Massive stars in the X-ray light

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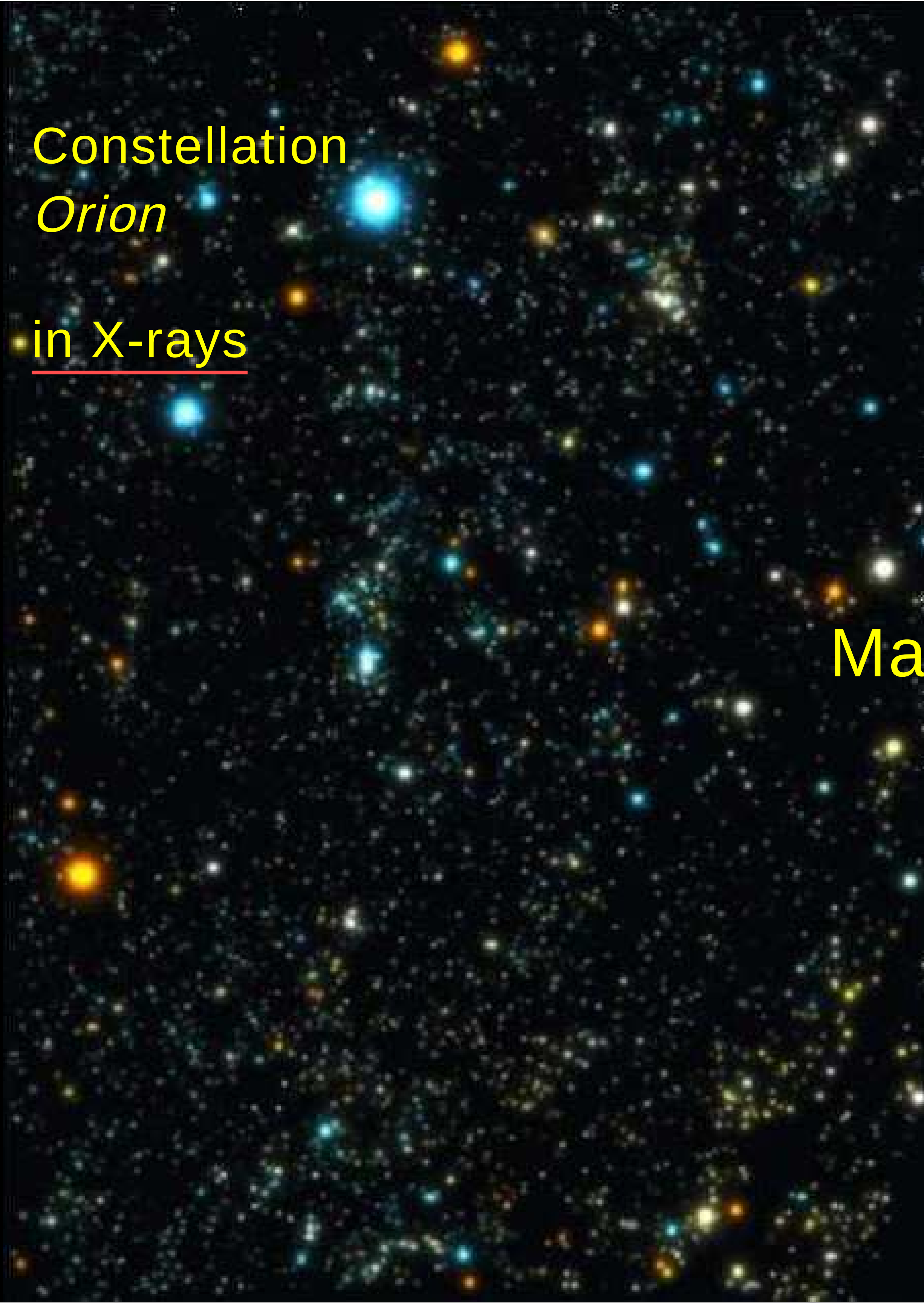
The X-ray Universe 2014

- Massive: $M_{initial} > 8\ M_{\odot}$
- Luminous: $L_{bol} > 10^4\ L_{\odot}$
- Hot: $T_{eff} > 20000$ K
- Young: 1Myr - 100 Myr

Final evolutionary stage:
neutron star or black hole

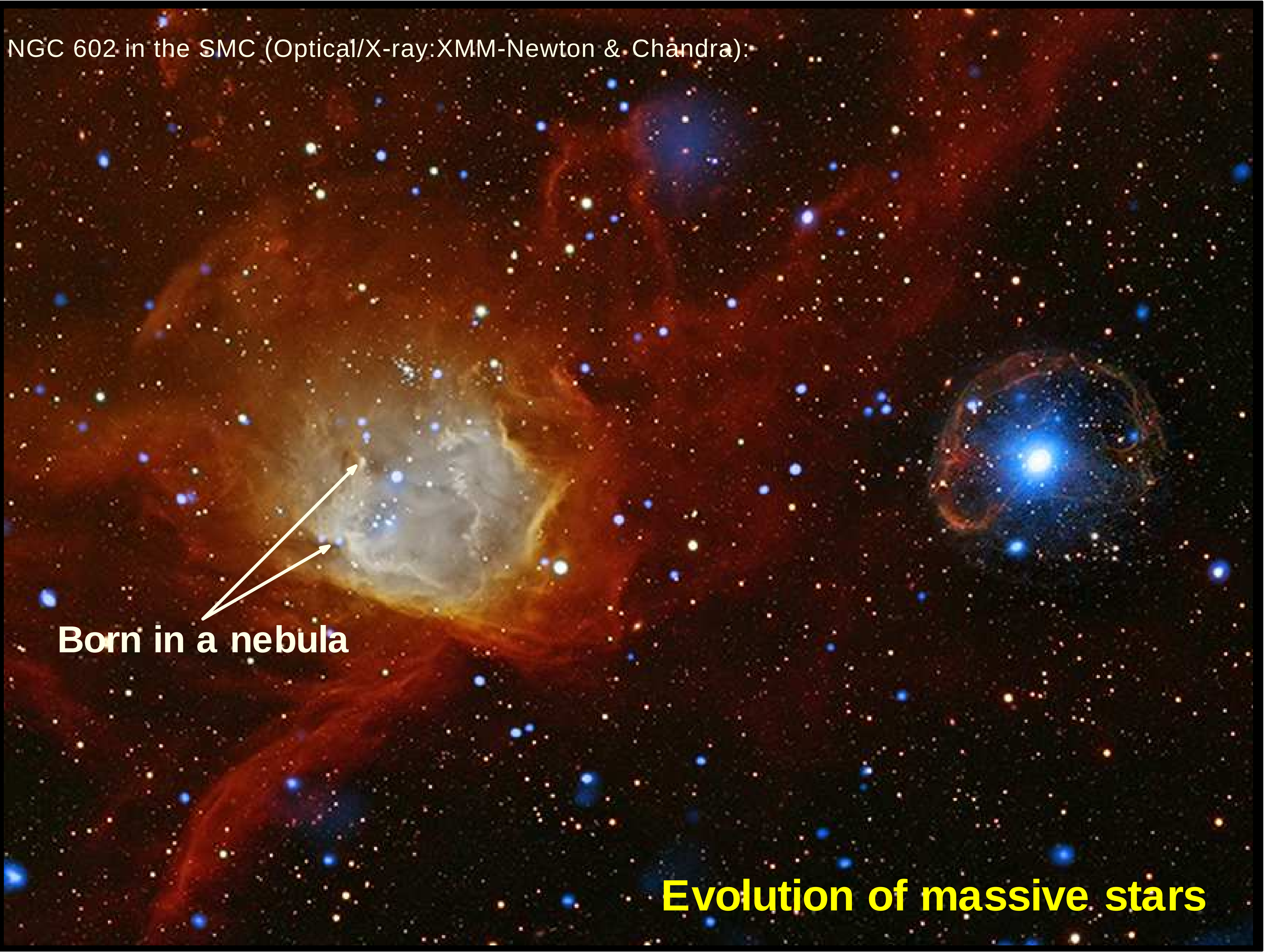
Only 0.4% of all stars

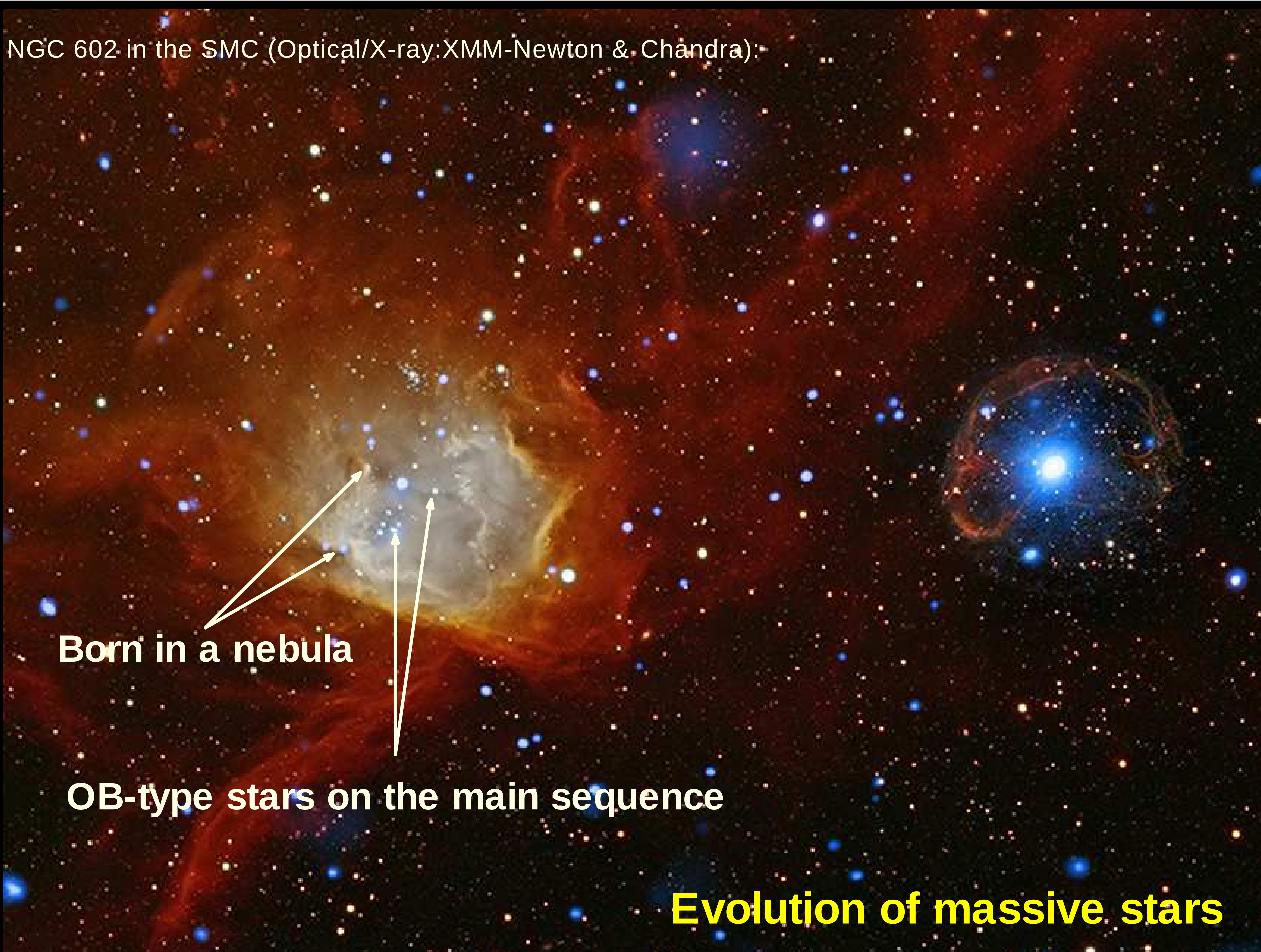


- Hot: T_{eff} > 20000 K

Massive stars emit X-rays

on nearly all stages of their lives


NGC 602 in the SMC (Optical/X-ray:XMM-Newton & Chandra):
Born in a nebula
Evolution of massive stars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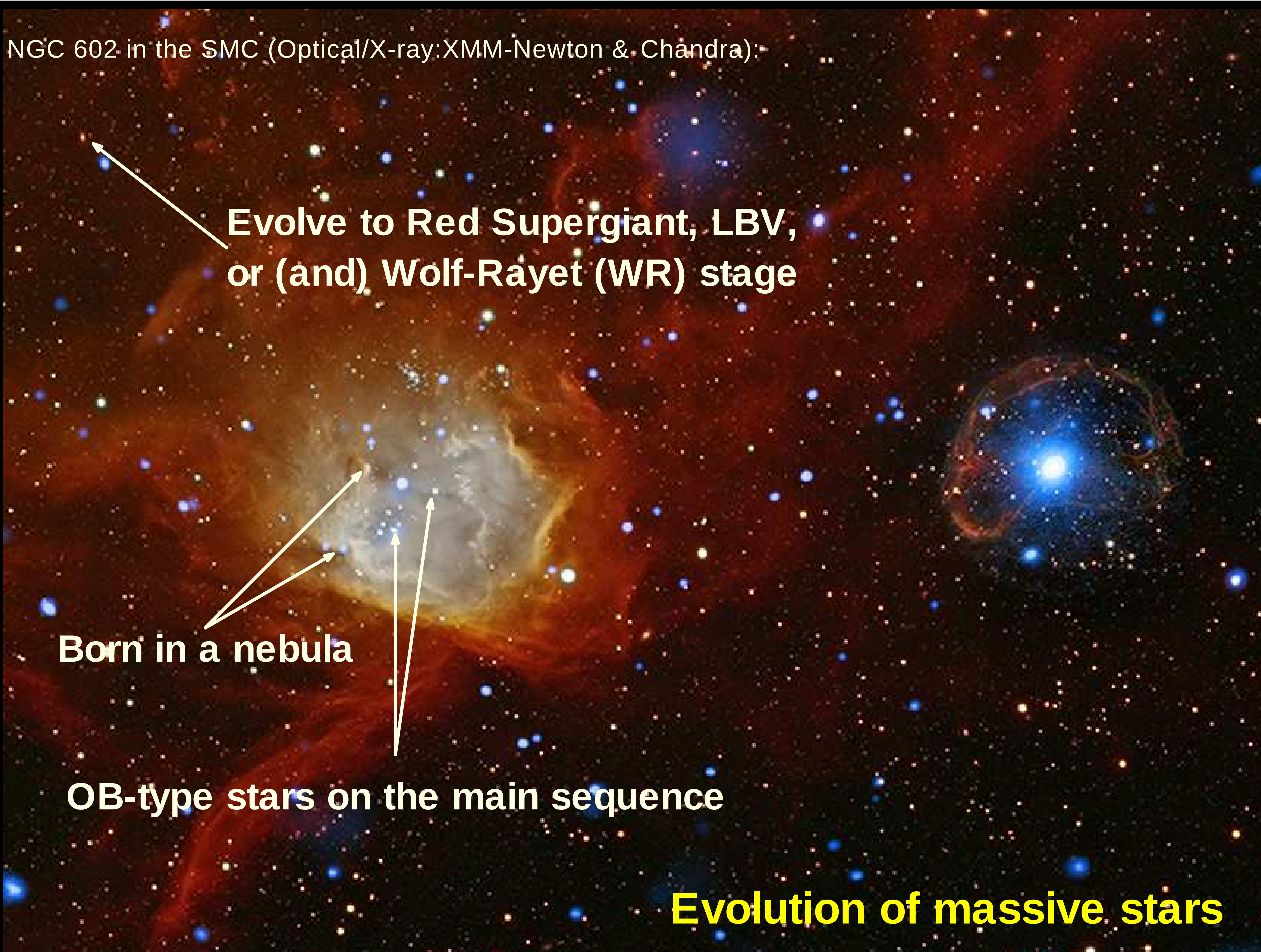
Born in a nebula
OB-type stars on the main sequence
Evolution of massive stars


NGC 602 in the SMC (Optical/X-ray:XMM-Newton & Chandra):
Evolve to Red Supergiant, LBV,
or (and) Wolf-Rayet (WR) stage
Born in a nebula
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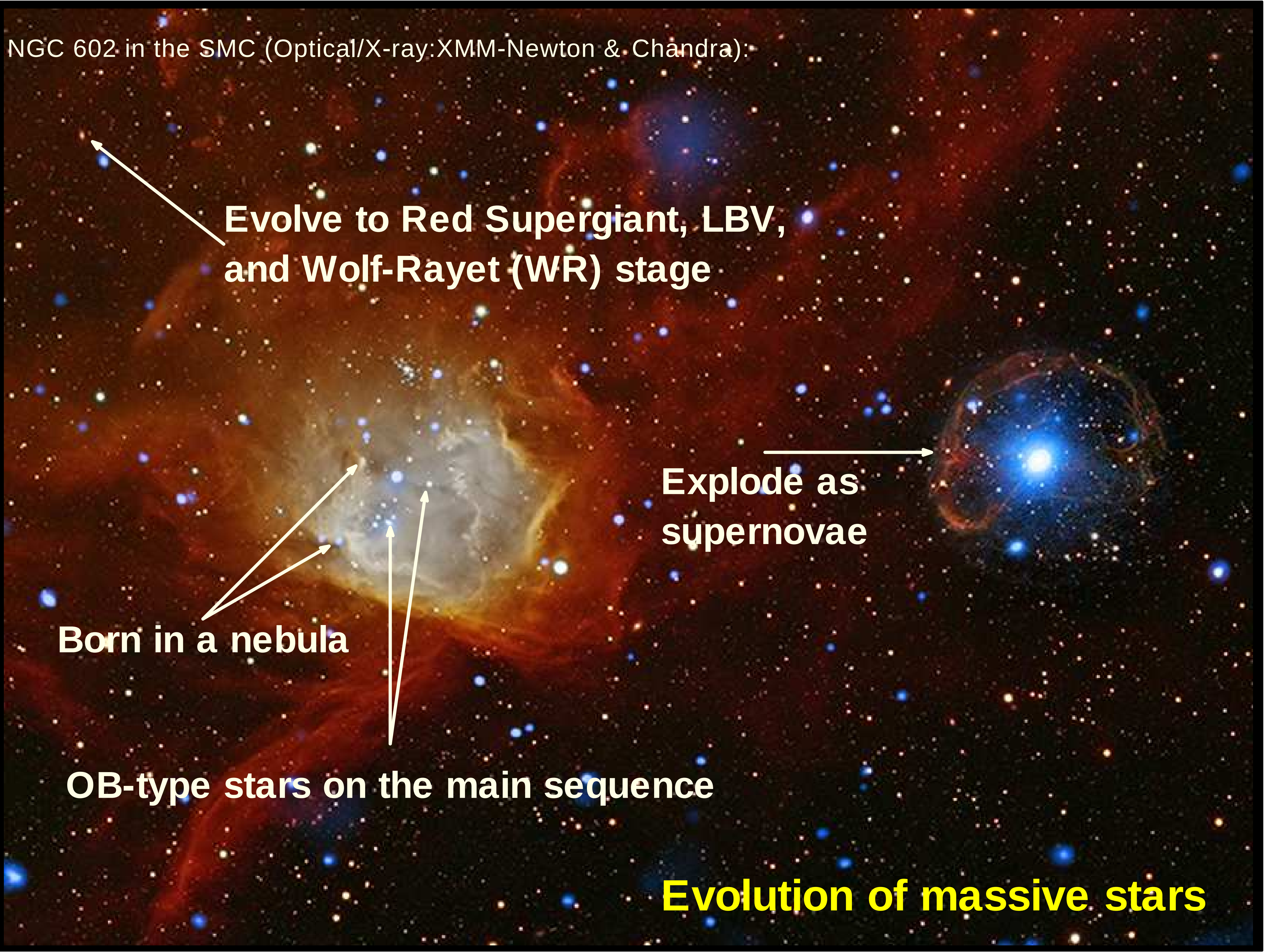
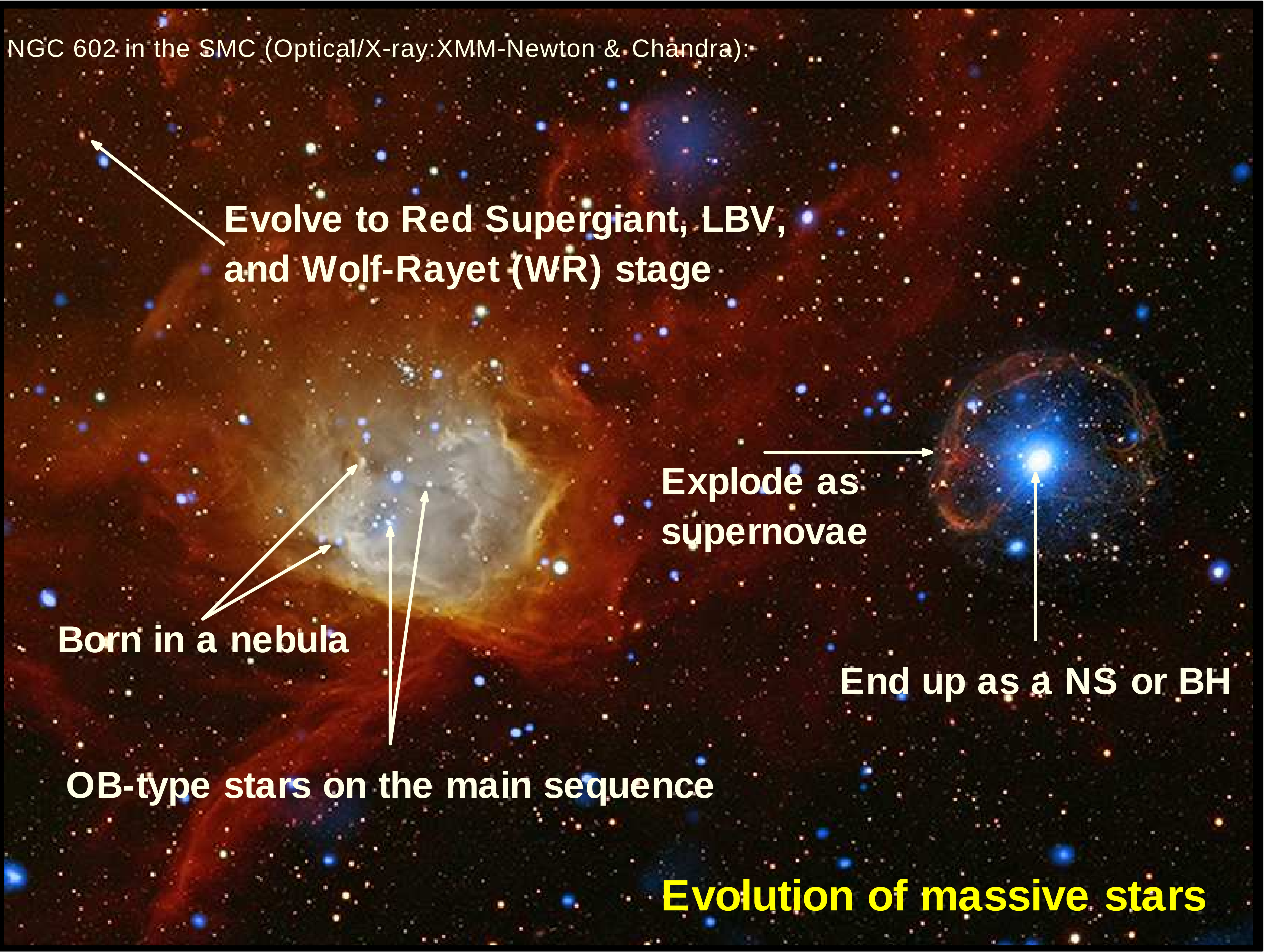
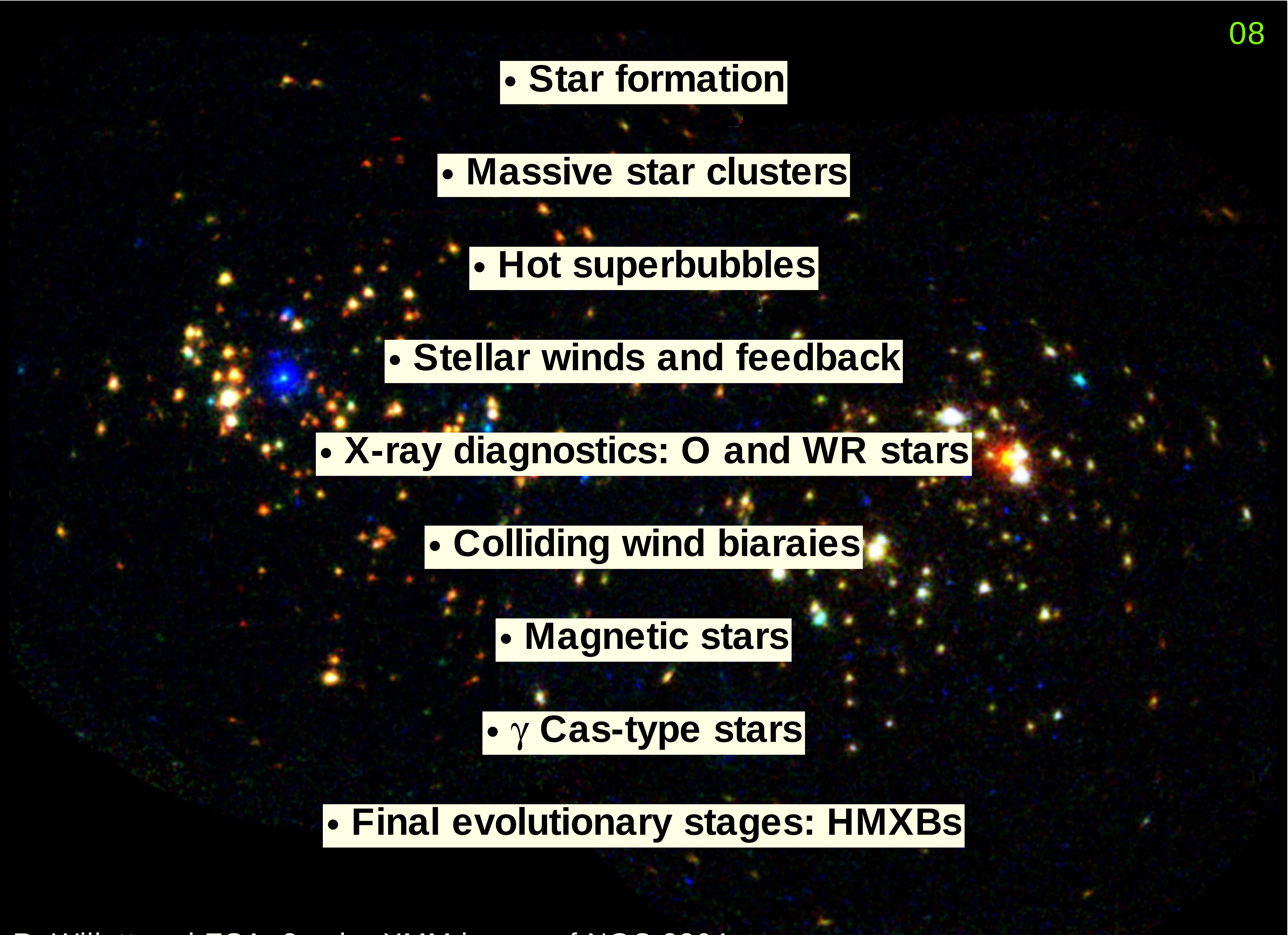

NGC 602 in the SMC (Optical/X-ray:XMM-Newton & Chandra):
Evolve to Red Supergiant, LBV, and Wolf-Rayet (WR) stage
Explode as supernovae
Born in a nebula
OB-type stars on the main sequence
Evolution of massive stars


NGC 602 in the SMC (Optical/X-ray:XMM-Newton & Chandra):
Evolve to Red Supergiant, LBV,
and Wolf-Rayet (WR) stage
Explode as
supernovae
Born in a nebula
End up as a NS or BH
OB-type stars on the main sequence
Evolution of massive stars

- Star formation
- Massive star clusters
- Hot superbubbles
- Stellar winds and feedback
- X-ray diagnostics: O and WR stars
- Colliding wind biaraies
- Magnetic stars
- γ Cas-type stars
- Final evolutionary stages: HMXBs



R. Willatt and ESA: 3 color XMM image of NGC 2264

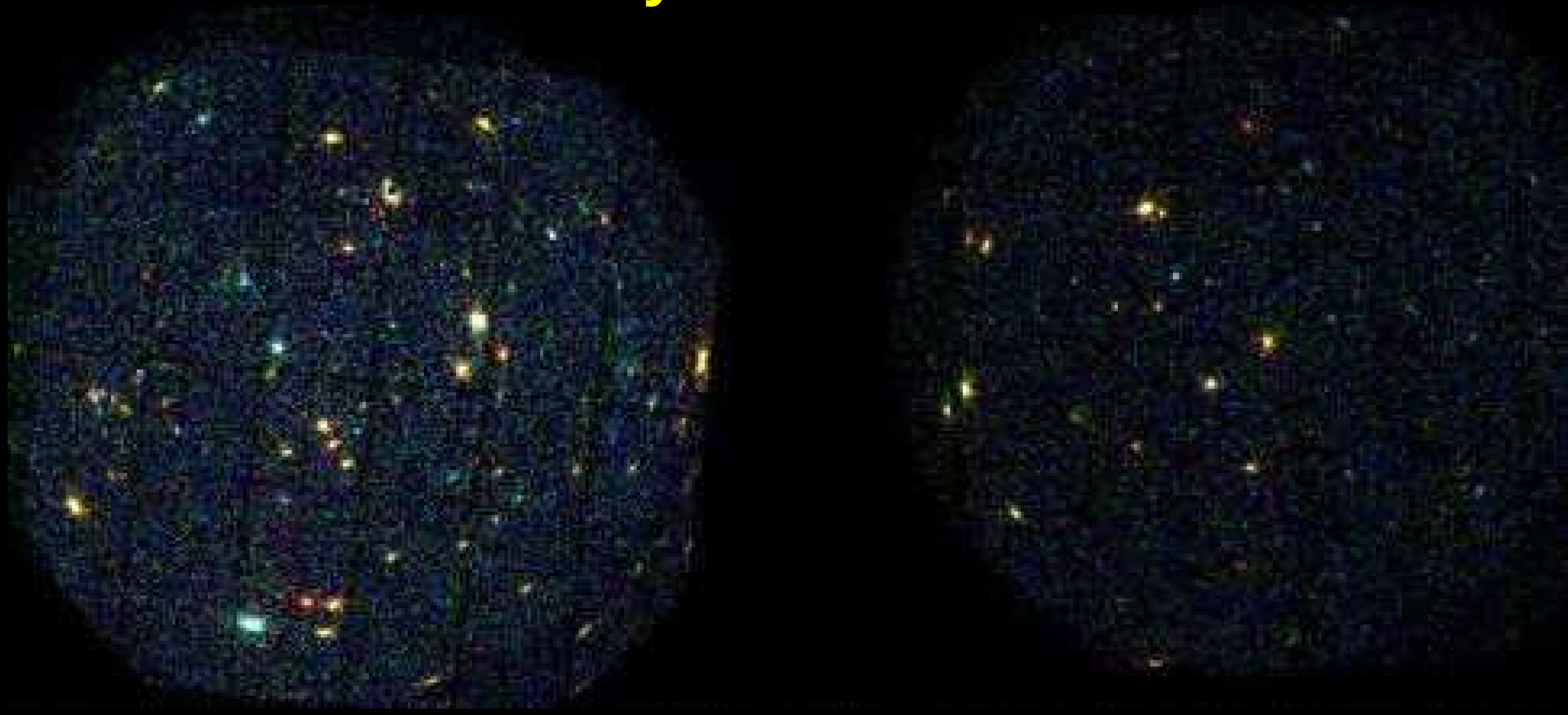
Eagle Nebula (Herschel IR/X-ray XMM-Newton: ESA/Boulanger)

Massive star formation

X-rays: Herbig-Haro objects (Lopez-Santiago+ 2013; Bonito+ 2010, 2011; Schneider+ 2011)

X-rays: massive protostars (Pravdo+ 2009; Anderson+ 2011; Munar-Adrover+ 2013) north and east fields in λ Orionis cluster (XMM-Newton, Barrado+ 2011)

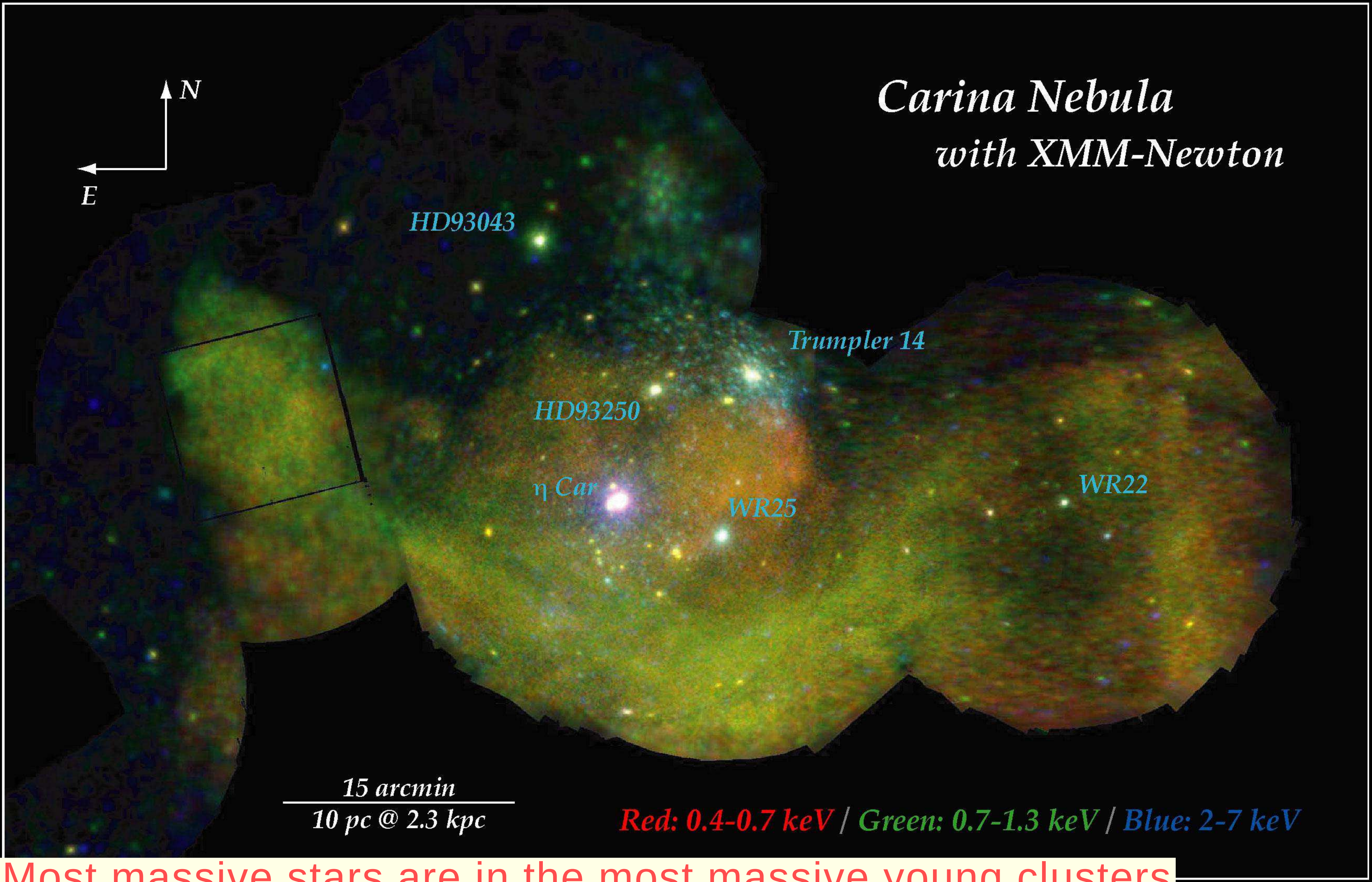
X-rays: studies of low-mass star populations in vicinity of massive stars



X-ray T Tau (Jeffries+ 2009; Naylor+ 2009; Franciosini+ 2011)

Do low-mass stars form earlier or later than the massive ones?

Clusters of massive stars

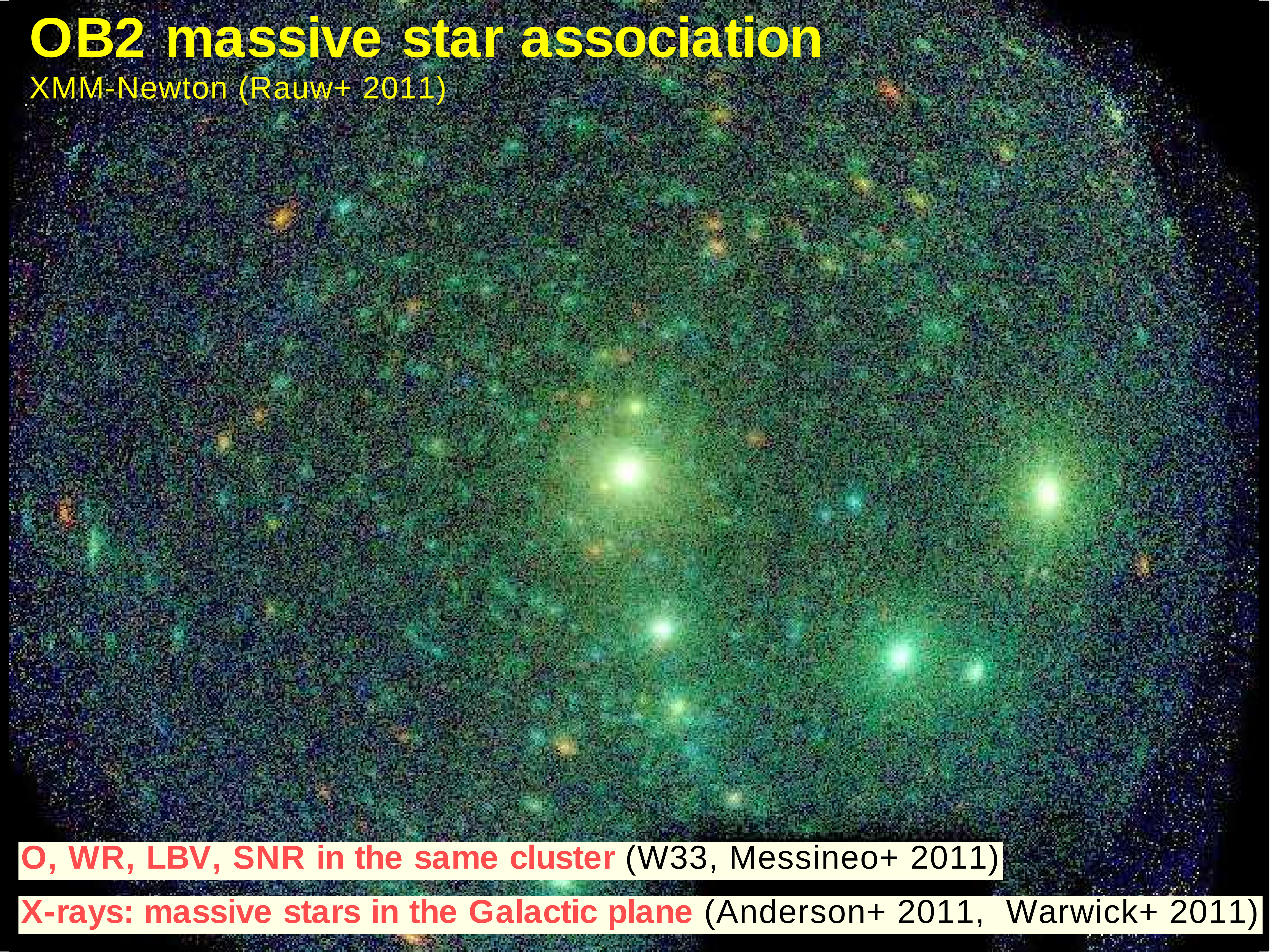


Most massive stars are in the most massive young clusters

For an OB star $L_X \approx 10^{-7} L_{bol}$ (Pallavicini+ 1981; Berghoefer+ 1997;Sana+ 2006; Naze 2009...)

OB2 massive star association

XMM-Newton (Rauw+ 2011)



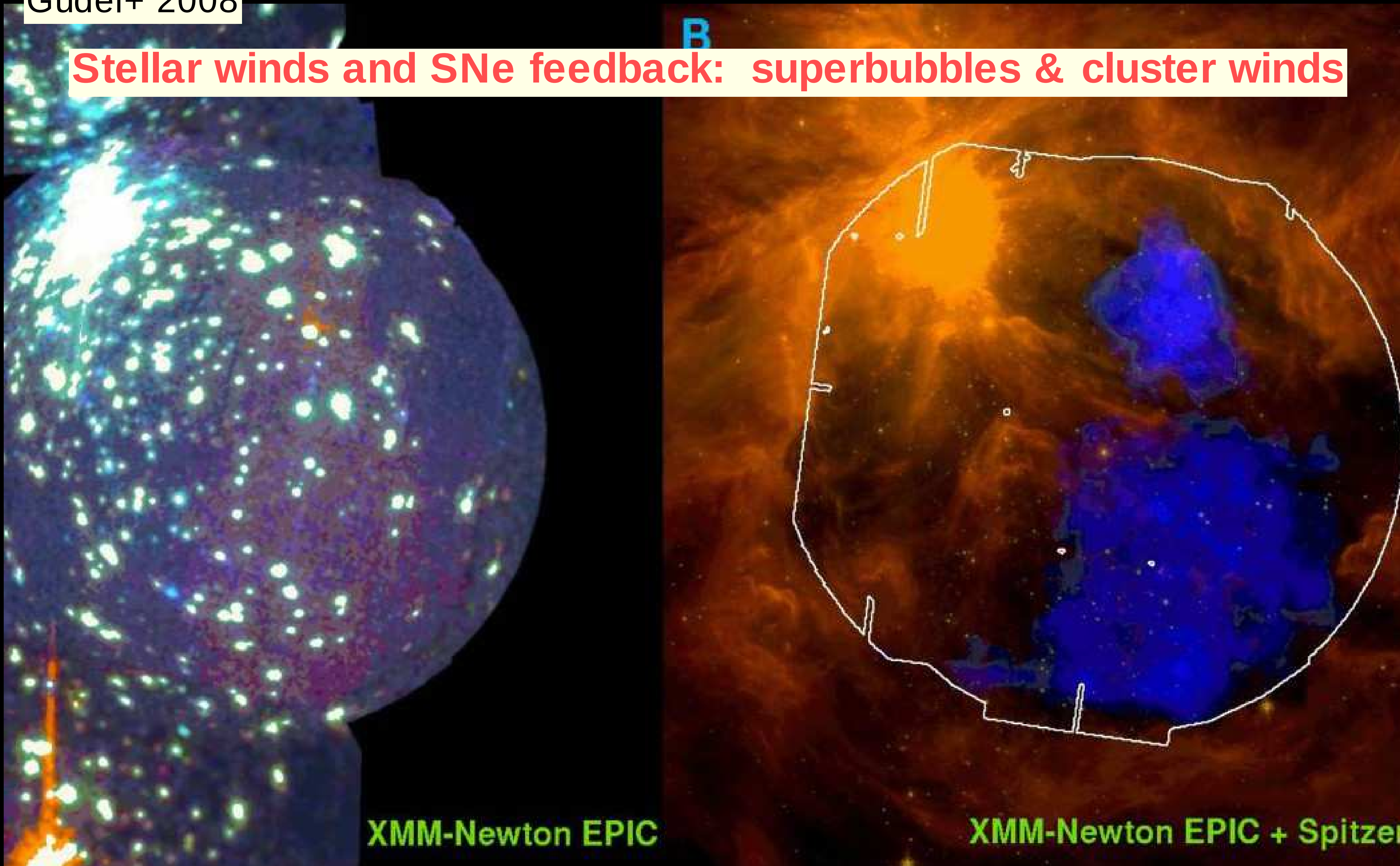
O, WR, LBV, SNR in the same cluster (W33, Messineo+ 2011)

X-rays: massive stars in the Galactic plane (Anderson+ 2011, Warwick+ 2011)

Million-Degree Plasma Pervading the Orion Nebula

Güdel+ 2008

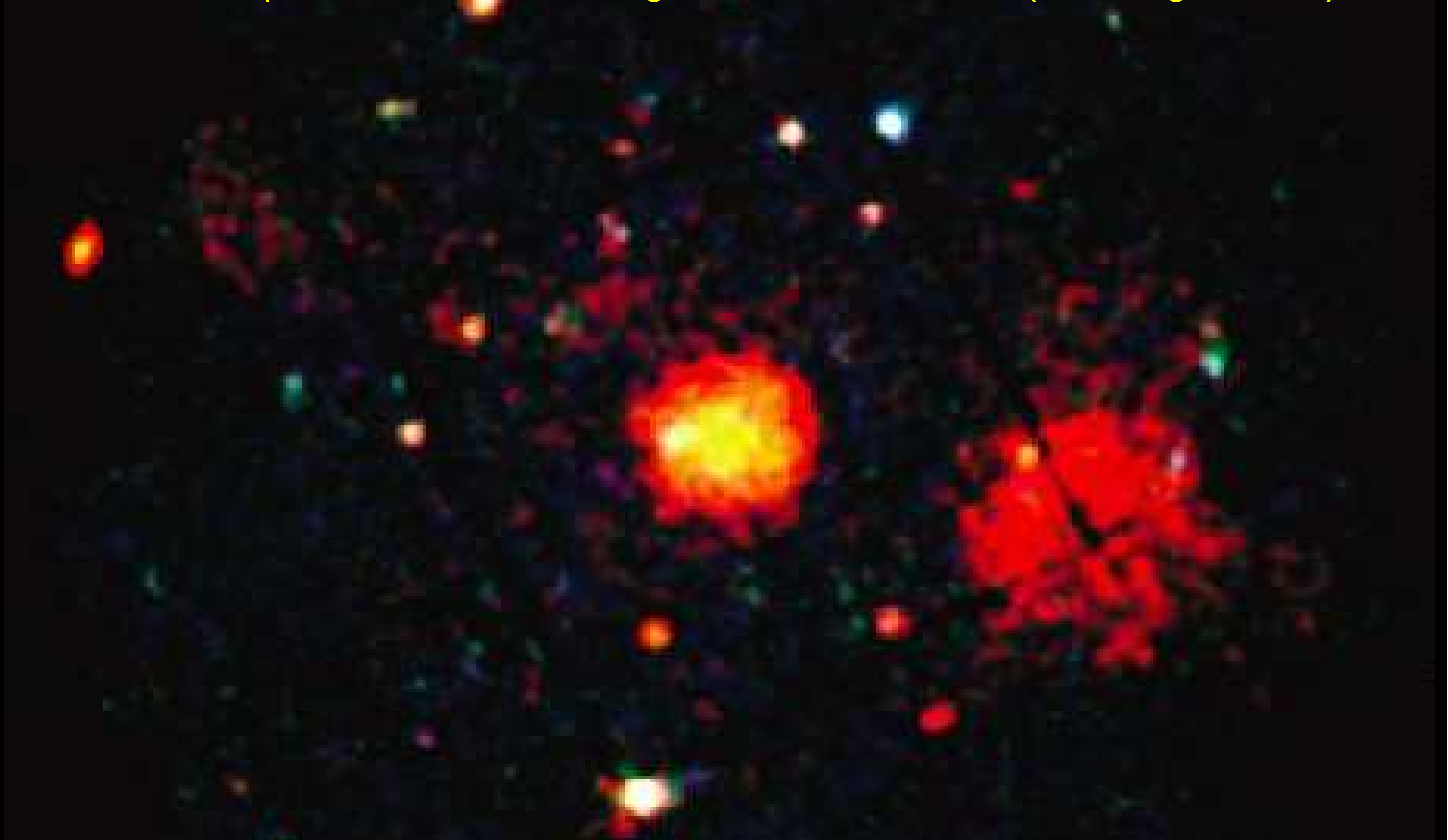
Stellar winds and SNe feedback: superbubbles & cluster winds



Townsley+ 2011; Rodriguez-Gonzalez+ 2011; Arthur 2012, Silich+ 2013; Roger & Pittard 2014; Krause+ 2014

Diffuse X-rays are well observed in the LMC

SNR and a superbubble in the HII region N206 in the LMC (Kavanagh+ 2012)

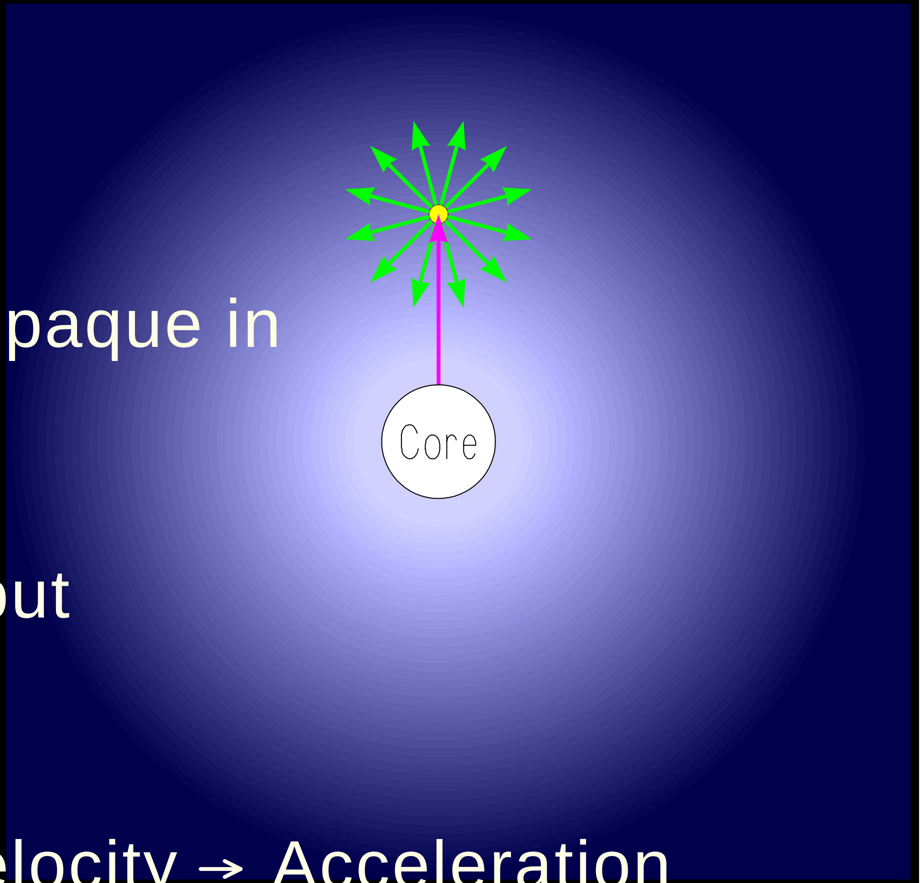


Type of equilibrium CIE vs NEI? The heating and cooling processes?

Does steller feedback provide enough energy to heat superbubbles?

Line-driven stellar winds

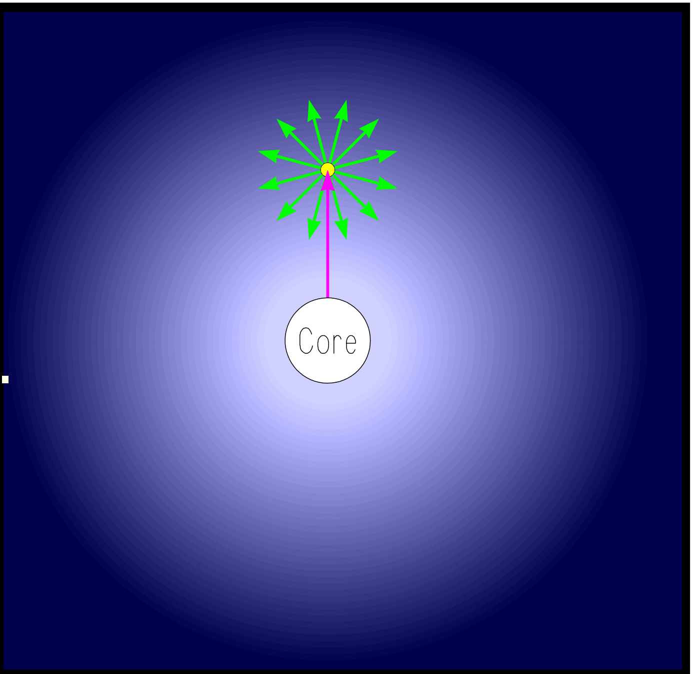
(Castor, Abbott & Klein 1975, “CAK”)

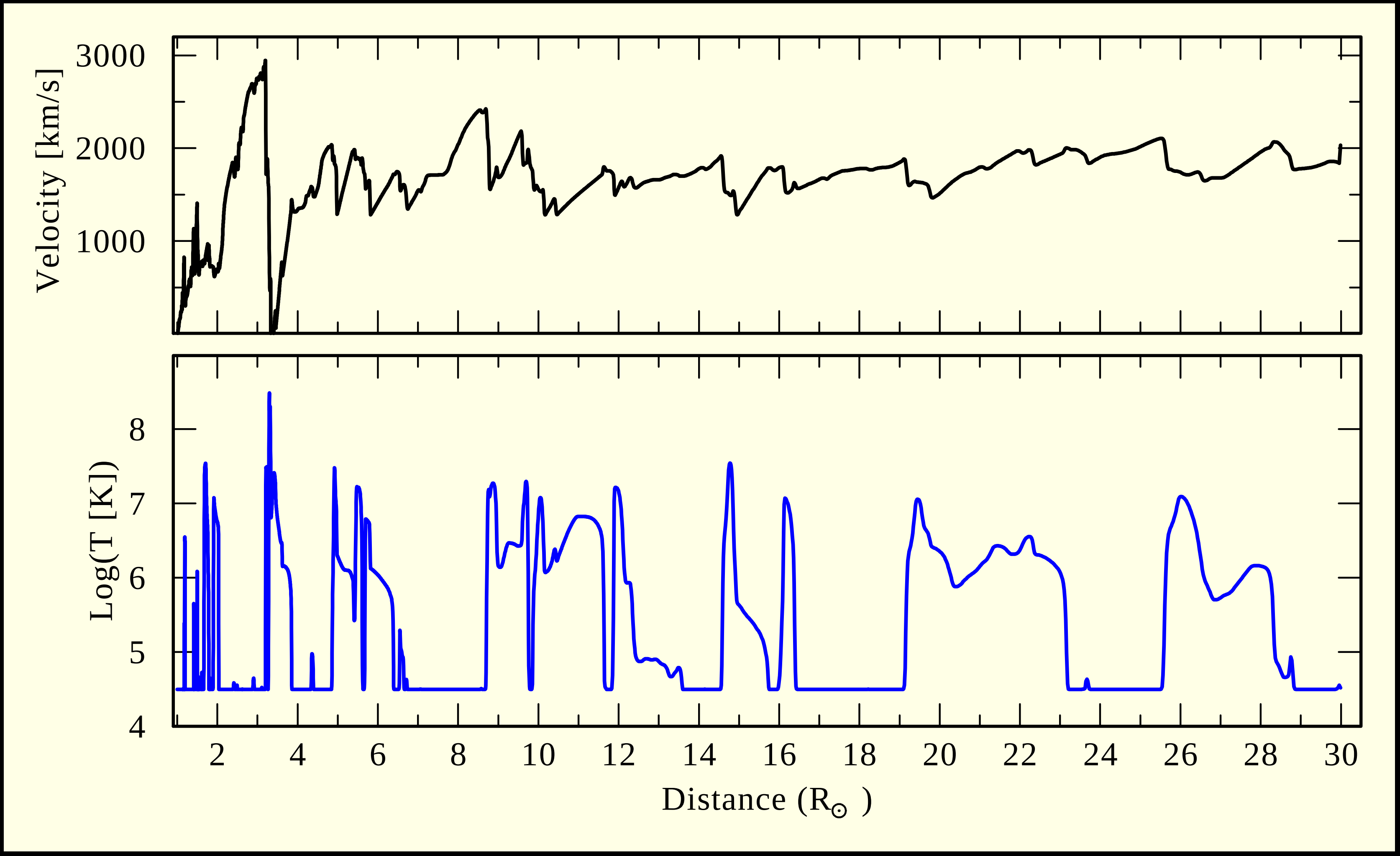


- Atmosphere transparent in continuum, opaque in many spectral lines
- UV photon comes from radial direction but scattered isotropically
- Momentum transfer → Acceleration → Velocity → Acceleration

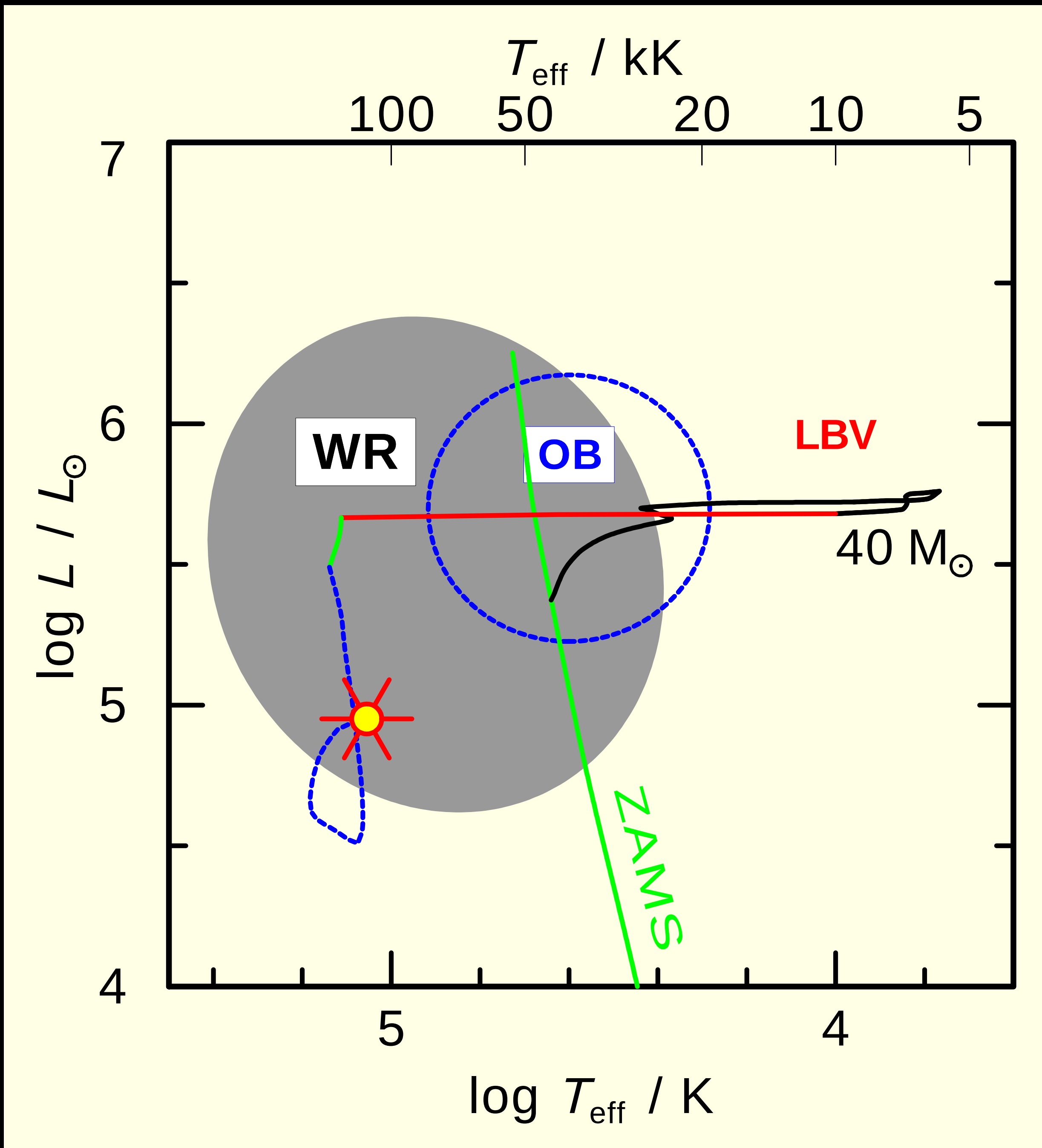
Theories of stellar wind instability

- Lucy & Solomon (1970): stellar winds are radiatively driven; **this mechanism is unstable.**
- Radiative Hydrodynamics: Wind shocks (Owocki+ 1983, Feldmeier+ 1997) → X-ray





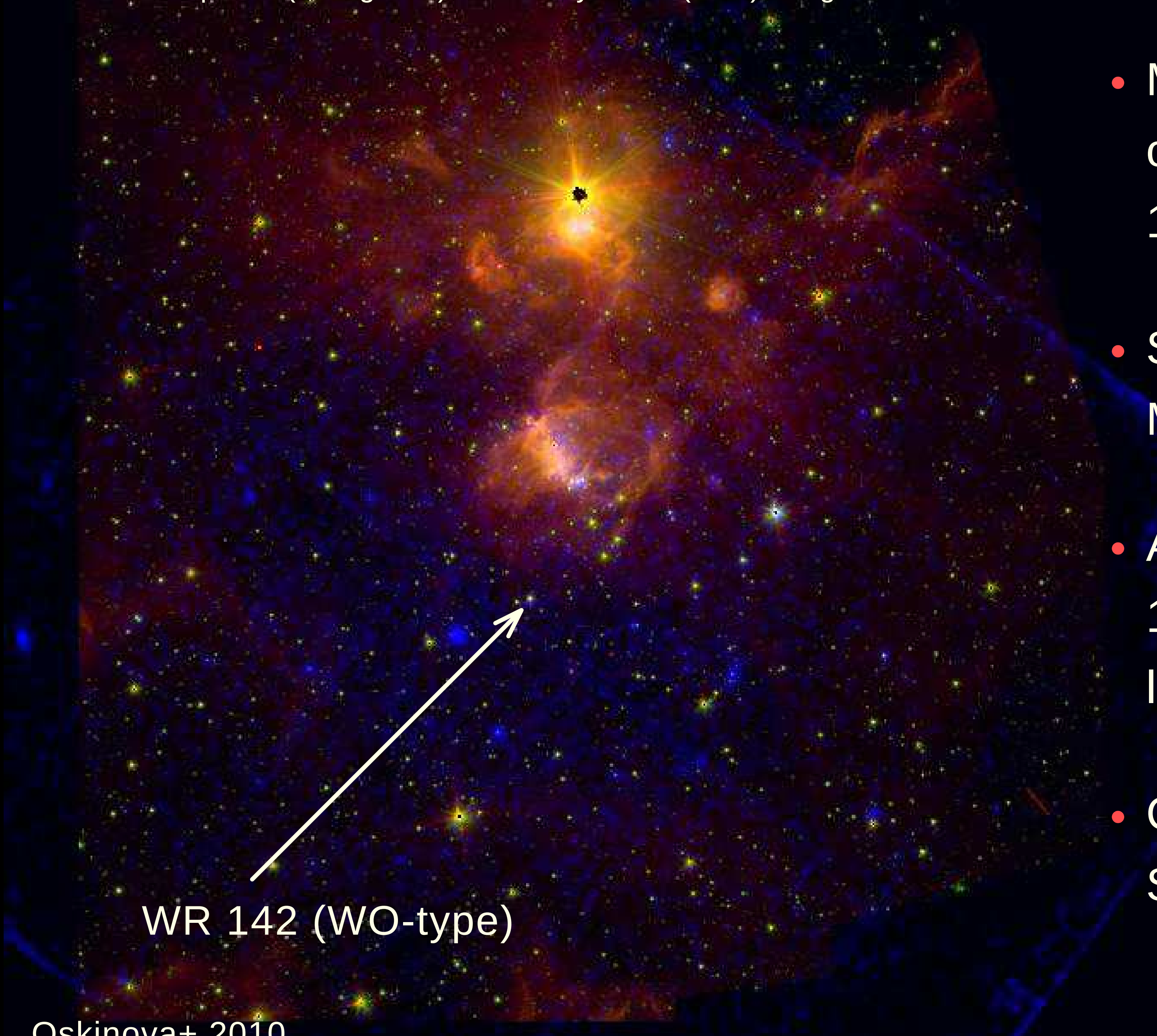
Mass removal by wind drives the evolution



$\dot{M}$ is a critical factor of stellar evolution

$$\dot{M}_{\rm CAK} \approx 10^{-6} - 10^{-5} M_\odot {\rm yr}^{-1}$$

Stellar wind feedback



Combined Spitzer (red+green) and X-ray EPIC (blue) image of the SFR ON 2

Oskinova+ 2010

- Mechanical energy of a wind: up to 10^{38} erg/s
- Stellar life-time: few Myr
- A star deposits ~ 10^{52} erg during its life-time!
- Comparable to to SN output

Stellar Winds

Ubiquitous in hot non-degenerate stars

Strongly affect the ISM

Spitzer IRAC image of ζ Oph (Hubrig, Oskinova, Schöller 2011)

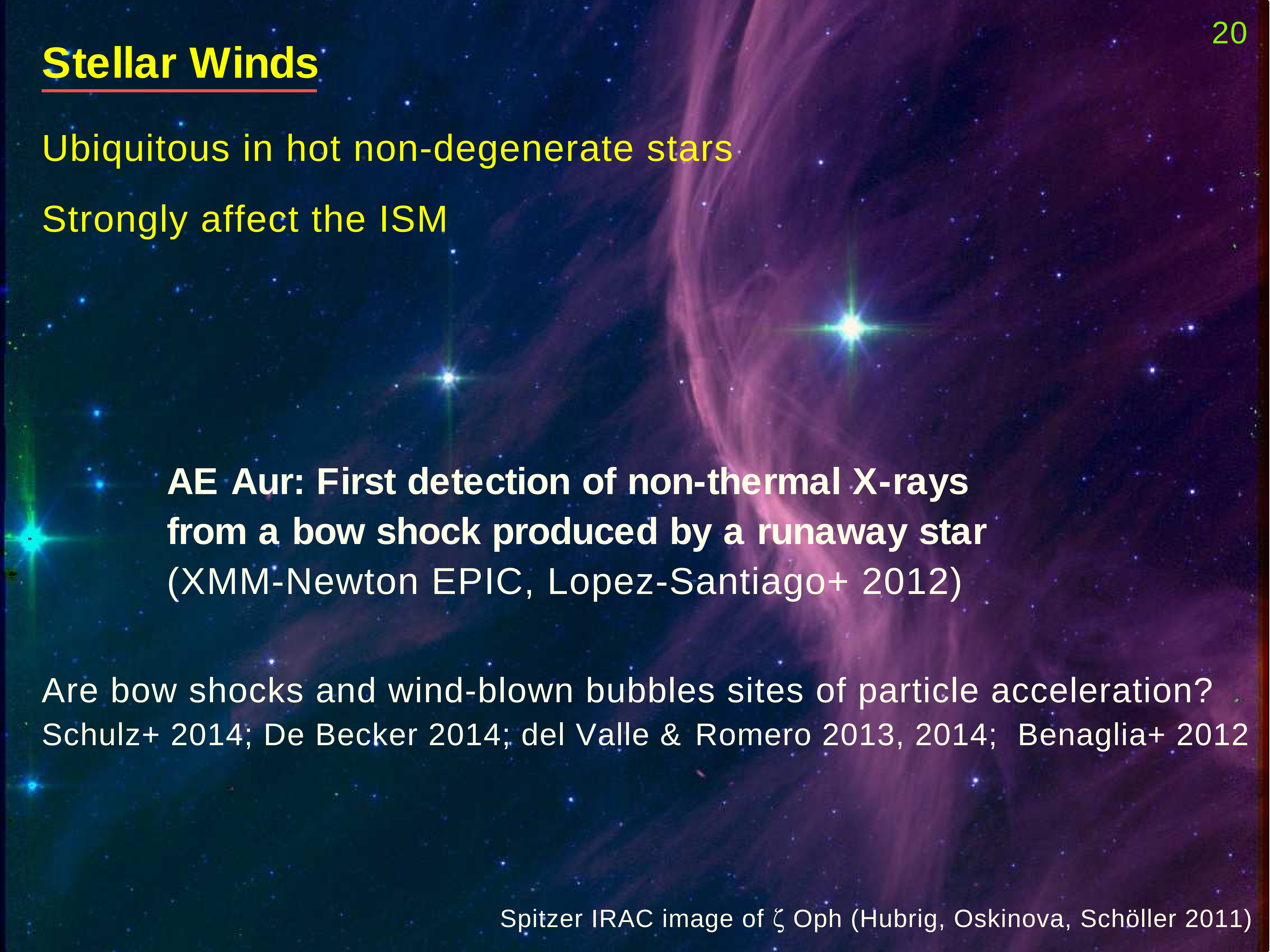
Stellar Winds

Ubiquitous in hot non-degenerate stars

Strongly affect the ISM

AE Aur: First detection of non-thermal X-rays from a bow shock produced by a runaway star
(XMM-Newton EPIC, Lopez-Santiago+ 2012)

Are bow shocks and wind-blown bubbles sites of particle acceleration?
Schulz+ 2014; De Becker 2014; del Valle & Romero 2013, 2014; Benaglia+ 2012



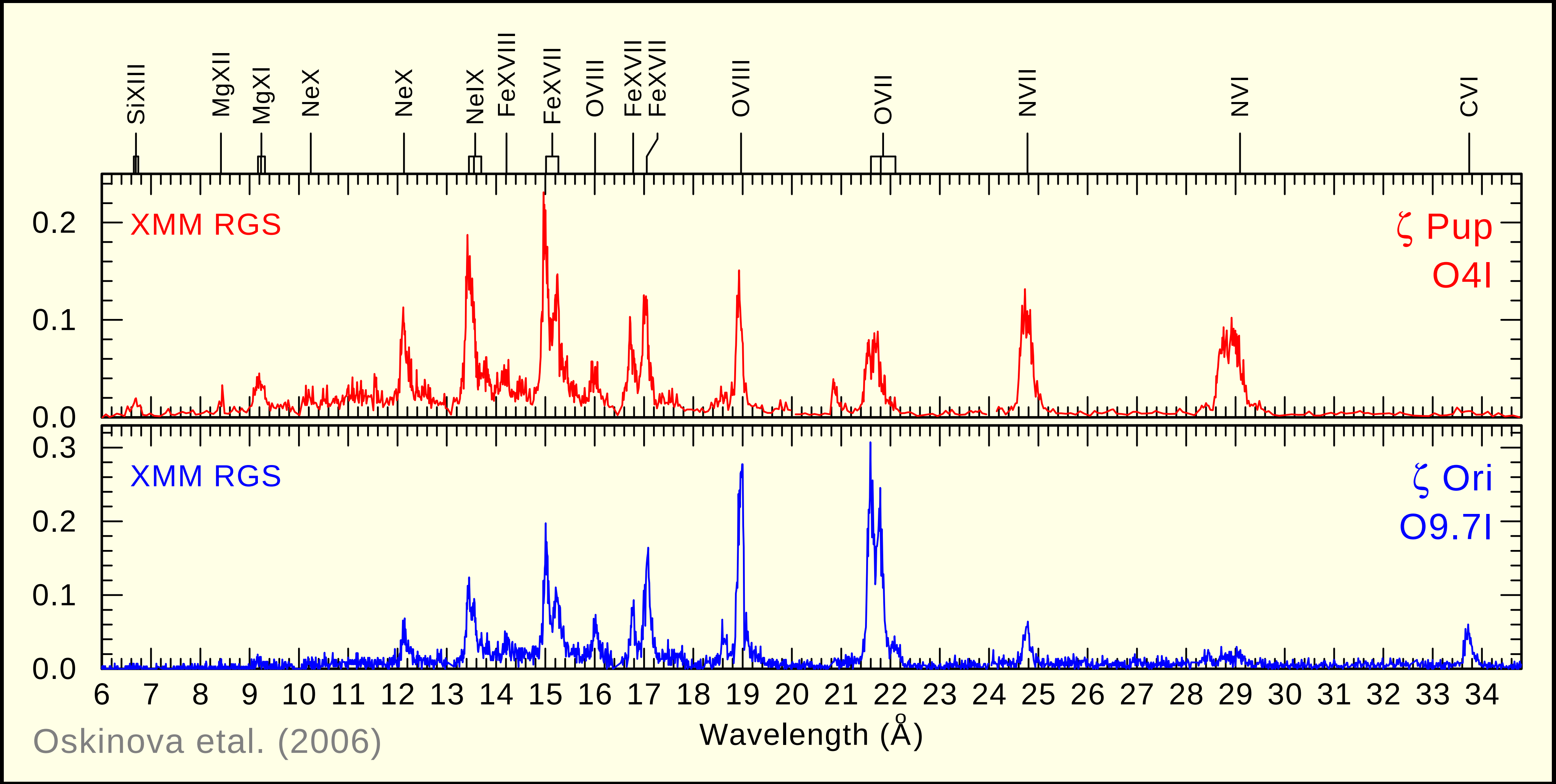
Spitzer IRAC image of ζ Oph (Hubrig, Oskinova, Schöller 2011)

Wind Blown Bubble S308 around the WR star EZ CMa

Toala+ 2012 (Soft X-rays 1MK, limb brighten morphology)

van Marle & Keppens 2012; Dwarkadas+ 2007; Toala & Arthur 2011; Zhekov 2014

X-ray diagnostics of stellar winds: RGS



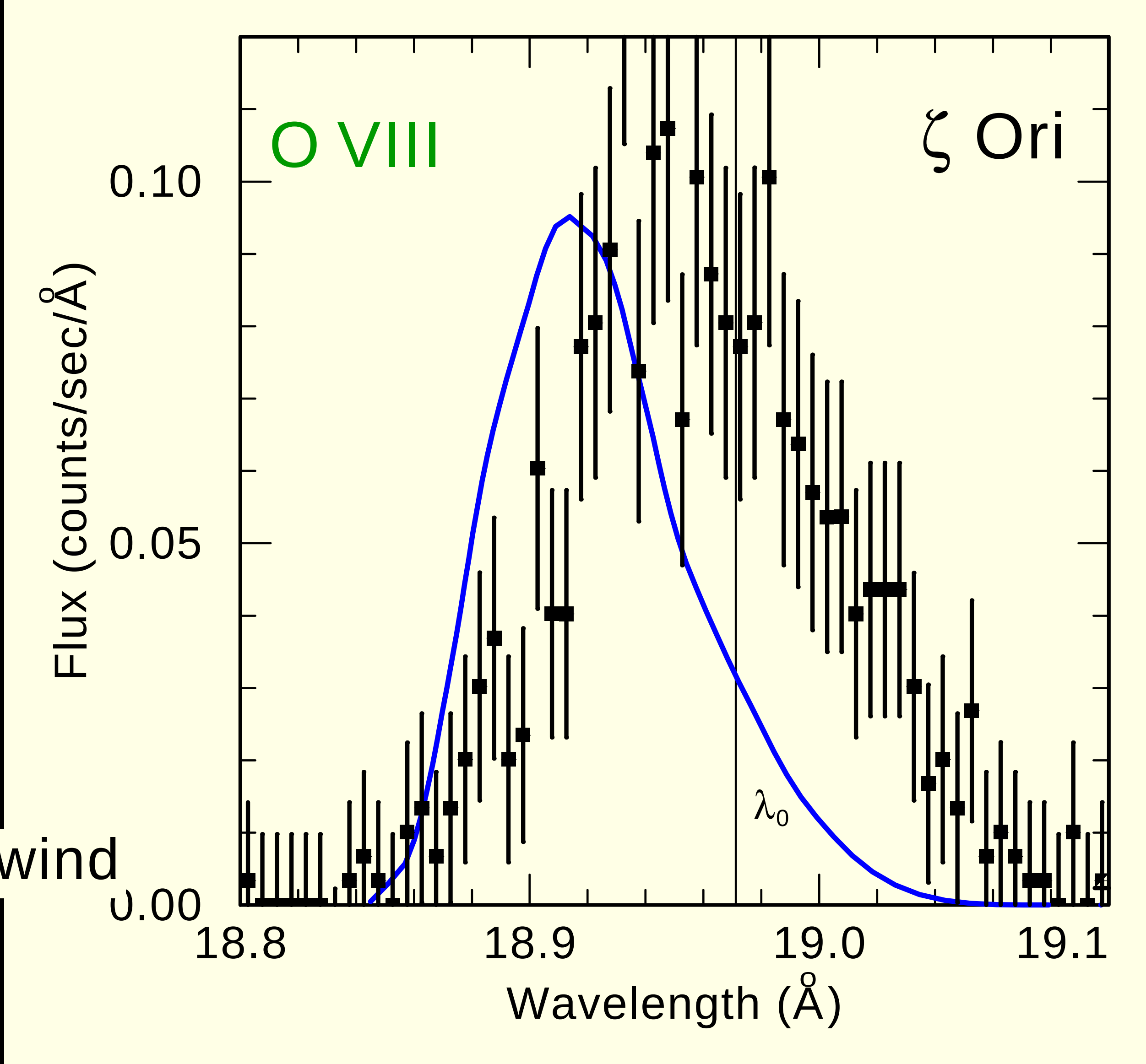
- First high-resolution X-ray spectra of O-stars - 2001 (Chandra and XMM-Newton)
- Emission of a hot 10^6 K plasma in stellar wind

Common X-ray diagnostics: line shapes

Line shapes

- Emission: opticaly thin lines
- Broad: wind velocity
- Blueshifted: wind opacity

Standard model vs. observed line



Marrying the model

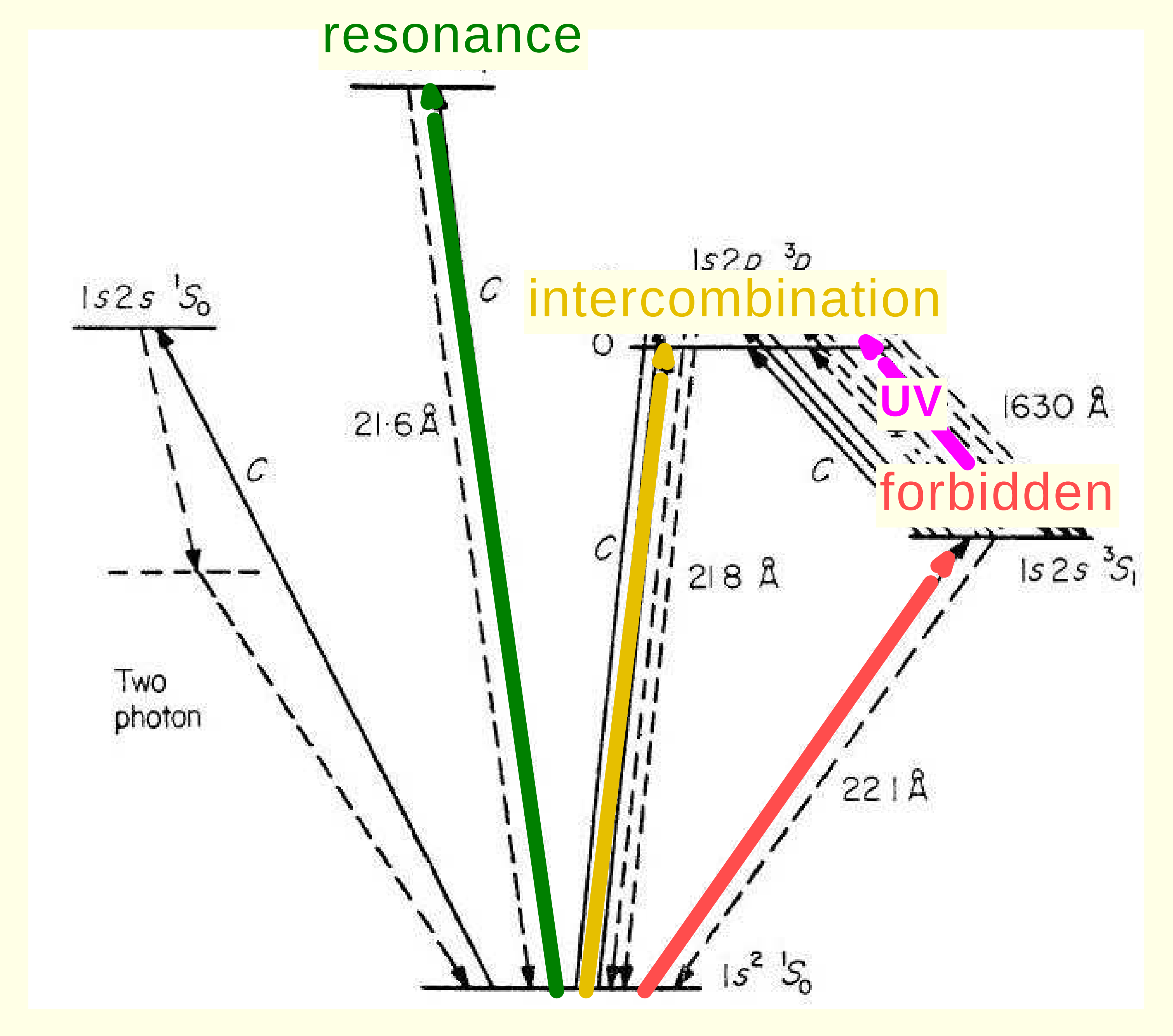
and observations:

- Severely reduced wind density
- Wind inhomogeneity
- X-ray production far out in the wind

Common X-ray diagnostics: lines of He-like ions

Ratio of forbidden to intercombination line flux depends on the UV radiation field

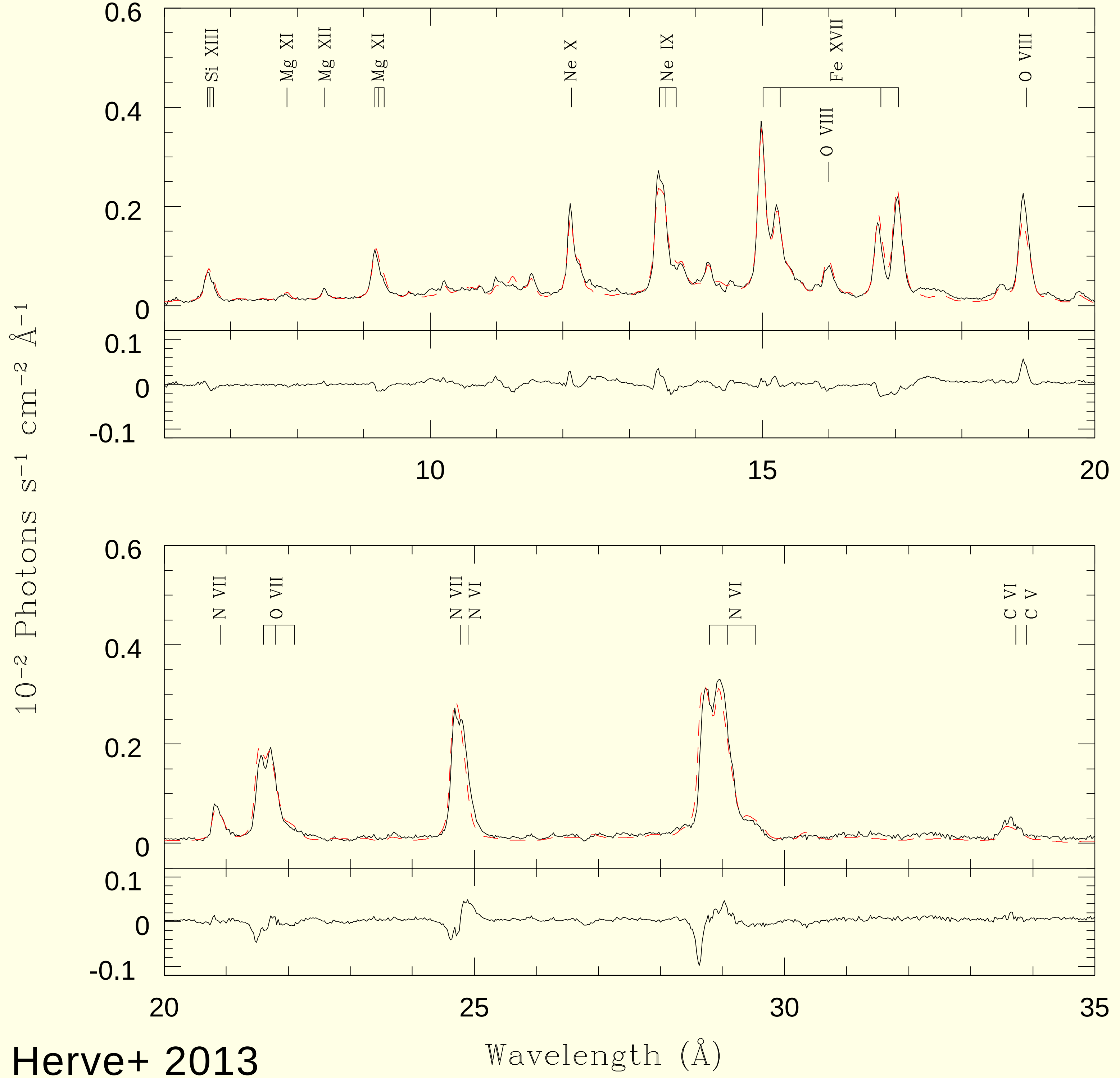
- UV flux dilutes with r^{-2}
- f/i ratio estimator for distance where the hot gas is located
- Requires knowledge of stellar UV field



Gabriel & Jordan 1969

Analysis of 0.7Ms RGS spectrum of O-supergiant ζ Puppis

- NLTE wind model
- APEC



Herve+ 2013

- Hot gas spread out
- Reasonable $\dot{M}$
- T_X distribution

(similar Leutenegger+ 2013)

Common X-ray diagnostics: time variability

10 years of EPIC observations: O-supergiant ζ Pup:

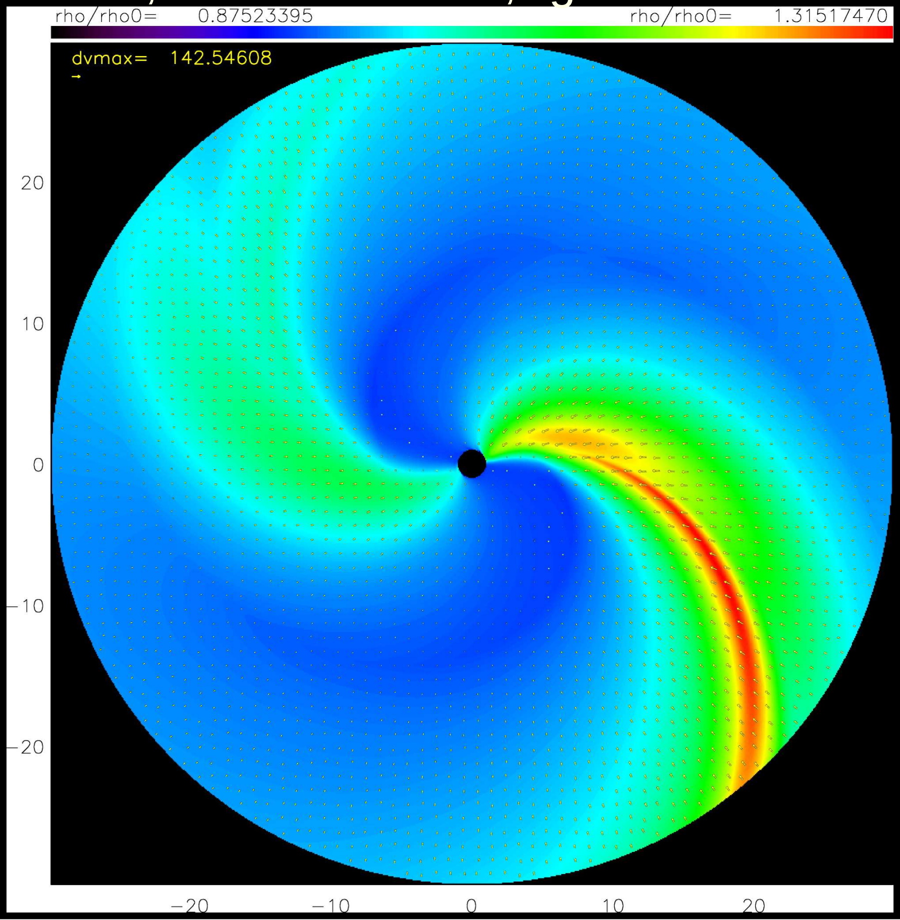
the quality of the data will not be surpassed for decades.

- No short term (~hours) variability is detected
- Variability on time-scale of days is detected
- Plausibly associated with rotation

Berghoefer+ 1996; Oskinova+ 2001; Naze+ 2013; Massa+ 2014; Pollock+ 2013; Ignace etal. '13

- Similar time-scale: UV & Hα lines
- Corotating intraction regions

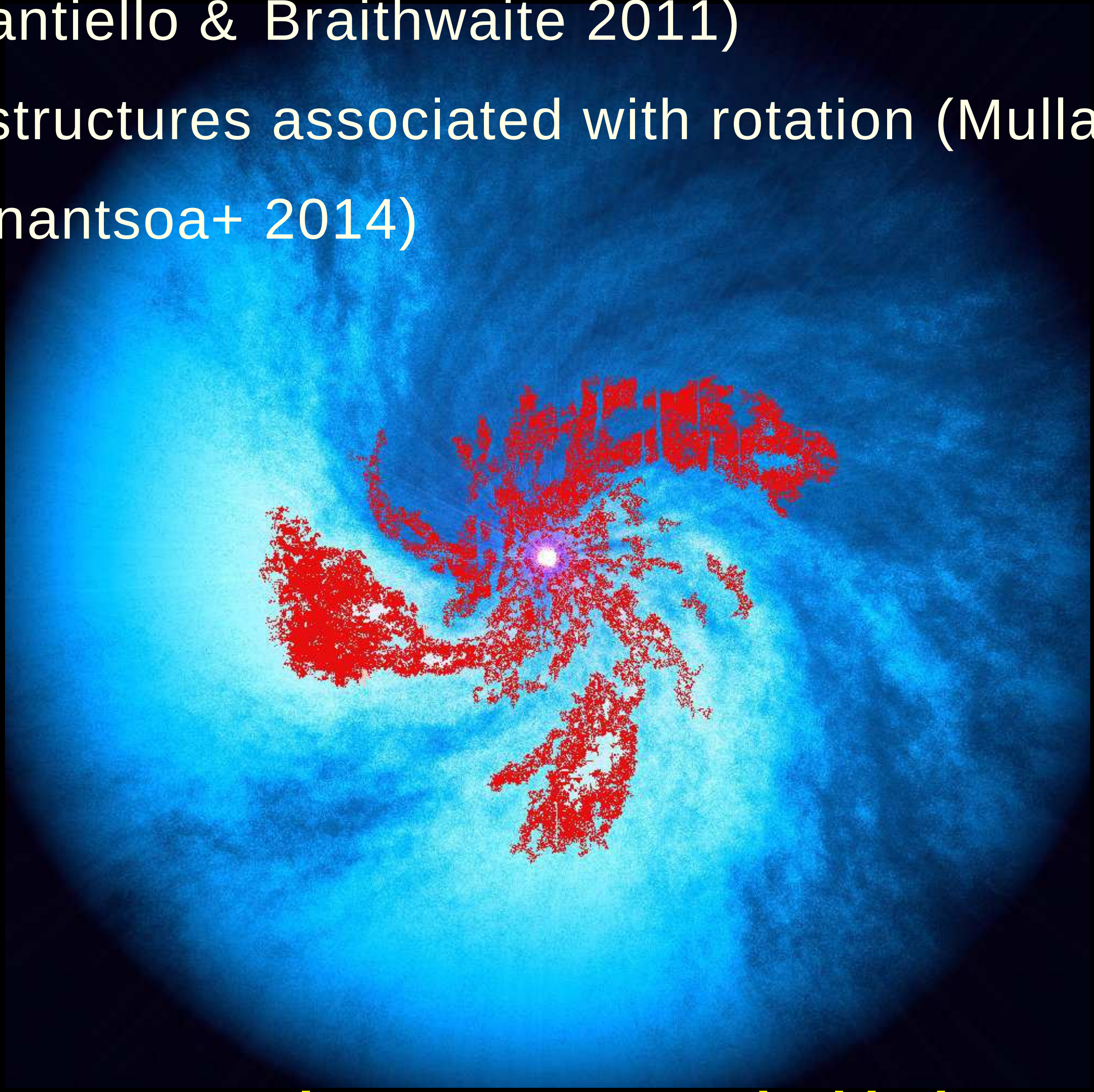
UV MEGA compaign; Mullan '84; Cranmer & Owocki '96;



Lobel+ 2008

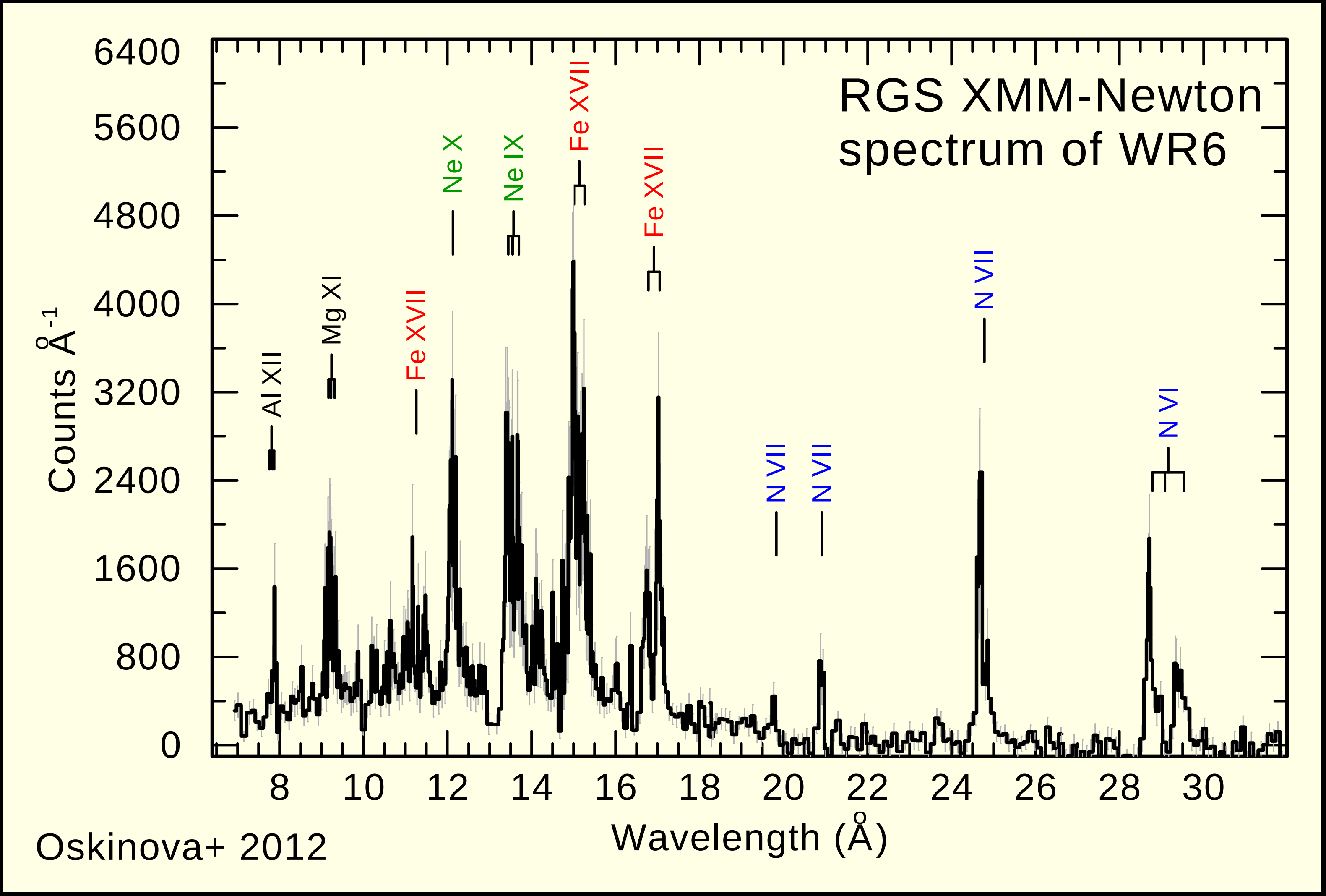
Emerging concept of stellar wind structure

- Small scale wind clumping triggered by sub-photospheric convection (Cantiello & Braithwaite 2011)
- Large scale structures associated with rotation (Mullan+ 1984; ...;Ramiaramanantsoa+ 2014)



Pockets of hot 1-10 MK plasma permeated with the cool 10kK wind

First high-resolution X-ray spectrum of a single WR Star

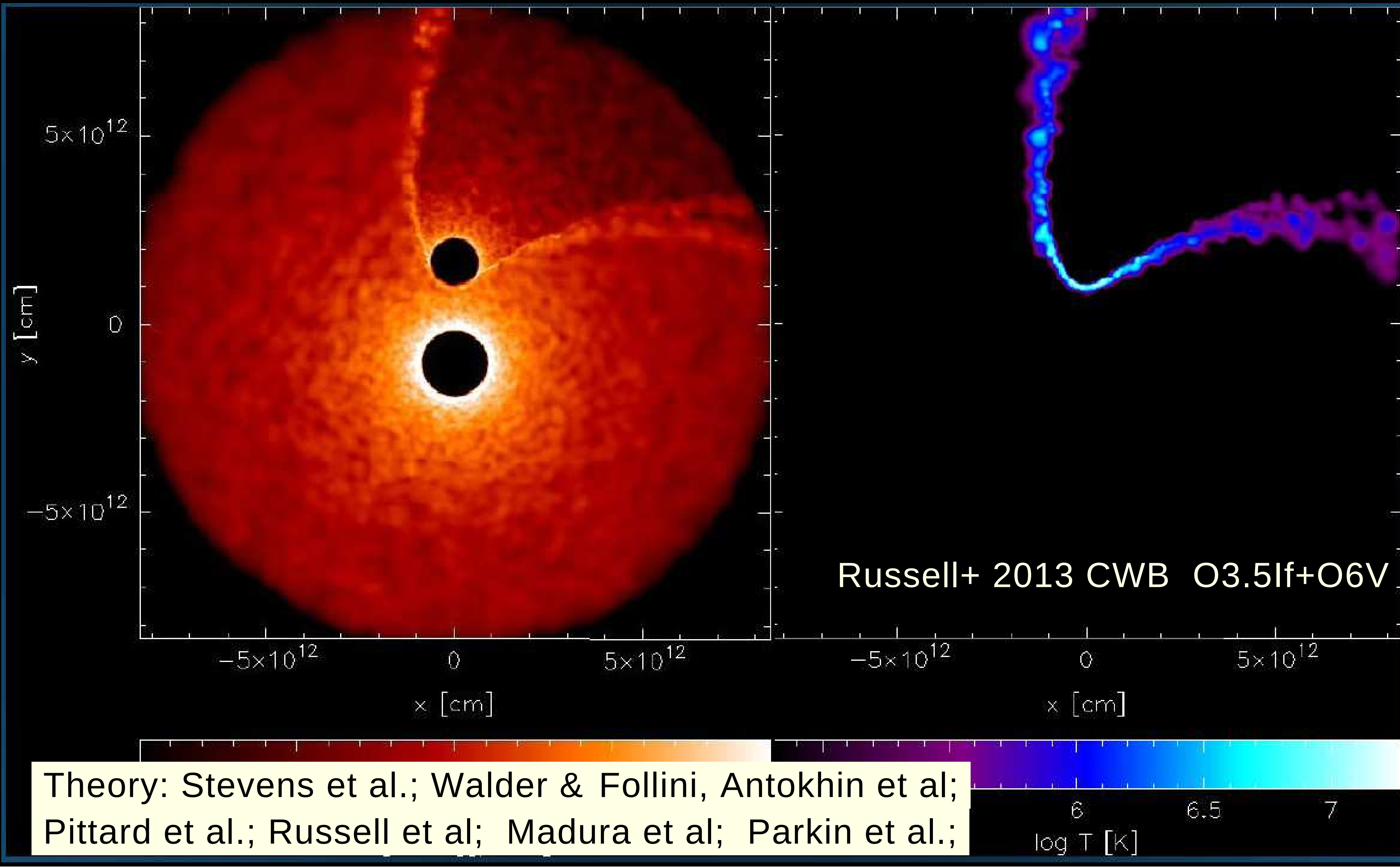


- X-ray spectra of WN stars are harder than O-stars (Skinner+ 2010, 12)
- Lines are broad, strongly blueshifted, forbidden lines are detected
- EPIC: X-ray variability (Ignace+ 2013) - corotating interaction regions

- X-rays + IR a new way to find new WR stars (Mauerhan+ 2009). **X-ray bright WR stars are binaries** (Pollock + 2009, Pandey+ 2014;...)

Colliding Wind Binaries

>80% of massive stars are binary or multiple (Chini+ 2012; Sana+ 2012)

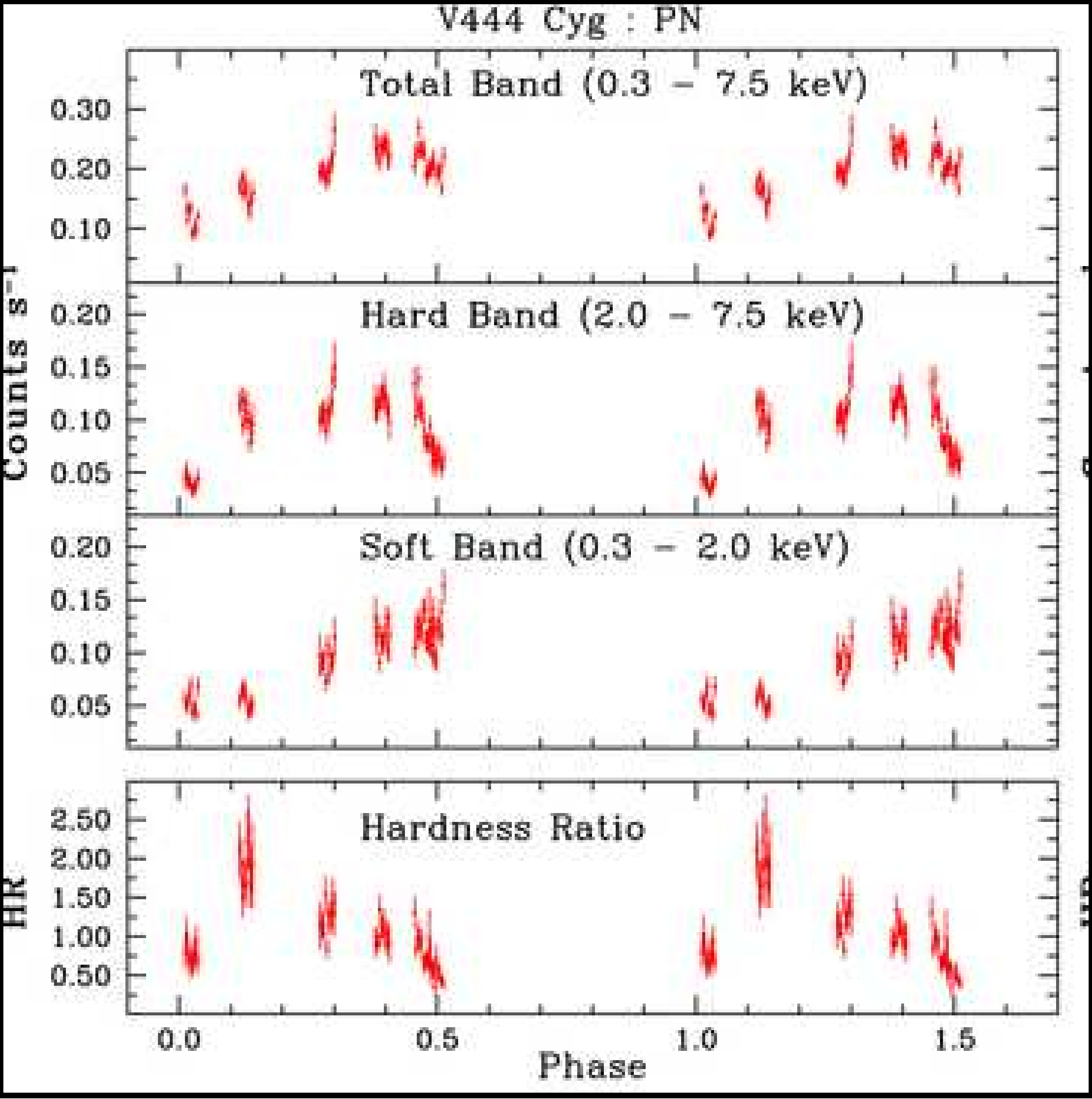


Theory: Stevens et al.; Walder & Follini, Antokhin et al;
Pittard et al.; Russell et al; Madura et al; Parkin et al.;

Colliding Wind Binaries: observations

Large XMM compaigns: η Car, WR 140, V444 Cyg

Example of X-ray light curve: Bhatt+ 2009



Comparison to models → key information about stellar properties

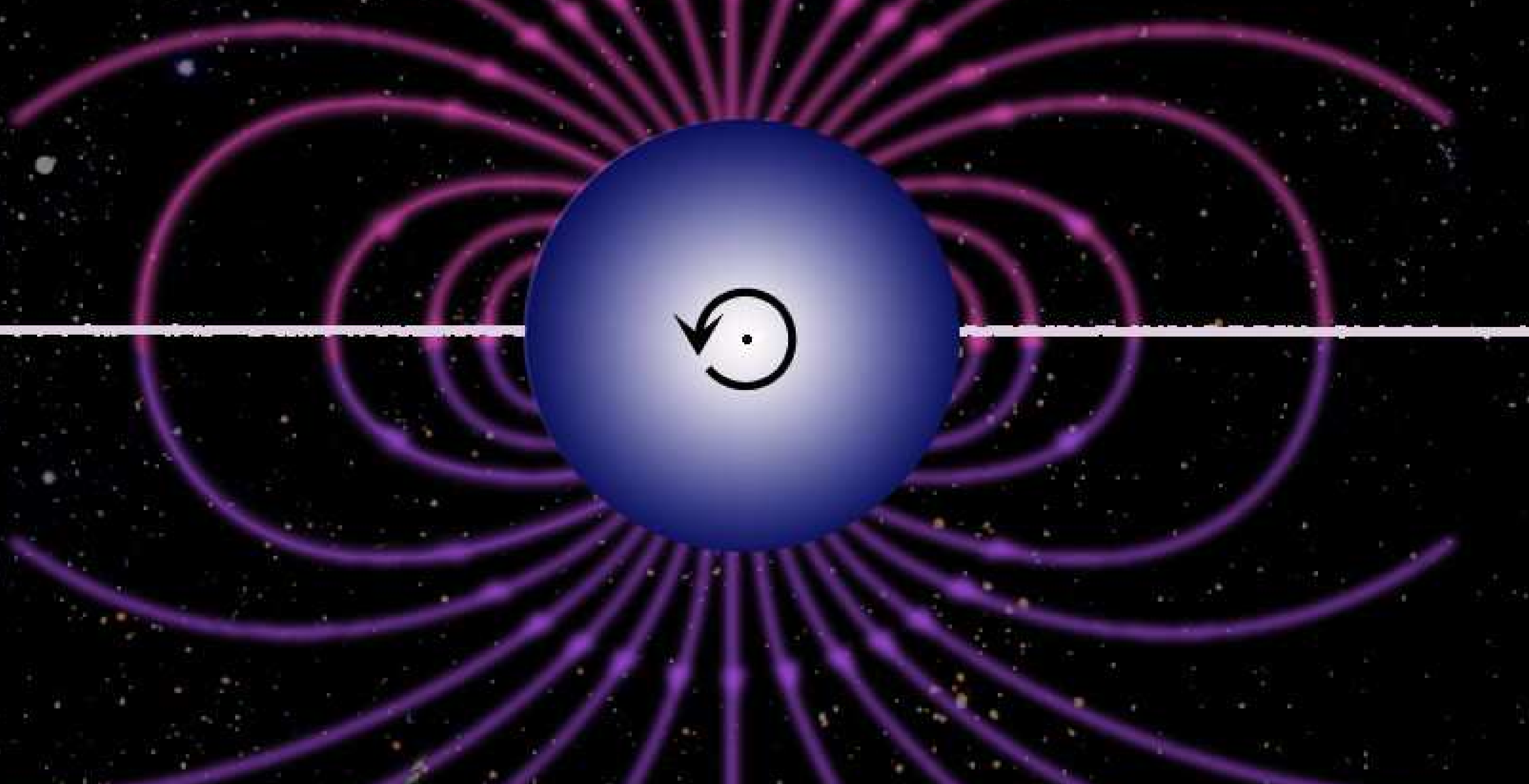
CWB sources of non-thermal radiation (de Becker 2011, 13; Ohm+ 2011; van Loo+ 2008, Blomme+ 2010)

WR and LBV binaries are significantly X-ray brighter than single stars. O+OB binaries are not. **Why?**

Cazorla+ 2014; Corcoran+; Williams+ 2011; Grunhut+ 2013; Zhekov+ 2012; Gosset+ 2012; Liege group;...

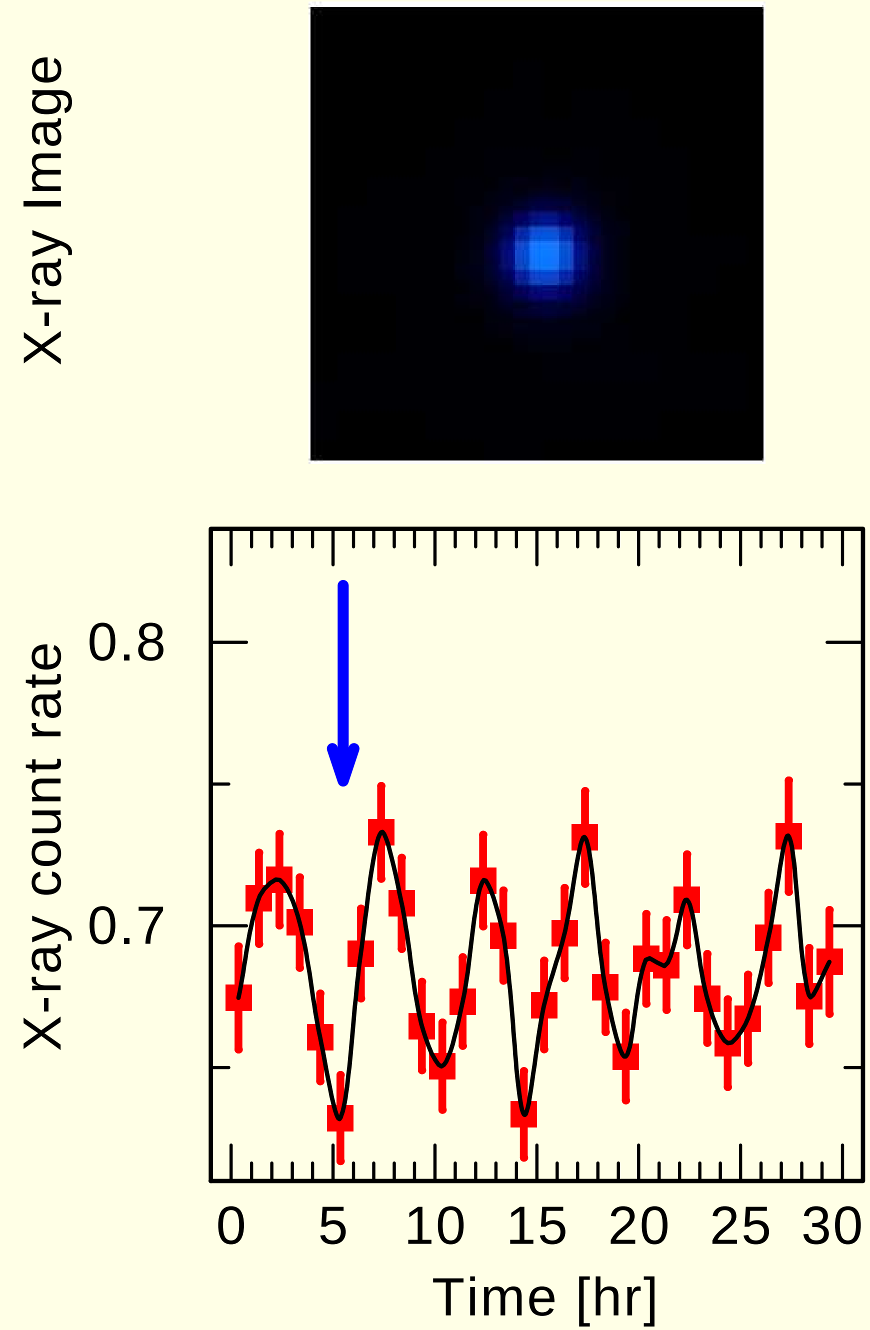
Magnetic massive stars

<10% of massive stars: large scale magnetc fields (Grunhut+ 2012)
X-rays reveal magnetically confined stellar winds



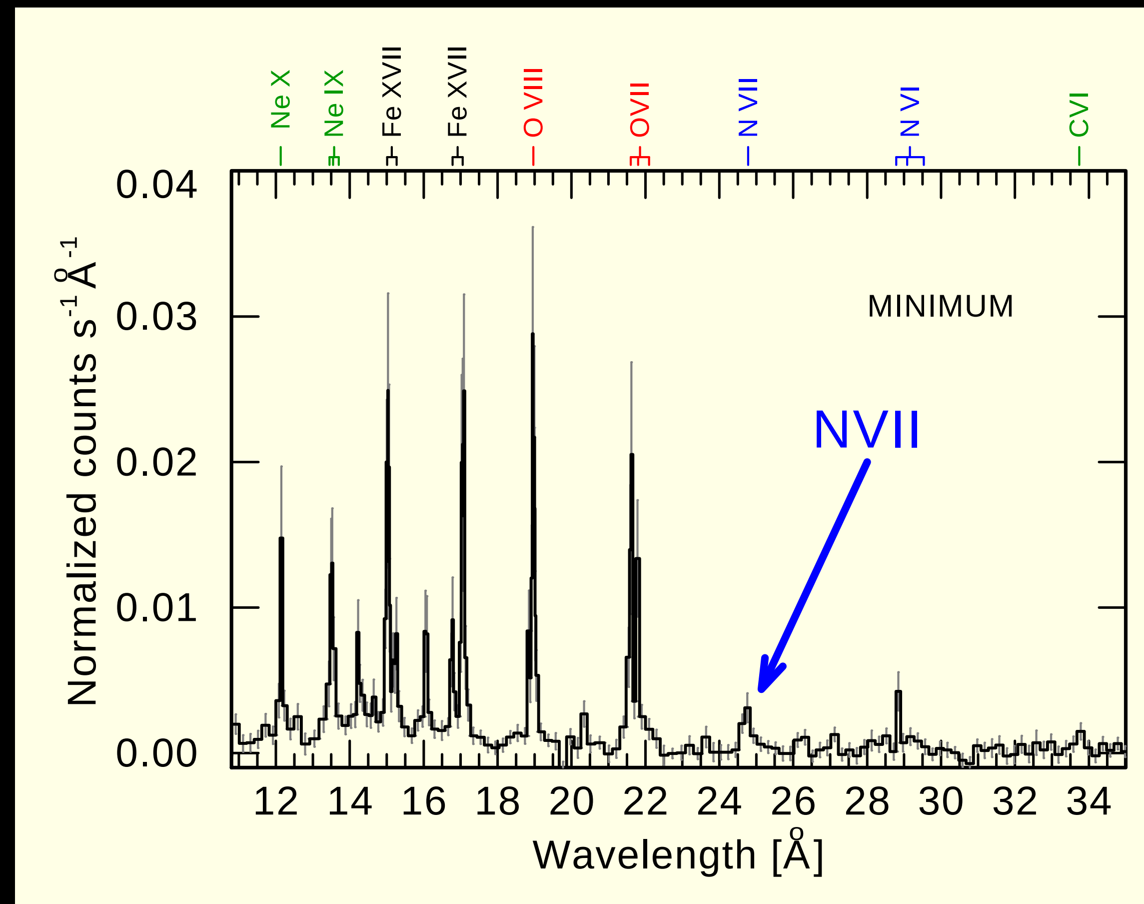
Wade+ 2012; Naze+ 2010; Oskinova+ 2012; Ignace+ 2013; Petit+ 2014; ud Doula+ 2014

X-ray pulsations in a non-degenerate massive star



Oskinova+ 2014 (Nature Com.)

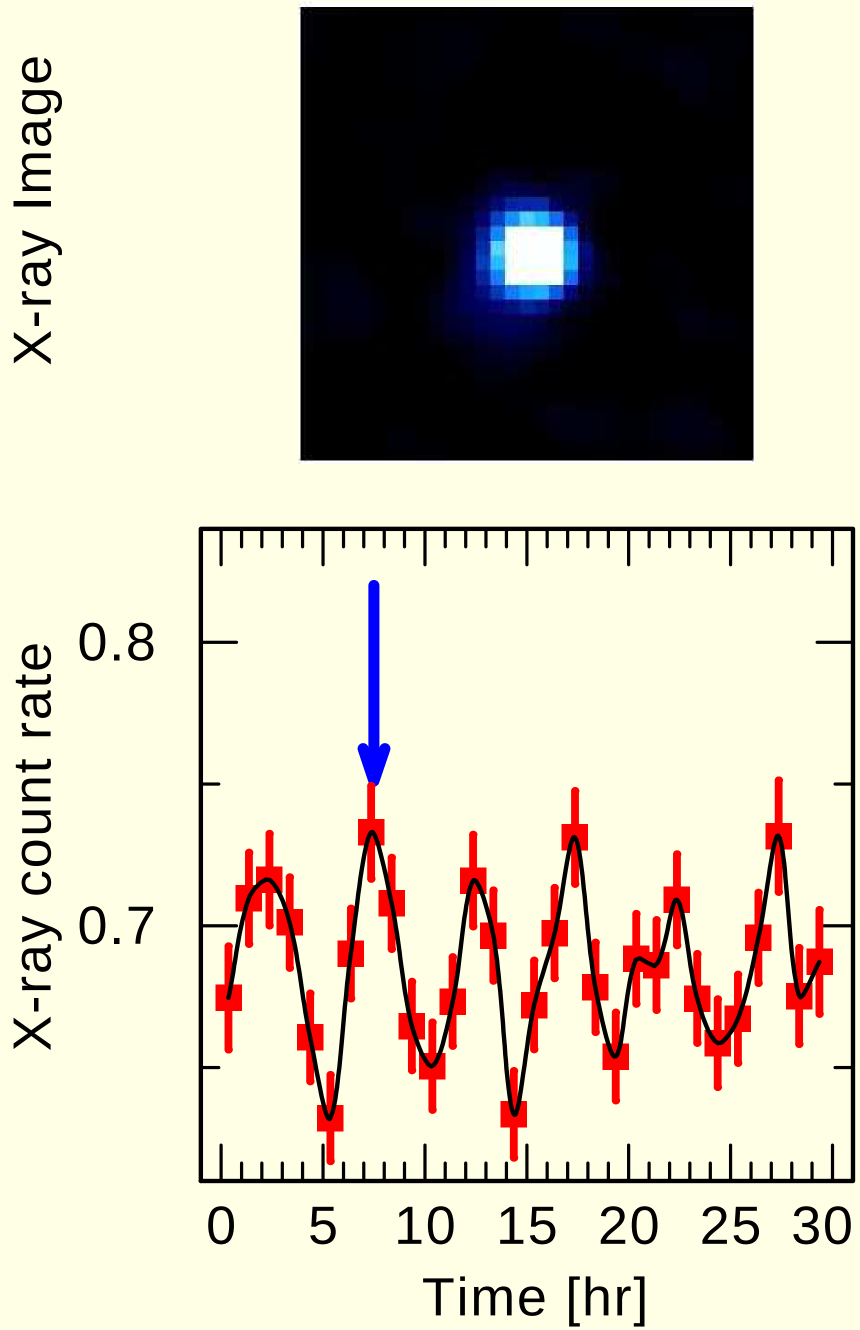
ξ^1 CMa: stellar radial pulsations
X-ray pulses in phase with optical



XMM-Newton observations:

- light curves
- phase-resolved spectroscopy

X-ray pulsations in a non-degenerate massive star



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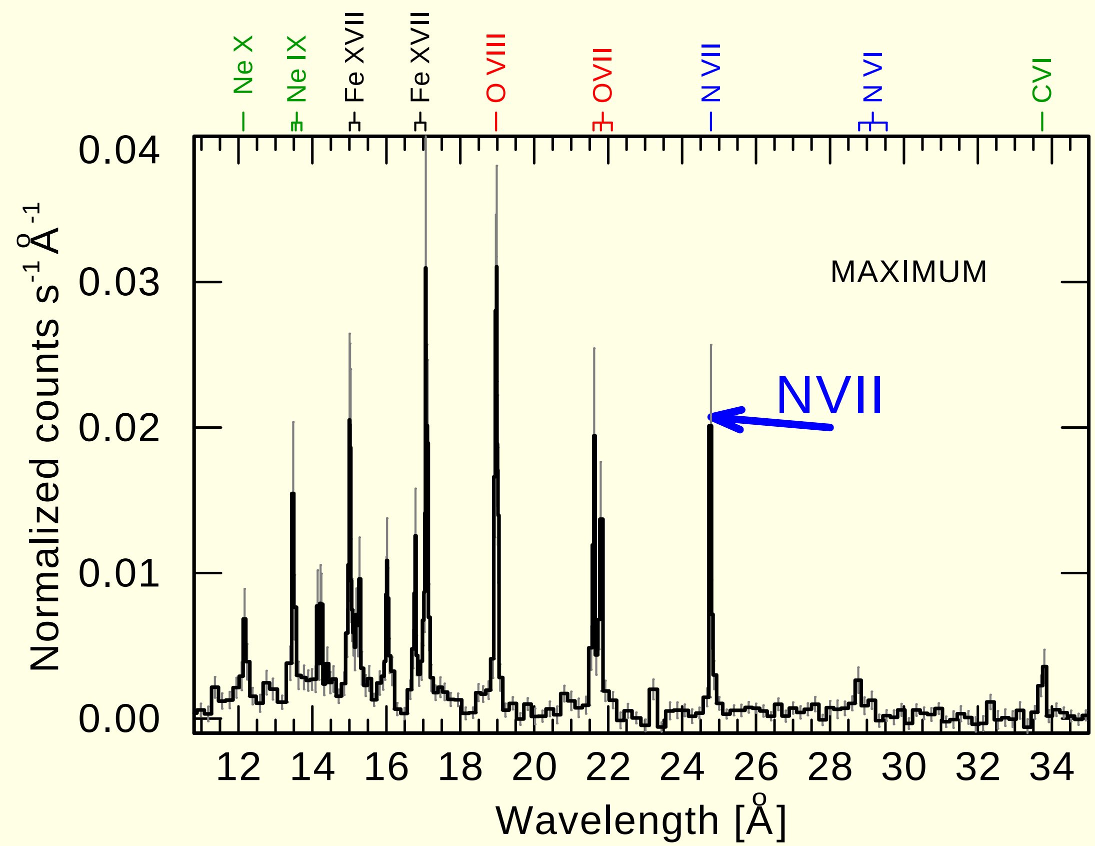
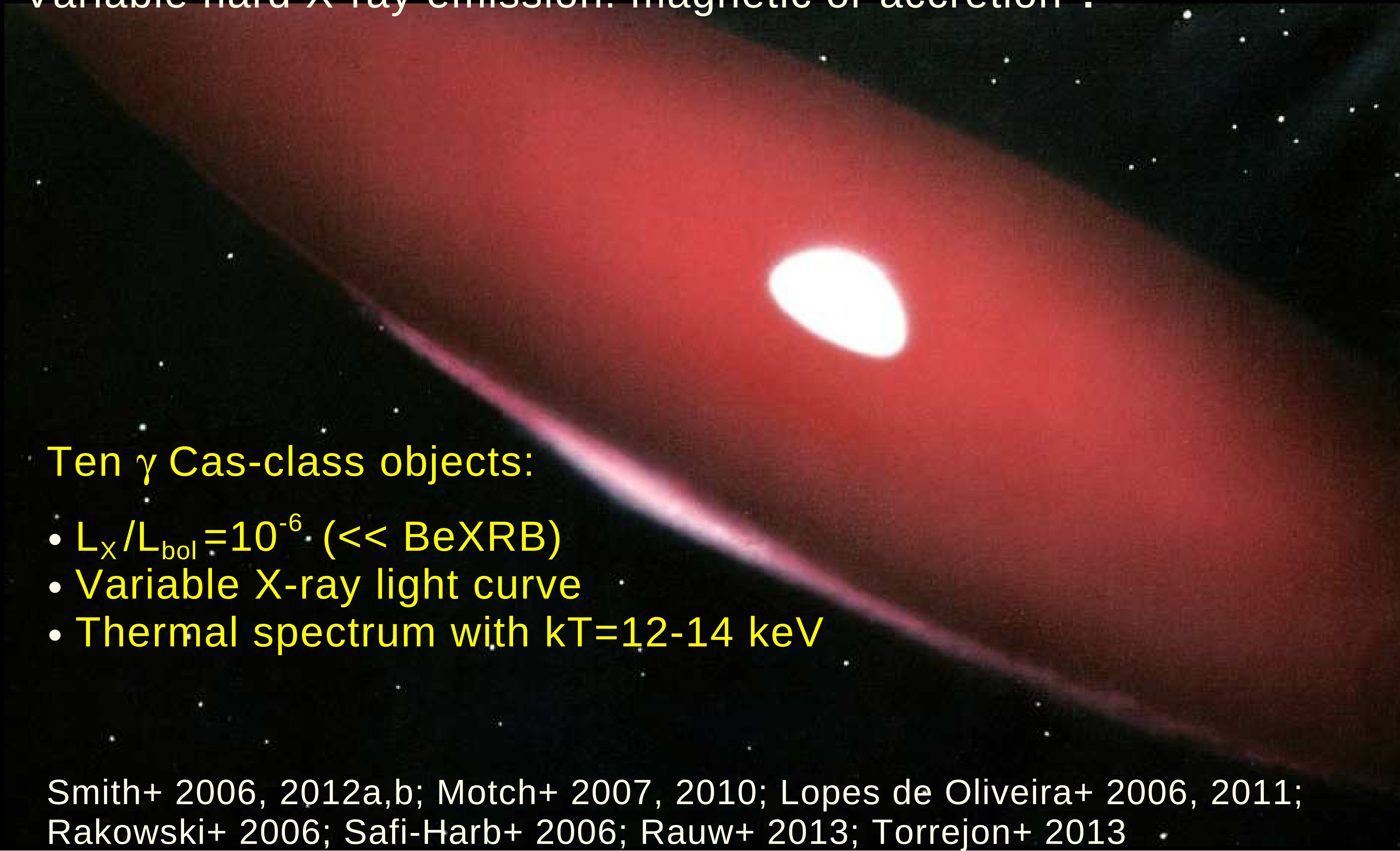


XMM-Newton observations:

- light curves
- phase-resolved spectroscopy

γ Cassiopeiae class of X-ray sources

γ Cas - Be-type star (B0.5 IVe), very fast rotator, binary
Variable hard X-ray emission: magnetic or accretion **?**



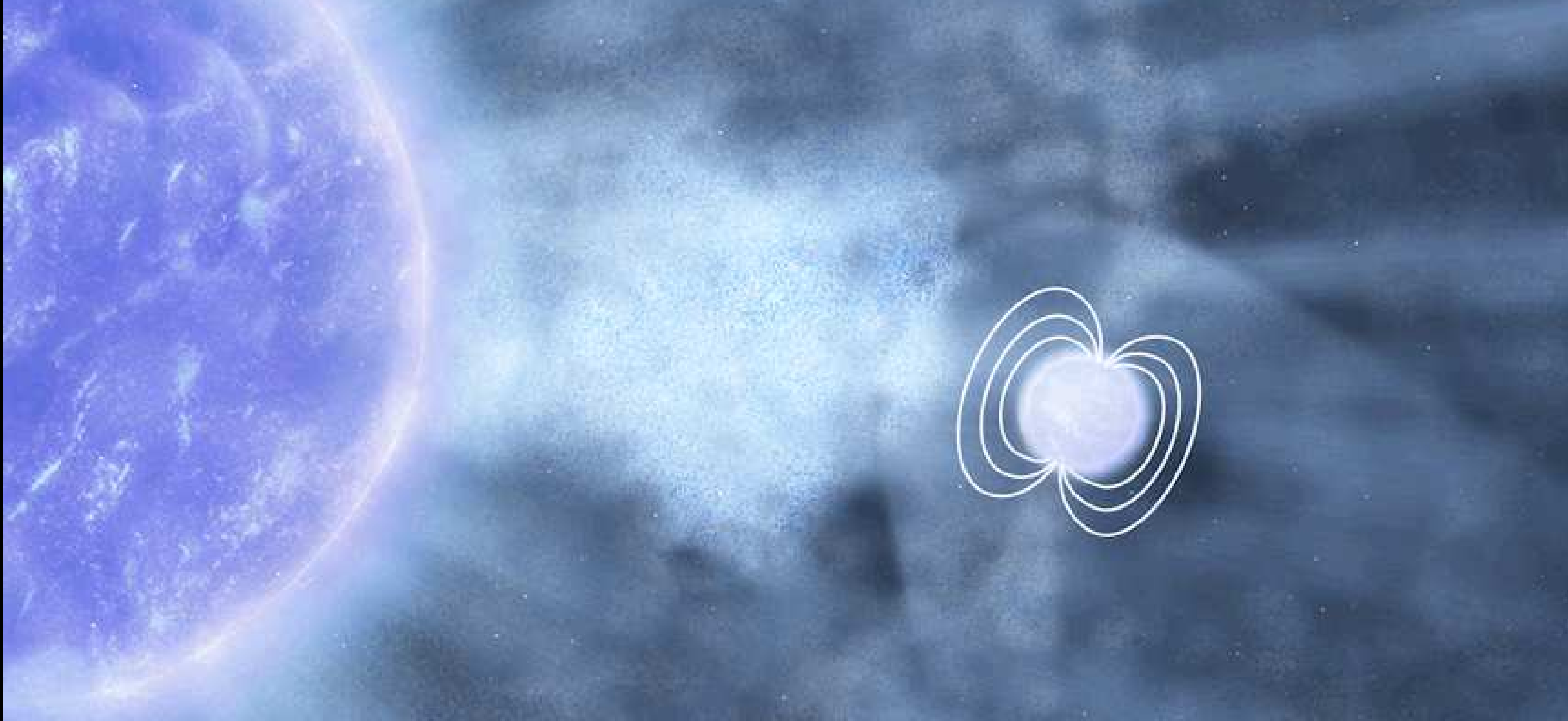
Ten γ Cas-class objects:

- $L_X/L_{bol}=10^{-6}$ (<< BeXRB)
- Variable X-ray light curve
- Thermal spectrum with kT=12-14 keV

Smith+ 2006, 2012a,b; Motch+ 2007, 2010; Lopes de Oliveira+ 2006, 2011; Rakowski+ 2006; Safi-Harb+ 2006; Rauw+ 2013; Torrejon+ 2013

High-mass X-ray binaries

- Accretion of OB star matter by a BH or a NS
- Massive star evolution, structure, winds are parts of this story

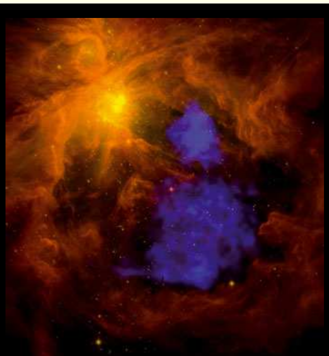
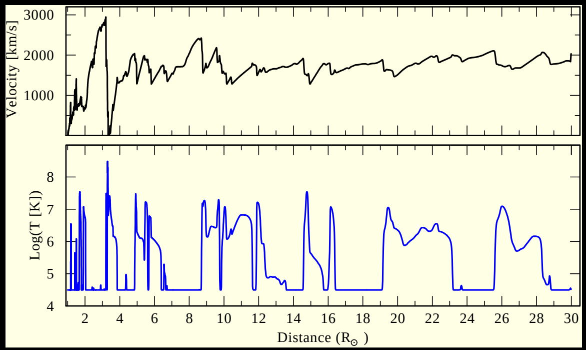


Bozzo+ 2011; Sidoli+ 2012; Manousakis+ 2012; Walter & Zurita Heras 2007; Doroshenko+ 2011; Ducci+ 2009; Fürst+ 2010; Negueruela+ 2008; Martinez-Nunez+ 2014; Duro+ 2011; …

X-ray look on massive stars with XMM-Newton

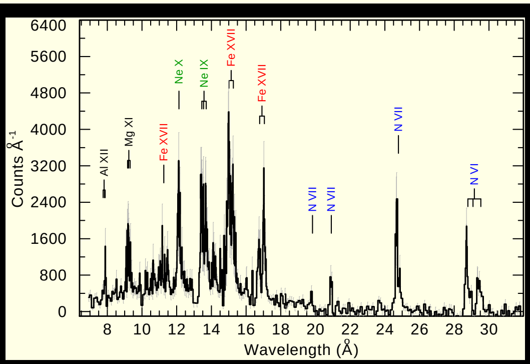
star formation • star clusters • star cluster feedback • stellar winds

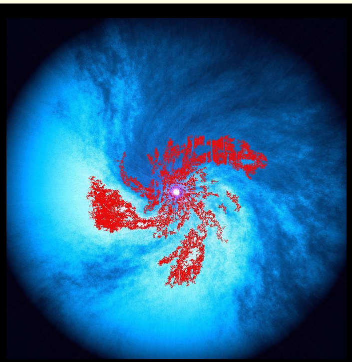


bow shocks • wind blown bubbles • RGS O & WR • wind structure







colliding wind binaries • magnetic stars • γ Cas-class • HMXBs