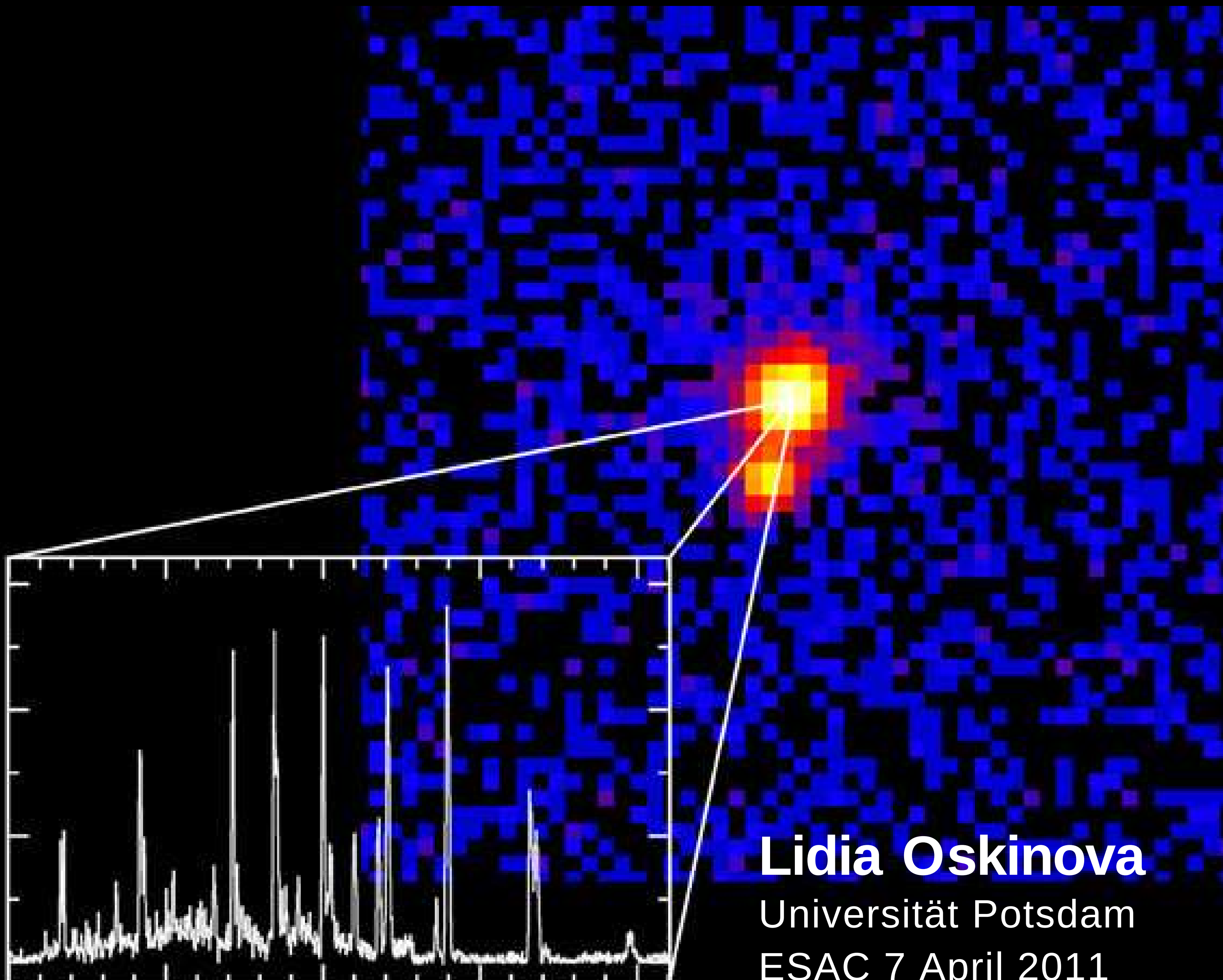
X-raying Hot Massive Stars



Lidia Oskinova
Universität Potsdam
ESAC 7 April 2011

Massive Stars and Stellar Winds

Initial mass $M_* > 15 M_\odot$

Main Sequence: OB-type

Fast evolution (~Myr) → trace star formation

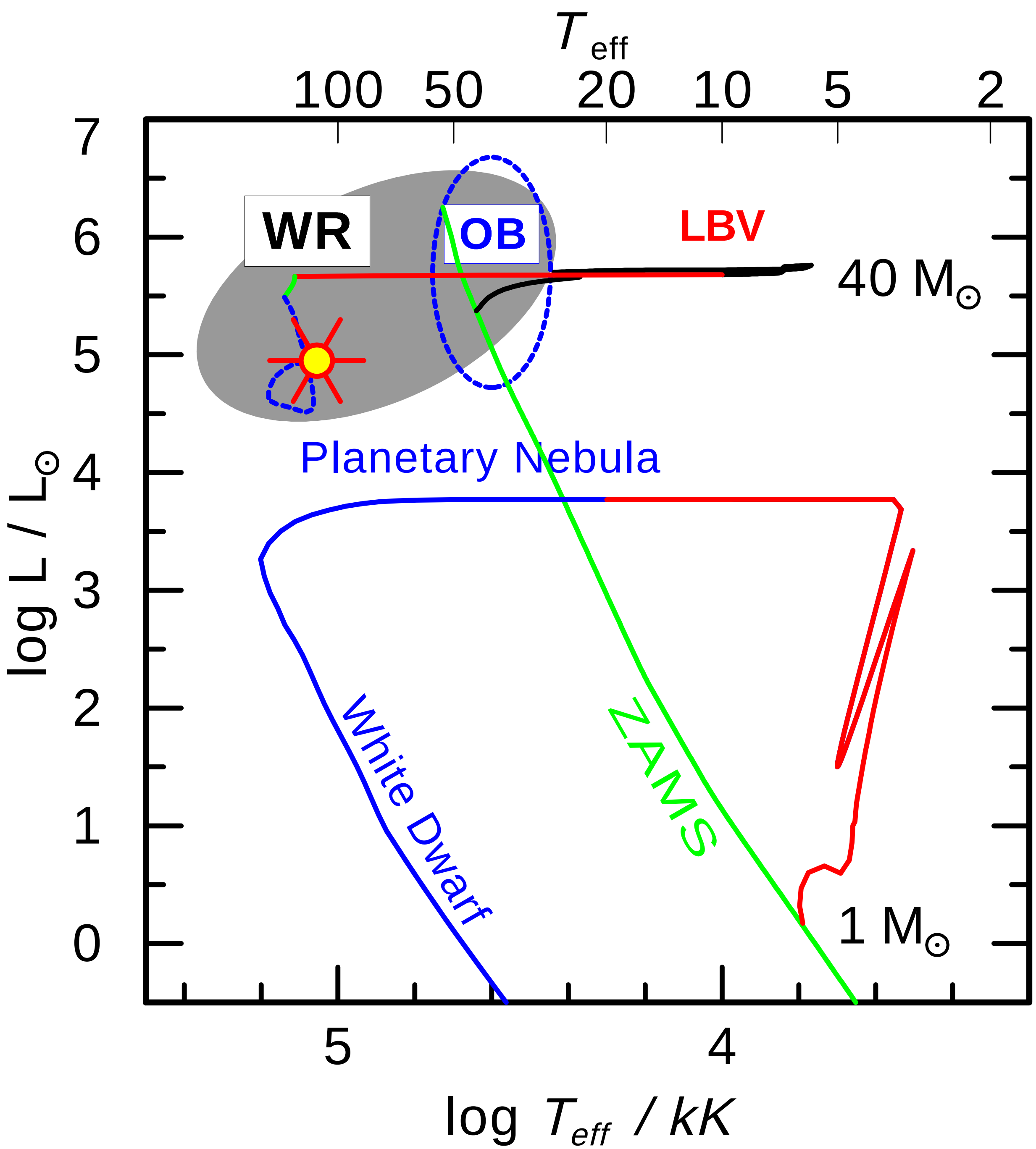
Hot. $T_{\rm eff} > 10\,000$ K $\longrightarrow$ high surface brightness

Photon momentum $\longrightarrow$ acceleration of matter

Radiative acceleration larger than gravitation $\longrightarrow$ supersonic **STELLAR WIND**

nasaimages.org

The evolution of (very) massive stars



Evolution ← stellar wind (!)

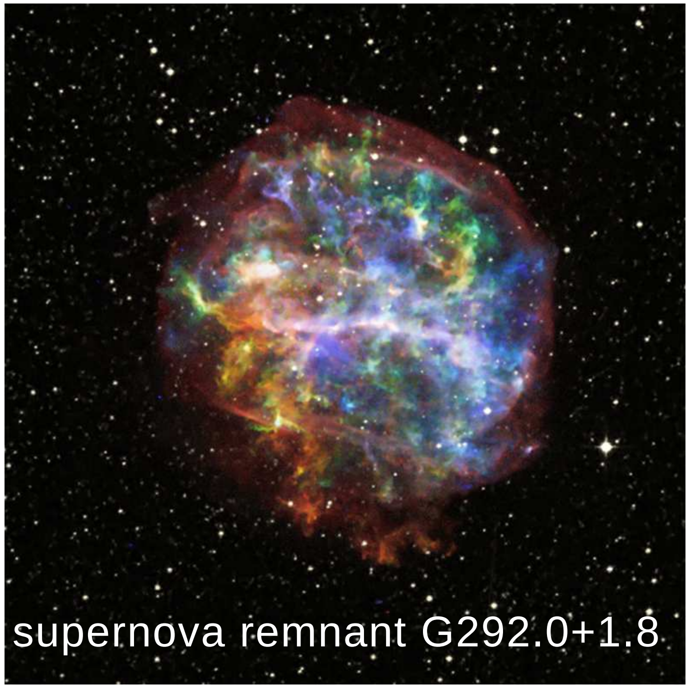
- O and B type stars
- Luminous Blue Variables
- Wolf-Rayet (WR) stars

According to dominant spectral lines

WN (nitrogen) →

WC (carbon) →

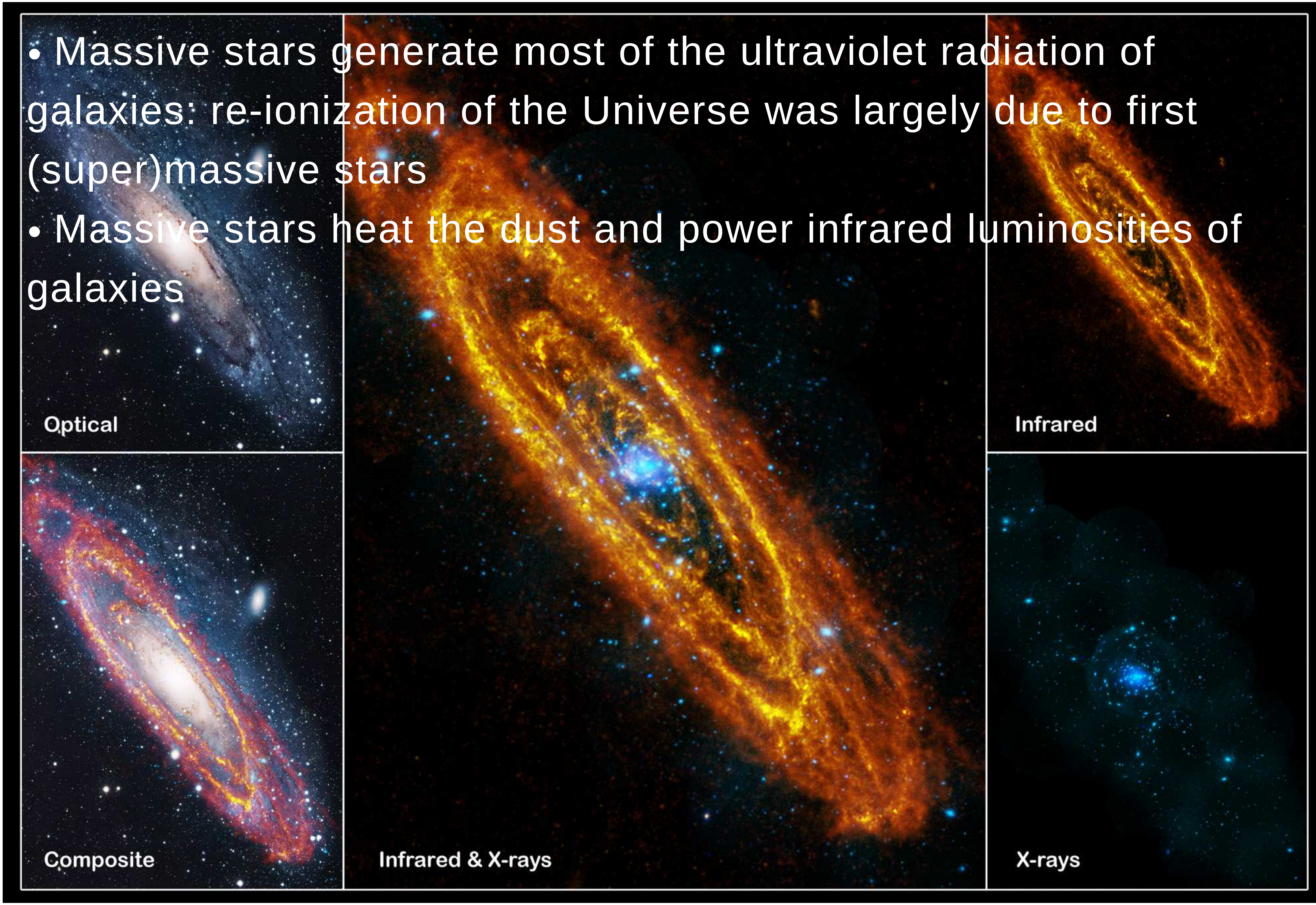
WO (oxygen) → SN



Massive stars: the cosmic engines

• Massive stars generate most of the ultraviolet radiation of galaxies: re-ionization of the Universe was largely due to first (super)massive stars

• Massive stars heat the dust and power infrared luminosities of galaxies



IR: ESA/Herschel/PACS/SPIRE/J. Fritz, U. Gent; X-ray: ESA/XMM-Newton/EPIC/W. Pietsch; optical: R. Gendler

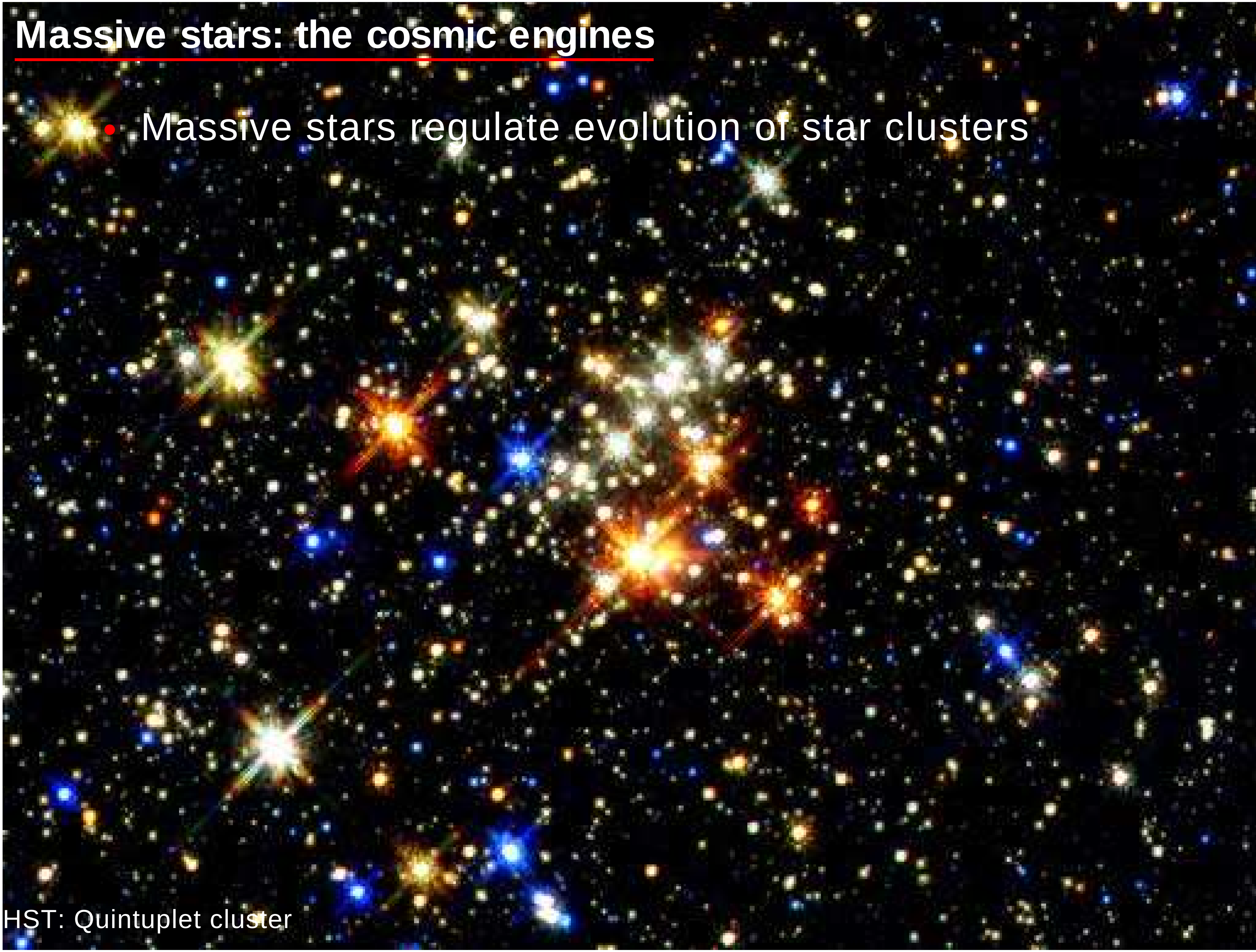
Massive stars: the cosmic engines

- Massive stars & their SNe input metals and energy in the ISM

HST: 30 Dor in the LMC

Massive stars: the cosmic engines

- Massive stars regulate evolution of star clusters



HST: Quintuplet cluster

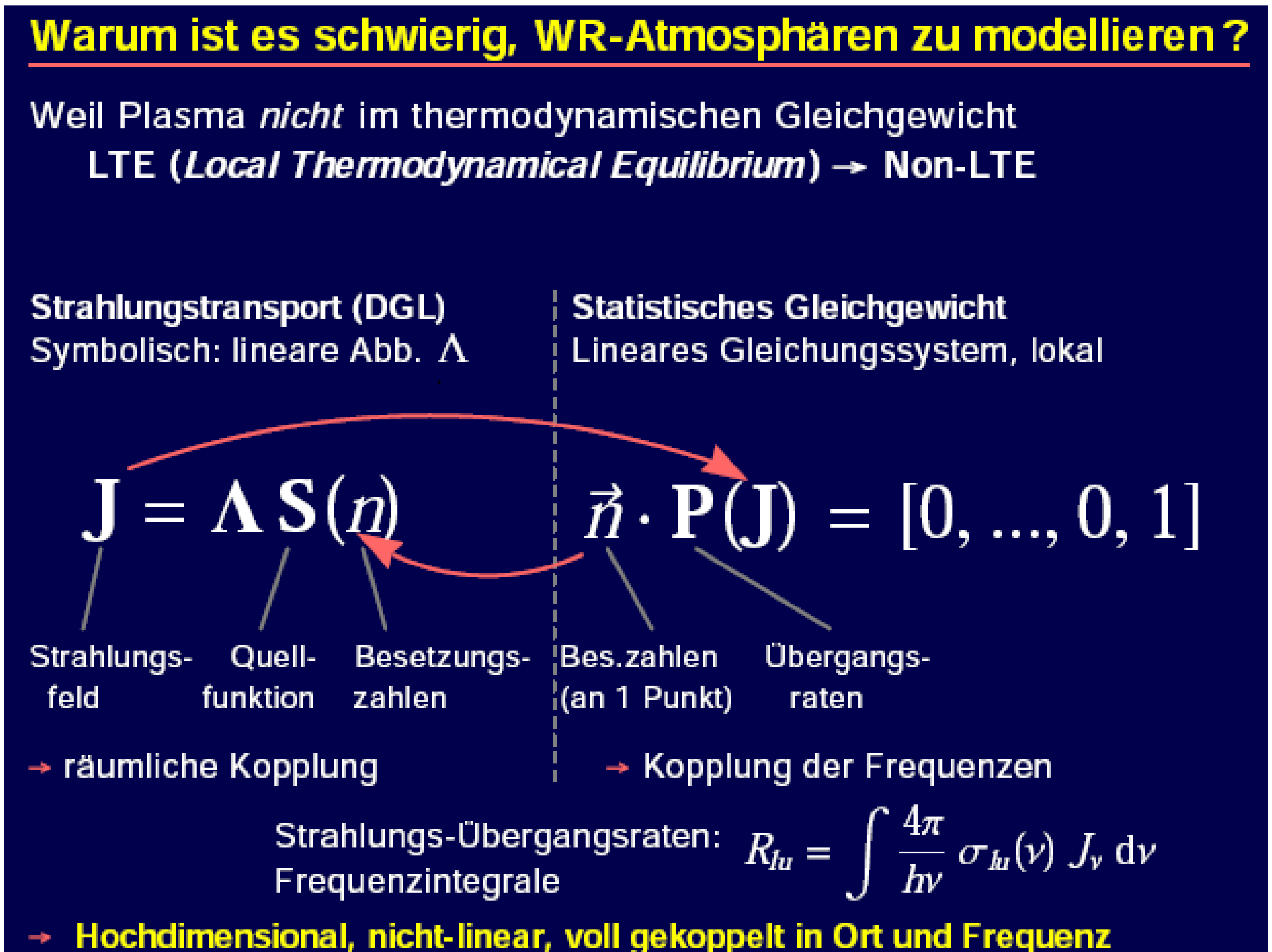
Massive stars: the cosmic engines

- Massive stars are progenitors of black holes and neutron stars born in core-collapse SNe and/or γ-ray bursts

Artist impression of γ-ray burst

Massive stars are unique physical laboratories

- Nucleosynthesis • Stellar interiors and evolution
- Interaction between radiation and matter • Magnetic fields
- Stellar wind hydrodynamics • Radiative transfer



X-ray astronomy is at the frontiers of observational astrophysics

Eight active missions:

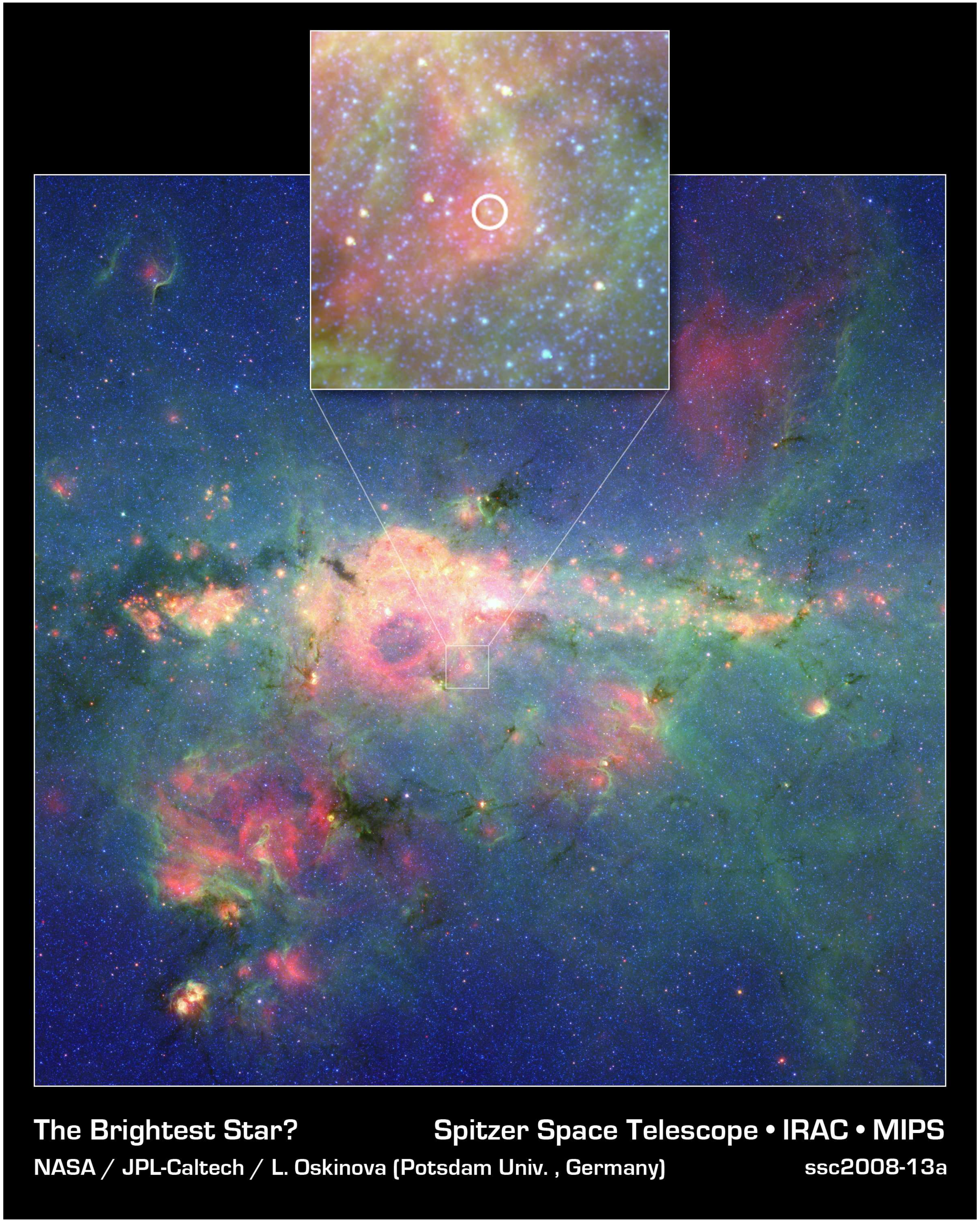
perhaps the most observed band of EM spectrum from space

XMM-Newton 2000

Chandra 1999

Suzaku 2005

Multiwavelength approach



- IR
- optical
- UV
- X-ray

Modern observational data - unprecedented quality.

New level of sophistication in modeling and theory is required to understand the data.

X-ray emission from massive stars: Science objectives

- Physics: how X-rays are produced in massive stars?
- X-ray spectroscopy is a sensitive probe of stellar winds
- X-ray emission is a sensitive probe of stellar feedback

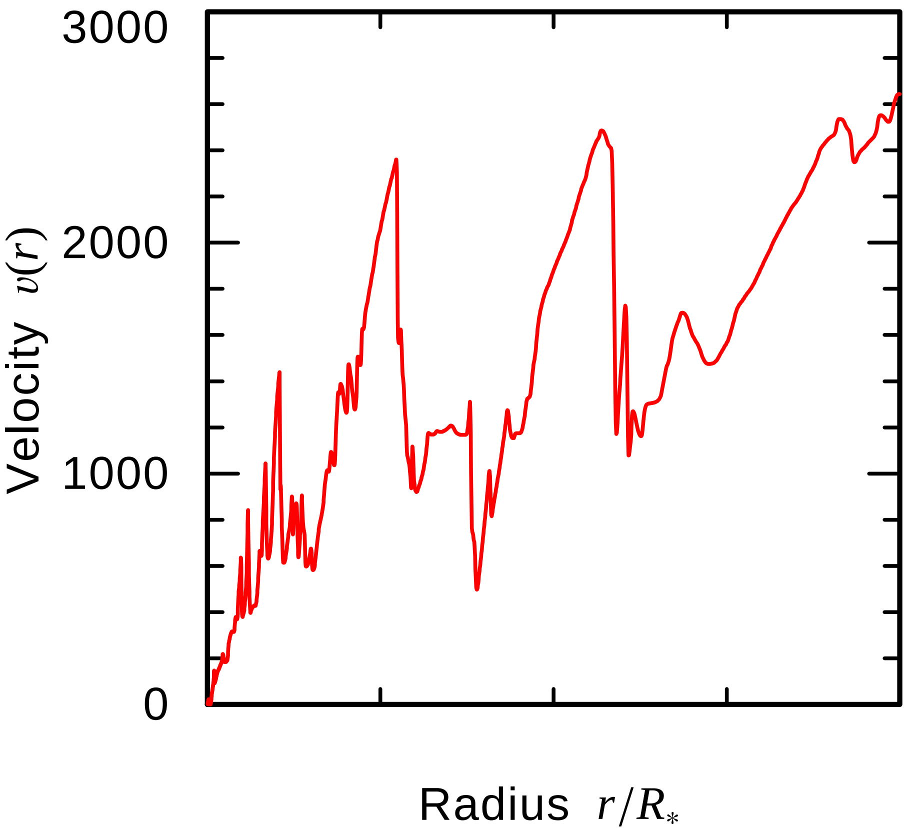
Massive star cluster Westerlund 2: Chandra NASA

1. How X-rays are produced in massive stars?

OB stars are X-ray active (Einstein observatory 1978)

Hot stars: radiatively driven stellar winds

Supersonic stellar winds are intrinsically unstable



Shocks

Heating

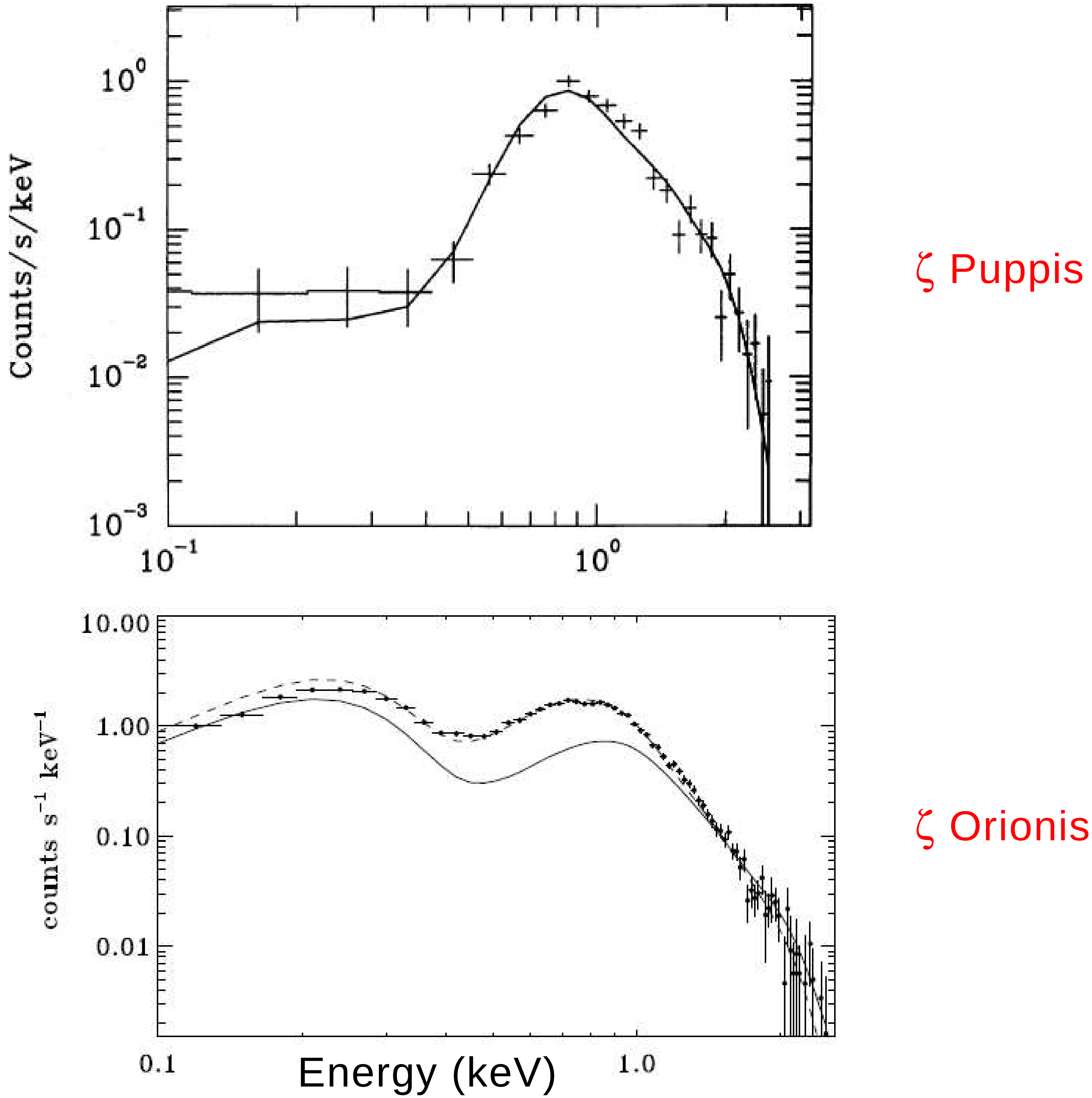
X-Rays

Lucy Solomon (1970) ... Feldmeier etal (1997)

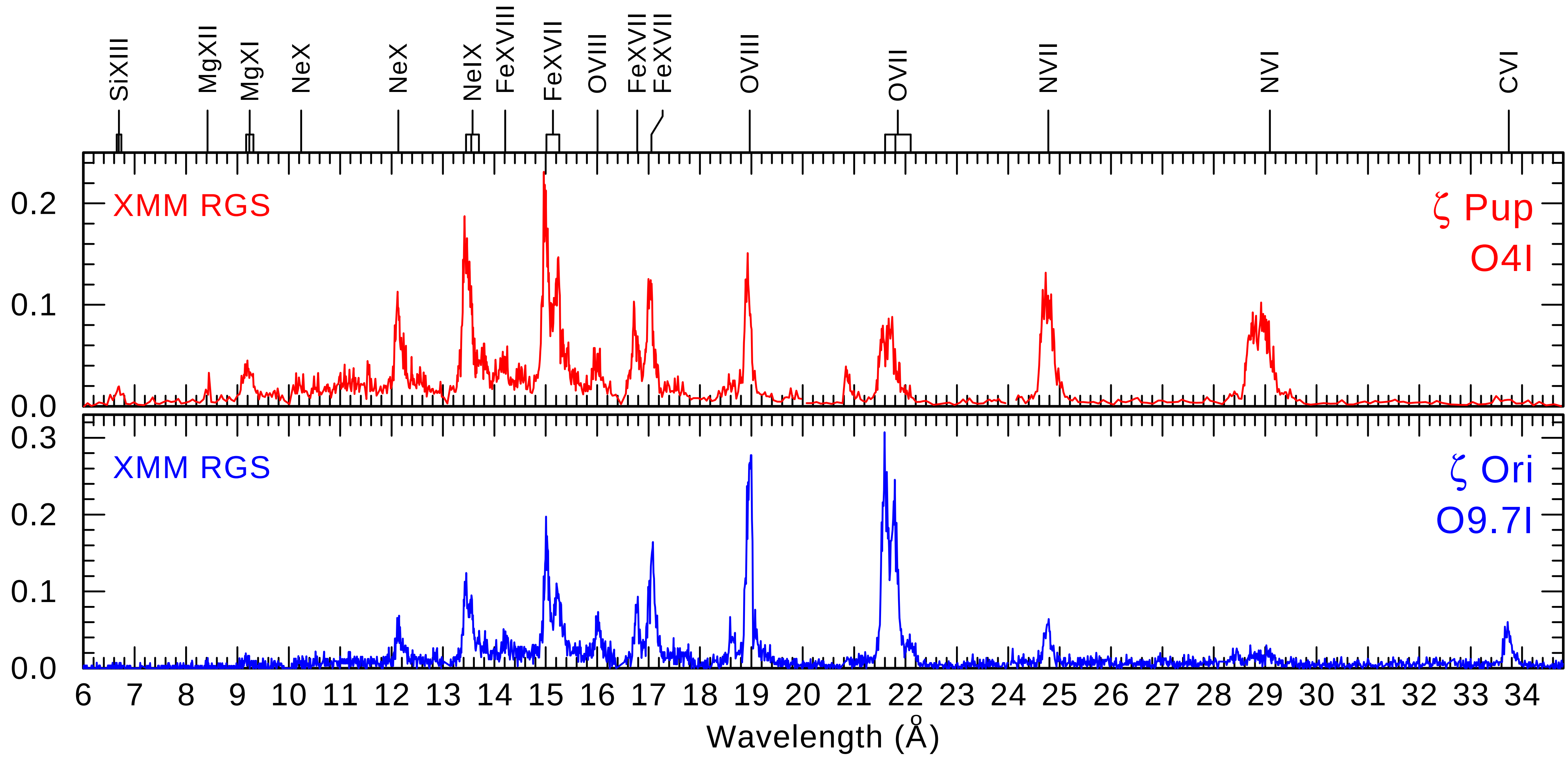
Shocks can also result from:

- Collision of streams in magnetically confined wind
- Collision of winds in binaries

Best quality X-ray spectra before year 2001 (ROSAT)



High-Resolution X-ray Spectra (XMM-Newton)



* Overall spectral fitting → plasma model, abundances
* Line ratios → $T_X(r)$, spatial distribution
* Line profiles → velocity field, wind opacity

Analyses of the X-ray spectra of O-stars

Temperature

- Range from 2 MK to 10 MK

Emission line profiles

- Broad; width scales with wind speed
- Similar accross the spectrum

Clumped wind (Feldmeier etal. 2003)

OR plasma is not in CIE (Pollock 2007)

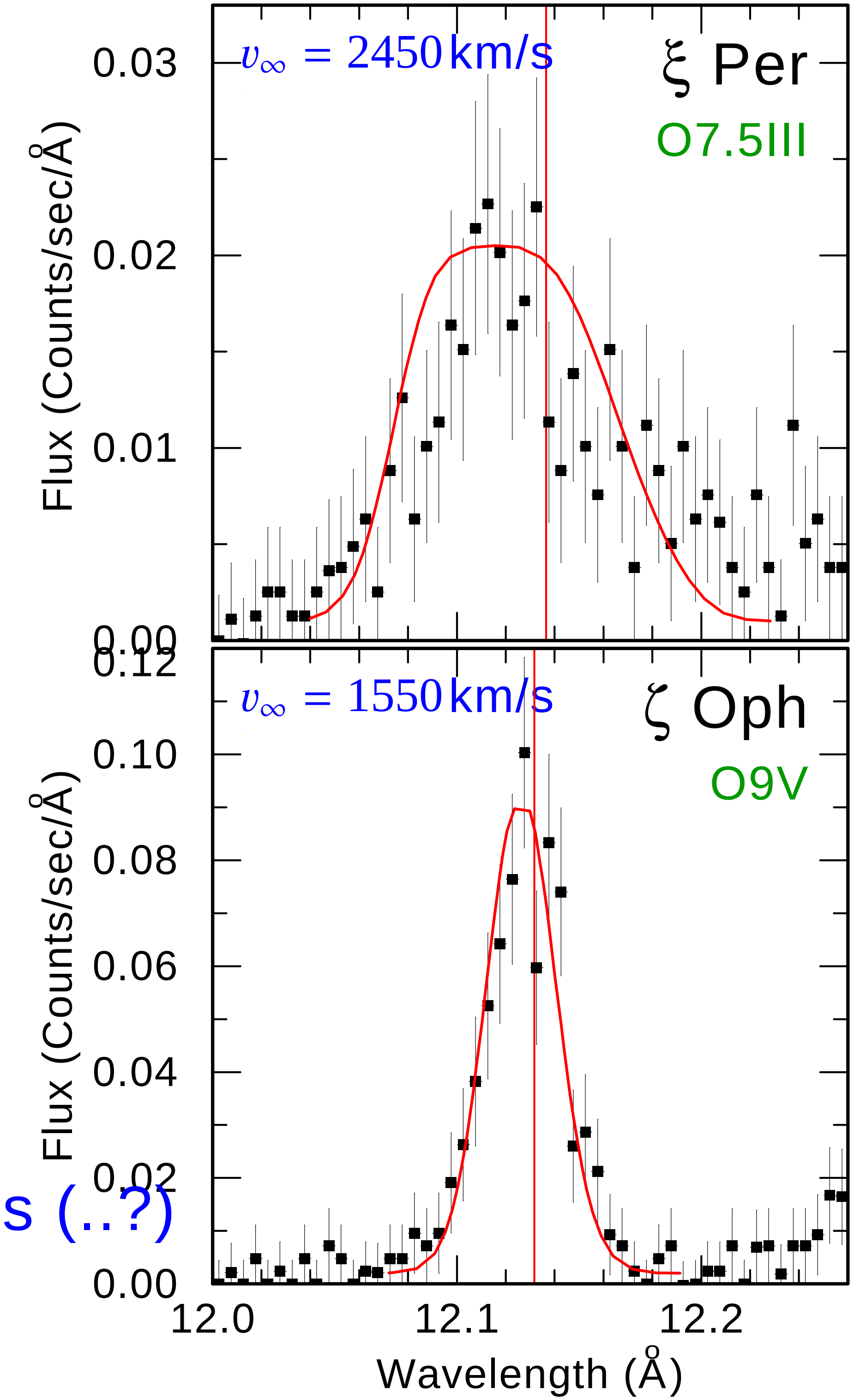
Line ratios in He-like ions

- Formed close to the photosphere
- Temperature decreases outward

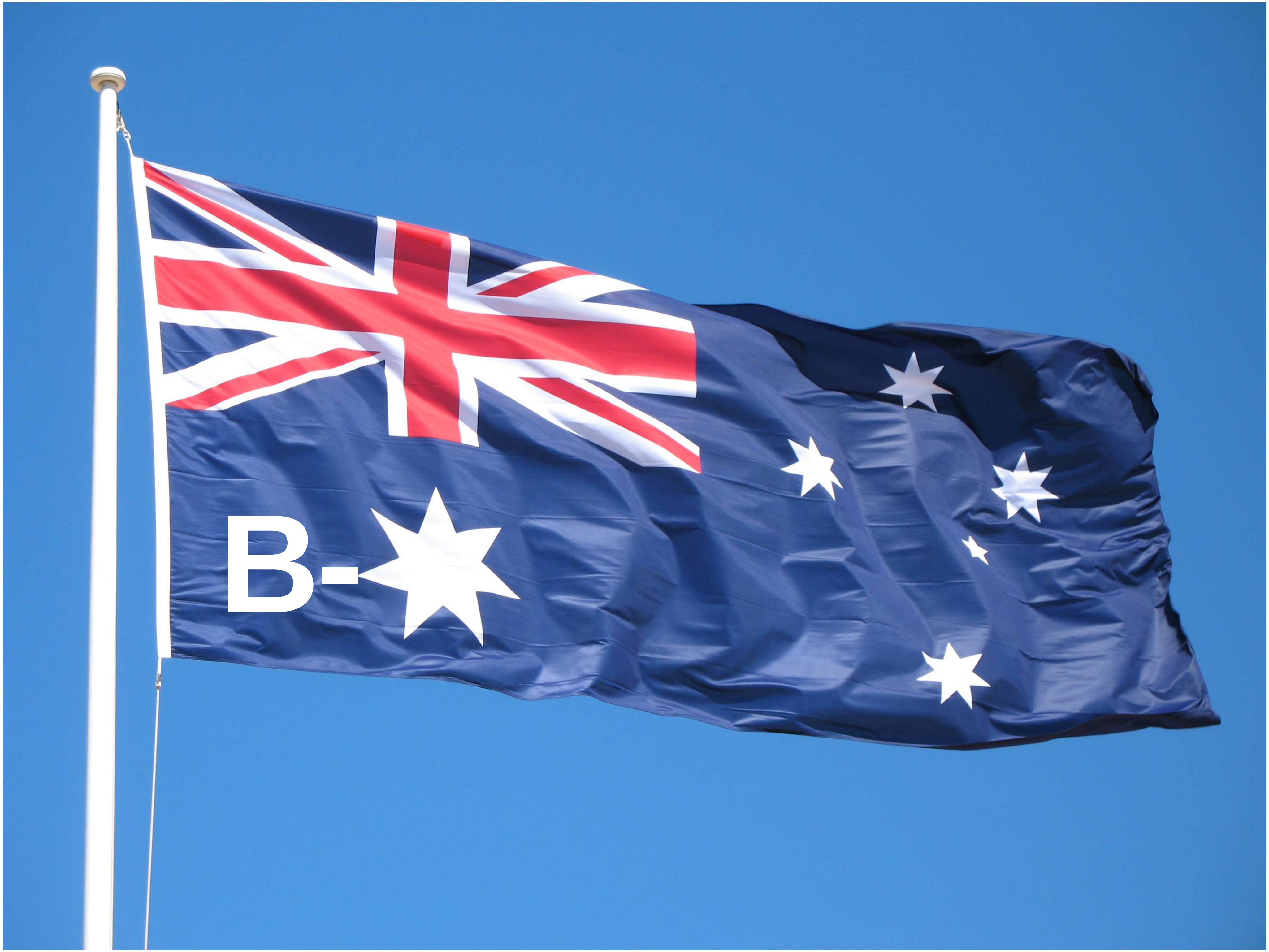
Abundances

- Agree with wind abundances

X-rays can be explained by wind shocks (..?)

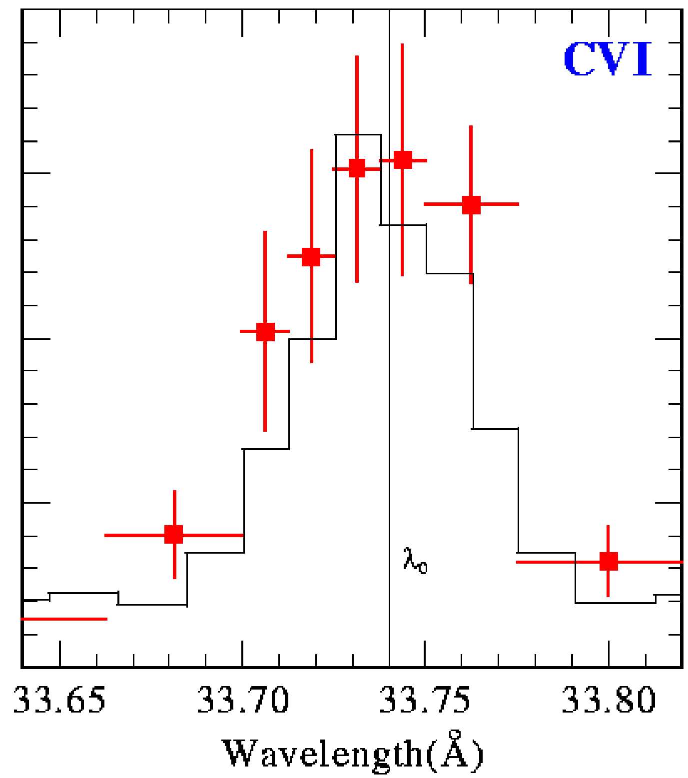


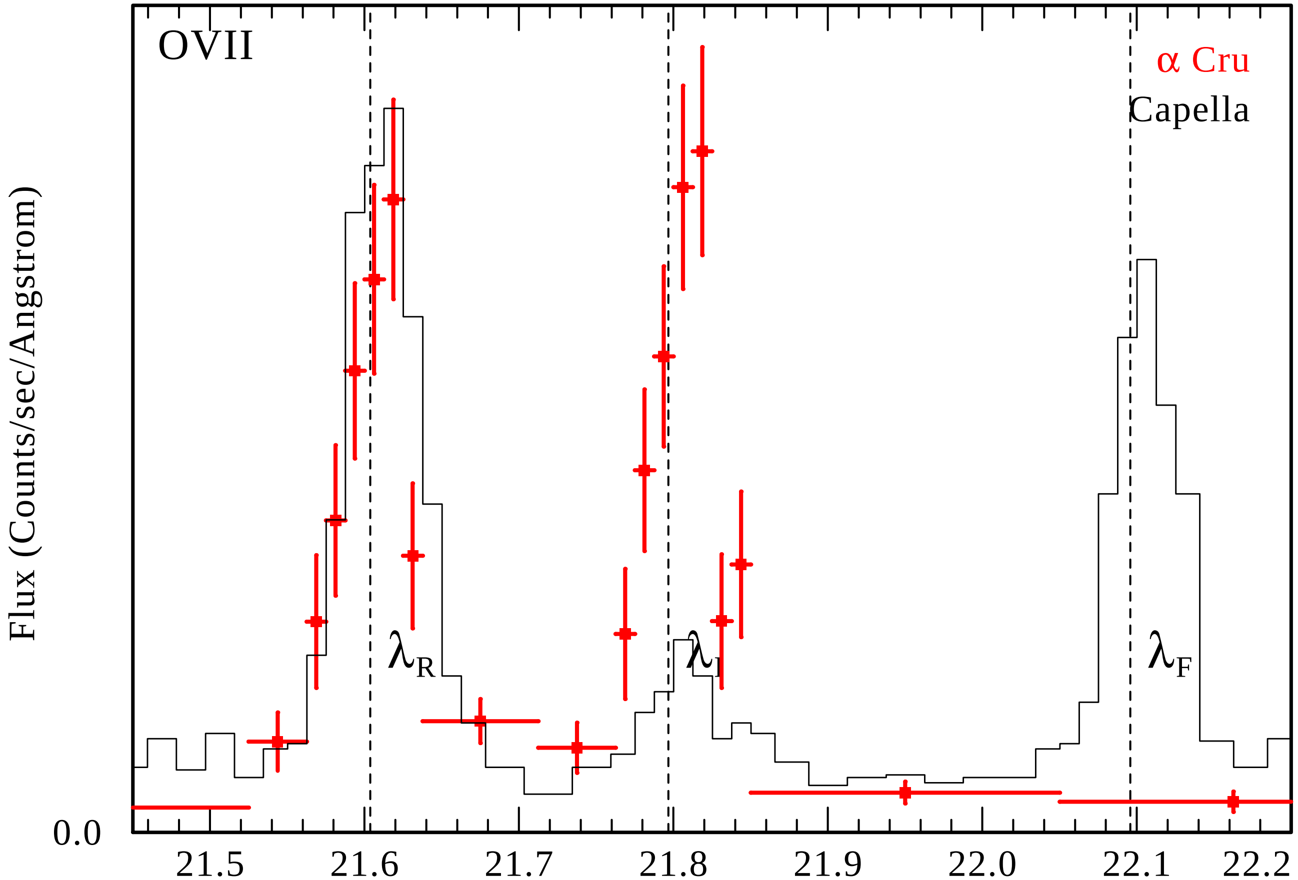
~100 papers based only on XMM data: e.g. Kahn etal. 01, Leutenegger etal. 2007, Naze etal. 2010, Raassen etal. 2005, Sana etal. 2004, Rakowski etal. 2006 ...


B-

Stationary plasma in B-stars

- Wind speed is 1500 km/s
- But lines are narrow Comparable to instrumental profile!
- He-like ions: f/i line ratio probes distance to stellar photosphere





X-ray plasma in B-stars

- Close to the photosphere
- Stationary

Different from shocks in O-type winds

Pulsations? Coronae?

Wolf-Rayet type stars

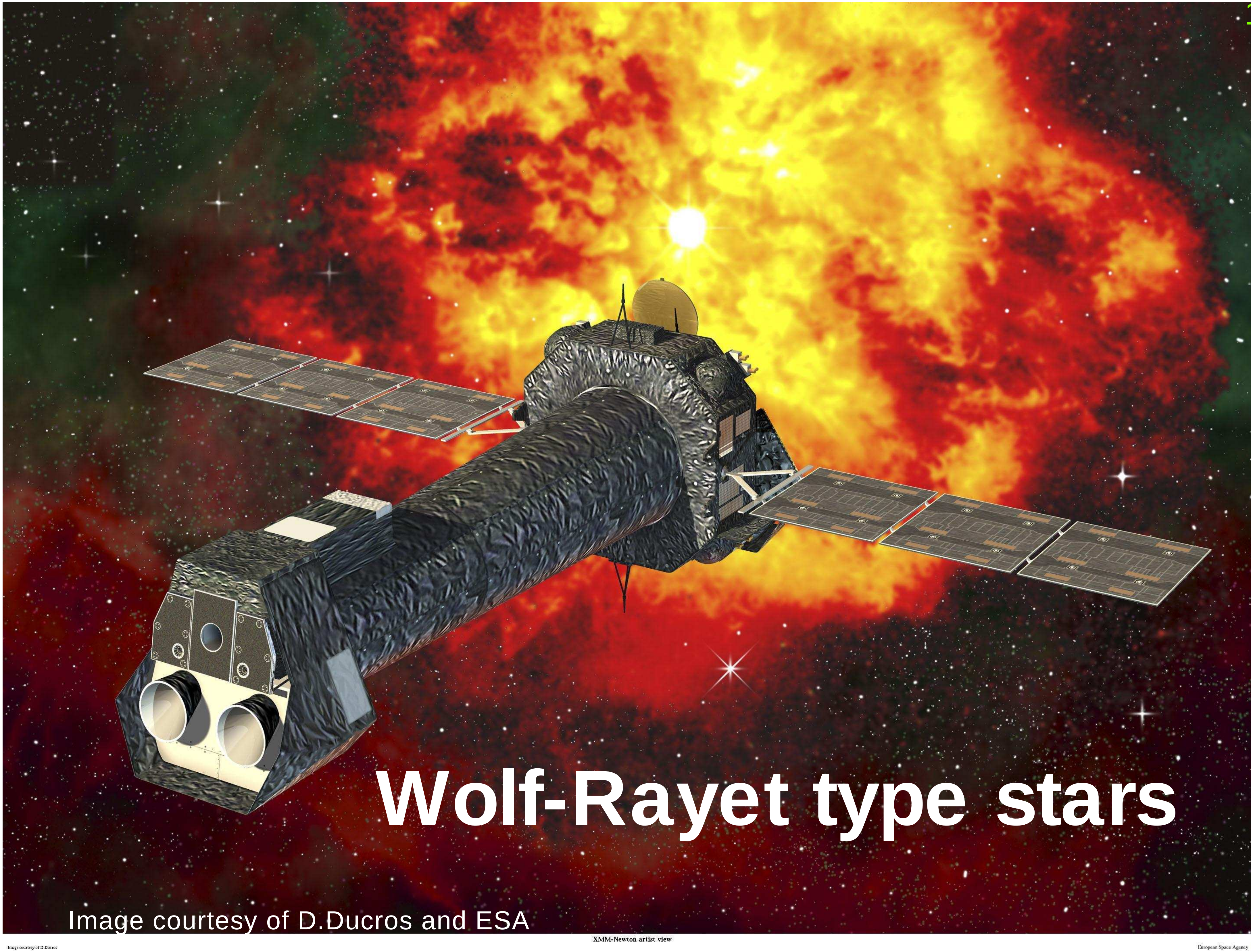
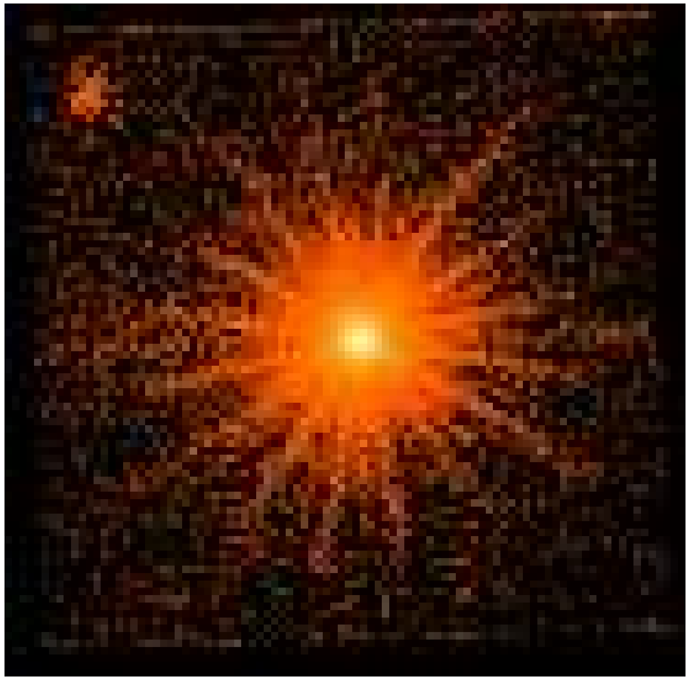


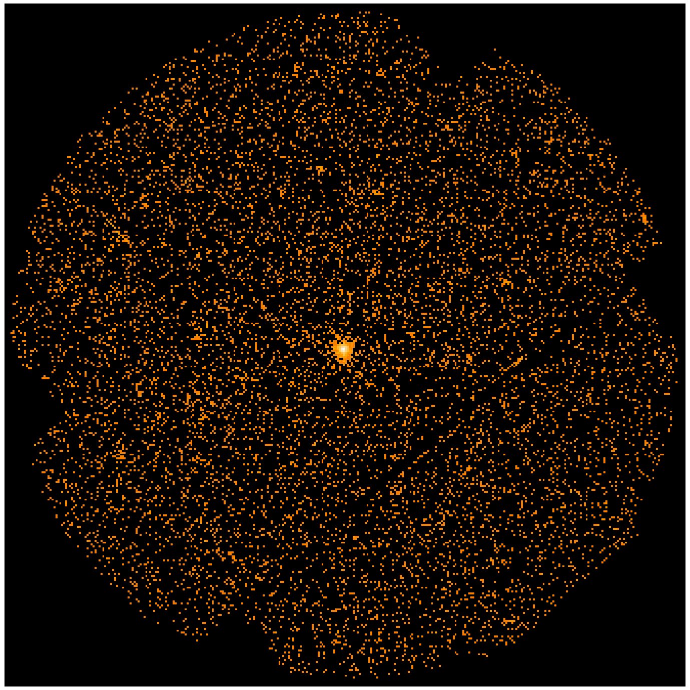
Image courtesy of D.Ducros and ESA

X-ray view on single Wolf-Rayet Stars

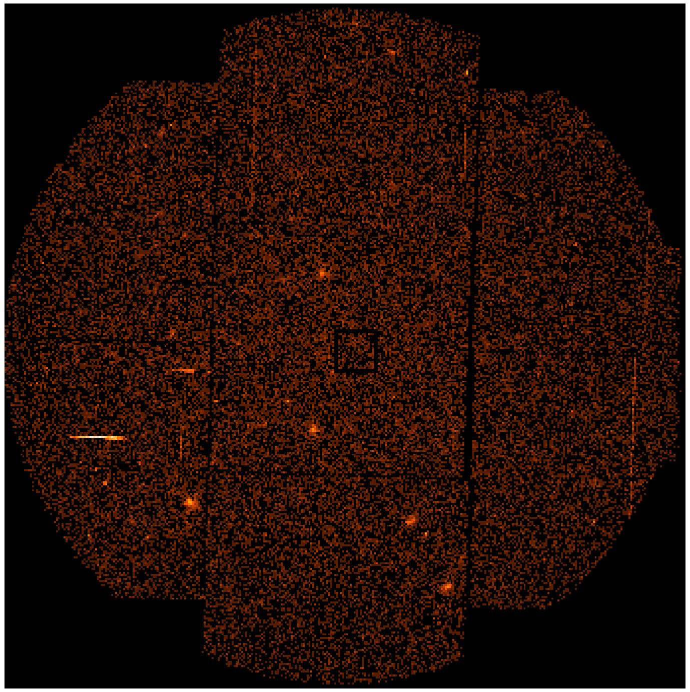
- Not all WR stars emit X-rays.
- X-ray spectra of X-ray emitting WR are harder than spectra of O-stars
- Single WR carbon stars are X-ray quiet
- X-ray bright WR stars are binaries



ζ Pup (O-type)



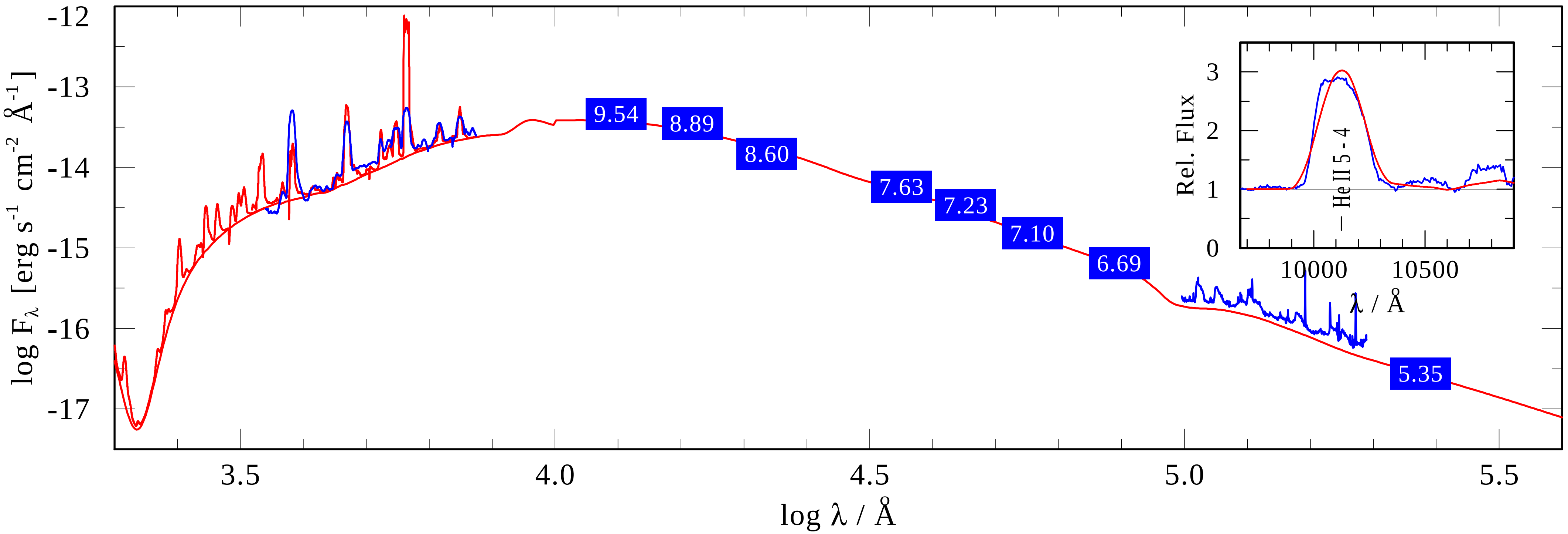
WR 1 (WN)



WR 114 (WR carbon)

Oskinova etal. 2003, Ignace etal. 2004, Skinner etal. 2010, Polock and Corcoran 2006, Gosset etal. 2005 ...

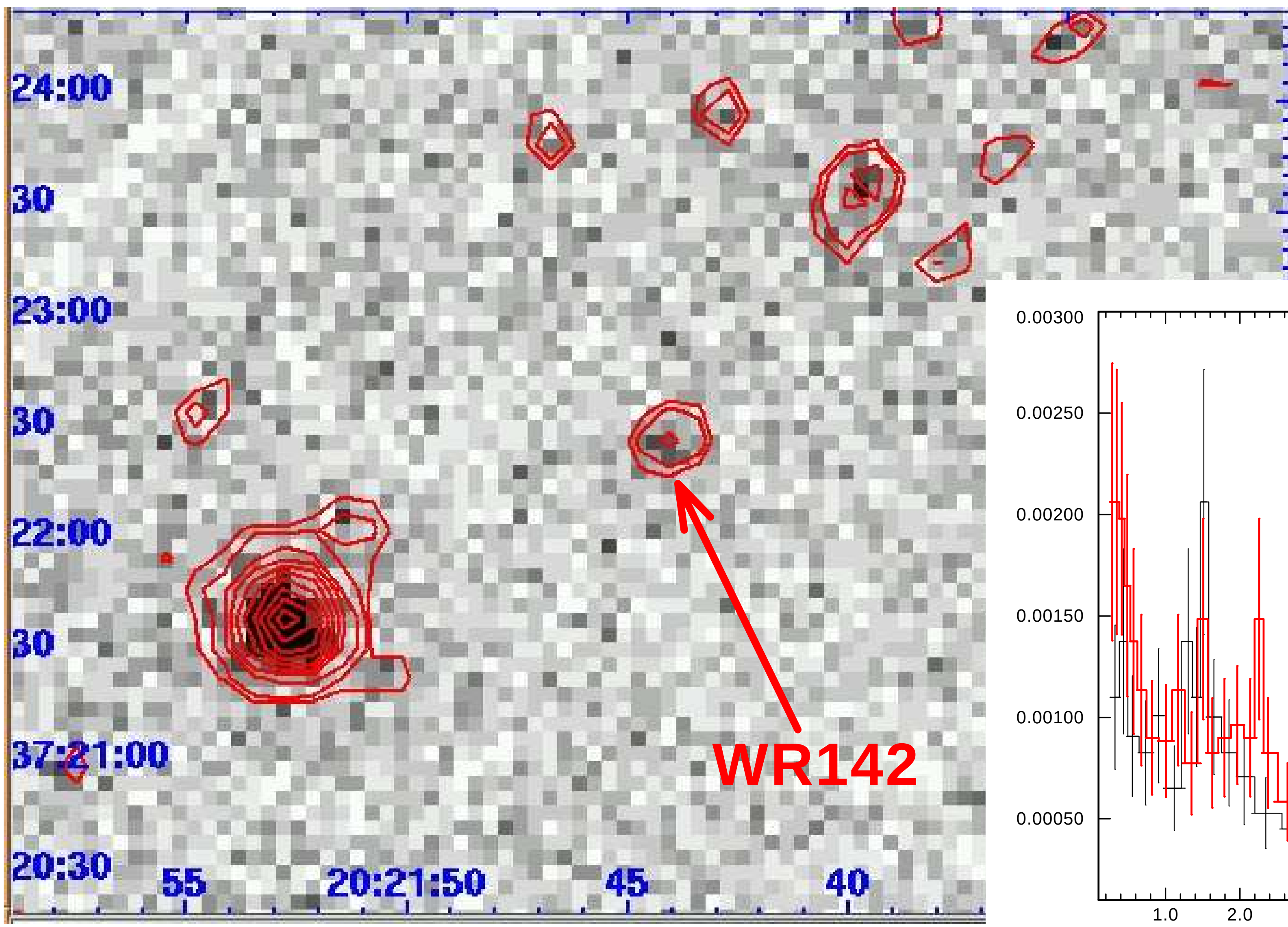
Glimpse at the pre core-collapse star WR142 (WO)

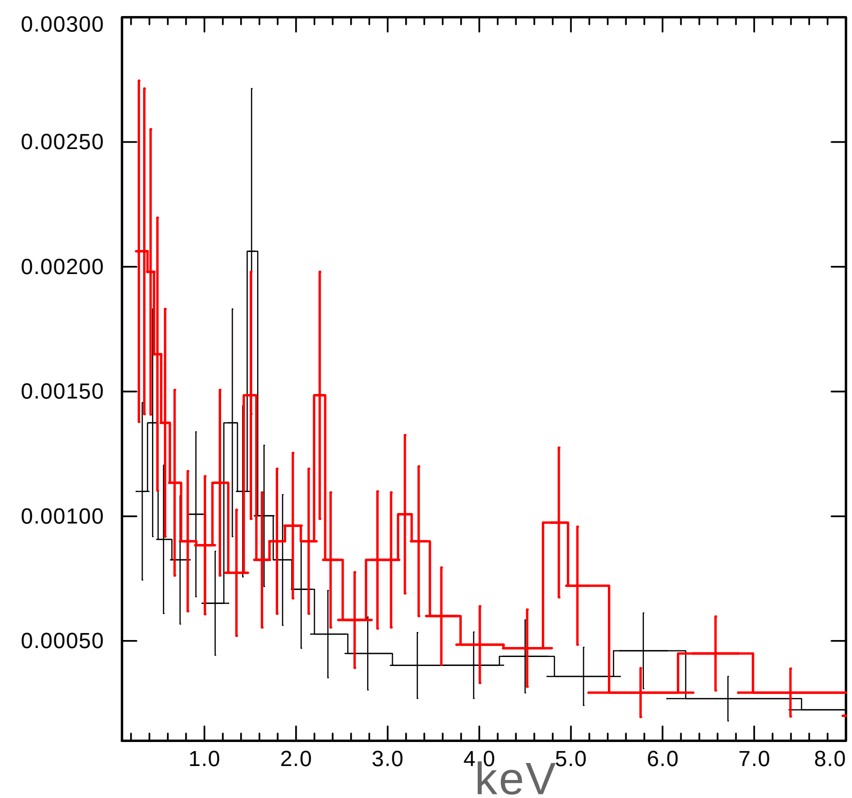


- Requires state-of-the art non-LTE models to fit observed optical and UV spectra. Such as PoWR code (Hamann et al. 2006)
- T_*=160 kK, **R_*=0.5$R_\odot$,** wind speed v=6000 km/s
- Our analysis indicates that star may be a **FAST ROTATOR** V_{rot} sin i =4000 km/s. **Current mass ~10 $M_\odot$**

XMM-Newton discovery of X-ray emission from a WO-type star

- X-rays are too hard to be explained by wind shocks
- Hint on the presence of magnetic field $B(r=2R_*) > 7$ kG





Oskinova et al. (2009)

Mystery of X-rays from WR stars: Connection With Collapsars (?)

THE ASTROPHYSICAL JOURNAL, 494:L45–L48, 1998 February 10

ARE GAMMA-RAY BURSTS IN STAR-FORMING REGIONS?

BOHDAN PACZYŃSKI
Princeton University Observatory, Princeton, NJ 08544-1001; bp@astro.princeton.edu
Received 1997 June 23; accepted 1997 December 4; published 1998 January 9

ABSTRACT

The optical afterglow of the gamma-ray burst GRB 970508 ($z = 0.835$) was a few hundred times n
than any supernova. Therefore, the name "hypernova" is proposed for the whole GRB/afterglow

"A very energetic explosion of a massive star is likely to create a … fireball…. the inner core of a massive, rapidly rotating star collapses into a ~10 $M_{\odot}$ Kerr black hole … A superstrong ~10^{15} G magnetic field is needed to make the object … a microquasar. Such events must be vary rare…to account for the … GRBs"

Do we indeed observe in our Galaxy massive, magnetic, rapidly rotating stars on latest stages of their evolution ?

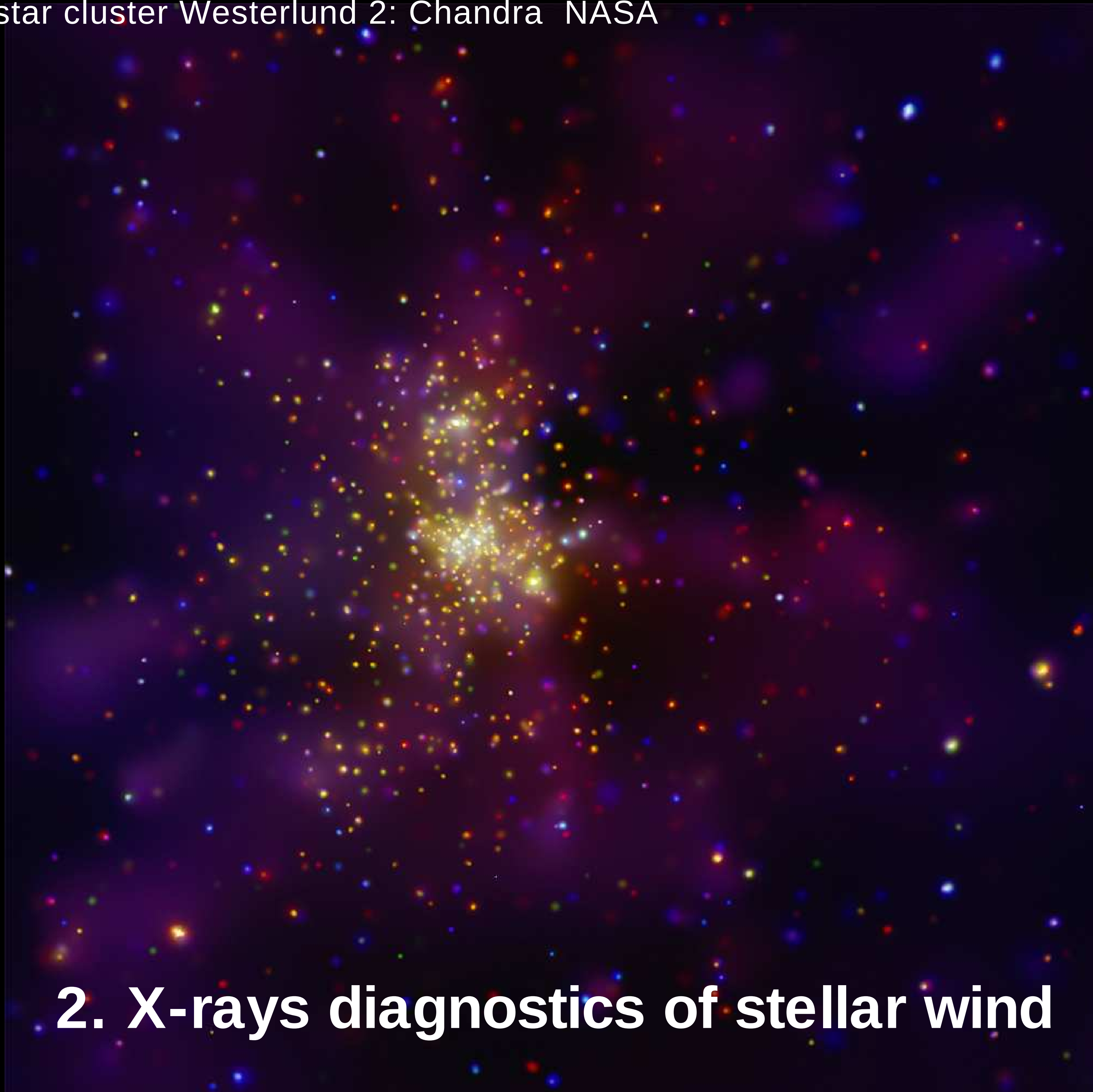
Physics of X-ray emission from massive stars

'Curiouser and curiouser!' cried Alice

Carroll (1865)

- B-stars: not clear: magnetic fields, pulsation, winds.
- O-stars: more or less clear: winds.
- WR-stars: absolutely unclear (First spectrum : XMM large program 2010)

Massive star cluster Westerlund 2: Chandra NASA



2. X-rays diagnostics of stellar wind

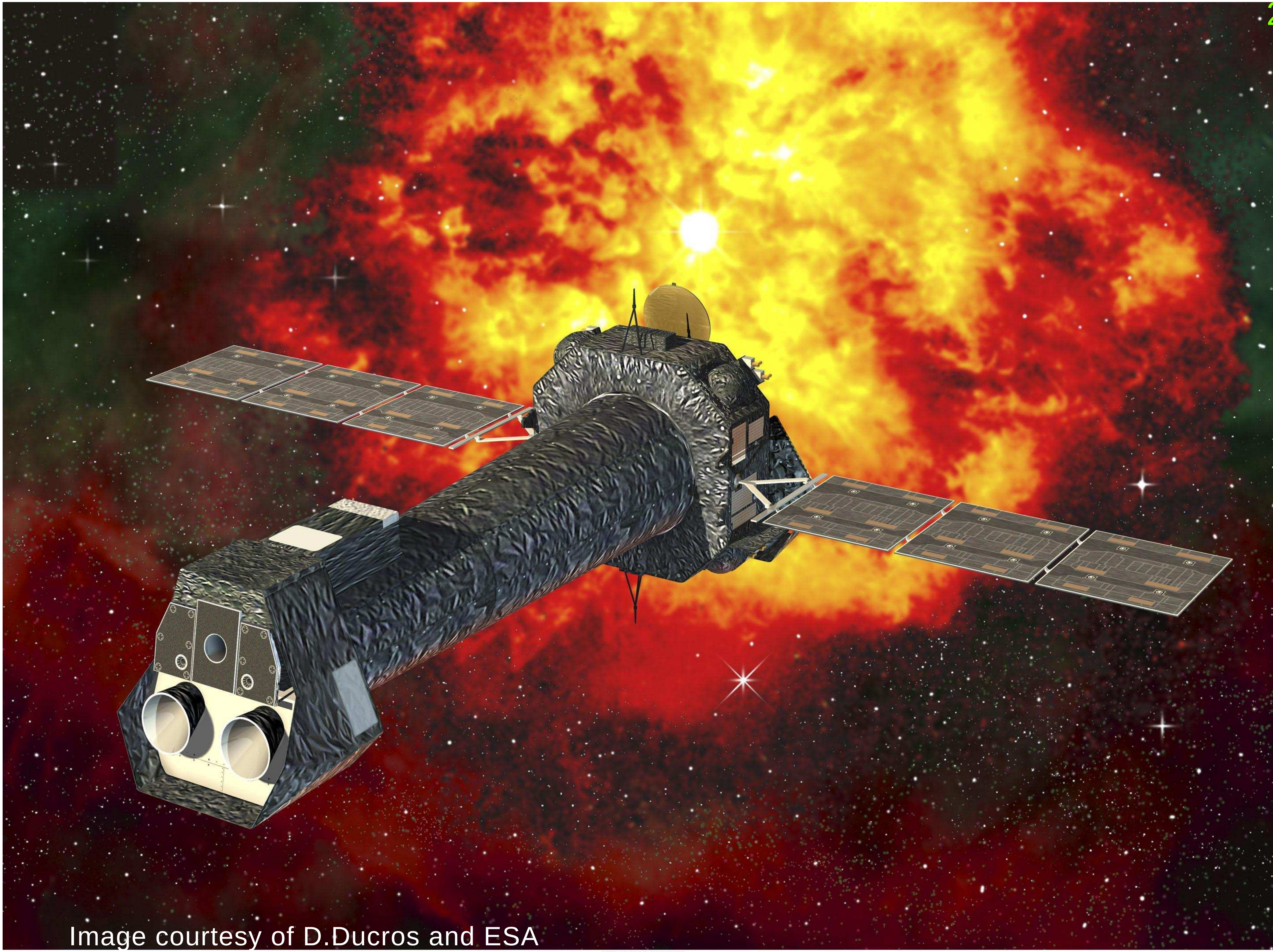


Image courtesy of D.Ducros and ESA

XMM-Newton artist view

Image courtesy of D.Ducros

European Space Agency

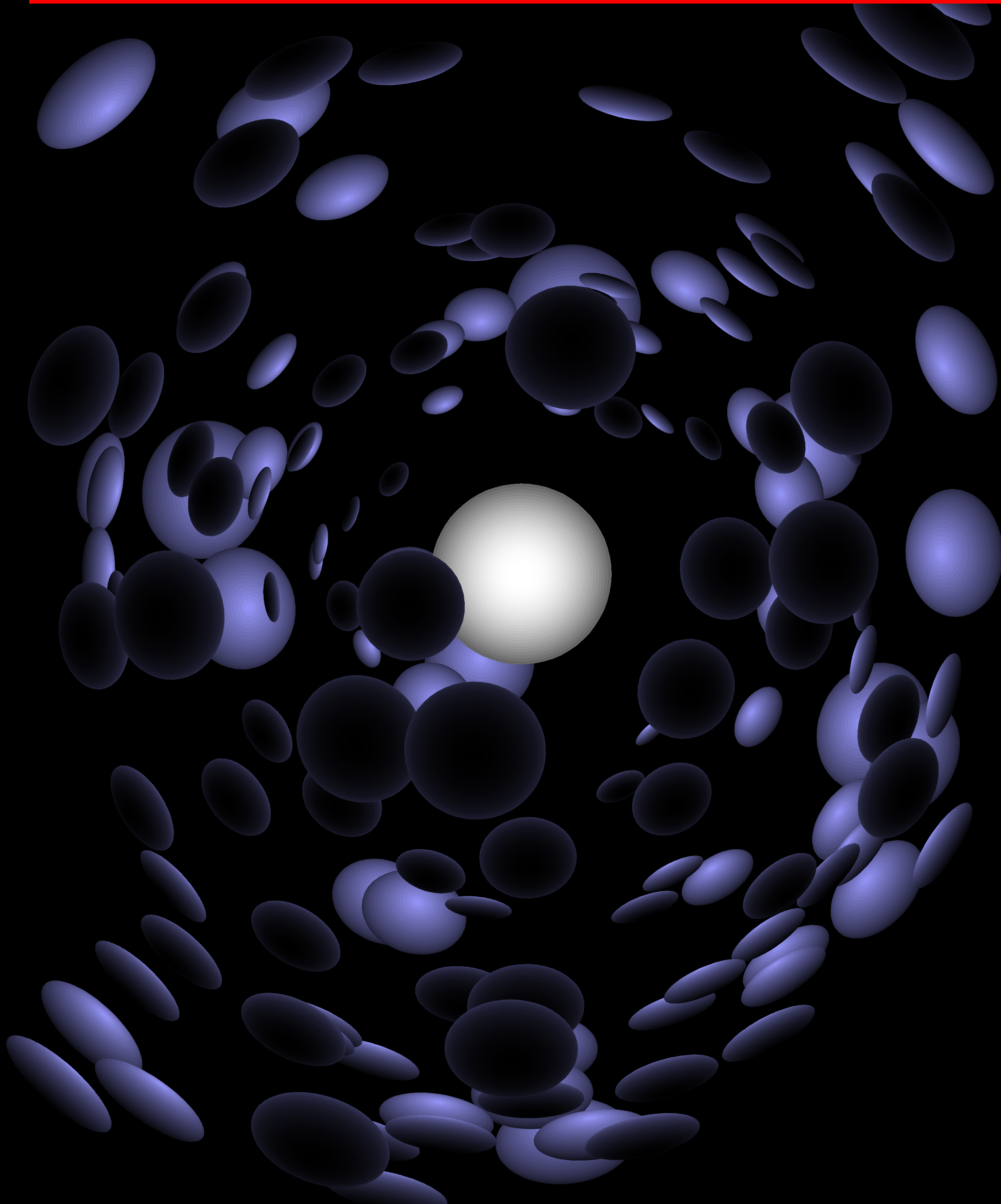
Microclumping vs Macroclumping.

- Observations → wind is inhomogeneous. Theory → density contrast in the wind
- **Microclumping:** **strong assumption** -- size is smaller than the photon free path.
- **Macroclumping:** New "break through" motivated by X-ray spectroscopy: clumps are realistic, i.e. allowed **not** to be optically thin.
- Standard situation porosity, e.g dust: Particles are **opaque**: radiation cannot go through.
- Our work: how does macroclumping affect spectral analysis.

Macroclumping: τ_{clump} >= 1

Microclumping: $\tau_{clump} << 1$

The impact of *clumping* on empirical mass-loss rates



"Macroclumping"

diagnostic line opt. *thick*

***Porosity effect*:**

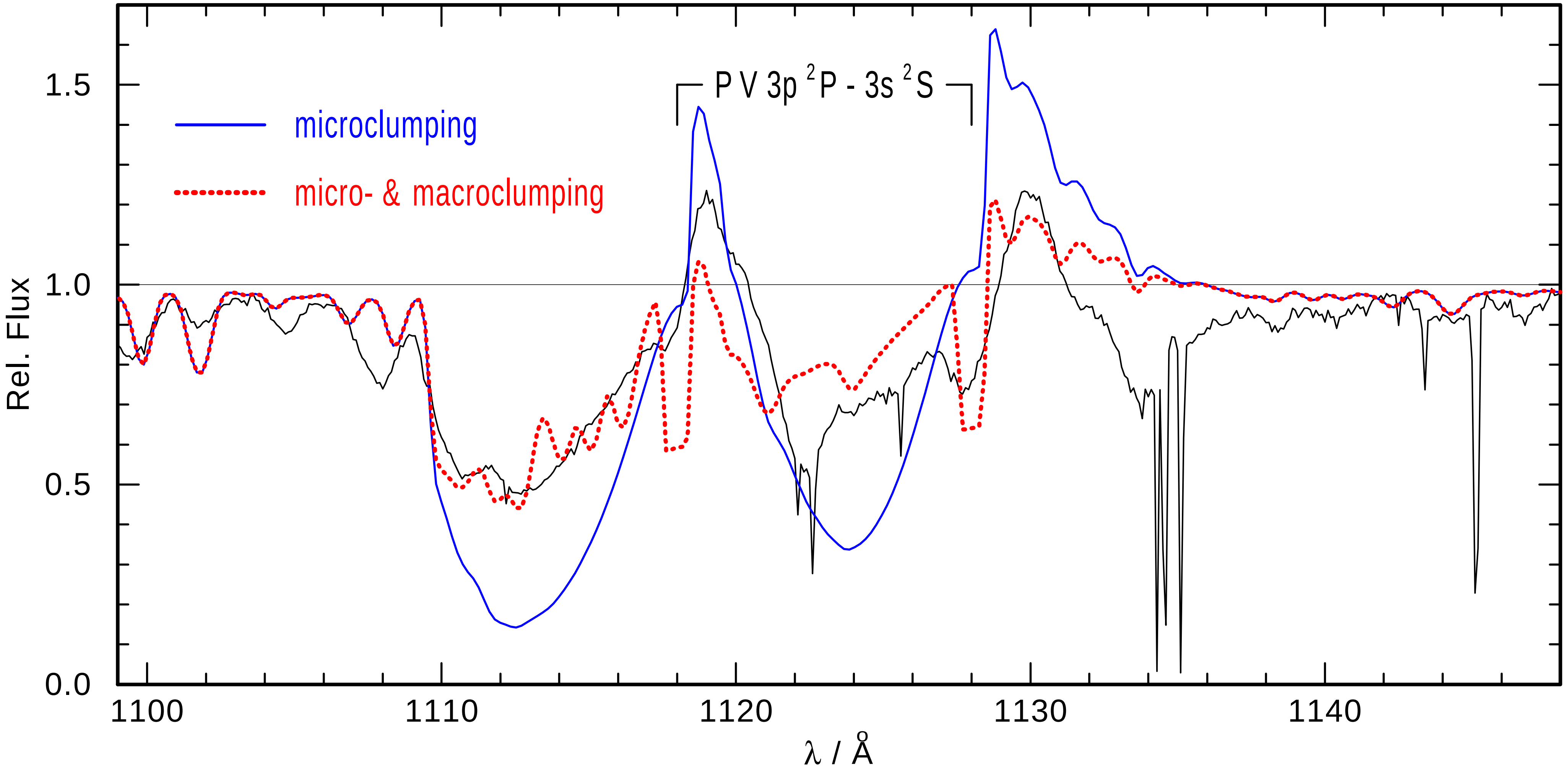
$\kappa_{eff} < \kappa_{smooth}$

Important consequence for mass-loss empirical estimates

Larger $\dot{M}$

Mass-loss: key parameter to stellar evolution models & stellar feedback

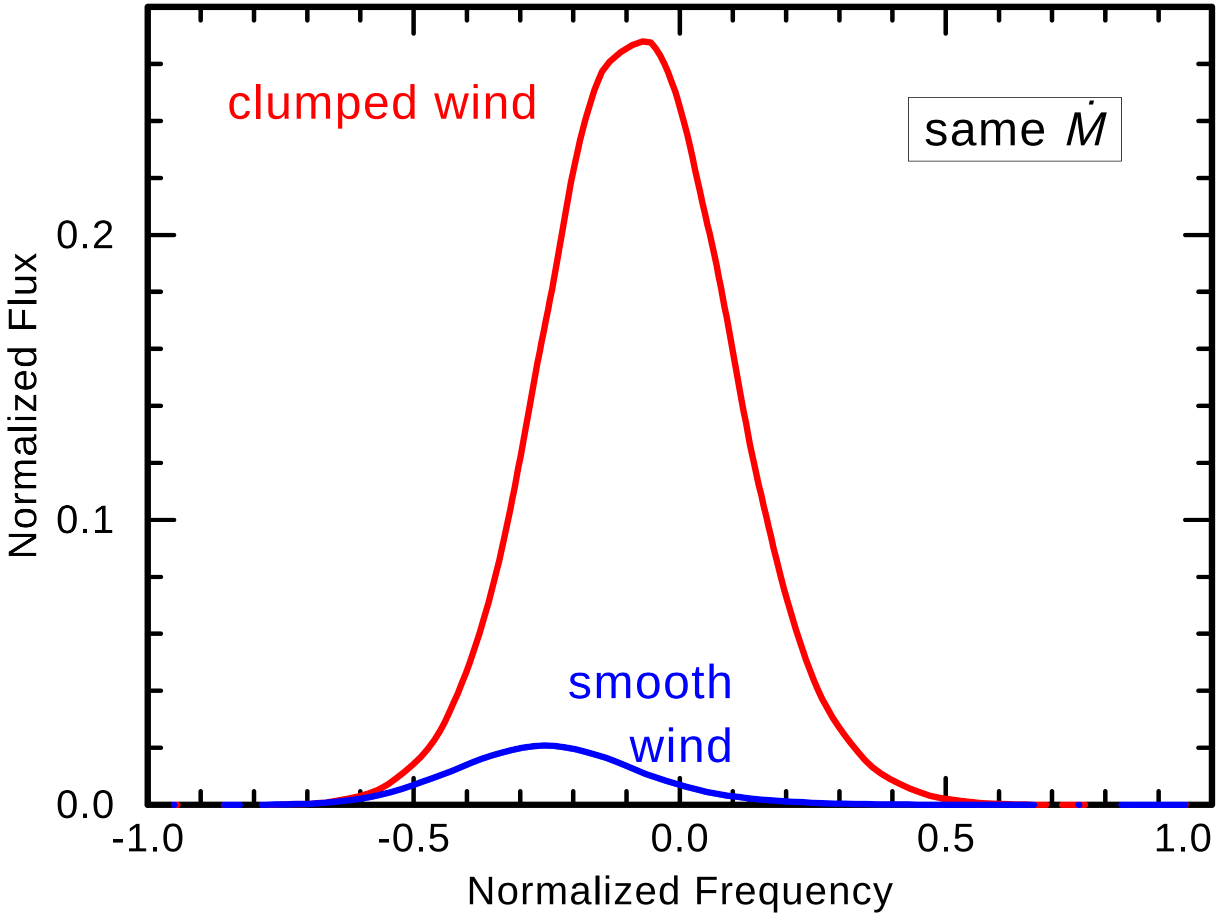
UV diagnostics: PV resonance doublet



- P V resonance doublet becomes much weaker if macroclumping is taken into account
- **This resolves the descrepancy between $\dot{M}$ from resonance line and ρ^2 diagnostics!**

X-ray diagnostics: X-ray emission lines

Model emission lines



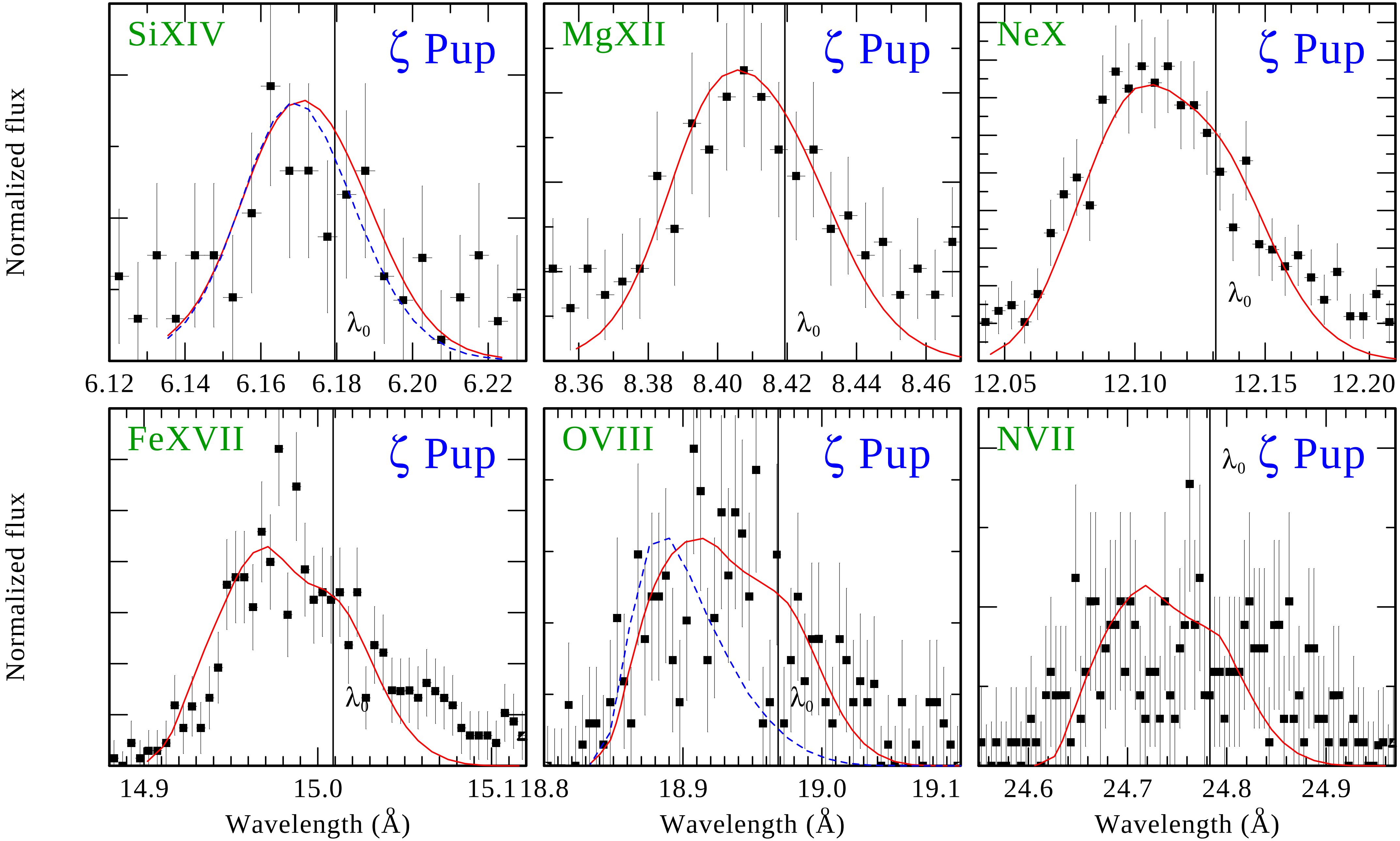
Wind opacity for X-ray drastically reduced by clumping

Opacity becomes "grey"

⇓

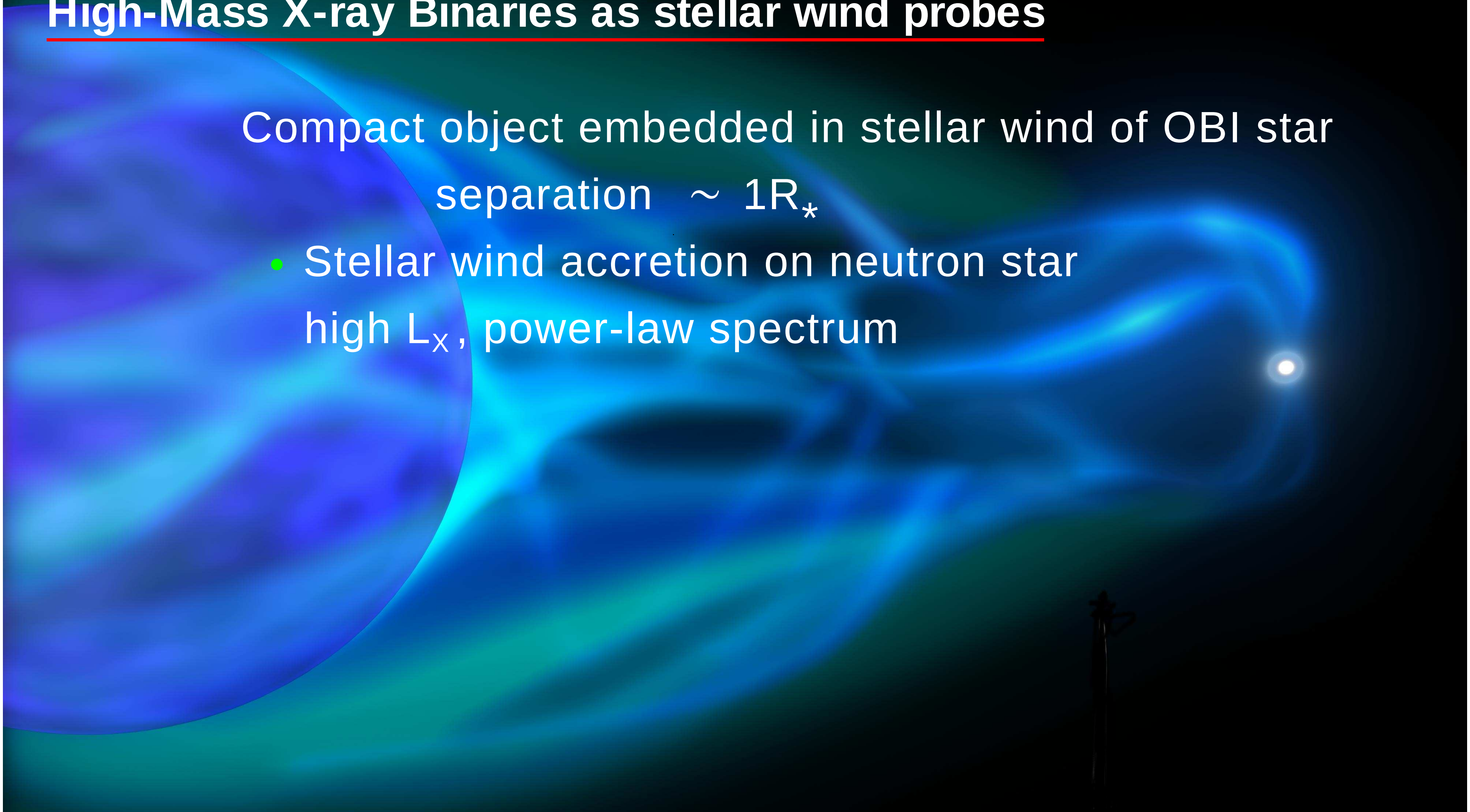
Similar line profiles accross the spectrum

Observed and model lines of ζ Puppis (no fitting!)



Oskinova et al. (2006)

High-Mass X-ray Binaries as stellar wind probes



Compact object embedded in stellar wind of OBI star

separation $\sim 1R_*$

- Stellar wind accretion on neutron star

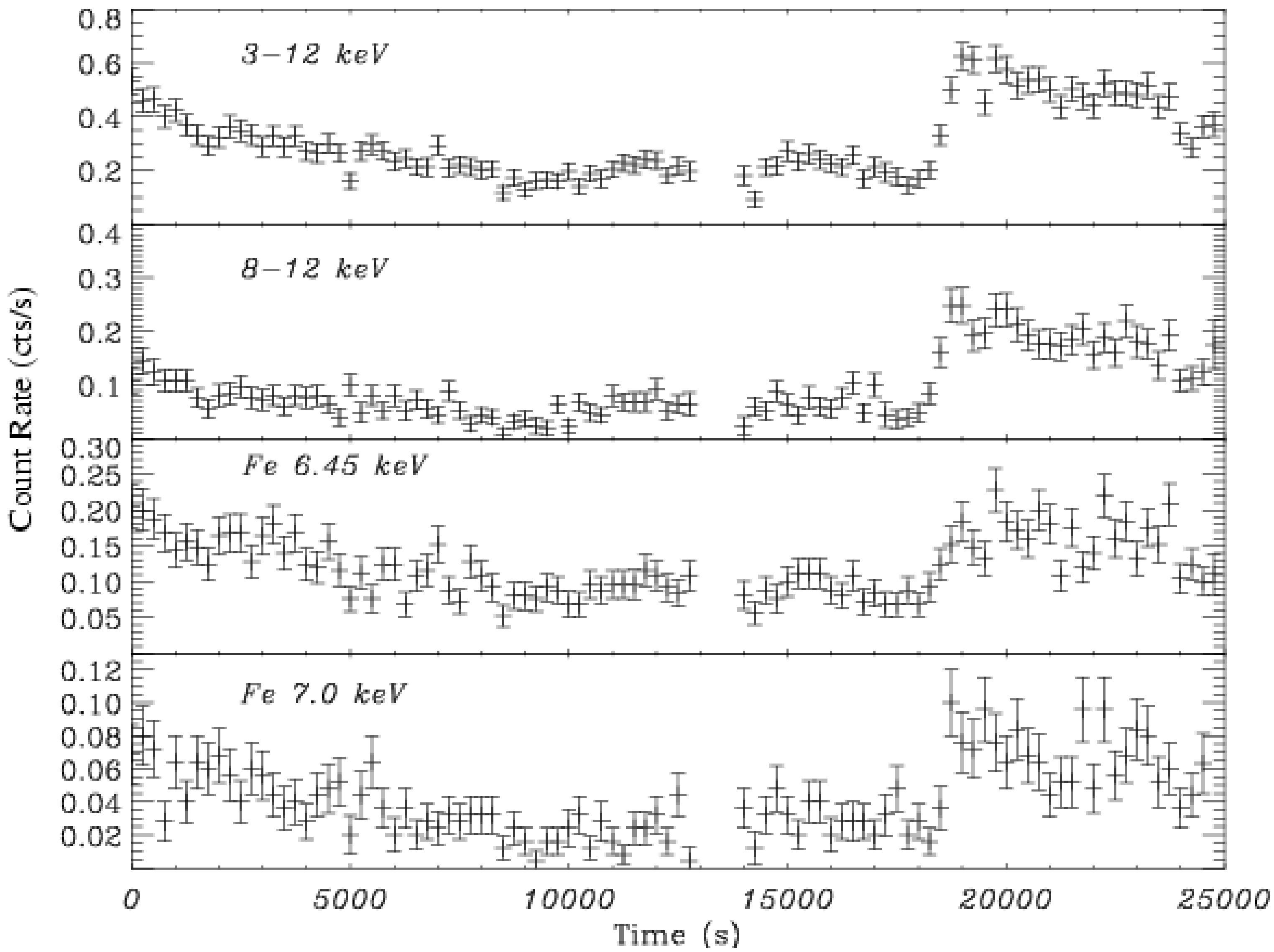
high L_X, power-law spectrum

- X-rays photoionize small part of stellar wind: recombination
- X-rays suffer absorption in stellar wind

Vela X-1

Kretschmar etal. 2008, 2009, 2010, Kreykenbohm etal. 2010

Fast temporal variability in X-rays - High Mass X-ray Binaries



- X-ray light curve: strong variability
- Optical donor star O-type supergiant
- $L_X \approx 10^{35}$ erg/s - accreting **black hole**

Accretion in clumped wind

4 *L. Ducci et al.*

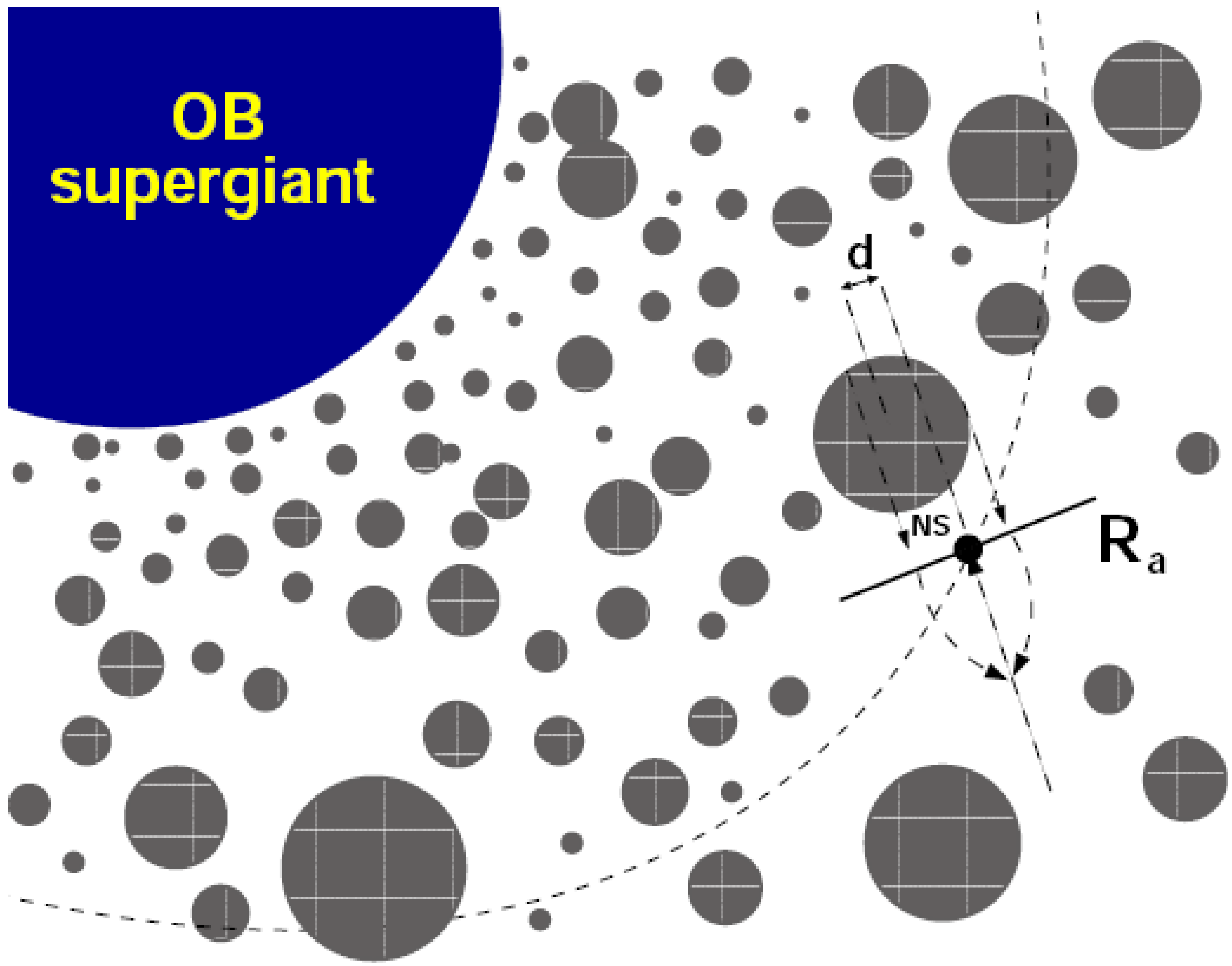


Figure 1. Schematic representation of our clumpy wind model. d is the distance between the centre of the clump and the cent
R_a is the accretion radius.

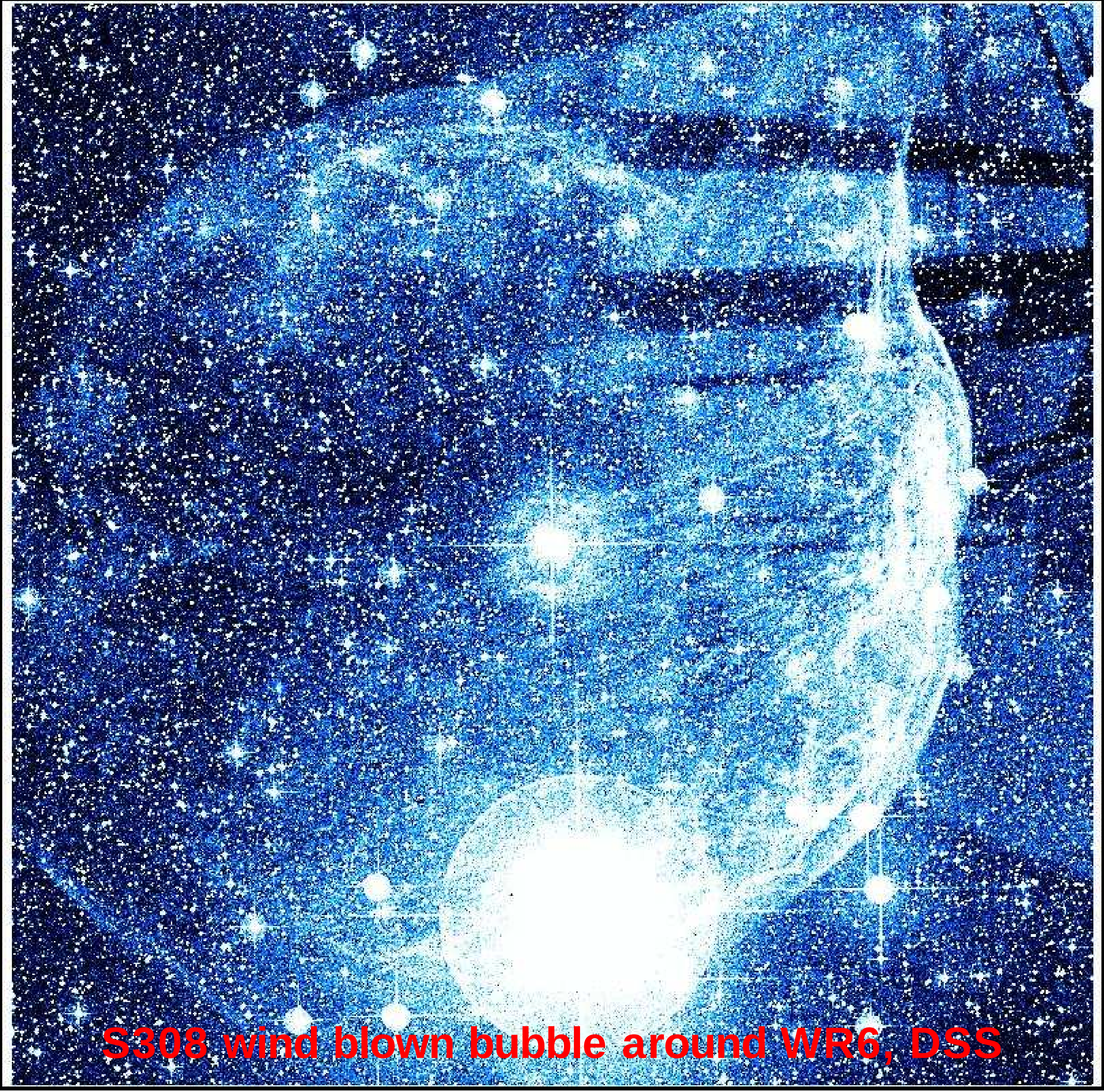
Stellar winds and X-ray spectroscopy

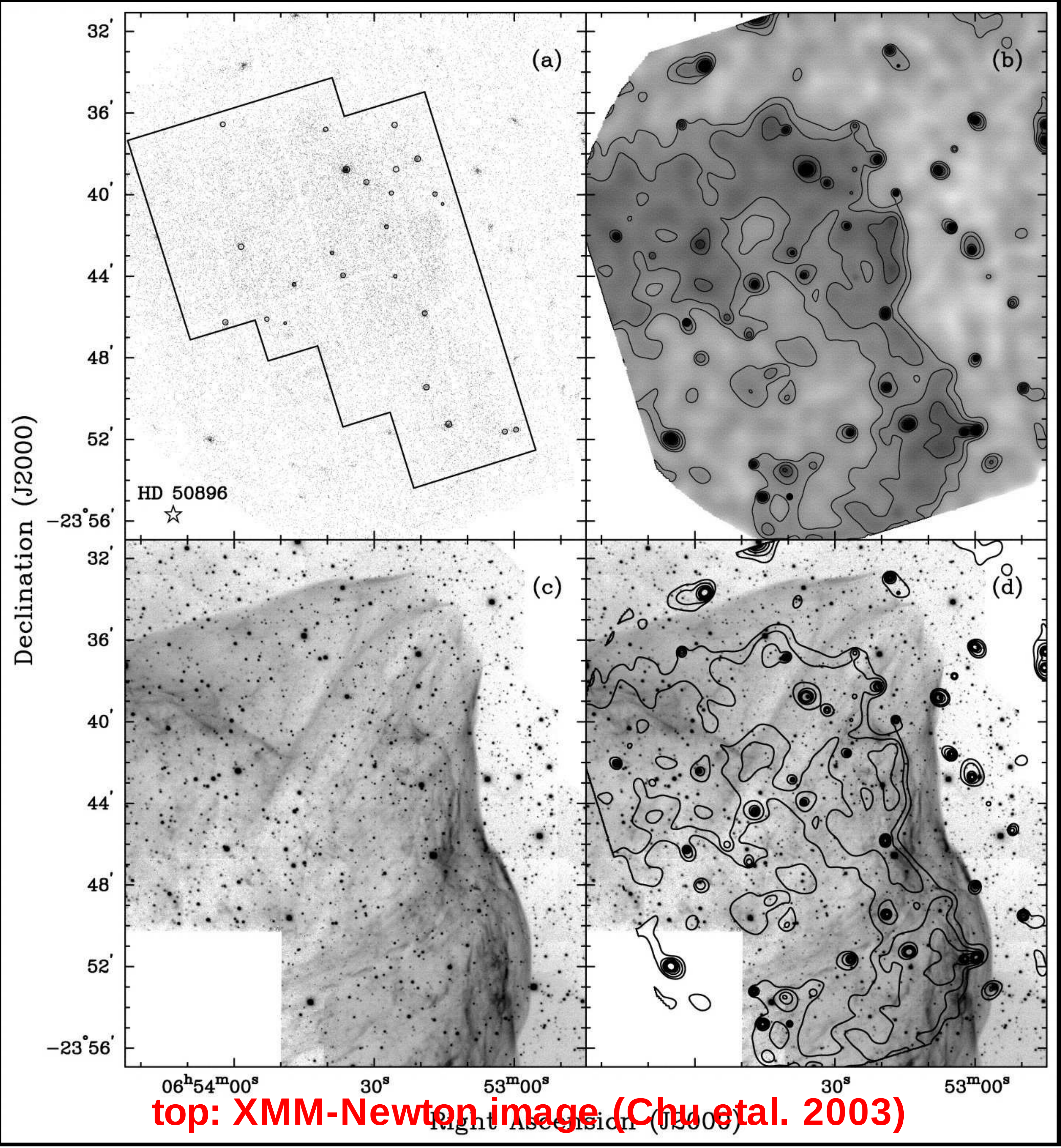
- Stellar wind is clumped
- Clumps are optically thick at some λ
- Clumps are most likely pancakes!
- Stellar mass loss rate is quite high

- New radiative transfer technique!

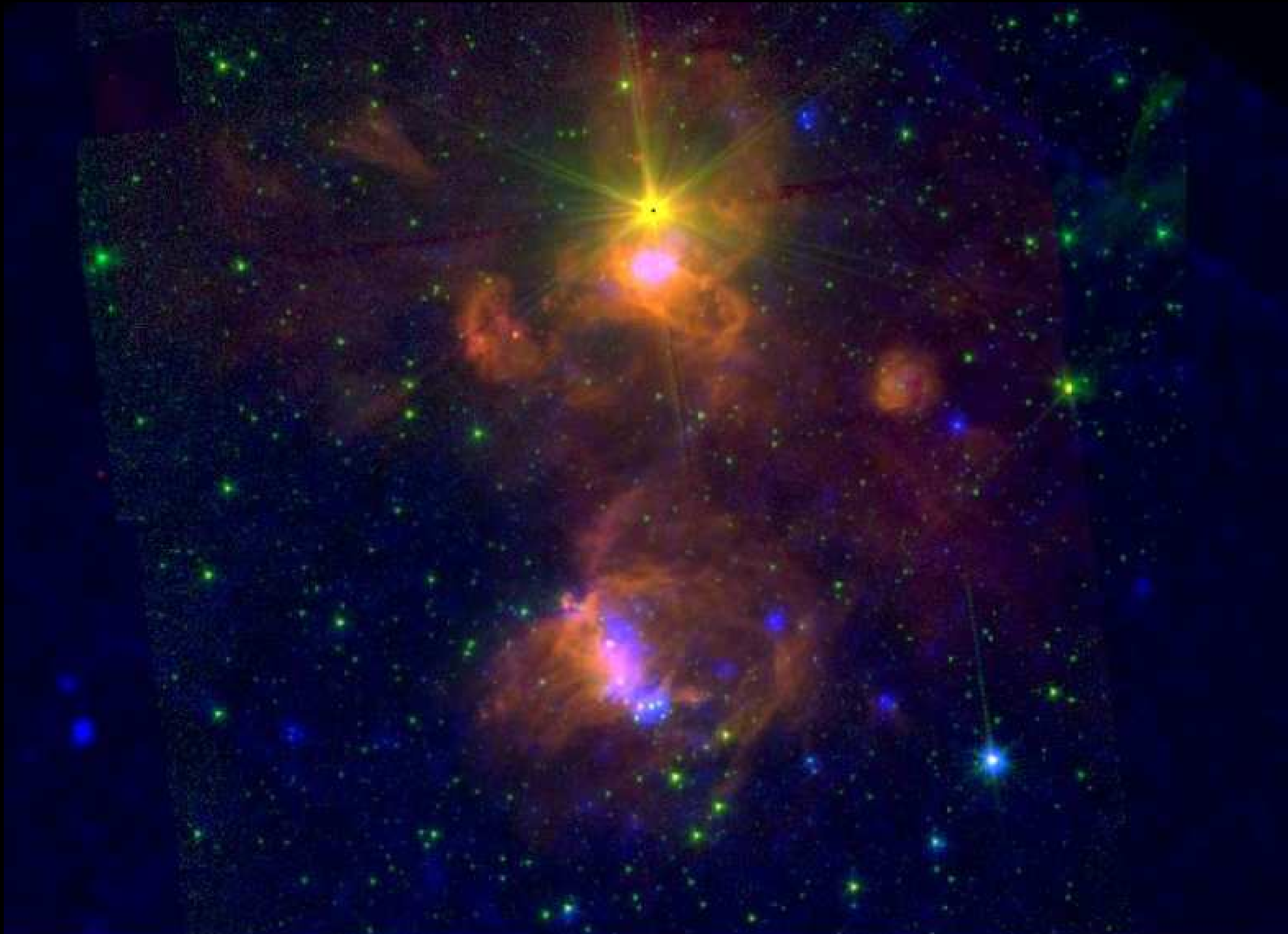
Massive star cluster Westerlund 2: Chandra NASA

3. X-rays diagnostics of massive star feedback


S308 wind blown bubble around WR6, DSS



top: XMM-Newton image (Chu etal. 2003)



Massive star forming region ON 2 and star cluster Berkeley 87

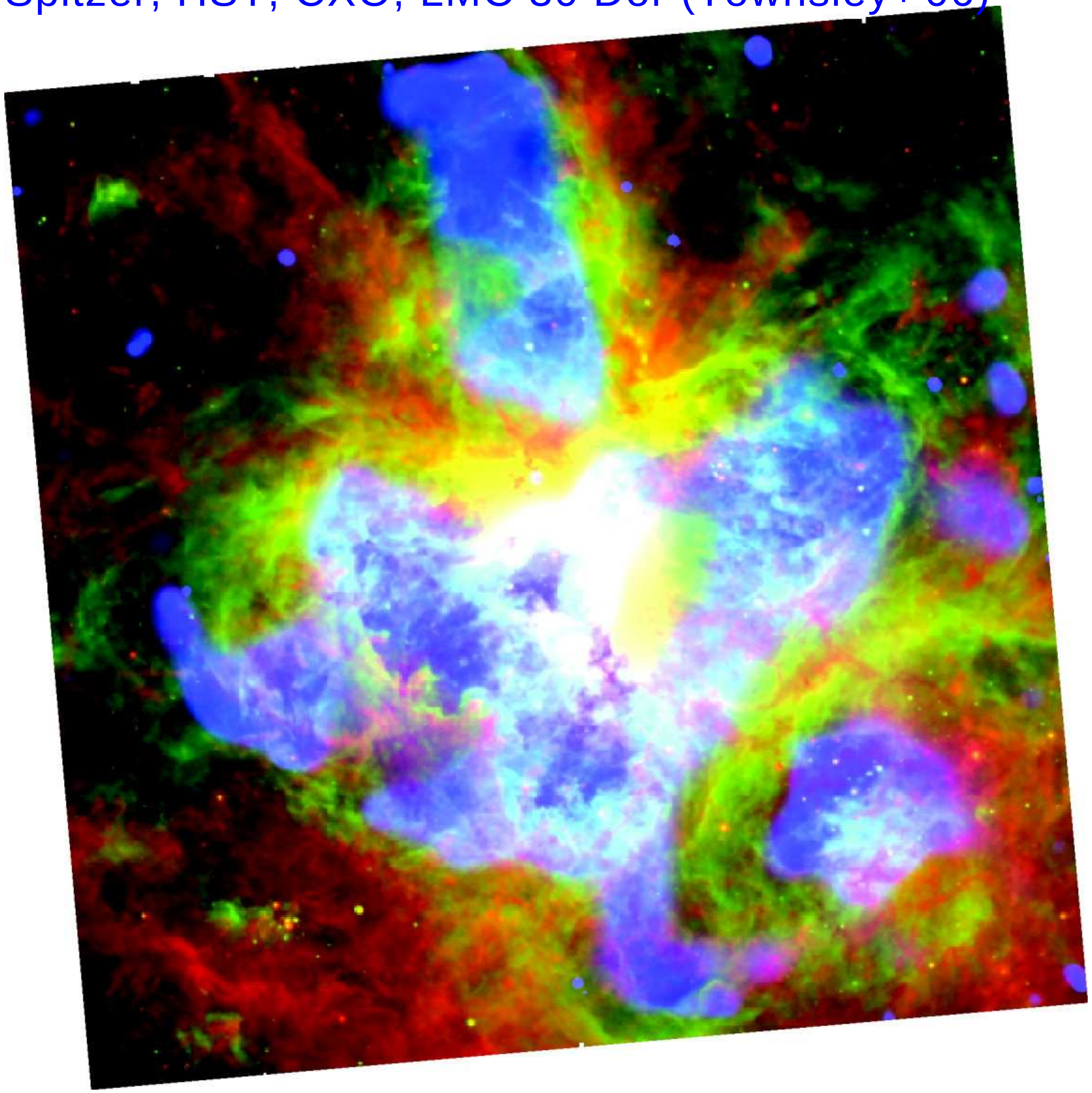
Image courtesy of L. M. Oskinova, R. A. Gruendl, Spitzer Space Telescope,

JPL, NASA

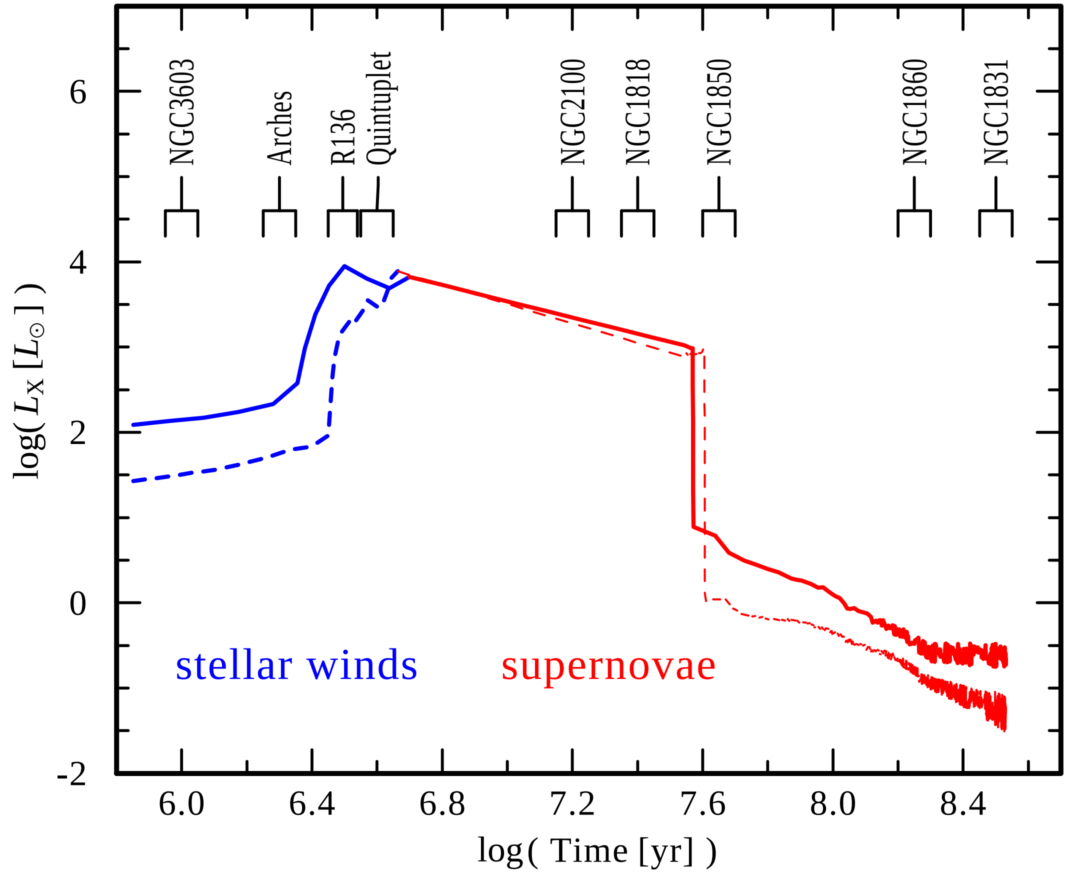
European Space Agency

X-ray observations help to understand feedback

Spitzer, HST, CXO, LMC 30 Dor (Townsley+'06)



Evolution of L_X from cluster wind



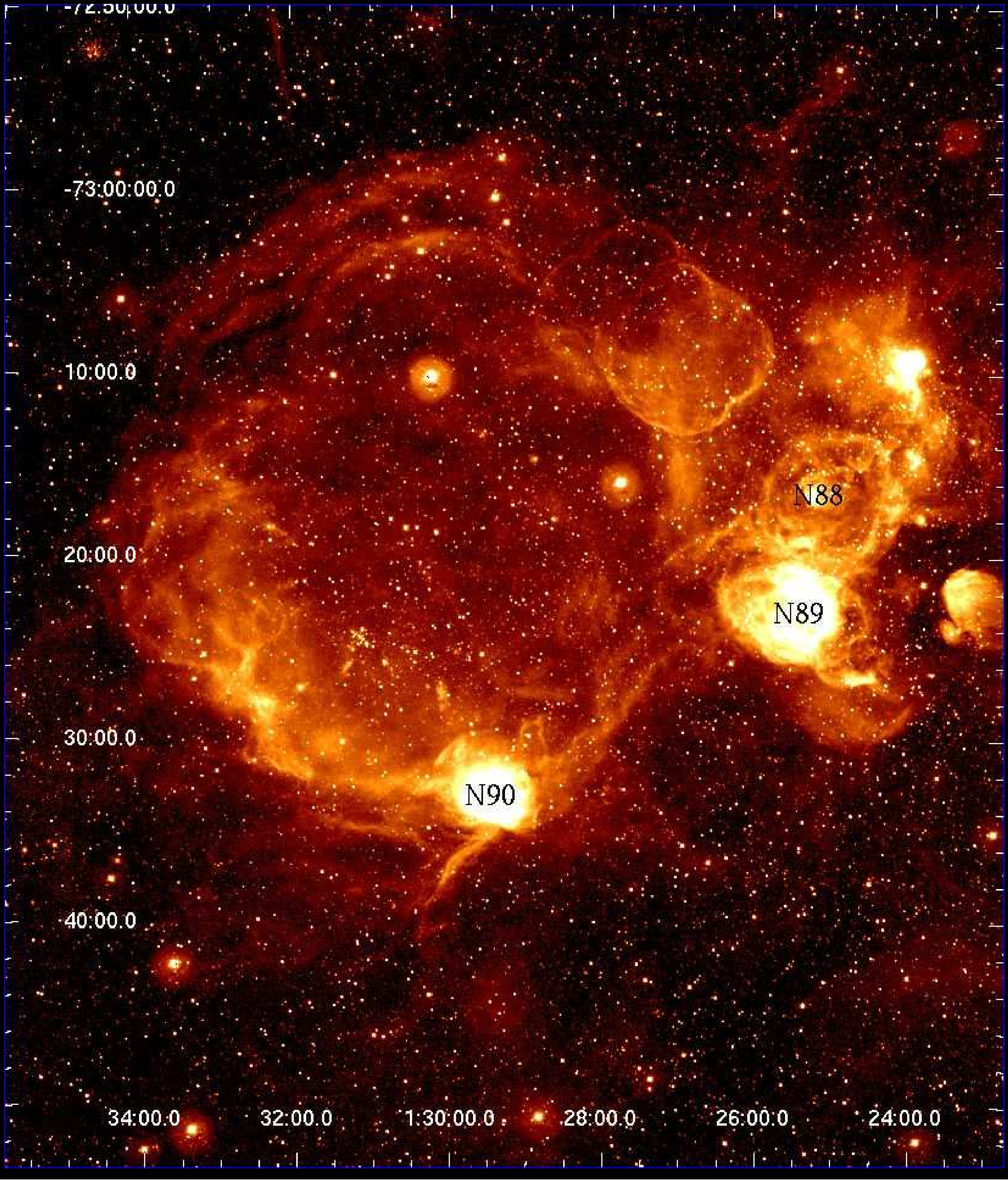
Oskinova 2005

• Spatial correlation of YSO and diffuse X-ray emission • Chemical gradients • Evolution of kinetic energy input • X-ray dating of low-mass stars (perhaps high-mass, too?)

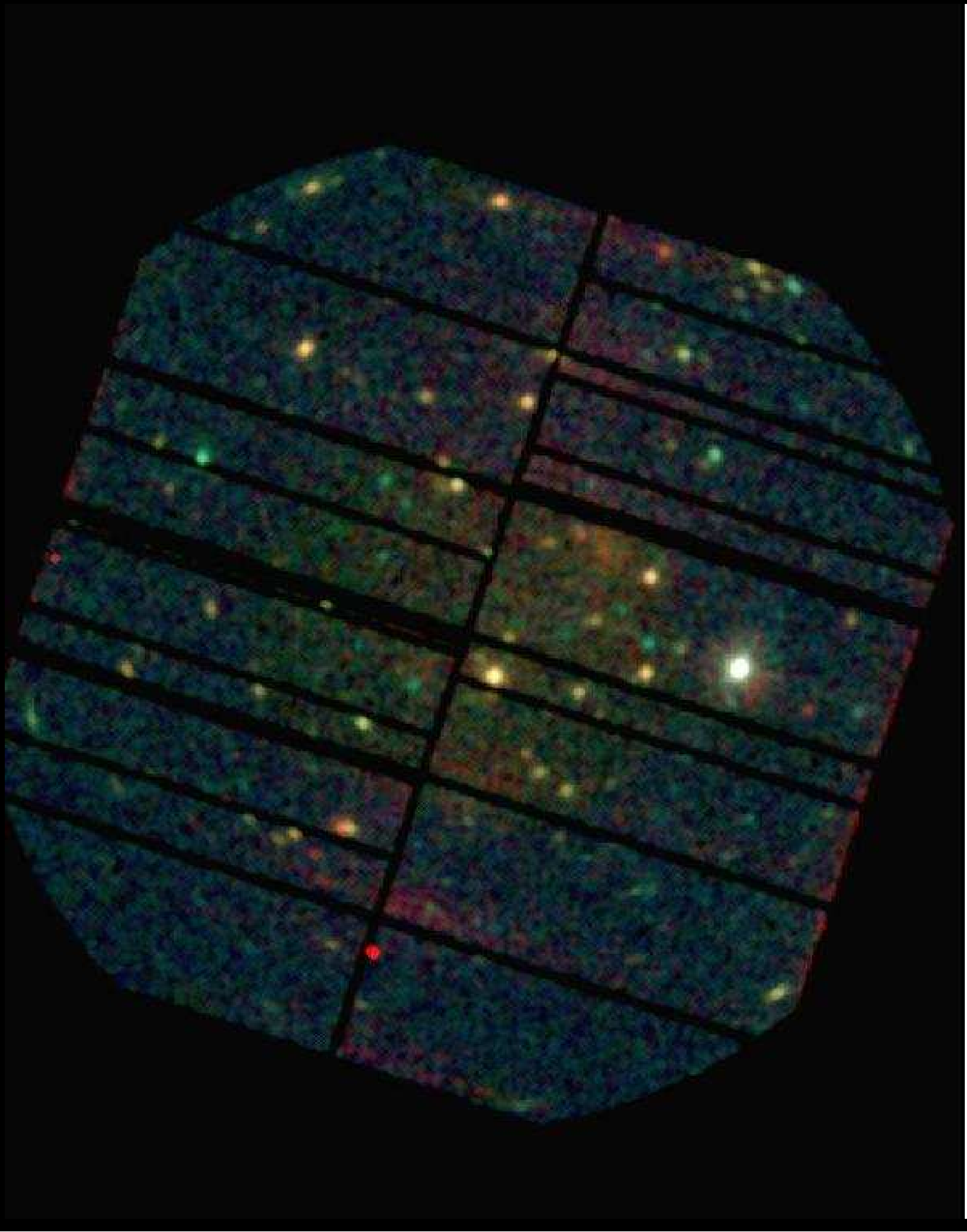
Cosmic archaeology

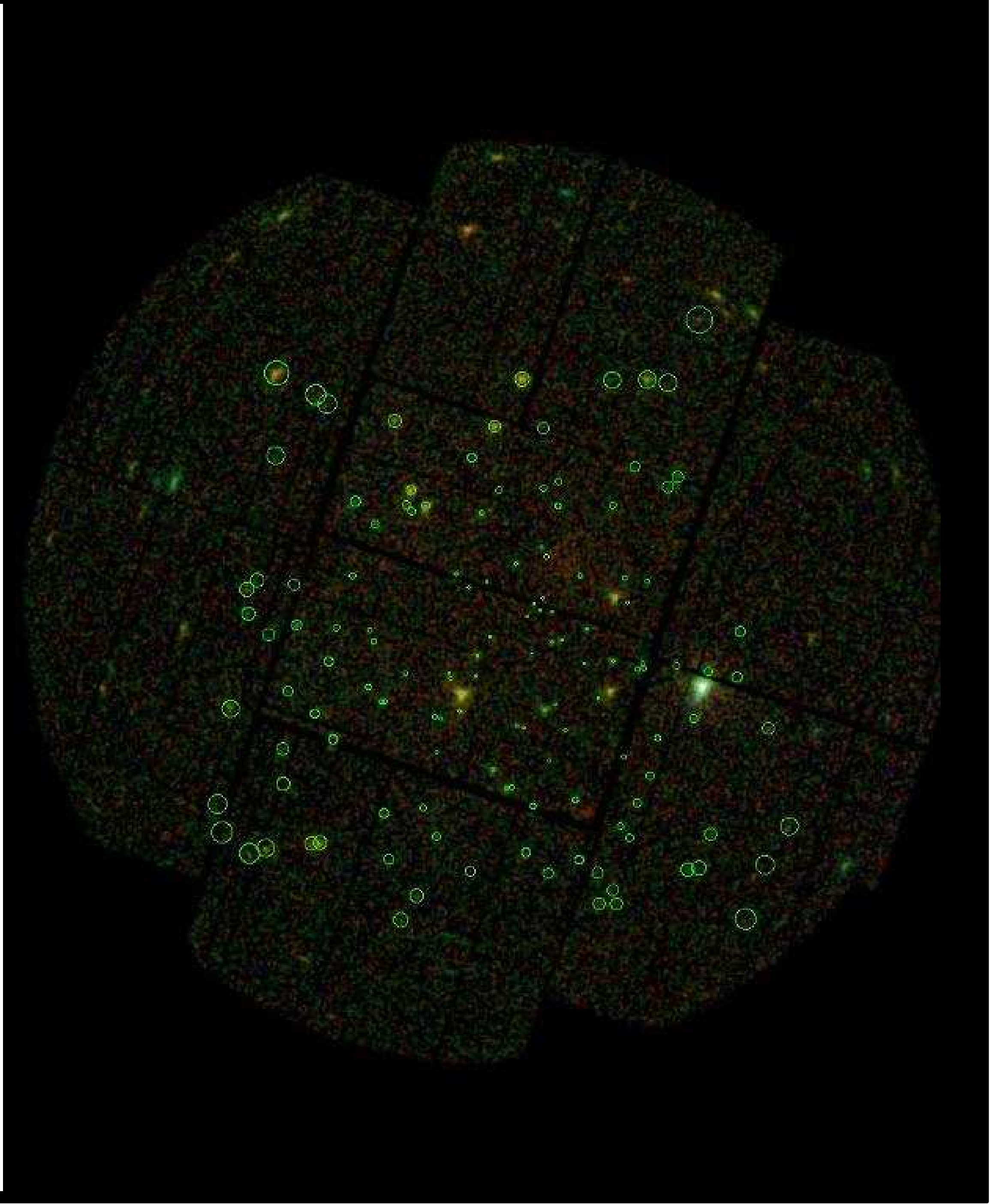
- NGC 602 a massive star cluster (HST image)
- Example of triggered secondary star formation with a large yield
- **X-rays trace hot plasma: how it is connected with star formation?**
- NGC 602 is at the edge of a SUPERGIANT SHELL. Largest structures in the interstellar medium

Supergiant shell in the SMC

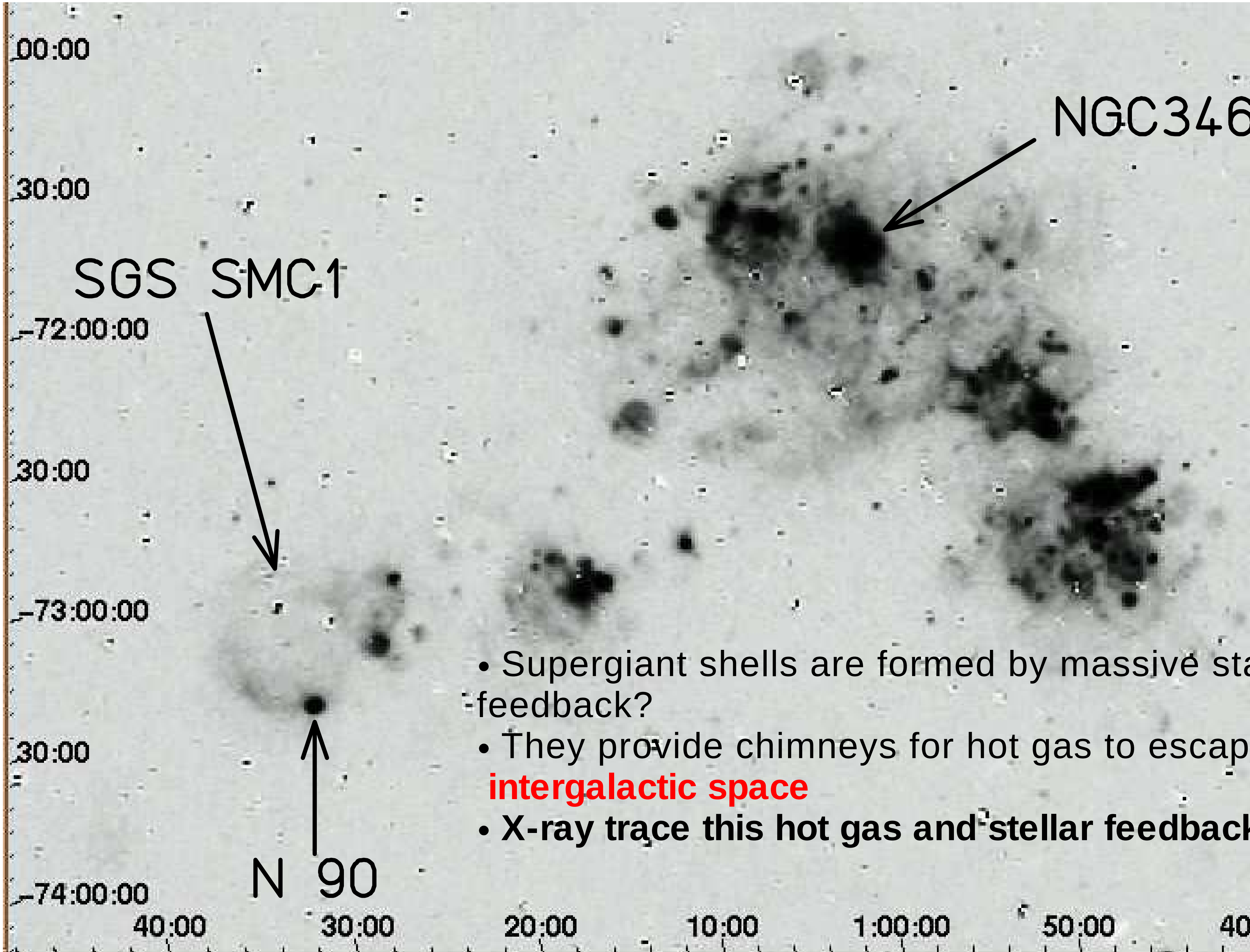


Part of the supergiant shell in the X-rays





From massive stars to structuring galaxies



- Supergiant shells are formed by massive star feedback?
- They provide chimneys for hot gas to escape to **intergalactic space**
- **X-ray trace this hot gas and stellar feedback**

X-ray emission from massive stars: Summary

- Physics: how X-rays are produced in massive stars?
  - Non-stationary processes in stellar winds: shocks, magnetic fields...
- X-ray spectroscopy is a sensitive probe of stellar winds
  - Mass- loss from massive stars is prodigious $10^{-4...-7}\,M_{\odot}$ /yr
  - Poorely known: standard methods need to be improved
  - X-rays: Winds are not stationary and not homogeneous - clumping
- X-ray emission is a sensitive probe of stellar feedback
  - Massive stars strongly affect the ISM by radiative (UV photons) and mechanic (winds) energy input.
  - How kinetic energy feedback affects the ISM and star formation ?