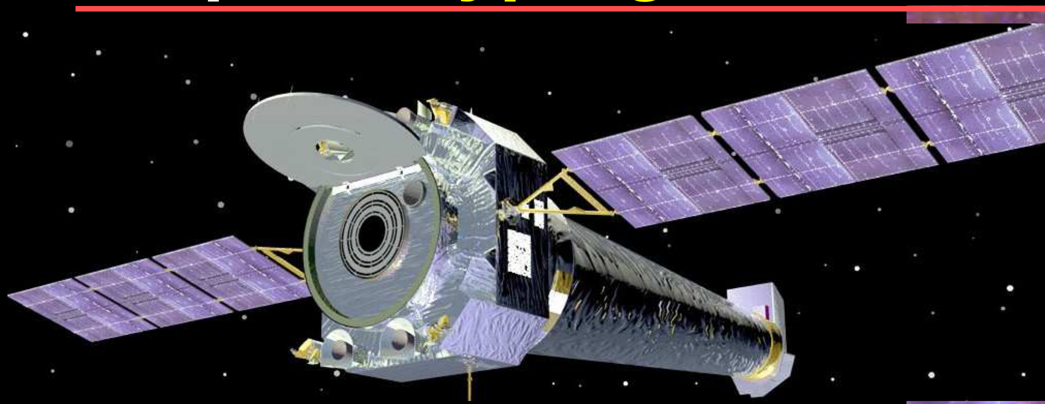
Observed vs model lines in an O-sta δ Ori: large CXO (PI Corcoran)

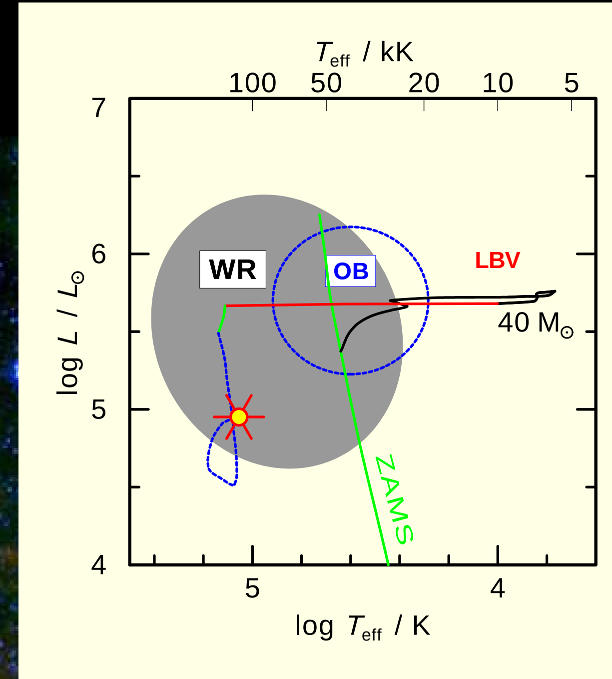
• Model lines: **2.5-D radiative transfer models in inhomogeneous stellar wind**

• Consistent wind parameters from modeling X-ray and UV/optical spectra: deriving realistic mass-loss rates

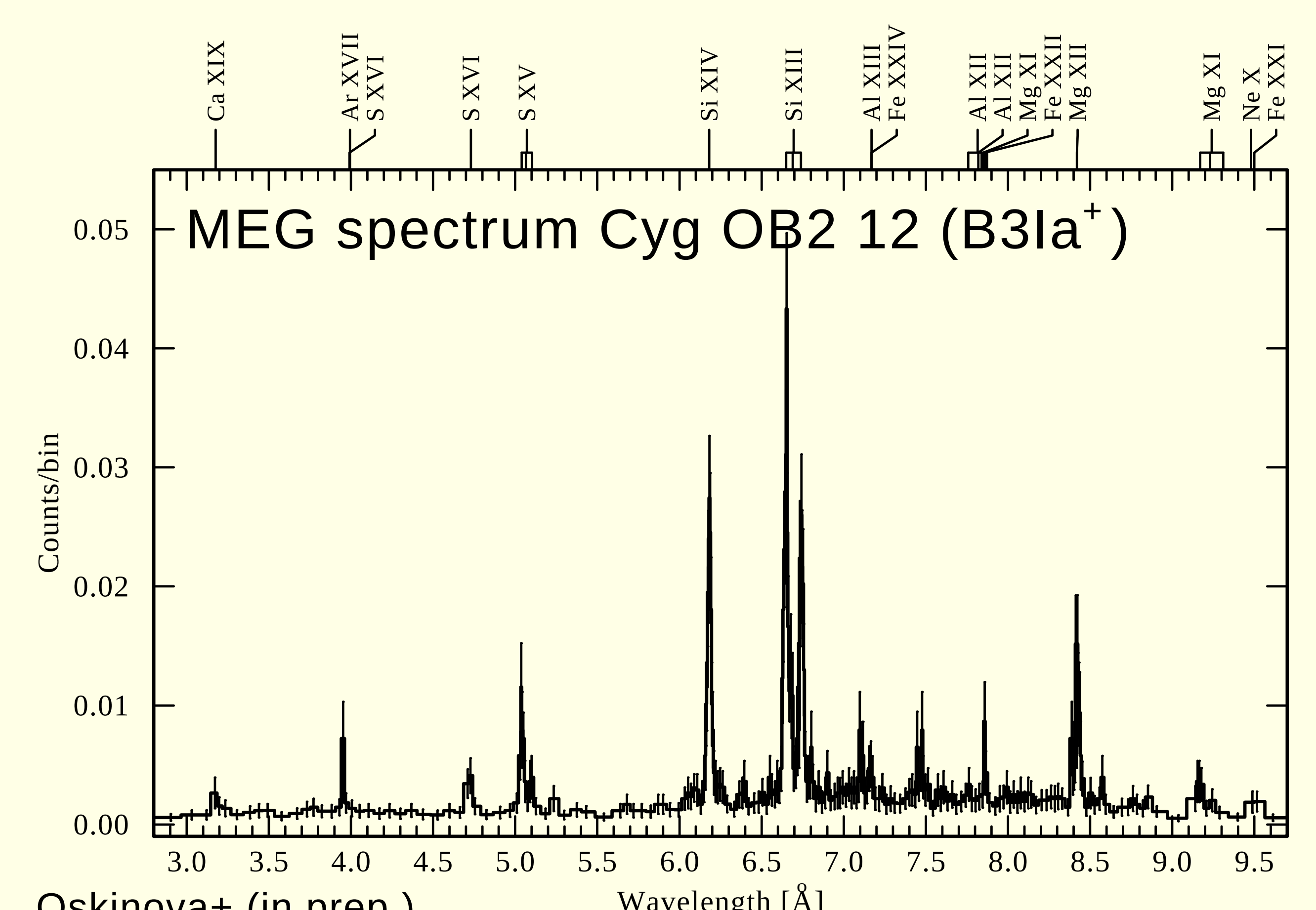
Community driven proposal ~1Ms to get the Legacy quality HETGS spectrum of an O star (PI Waldron) ζ Pup: much needed!

Stop III: Hypergiants & LBVs





Hypergiants and LBVs are X-ray dark



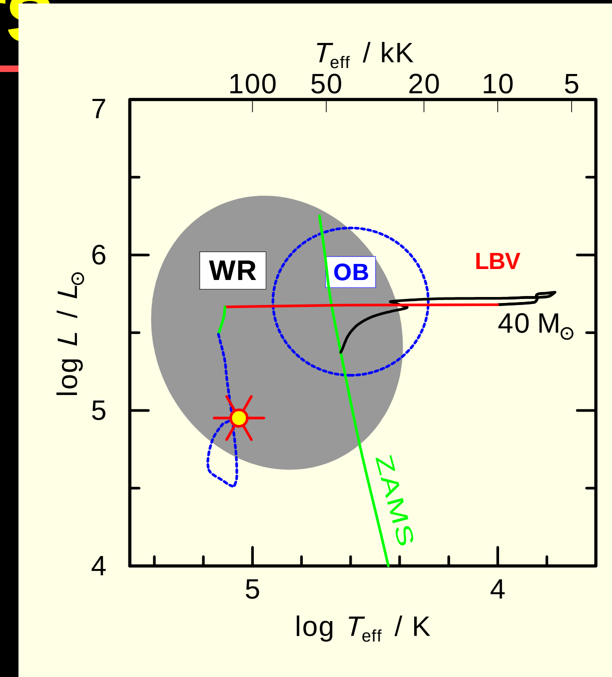
Oskinova+ (in prep.)

unless in a binary

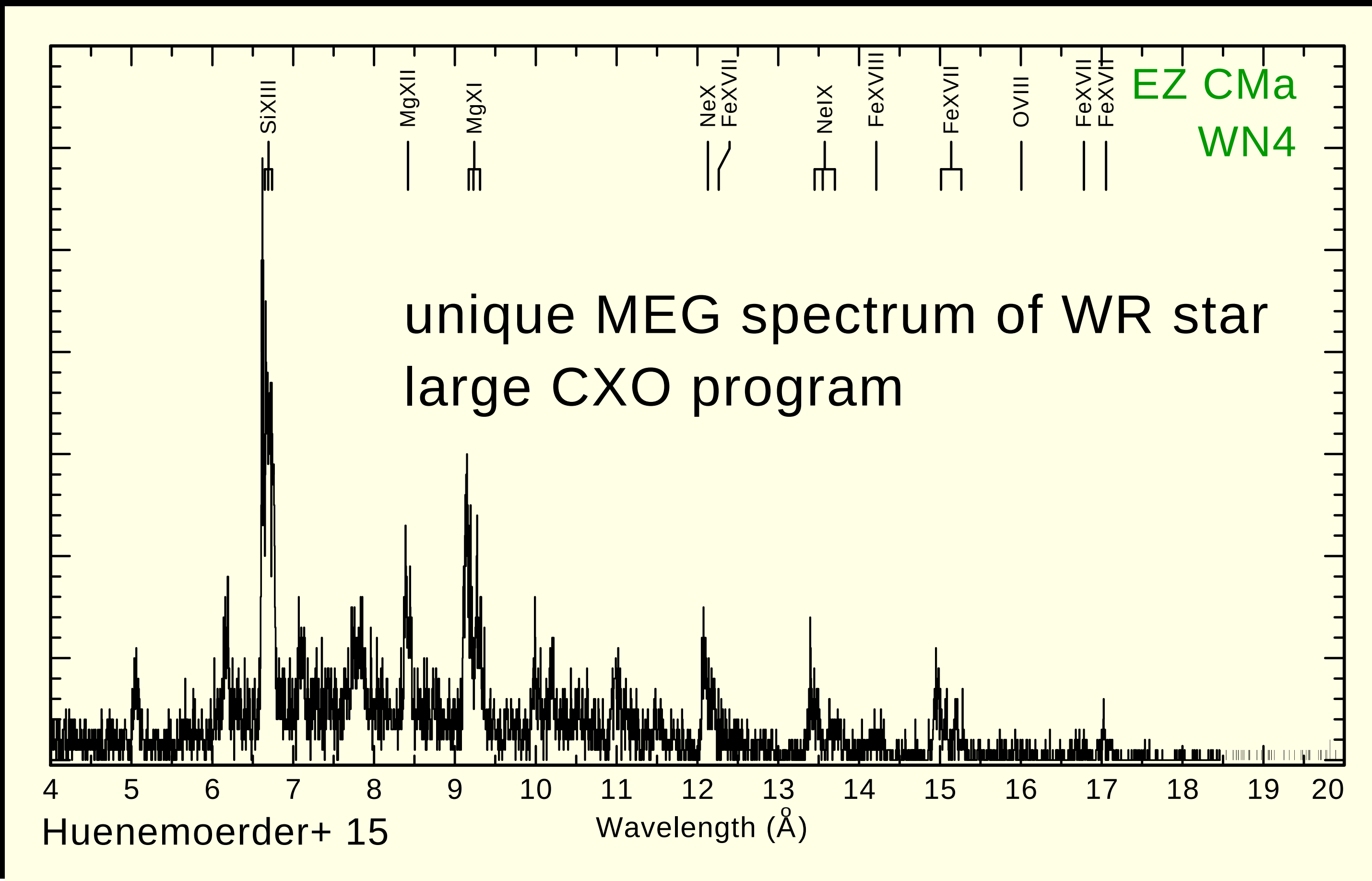
HETG spectrum of Cyg OB2 12
non-LTE wind analysis
previous XMM observations
HST observations

Colliding wind binary
primary mass M>120M$_{\odot}$

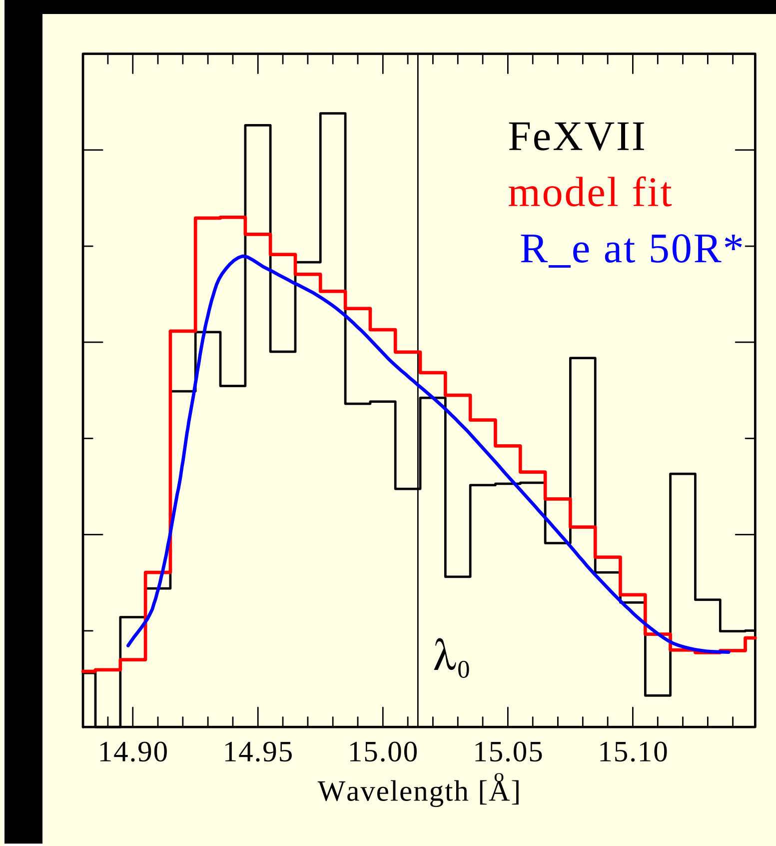
Stop IV: Wolf-Rayet stars



- Wolf-Rayet stars - final evolutionary stage
- Metal enhanced (e.g. Na X-ray lines)
- very strong dense winds
- how X-rays are produced? (Gayley' 16)

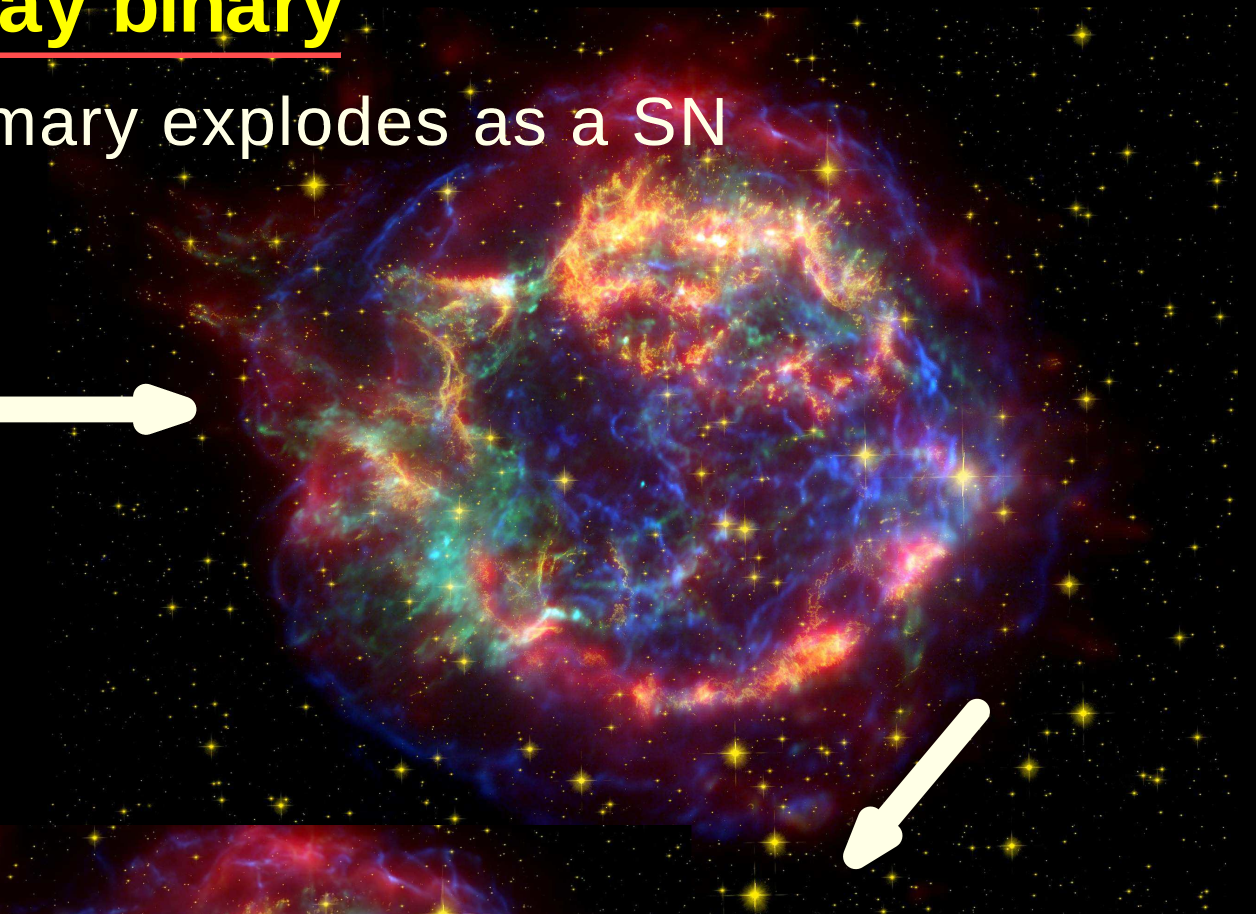


Broad skewed lines: opaque wind

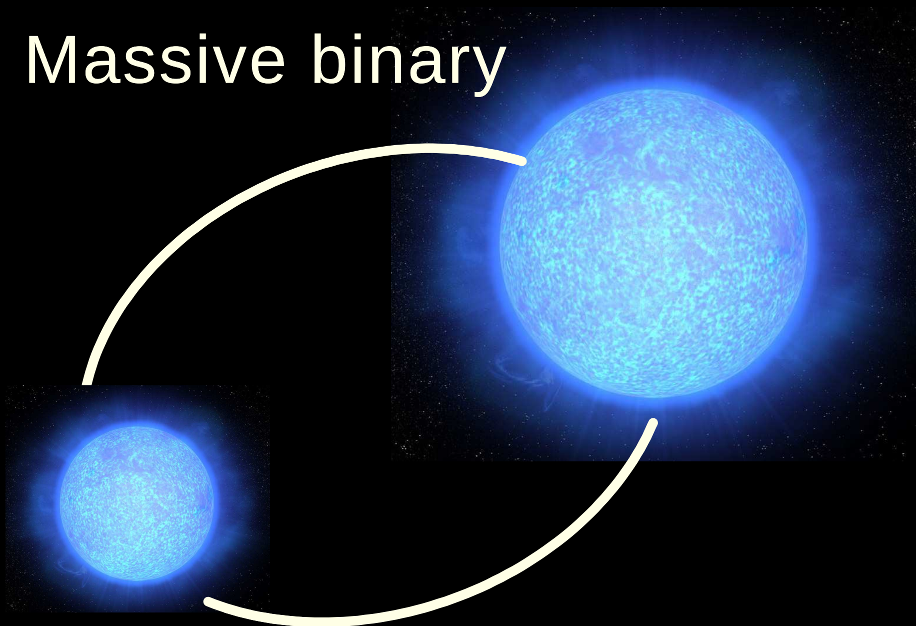


Final stop: high-mass X-ray binary

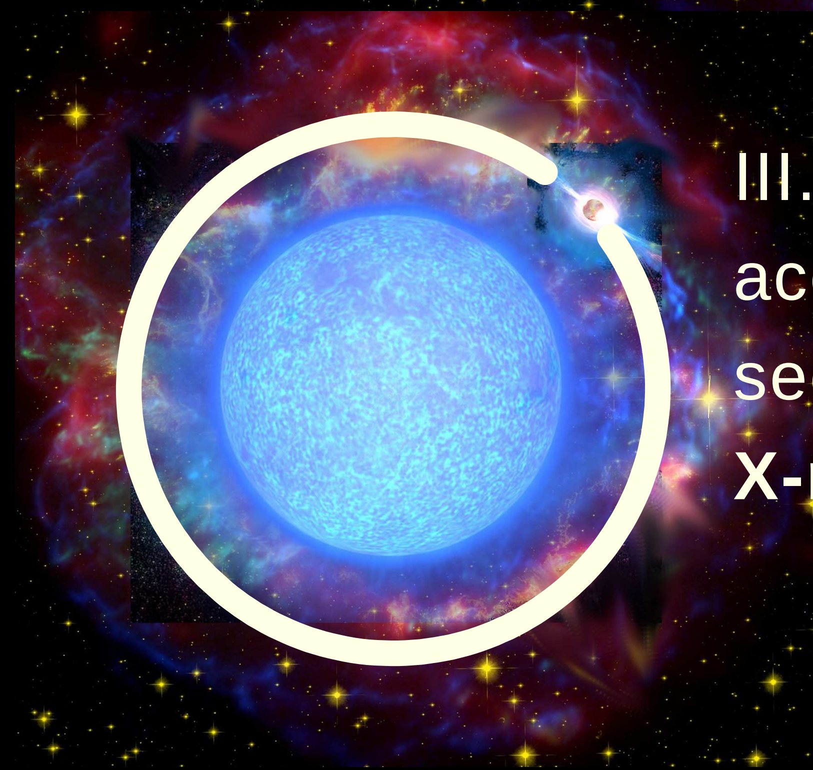
II. Primary explodes as a SN



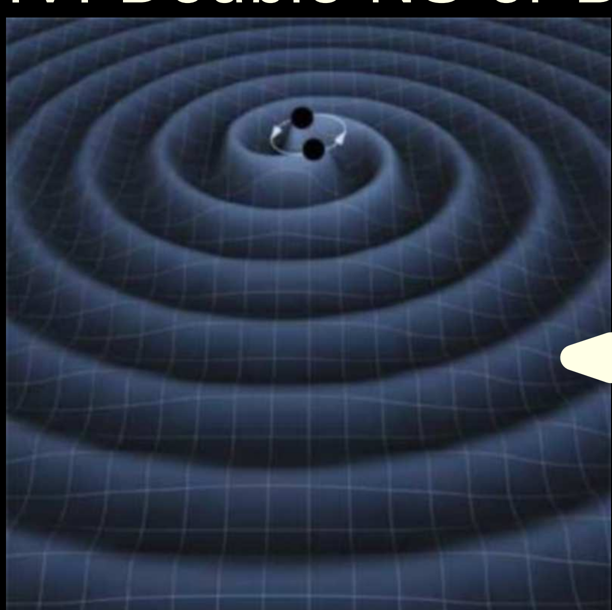
I. Massive binary



III. Neutron star accretes secondary’s wind: **X-ray pulsar**



IV. Double NS or BH

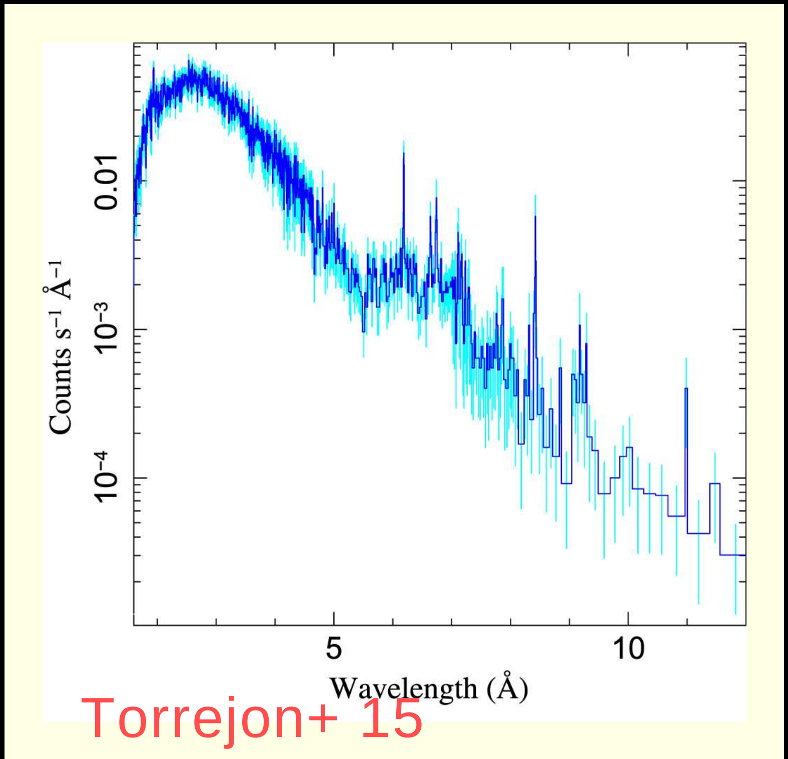


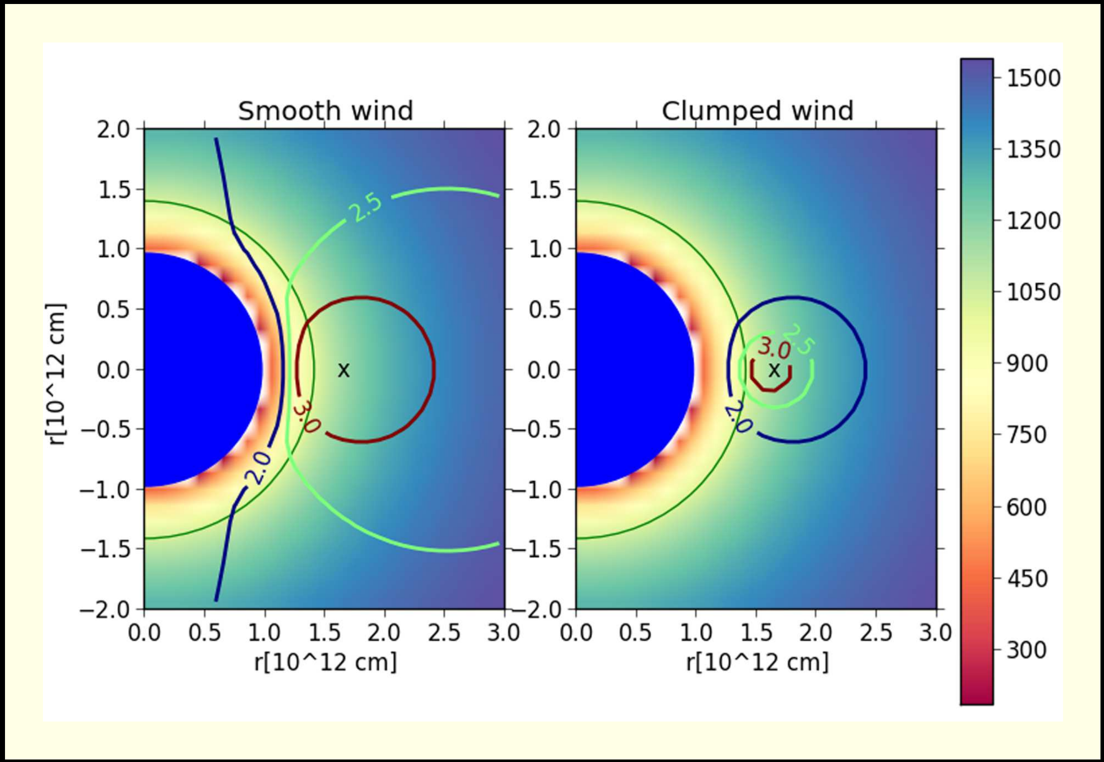
Sealed by Chandra: accreting X-ray pulsar within a SNR

SXP 1062: young long period X-ray pulsar (10-20 kyr) in the SMC

Image: CXO & optical   (Henault-Brunet+ 12, CXO Large program)

Using neutron stars to probe supergiants winds



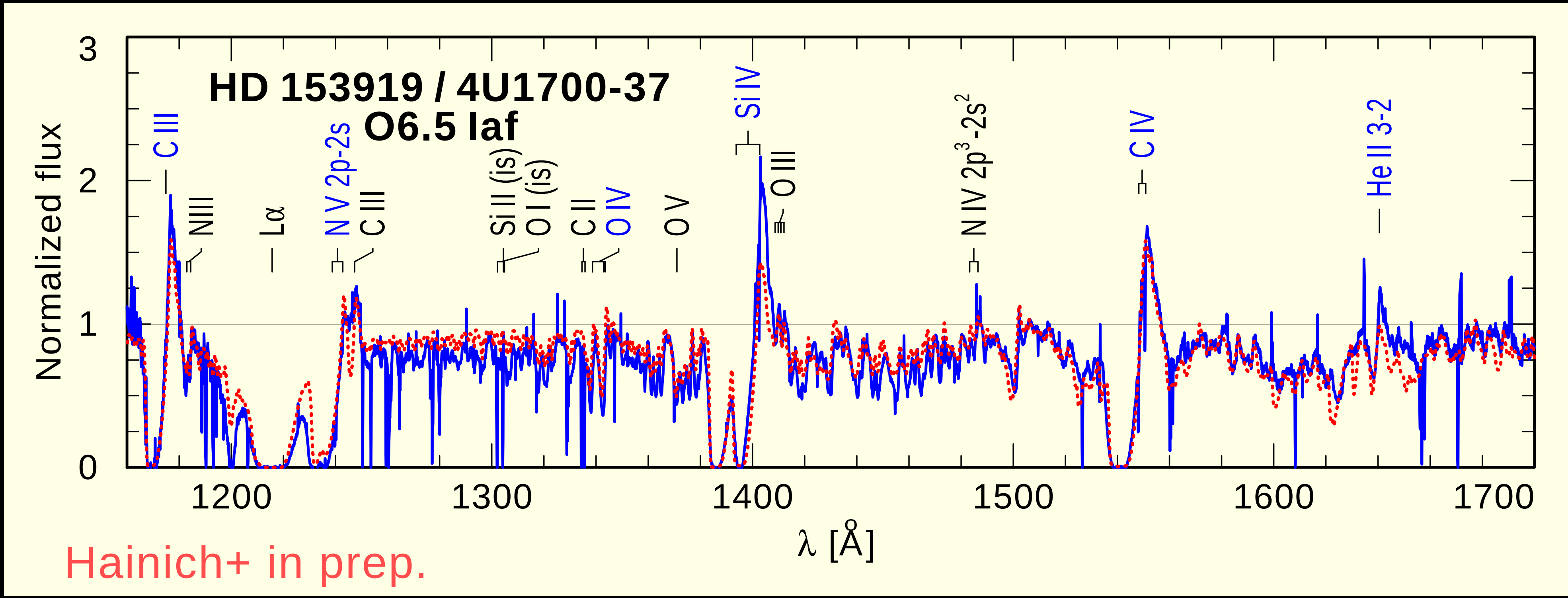


HETGS spectra of QV Nor (4U153852), B0I + NS embedded in stellar wind (a_{NS} <1.4 R*).

- Monitoring around eclipse: FeK is partially eclipsed → formed close to the NS
- 3-D wind simulatins of X-ray variability - stellar wind is strongly clumped at < 1.2 R*

Clumping affects photoionized region (Oskinova' 12)

Simultaneous UV-ray observations of massive donors



Simultaneous Hubble Space Telescope and X-ray (Swift and Chandra) survey of HMXBs

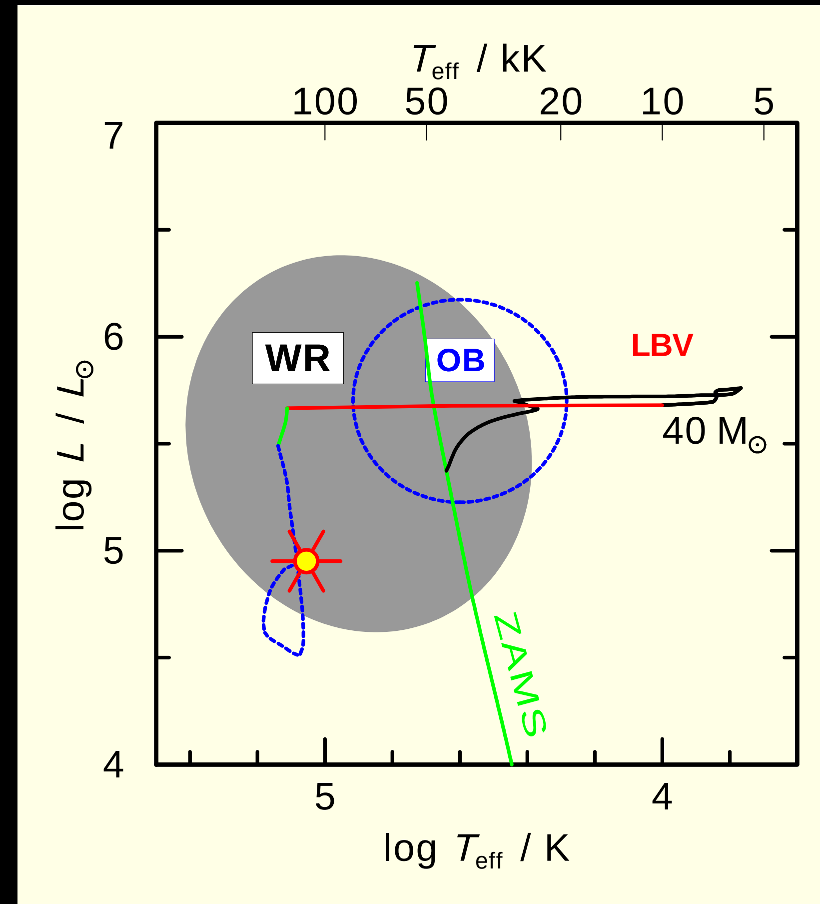
• Stellar wind spectrum and model fit: HST STIS strictly simultaneous with Chandra (DDT time).

• Stellar spectrum is obtained during flare: X-rays illuminate but do not quench the wind

X-rays observations of massive stars are indispensable

neXt

CHANDRA SCIENCE
FOR THE NEXT DECADE



- **Long exposures** for single objects are requested
- **Monitoring observations** to probe wind dynamics
- **Joint observations** are requested to obtain a multiλ view

(...emotional appeal: we need UV spectrometer in space!)

- **Joint Chandra, XMM-Newton, Swift** observations!!