

Diffuse X-ray Emission as a probe of Stellar Evolution

(Single Massive Stars!)

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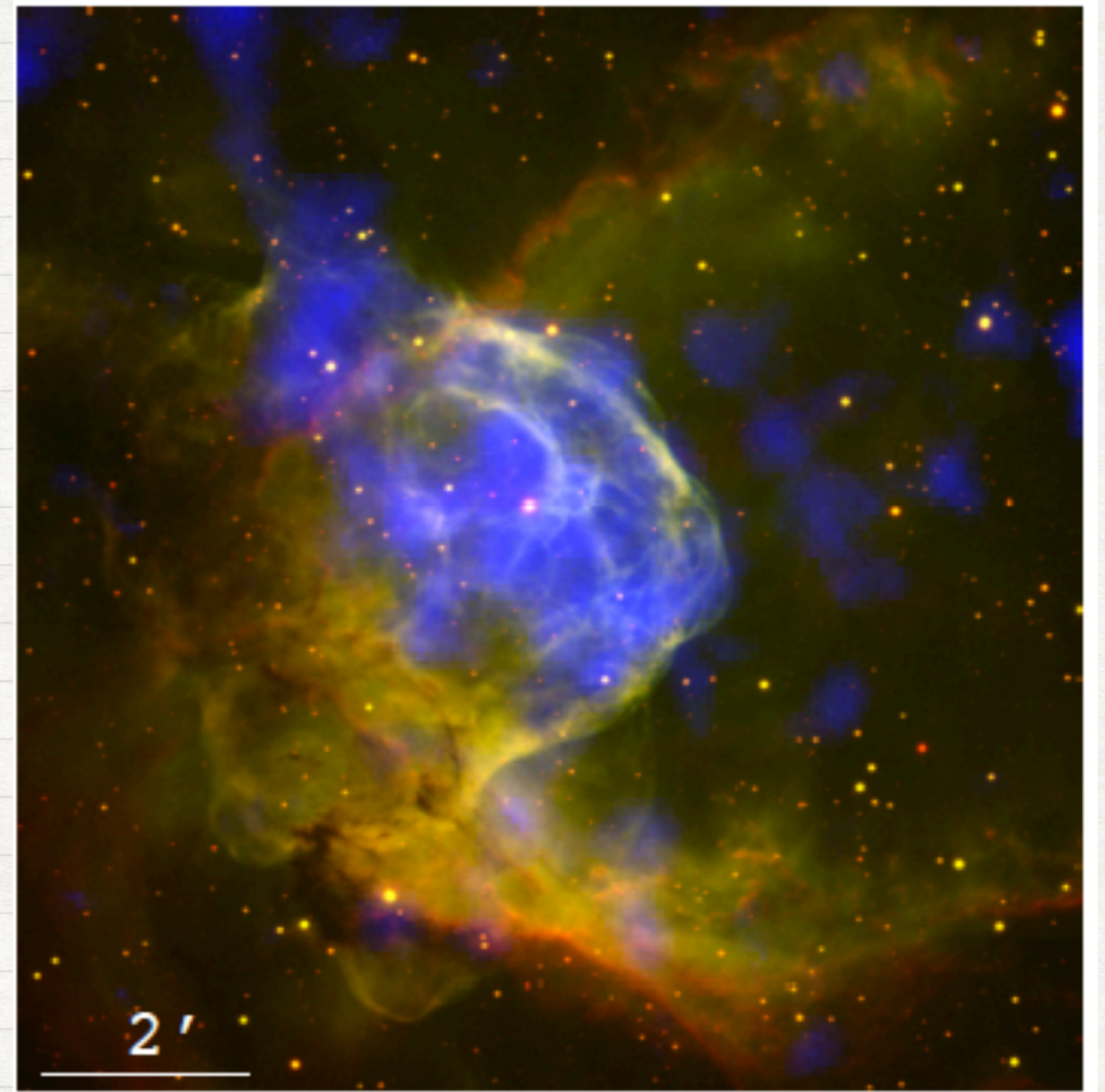
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Quy Nhon, Vietnam, August 2016

OUTLINE

- Massive Stellar Evolution
- Hot Bubble Formation
(Theory)
- Diffuse X-ray emission
(Observations)
- Remarks

Massive Stellar Evolution

$$M_i > 20 M_{\odot}$$

Depending on their initial masses (and other parameters...)



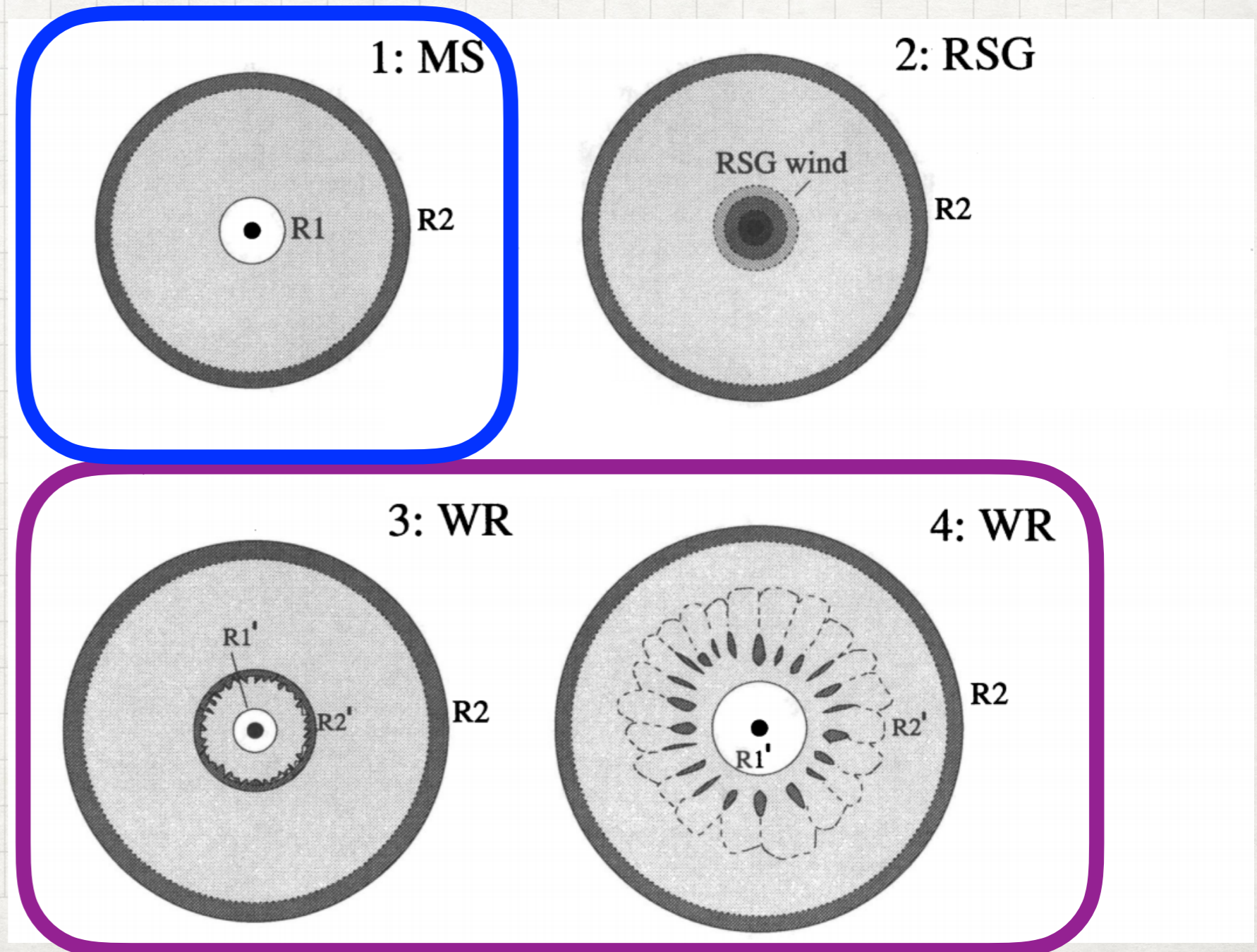
Massive Stellar Evolution

Three-wind model

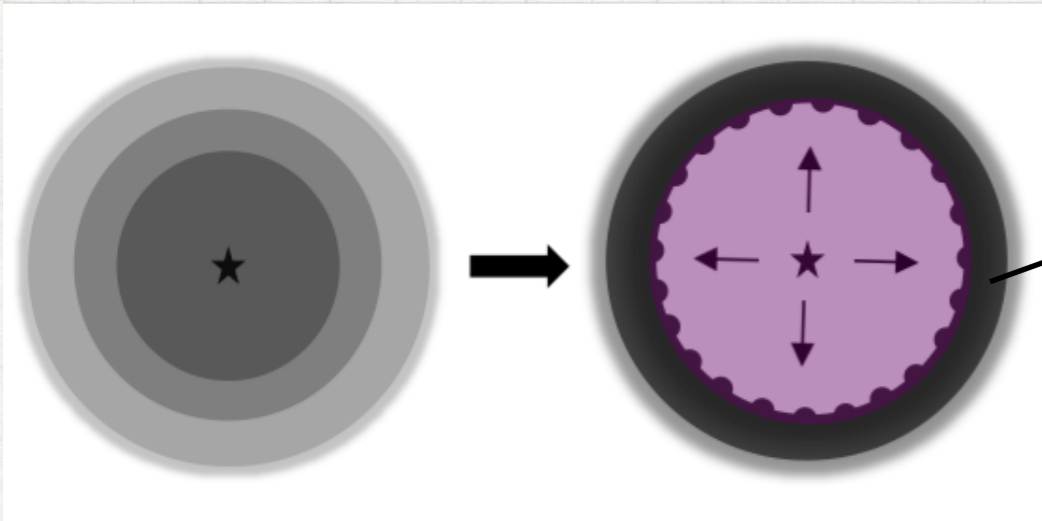
García-Segura & Mac Low (1995)

Interstellar
Bubbles

WR Nebulae



Hot Bubble Formation



**Dense and
Slow Material**

vs.

**Current
Fast WR wind**

Adiabatically shocked wind
(e.g., Dyson & Williams 1997):

$$T = \frac{3}{16} \frac{\mu}{k_B} m_H v_\infty^2$$
$$= 2.3 \times 10^7 \mu \left(\frac{v_\infty}{1000 \text{ km s}^{-1}} \right)^2 \text{ [K]}$$

i.e., for $v_\infty = 1000 - 2000 \text{ km s}^{-1}$

Produce diffuse and Hot Bubbles!
 $T = 10^7 - 10^8 \text{ K}$
 $n = 0.001 - 0.01 \text{ cm}^{-3}$

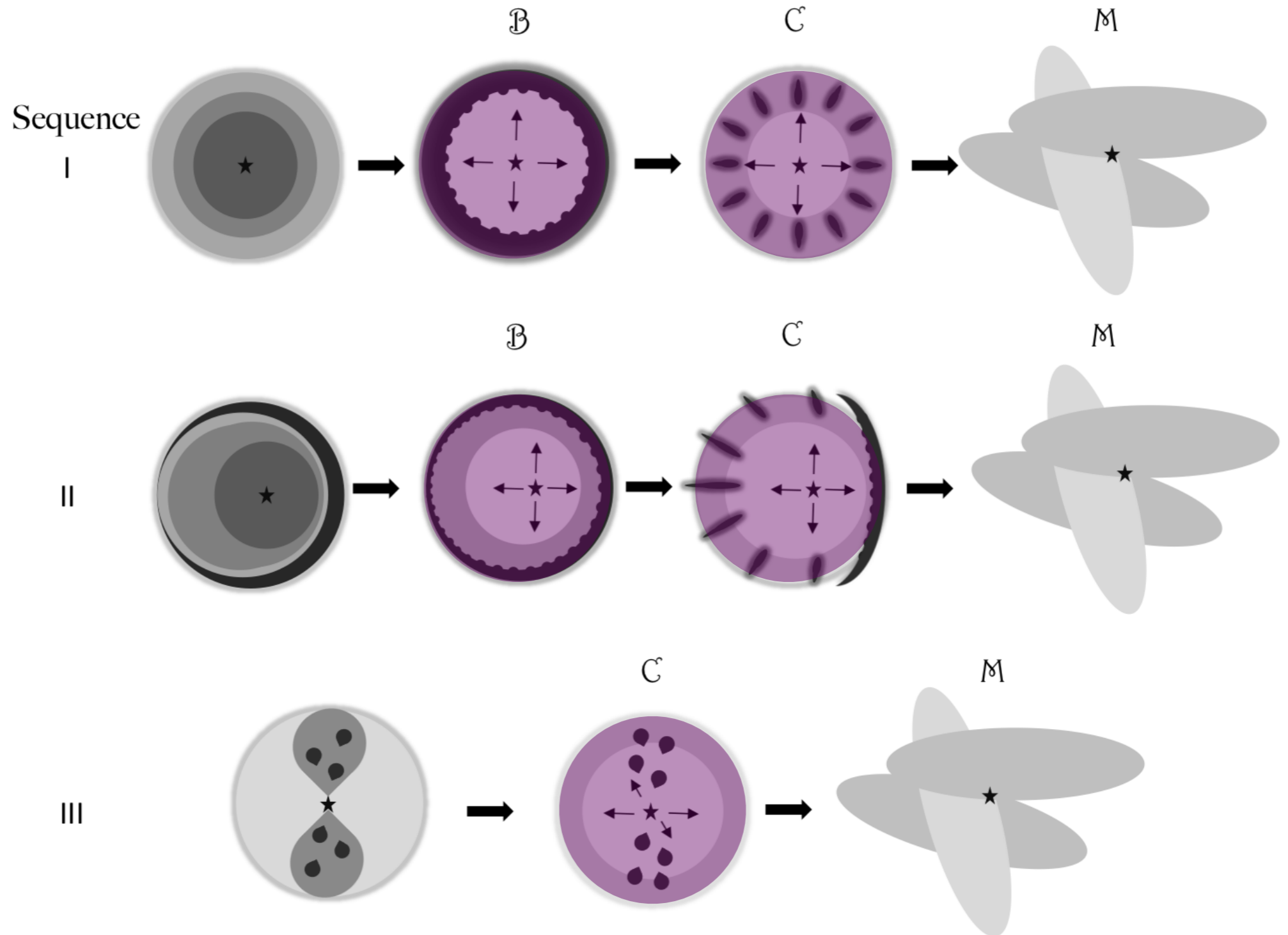
Hot Bubble Formation

B - Bubble

C - Clumpy/Disrupted

M - Mixed

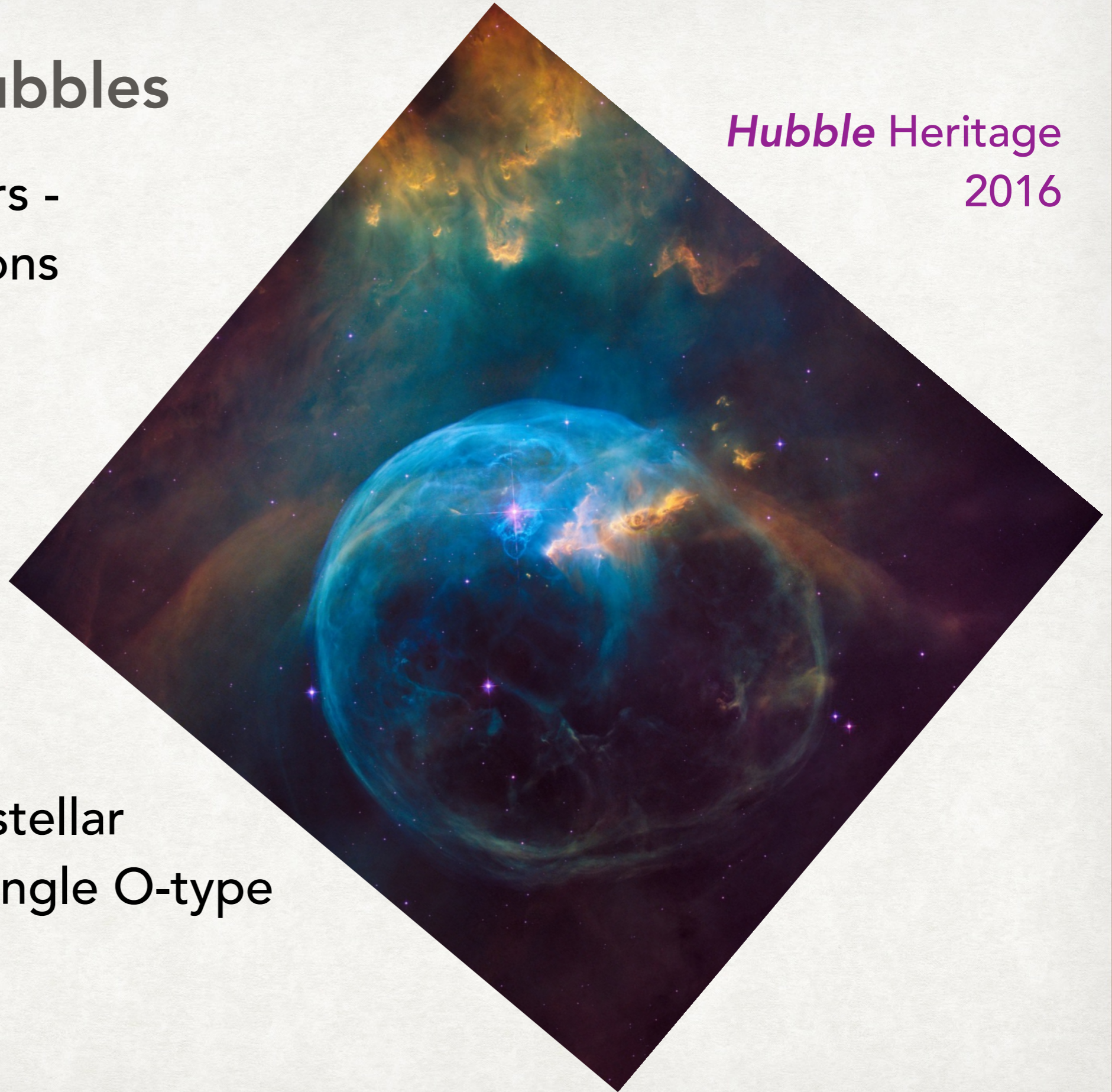
X-rays



Interstellar Bubbles

Single O-type stars -
negative predictions
(X-rays)

Hubble Heritage
2016



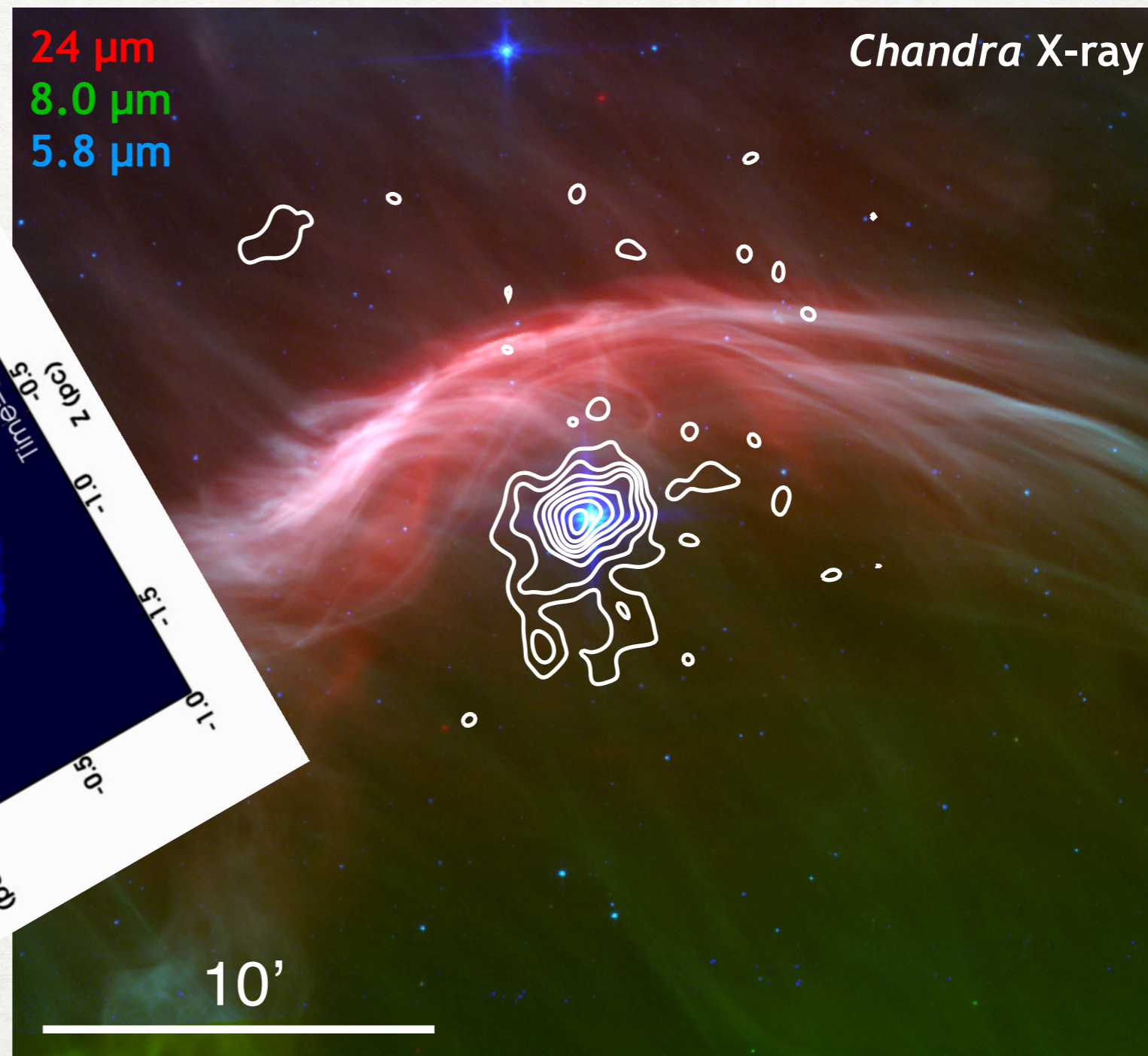
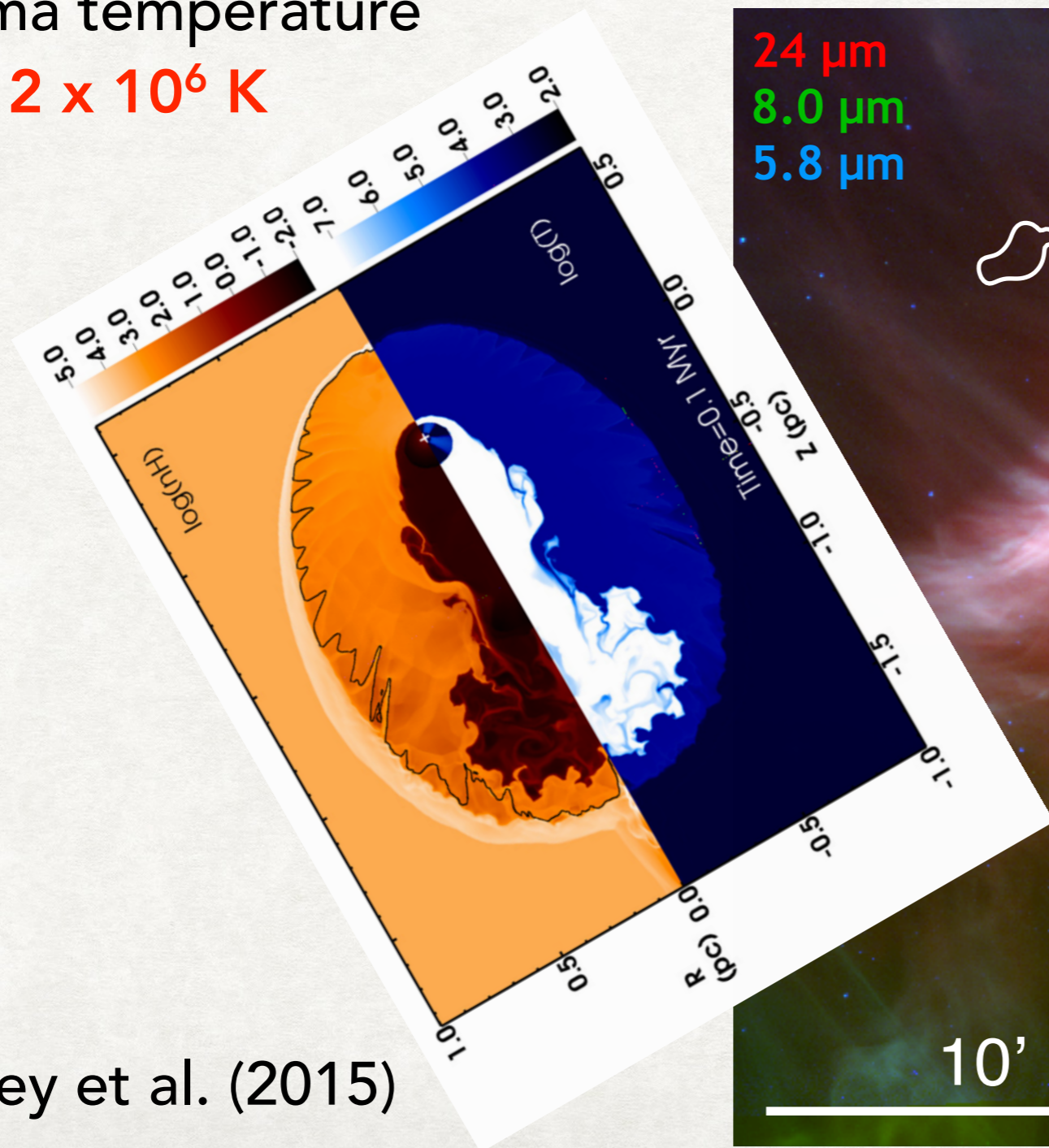
"Why aren't interstellar
bubbles around single O-type
stars visible?"

Chu (2008)

ζ Oph (O9.2IV)

Plasma temperature

$$T_x = 2 \times 10^6 \text{ K}$$



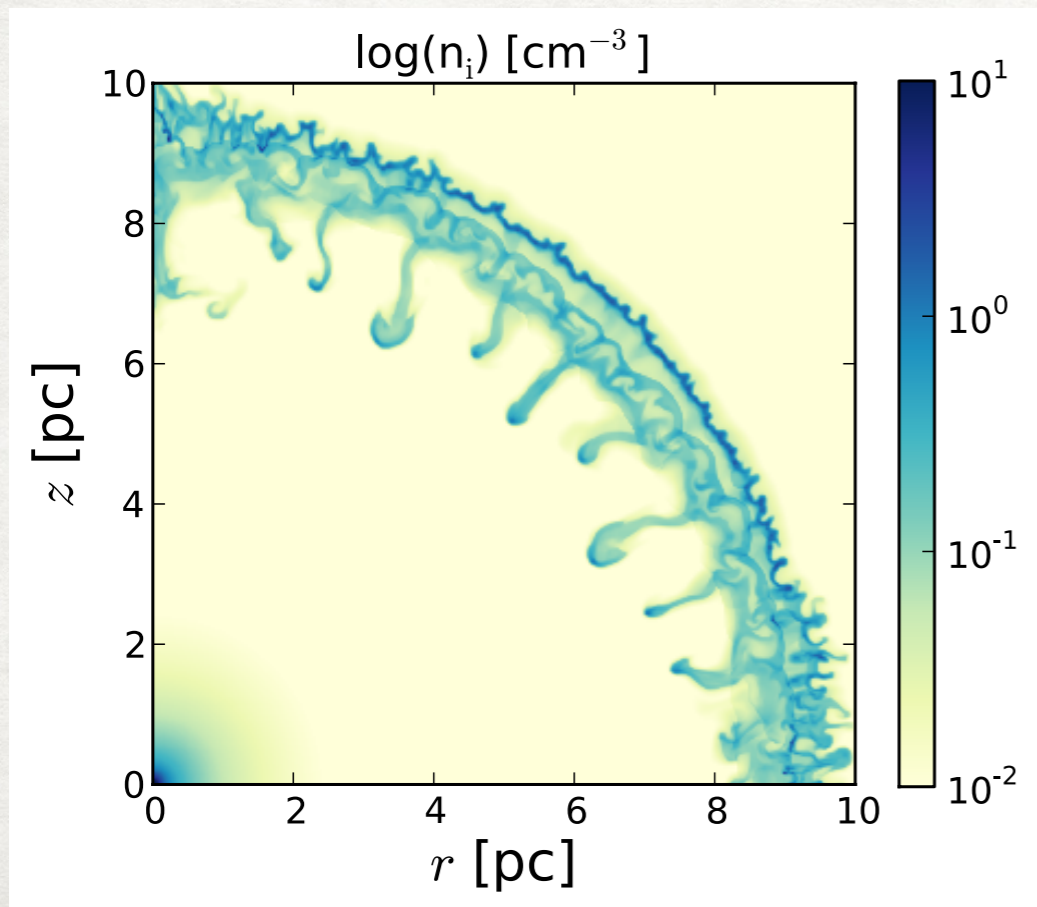
S 308 (WR6)

The most extended WR nebula!
(~40' in diameter)

Yellow Supergiant

Toalá & Arthur (2011)

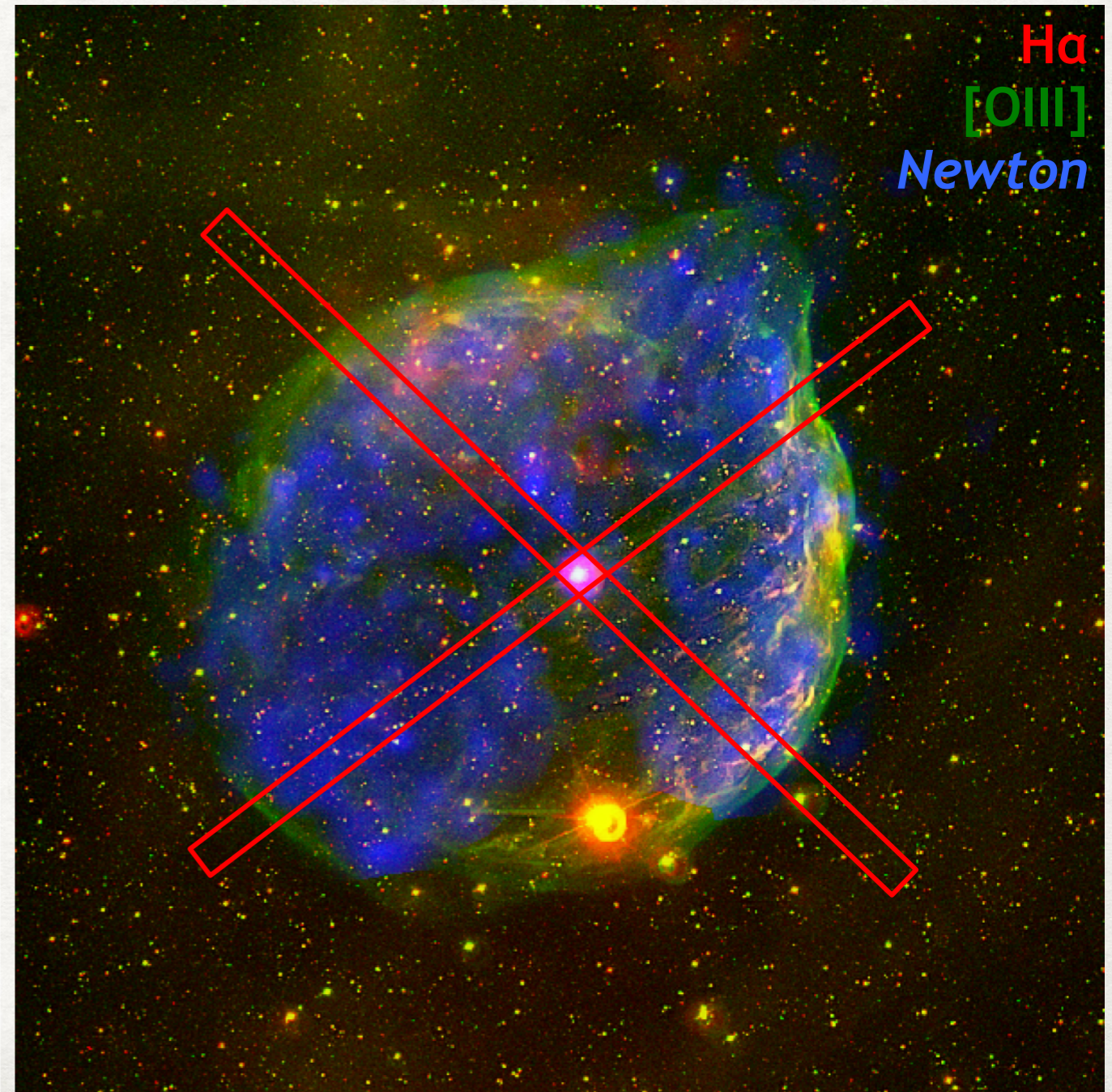
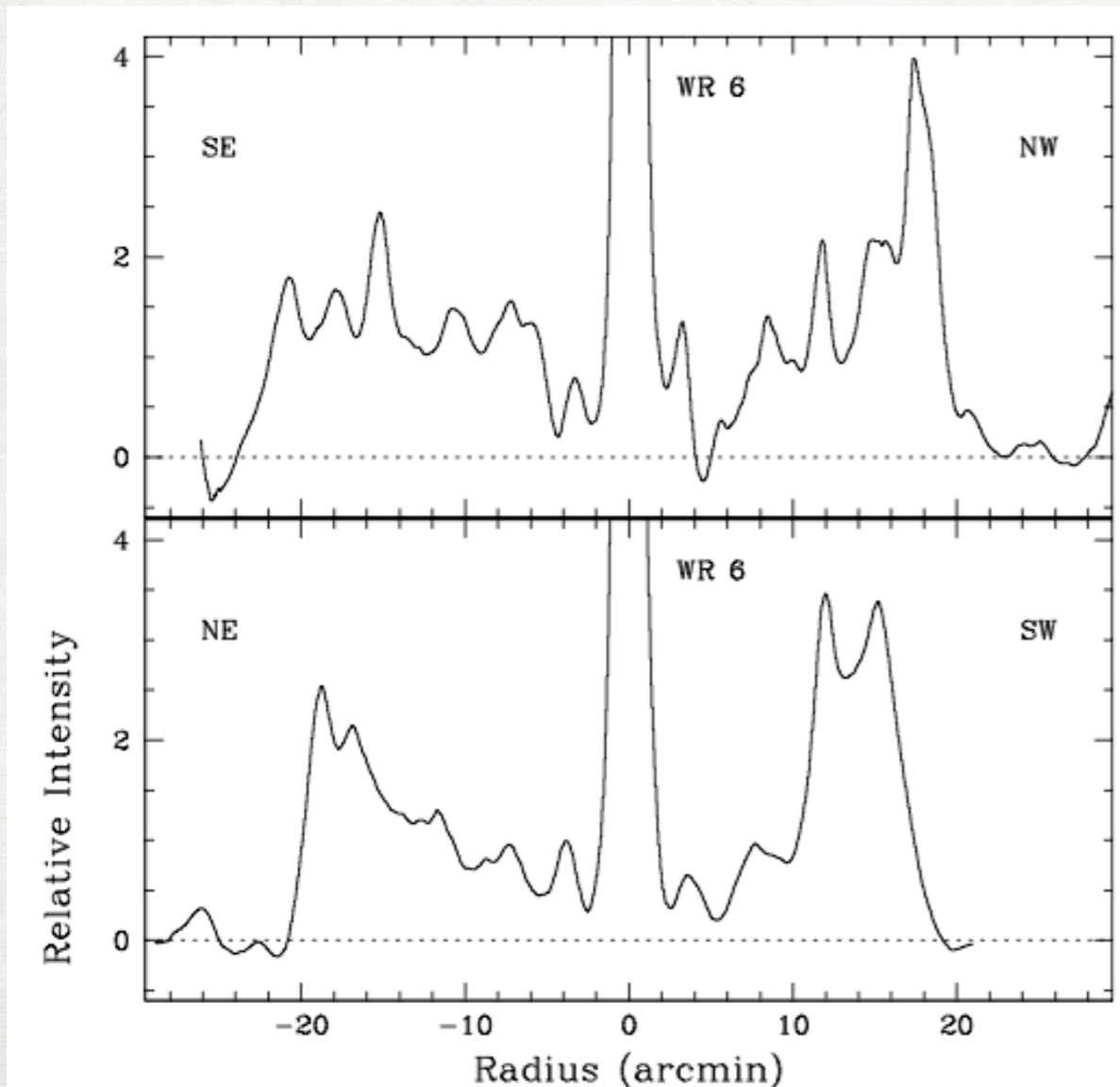
40 M_{\odot} (Meynet & Maeder 2003)



S 308 (WR6)

4 *XMM-Newton* Observations

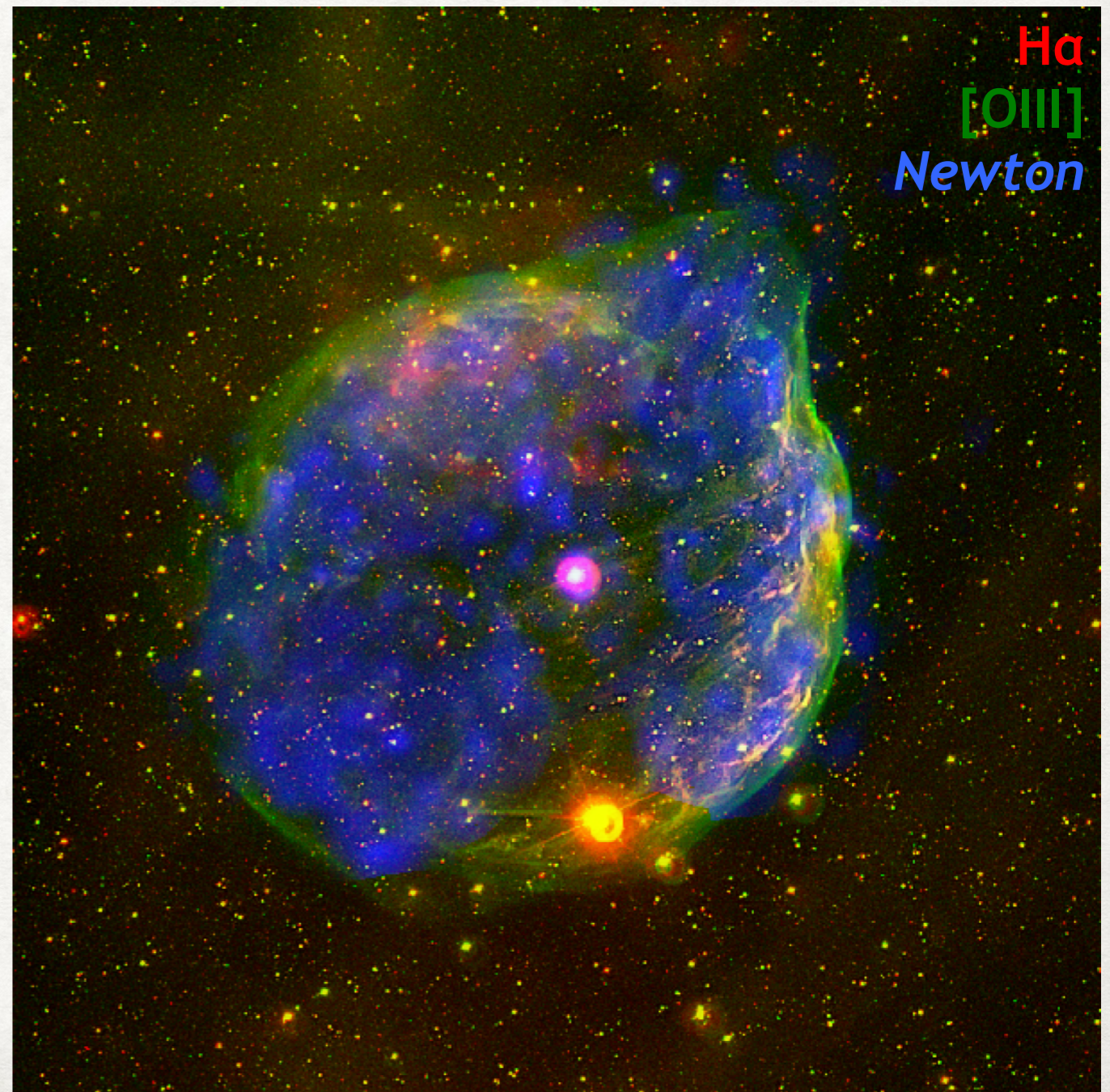
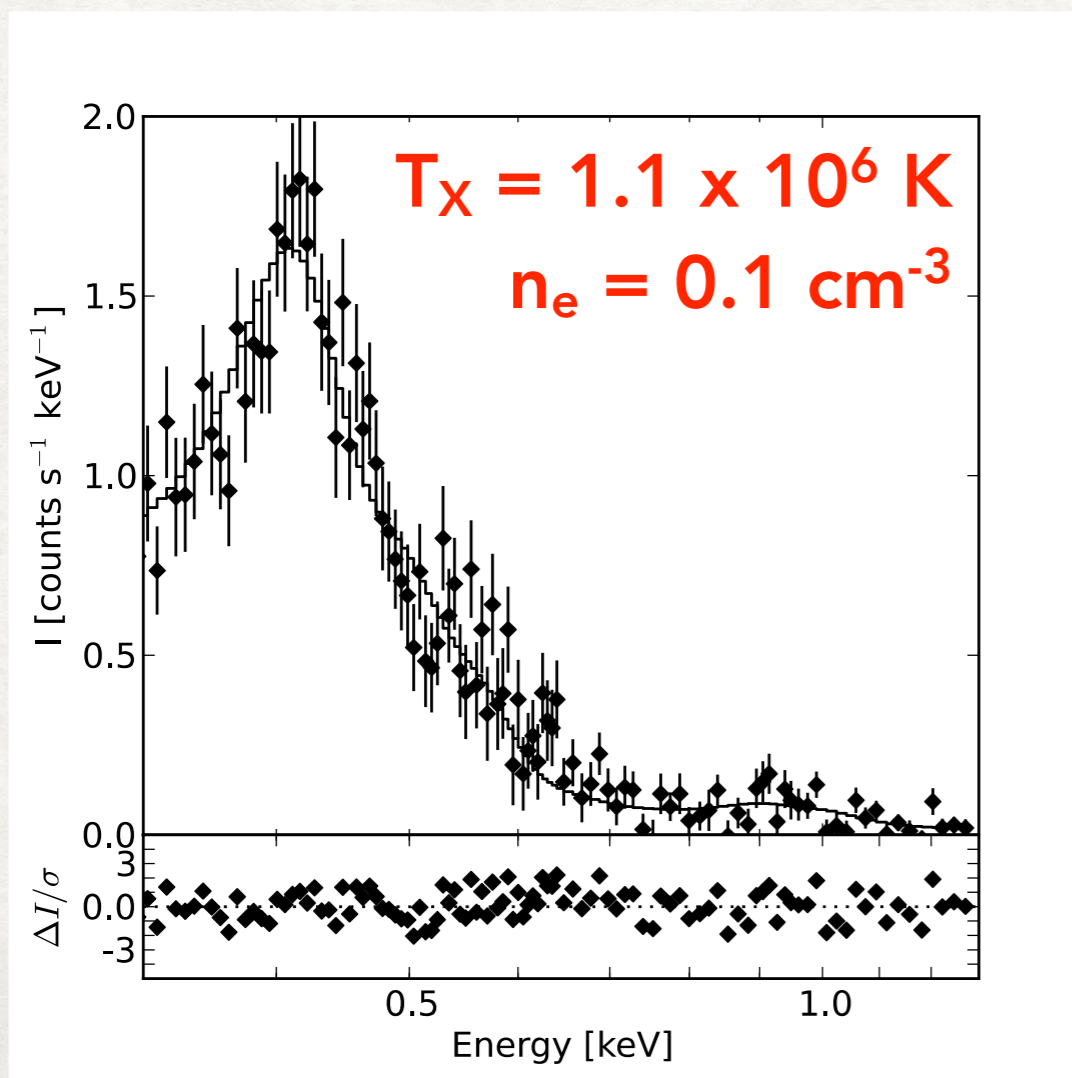
A textbook hot bubble



S 308 (WR6)

4 *XMM-Newton* Observations

A textbook hot bubble



NGC 2359 (WR7)

Thor's Helmet Nebula

LBV - Eruptive

(Rizzo et al. 2003)

Re-analysed

XMM-Newton

(Zhekov 2014)

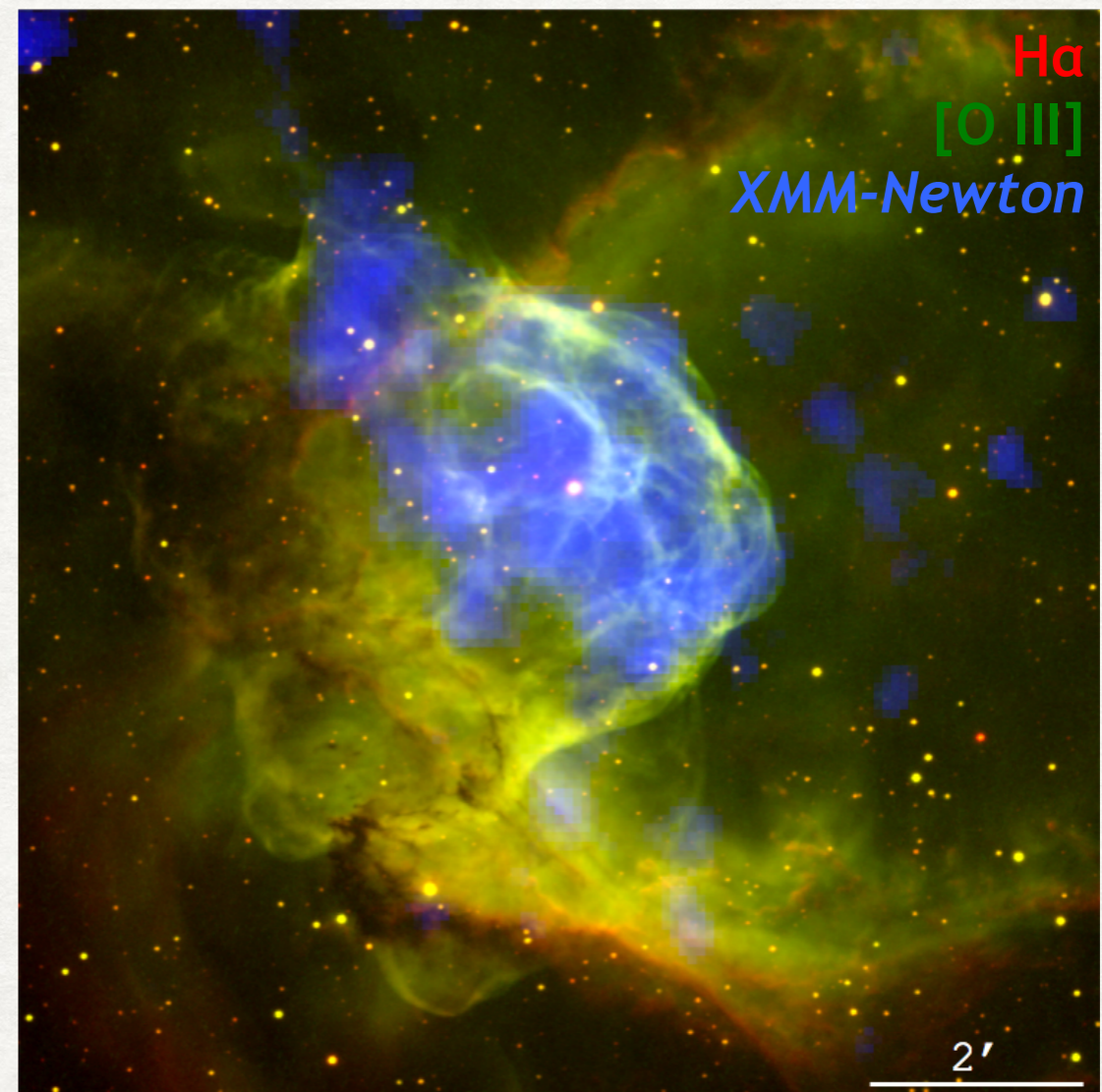
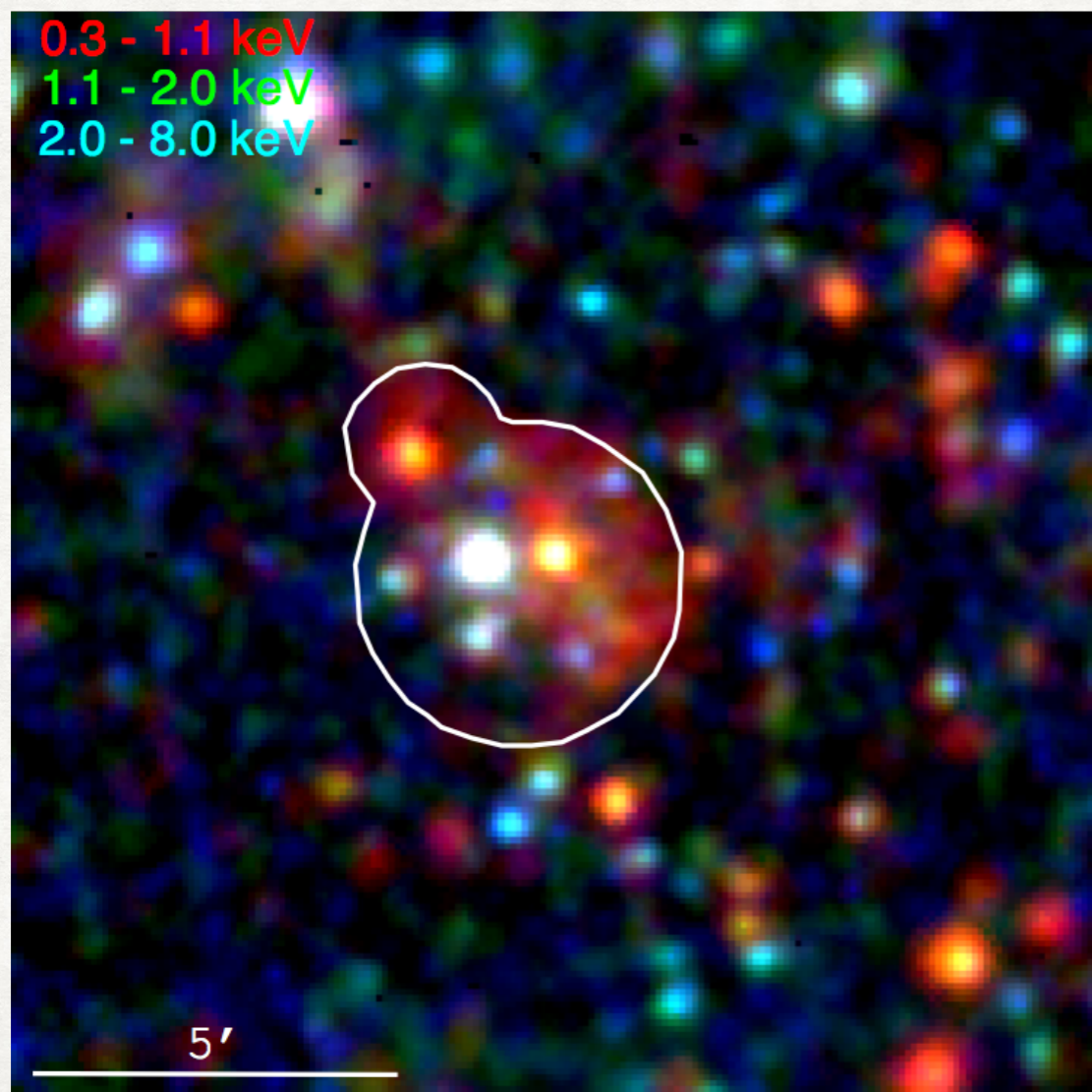
Astronomy Picture of the Day
(2010 June 5)

Amateur astronomers
Steve Mazlin, Jack Harvey,
Rick Gilbert, and Daniel Verschatsse



NGC 2359 (WR7)

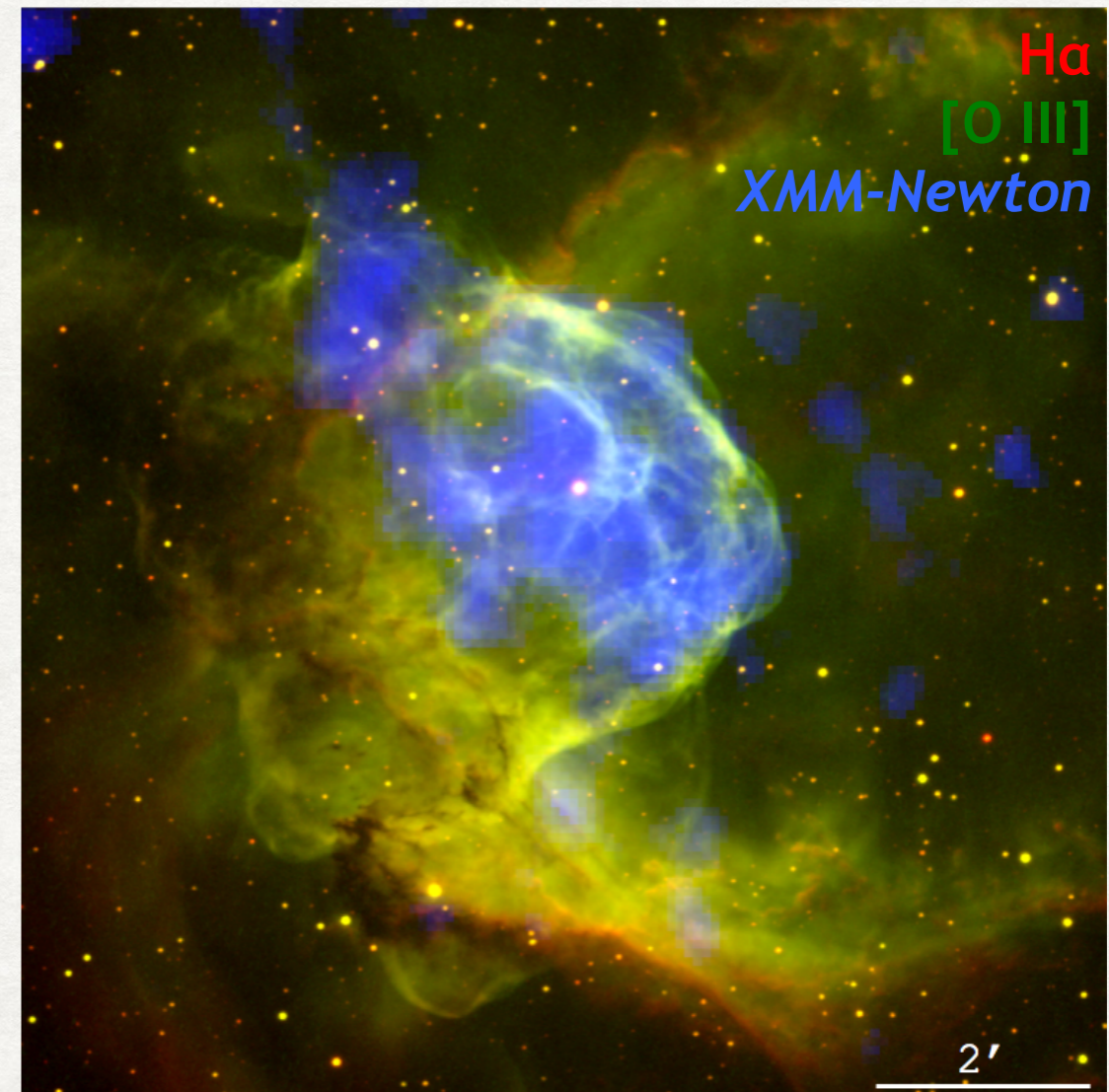
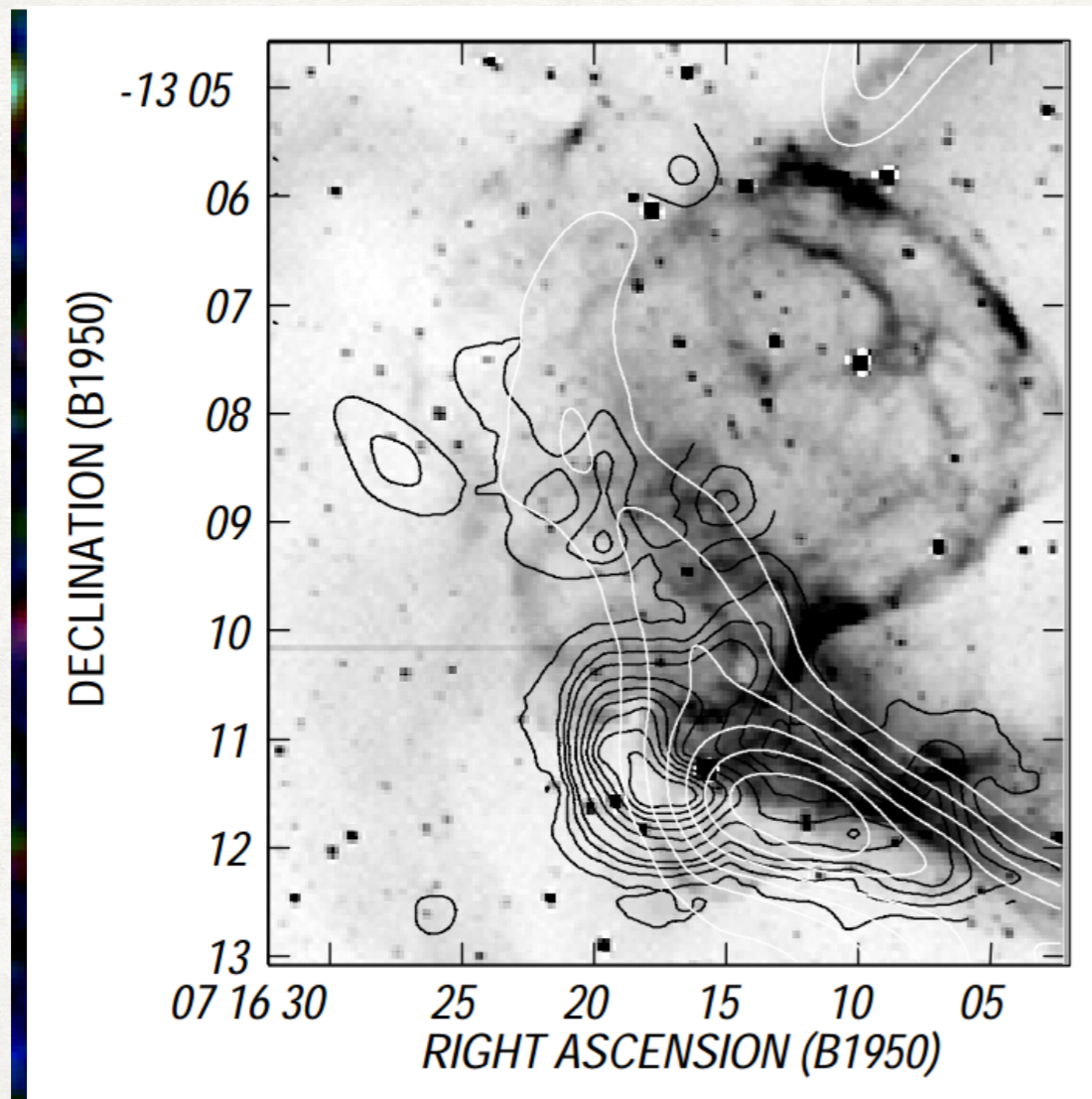
Toalá et al. (2014)



NGC 2359 (WR7)

Toalá et al. (2014)

Cappa et al. (2001)

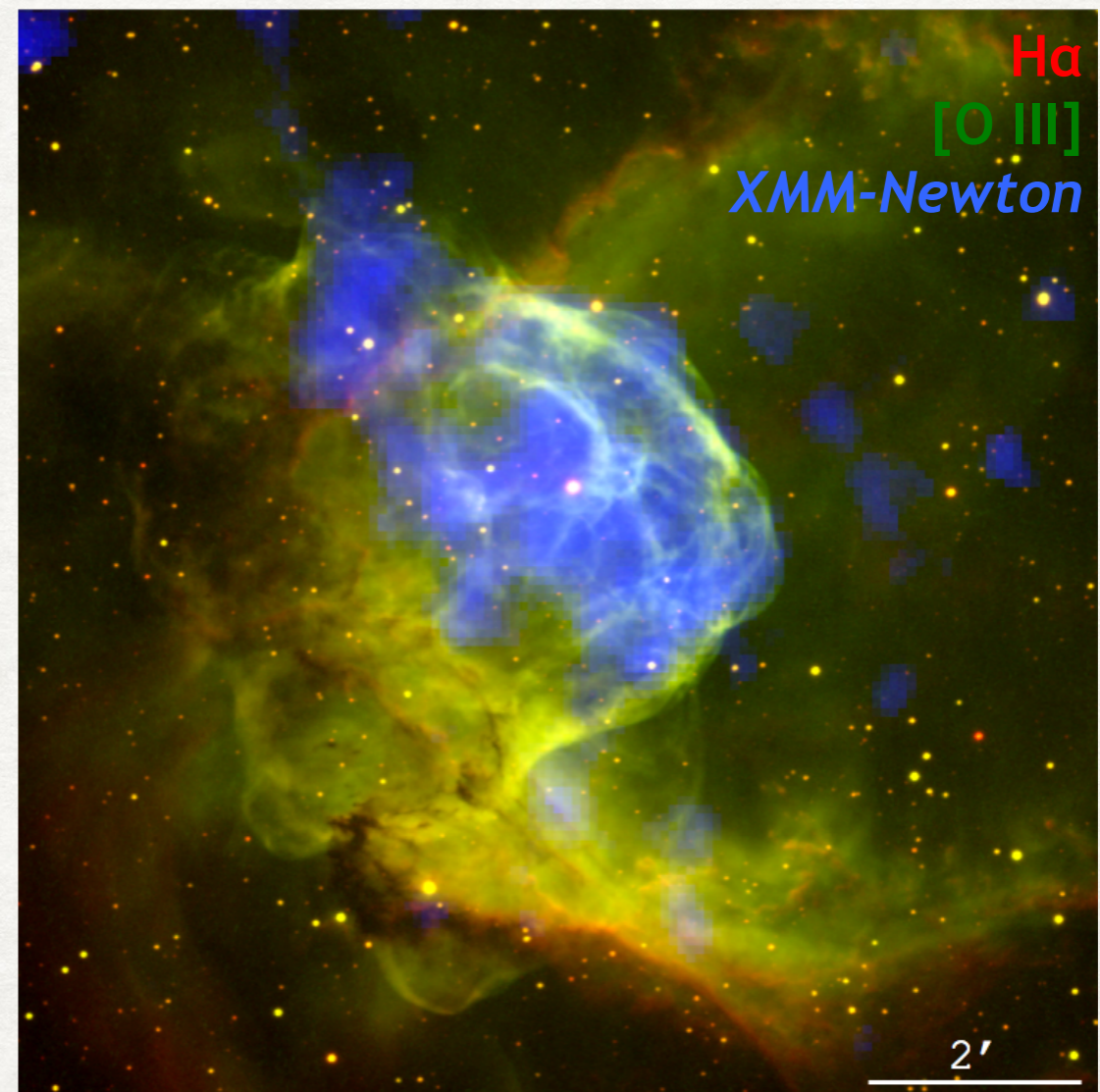
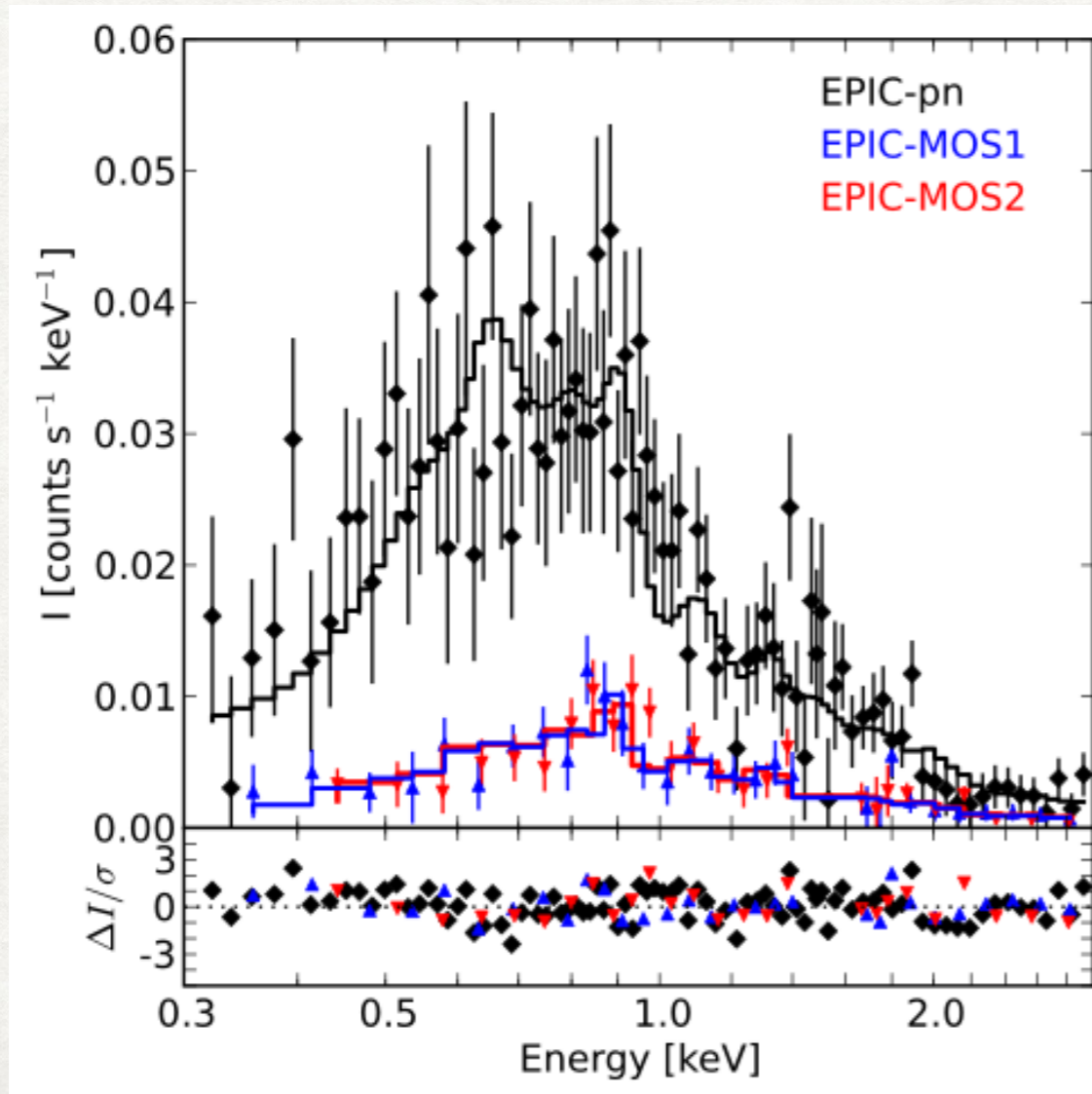


NGC 2359 (WR7)

Toalá et al. (2014)

$$T_x = 2 \times 10^6 \text{ K}$$

$$n_e = 0.6 \text{ cm}^{-3}$$



NGC 6888 (WR136)

The most studied WR nebula
in X-rays!

Low resolution:

Einstein (Bochkarev et al. 1988)

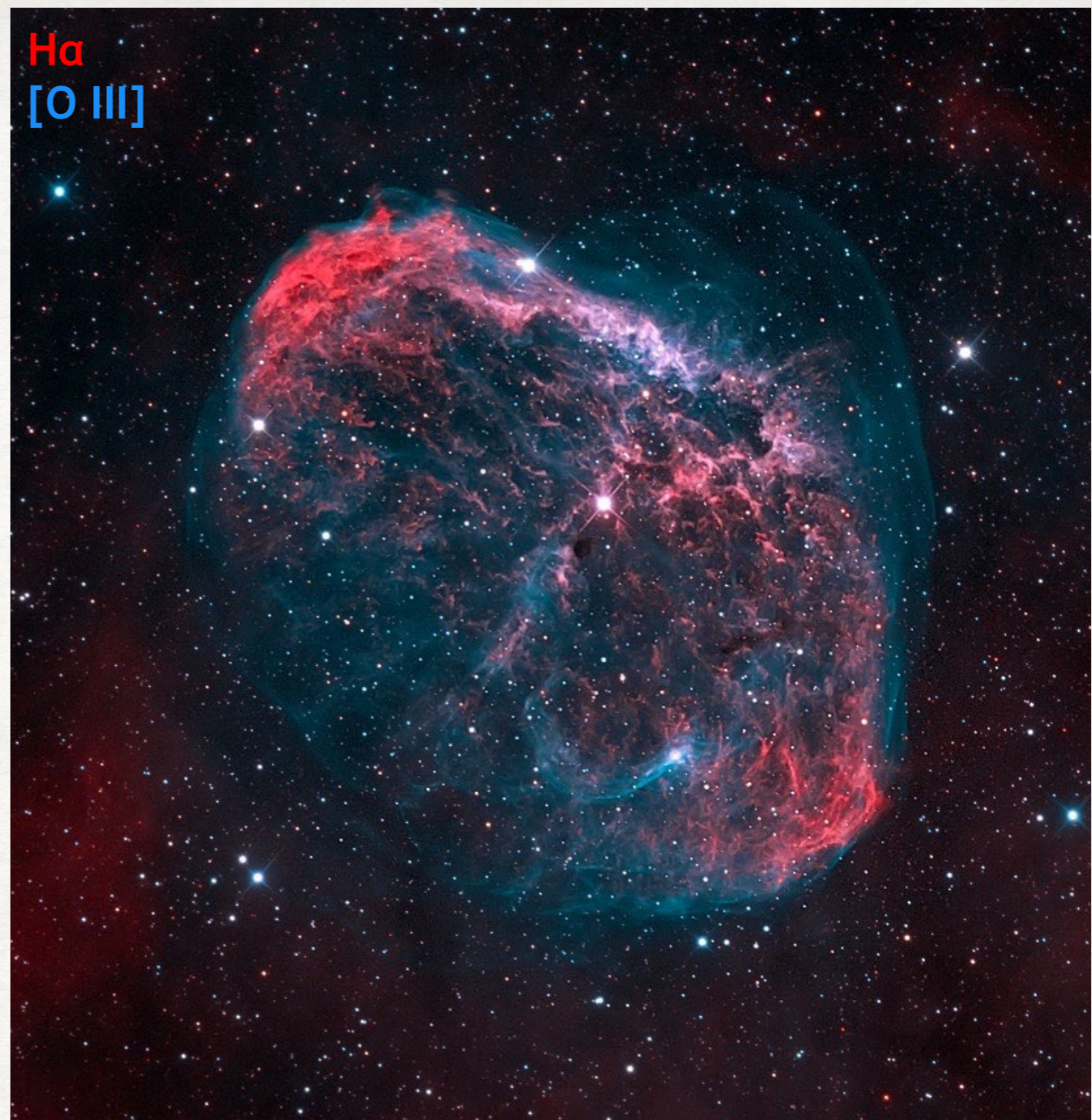
ROSAT (Wrigge et al. 1994, 2005)

ASCA (Wrigge et al. 2005)

Not completely mapped:

Suzaku (Zhekov & Park 2011)

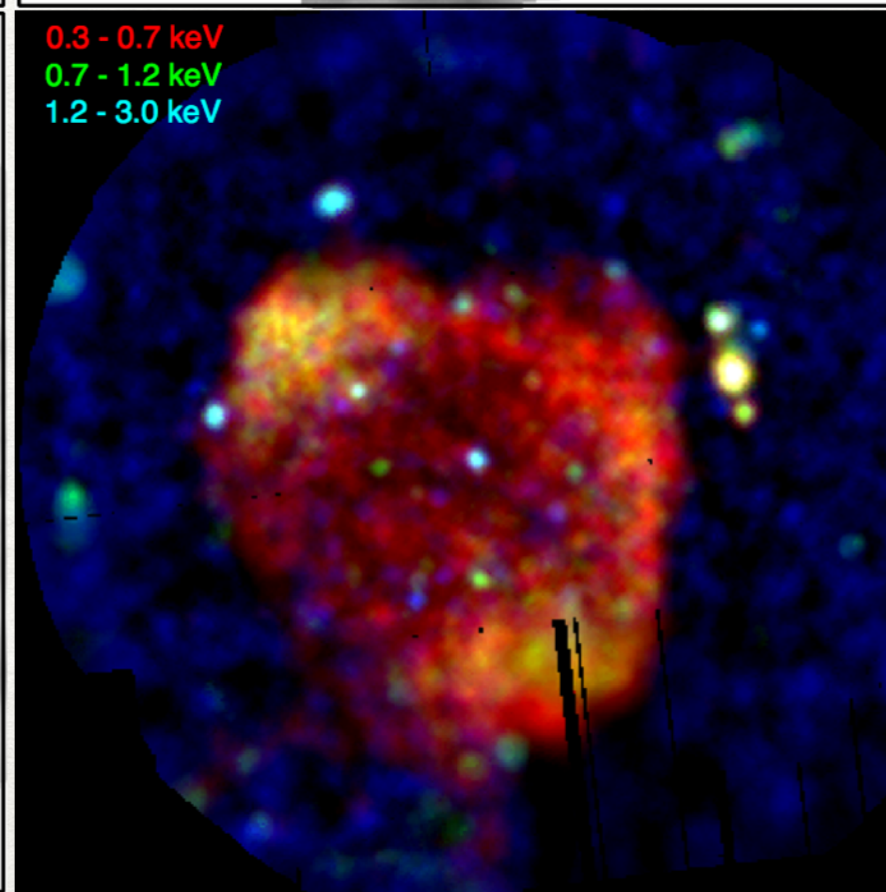
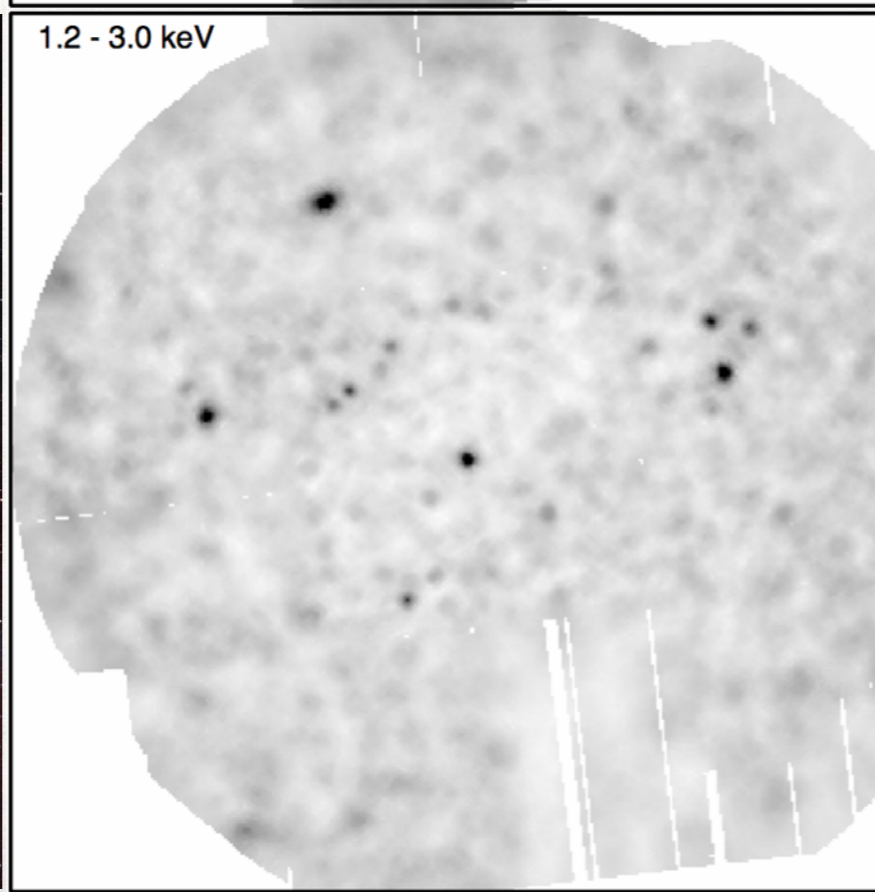
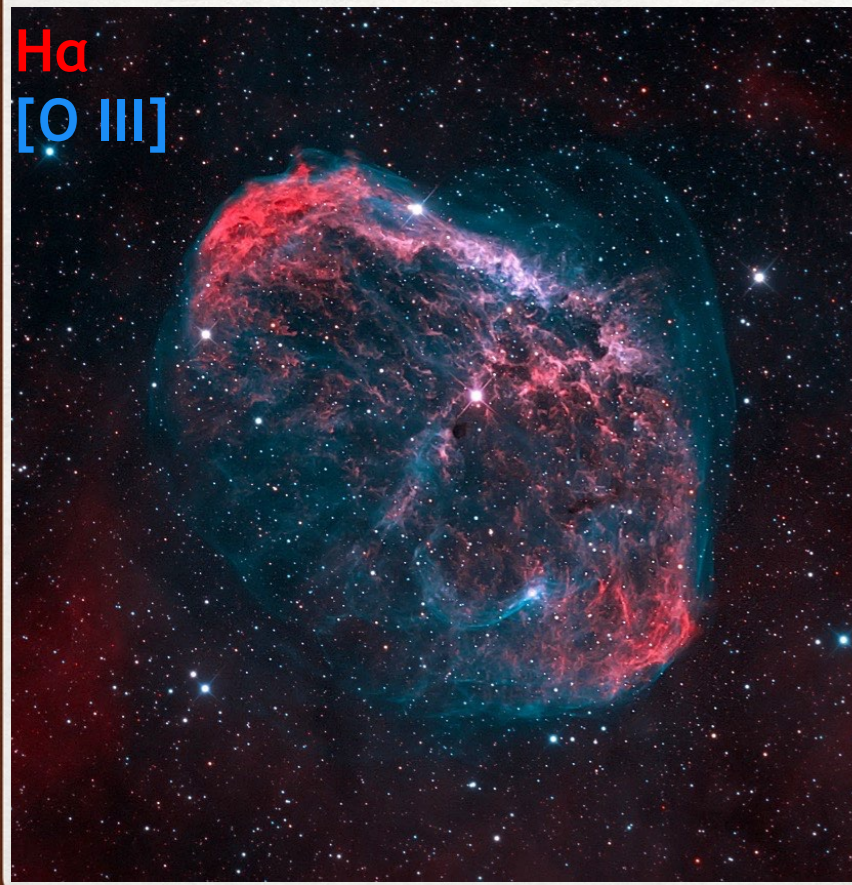
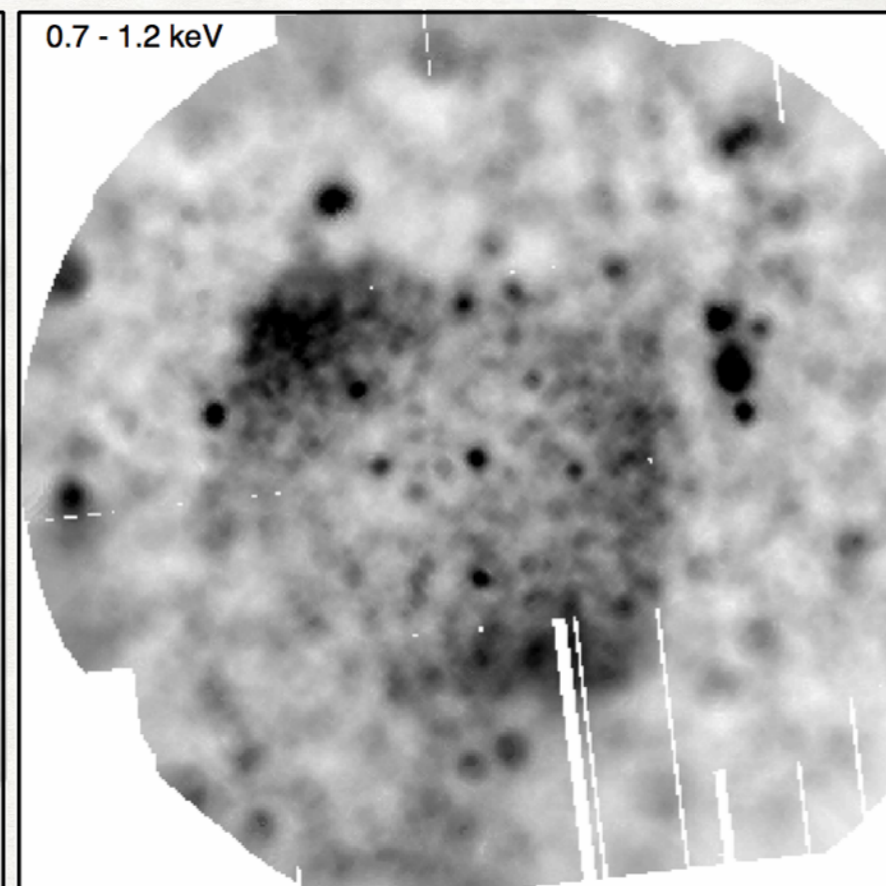
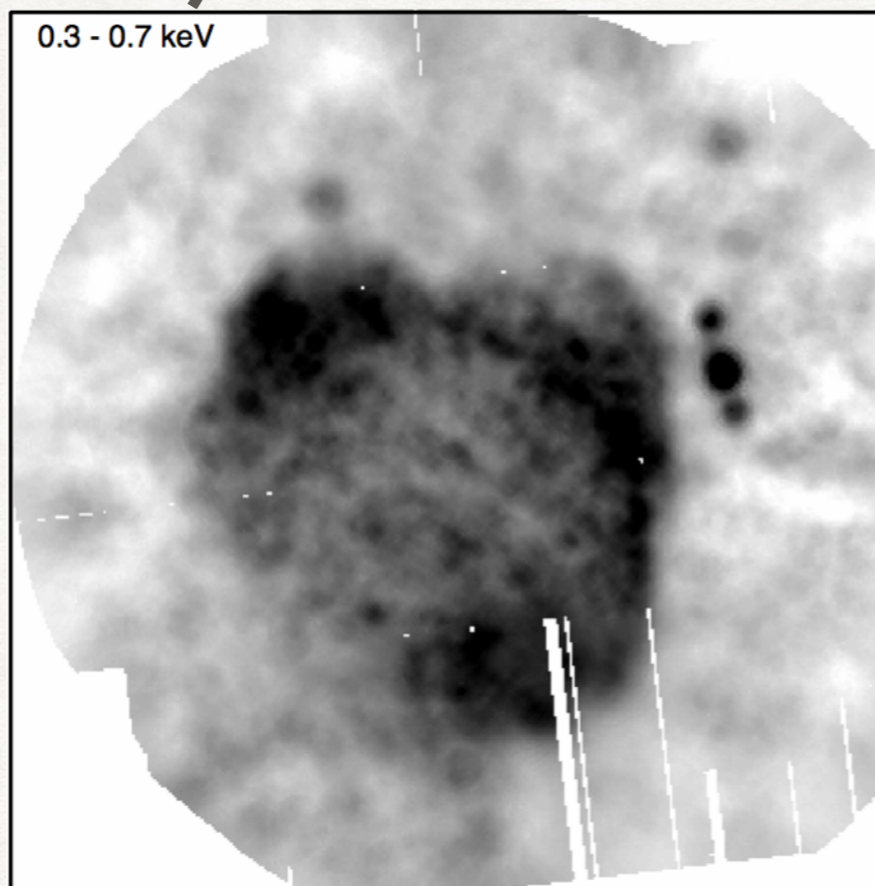
Chandra (Toalá et al. 2014)



NGC 6888 (WR136)

Toalá et al. (2015)

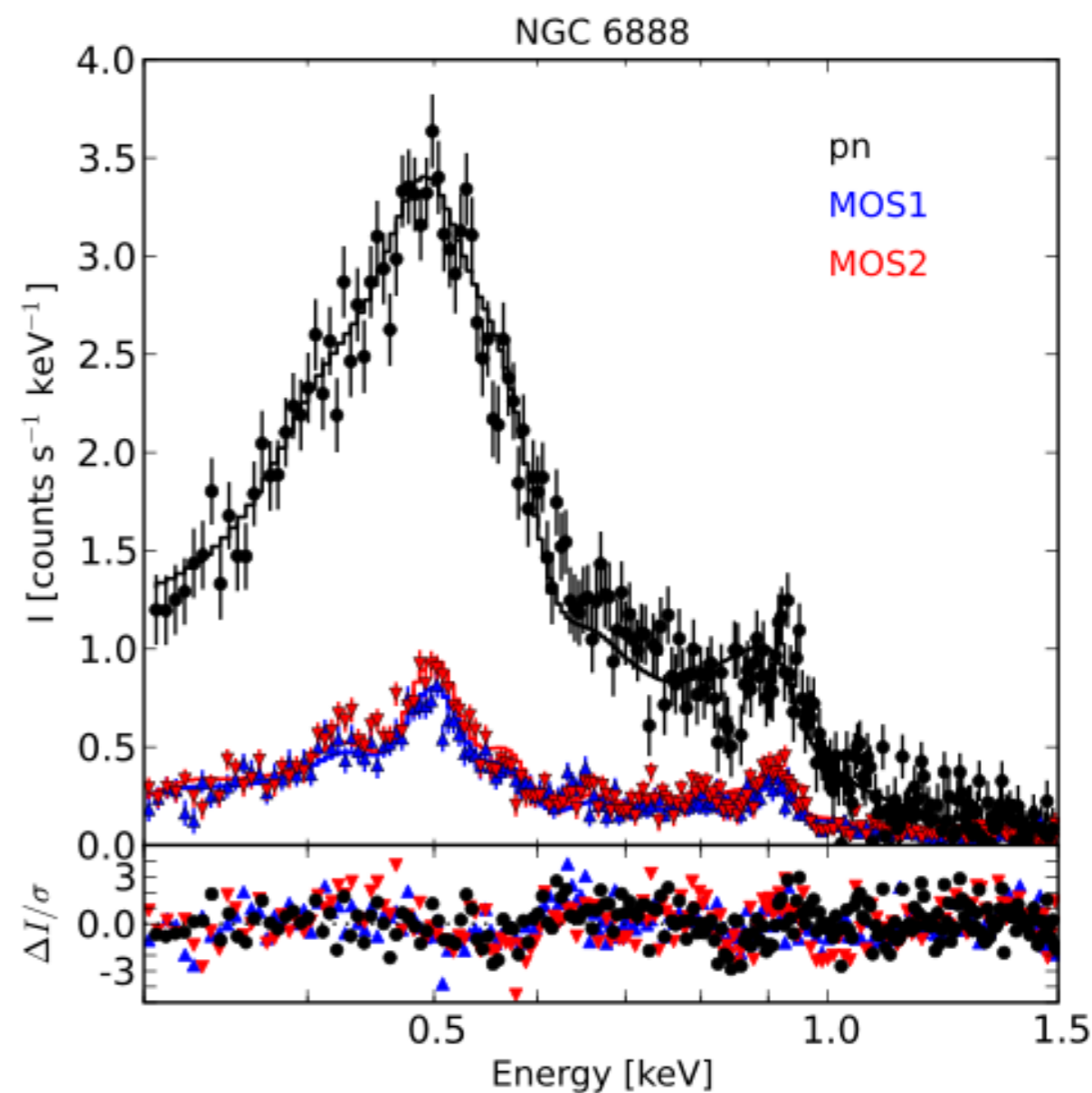
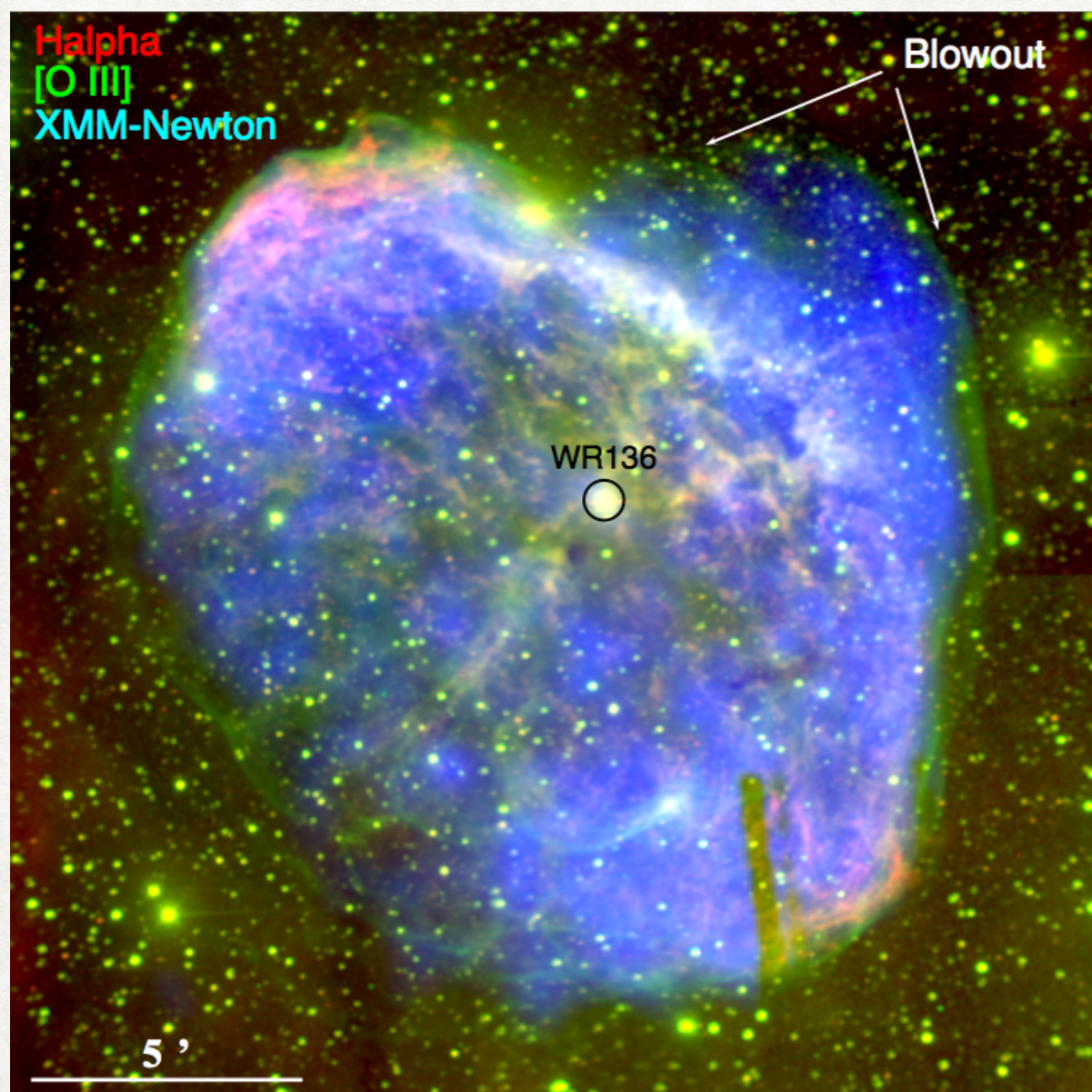
XMM-Newton



NGC 6888 (WR136)

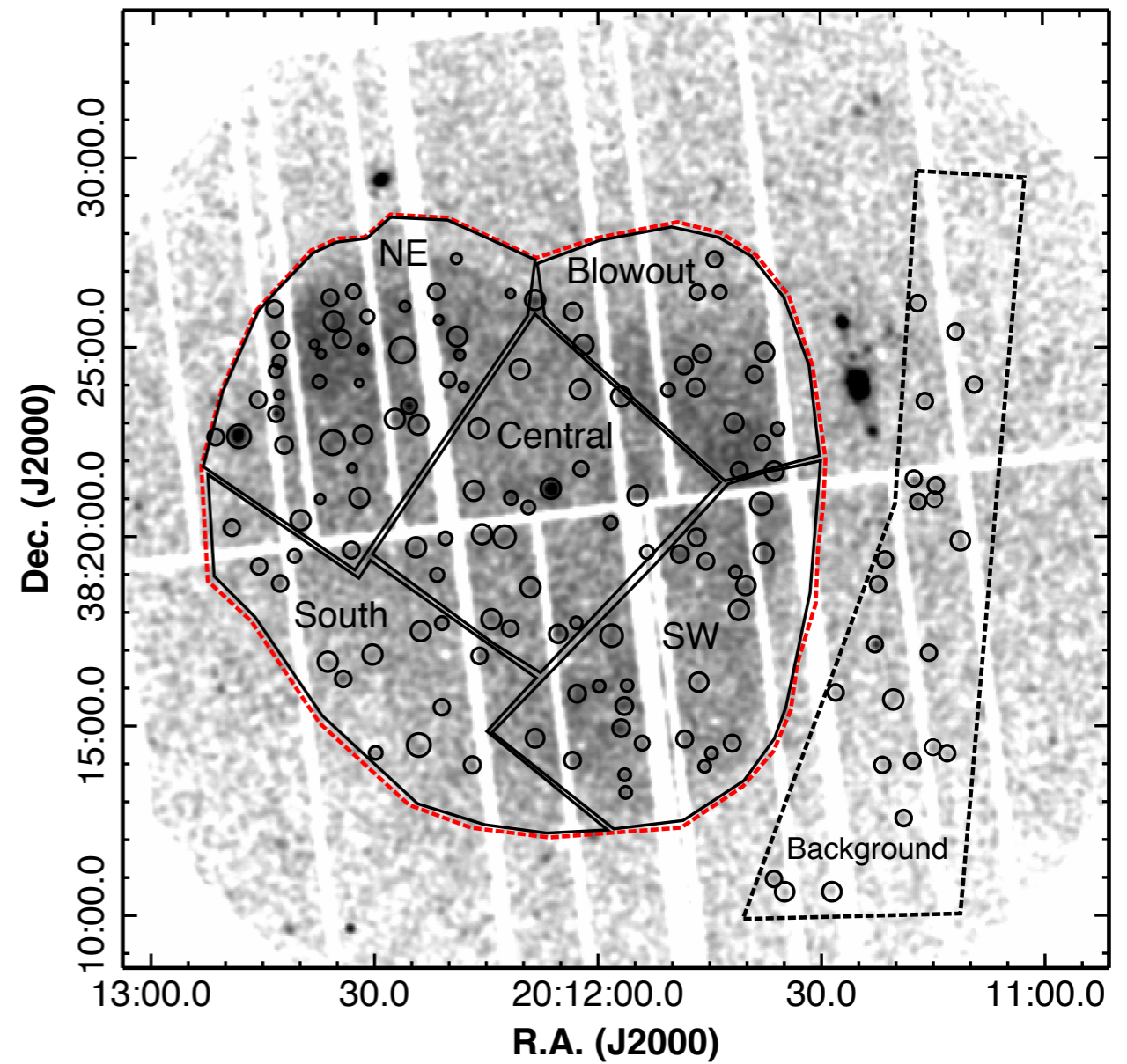
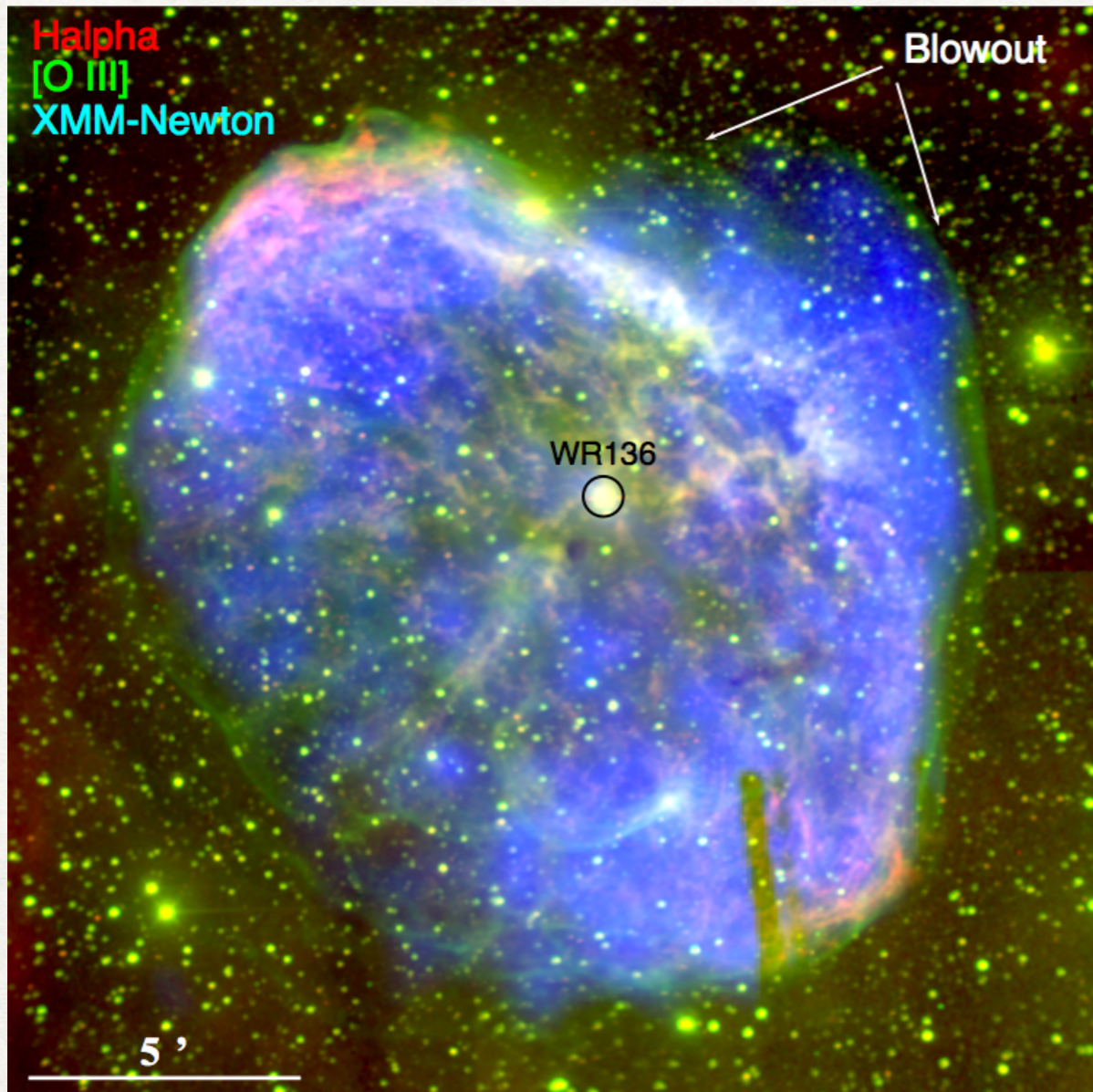
Toalá et al. (2015)

$$T_x = 1.4 \times 10^6 \text{ K}$$
$$n_e = 0.4 \text{ cm}^{-3}$$

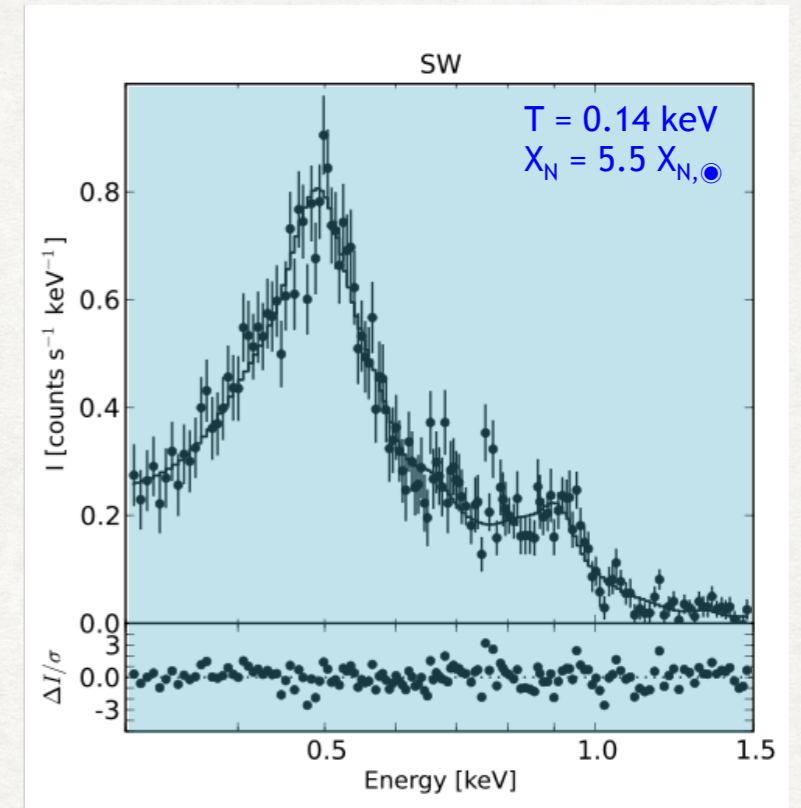
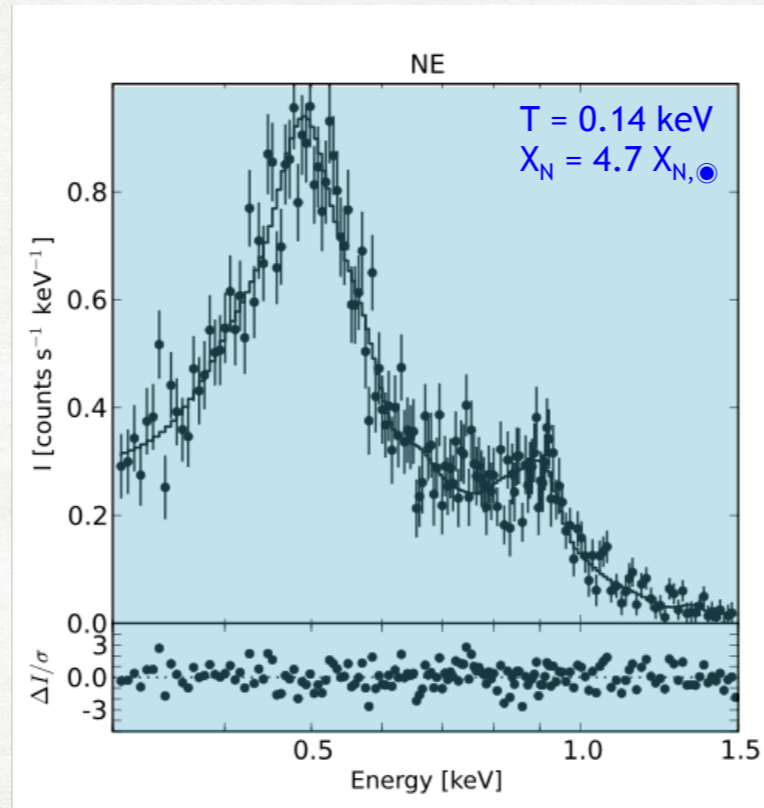
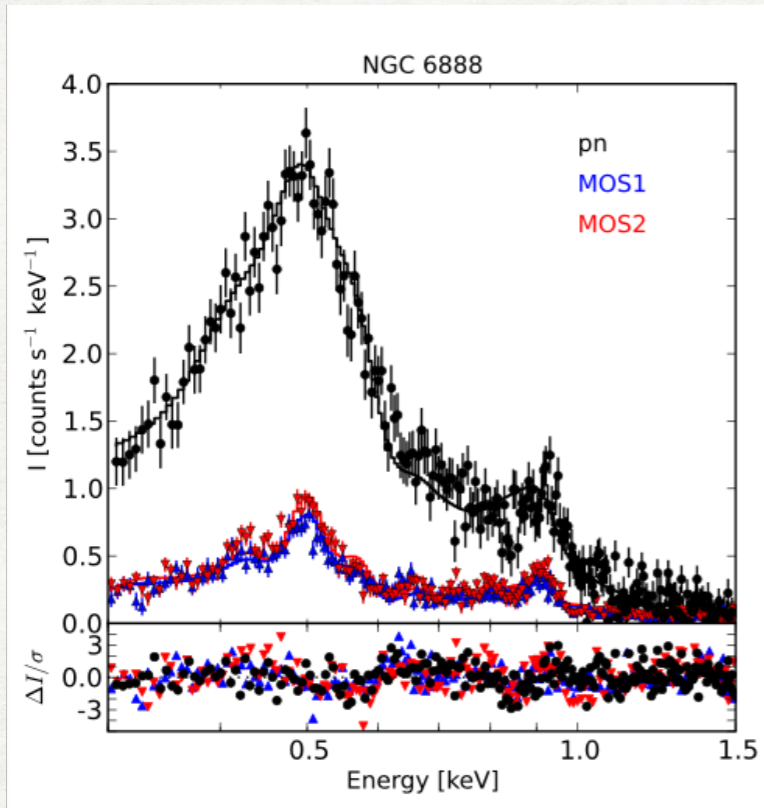


NGC 6888 (WR136)

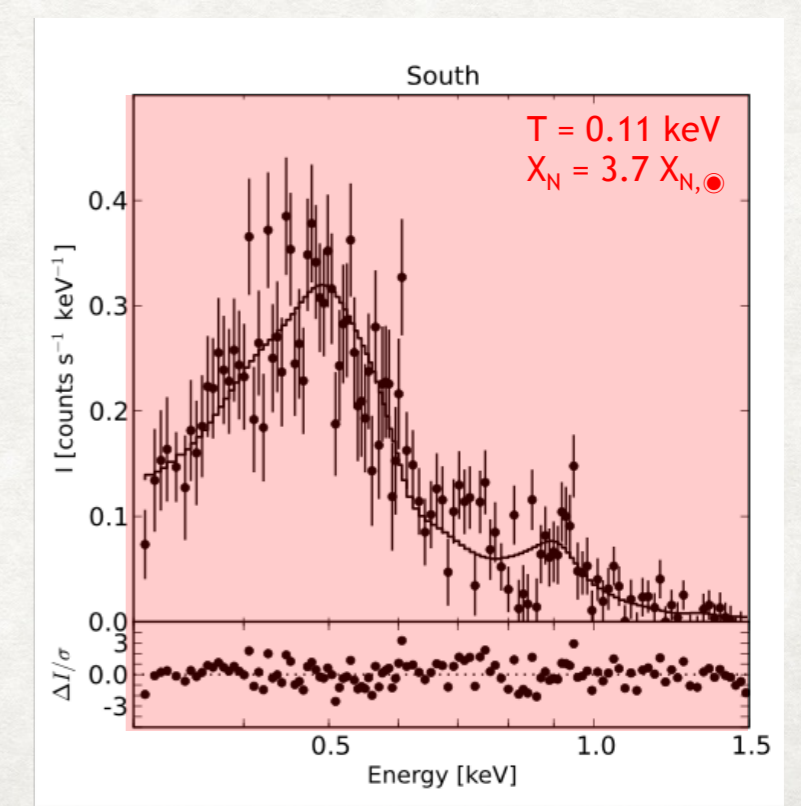
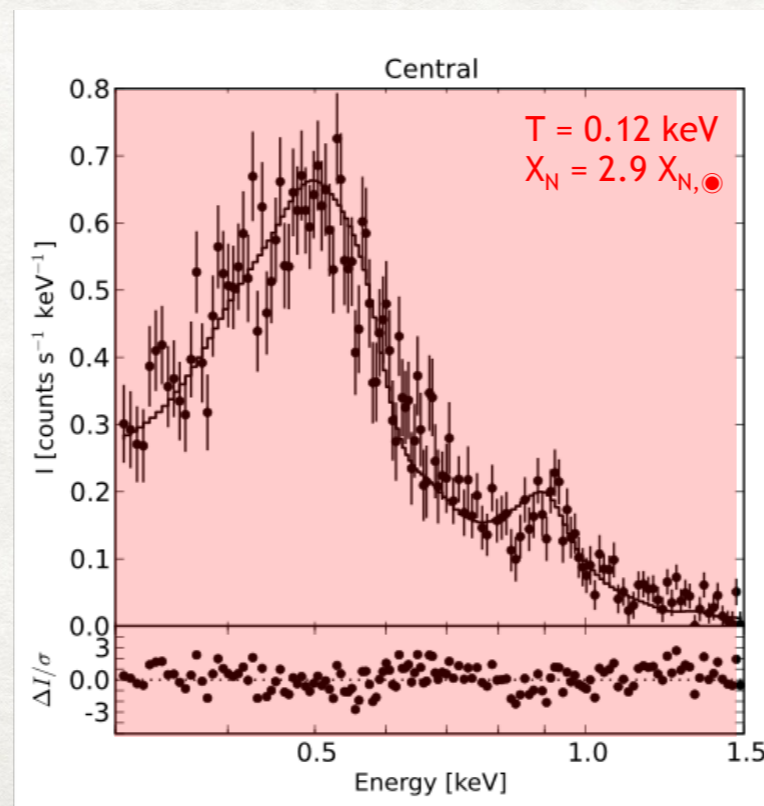
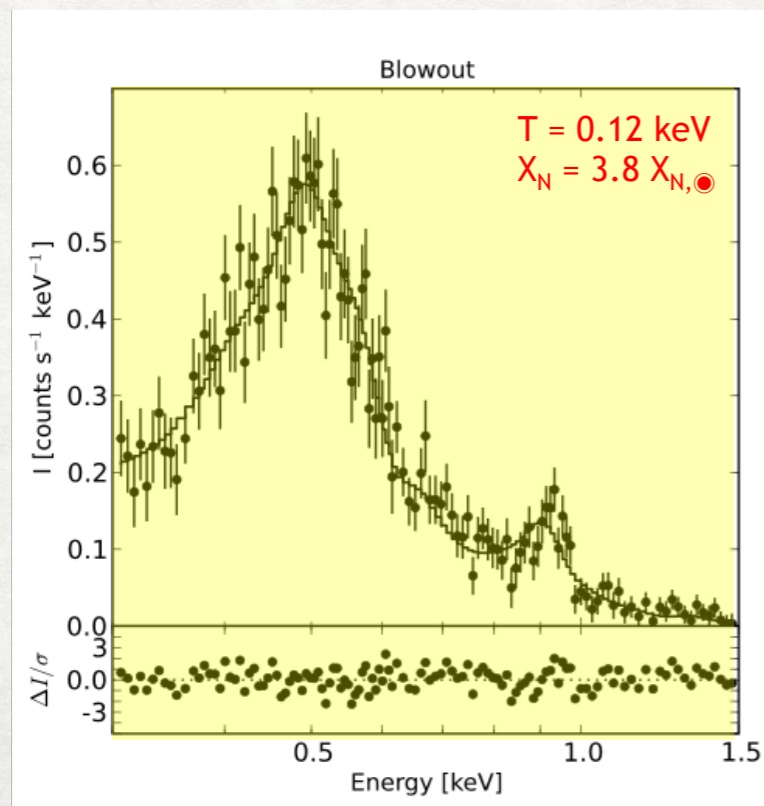
Toalá et al. (2015)



Nitrogen close to WN



Nitrogen close to nebular



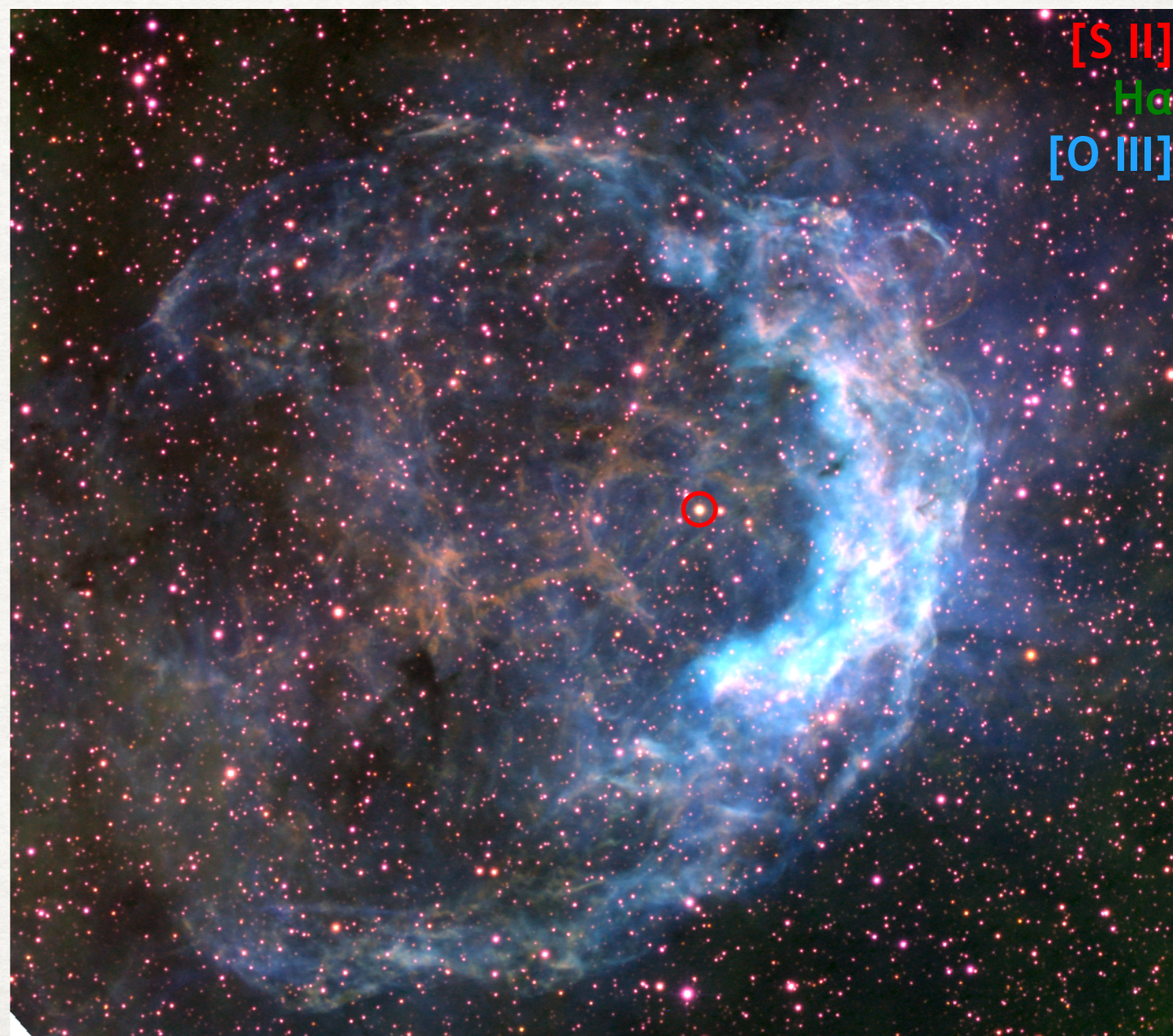
NGC 3199 (WR18)

Runaway star!

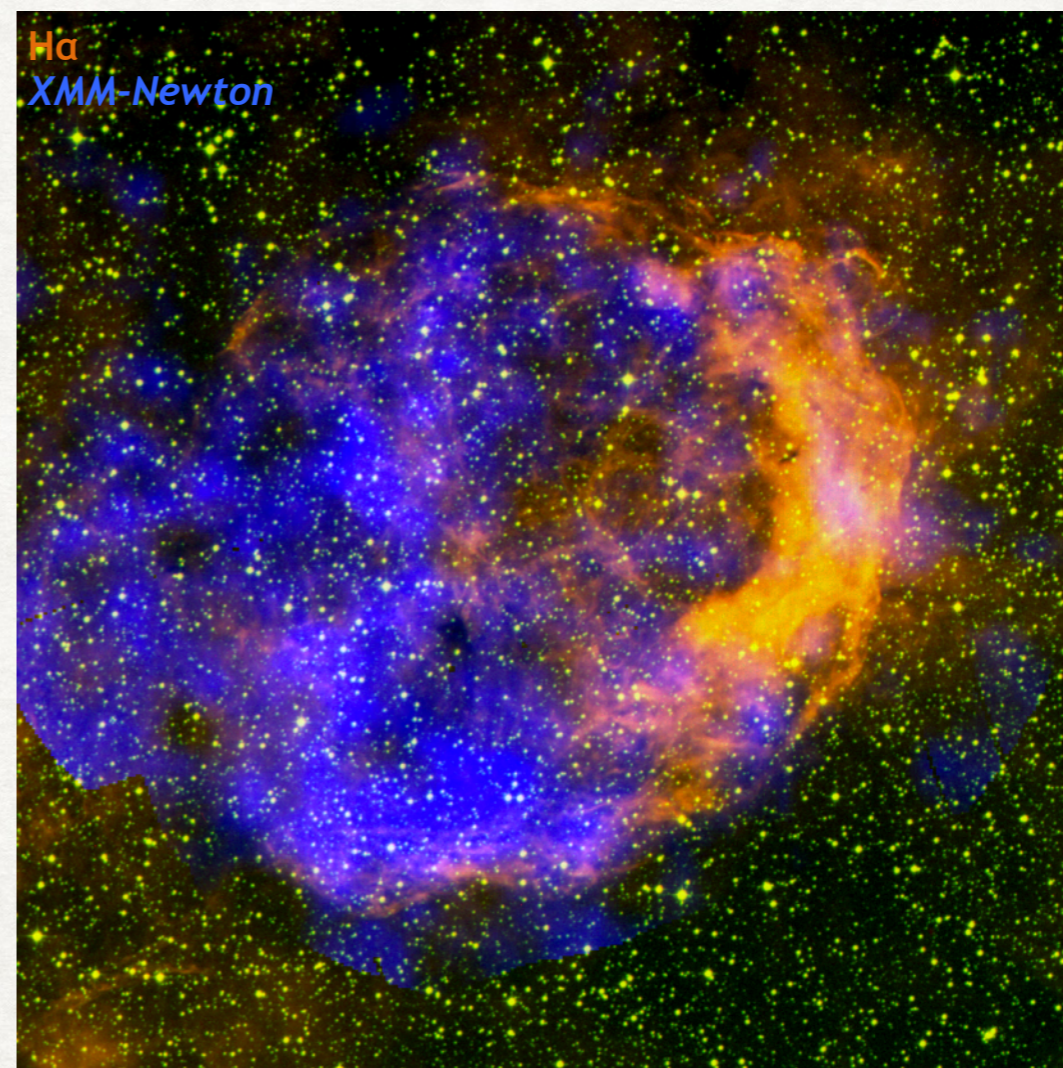
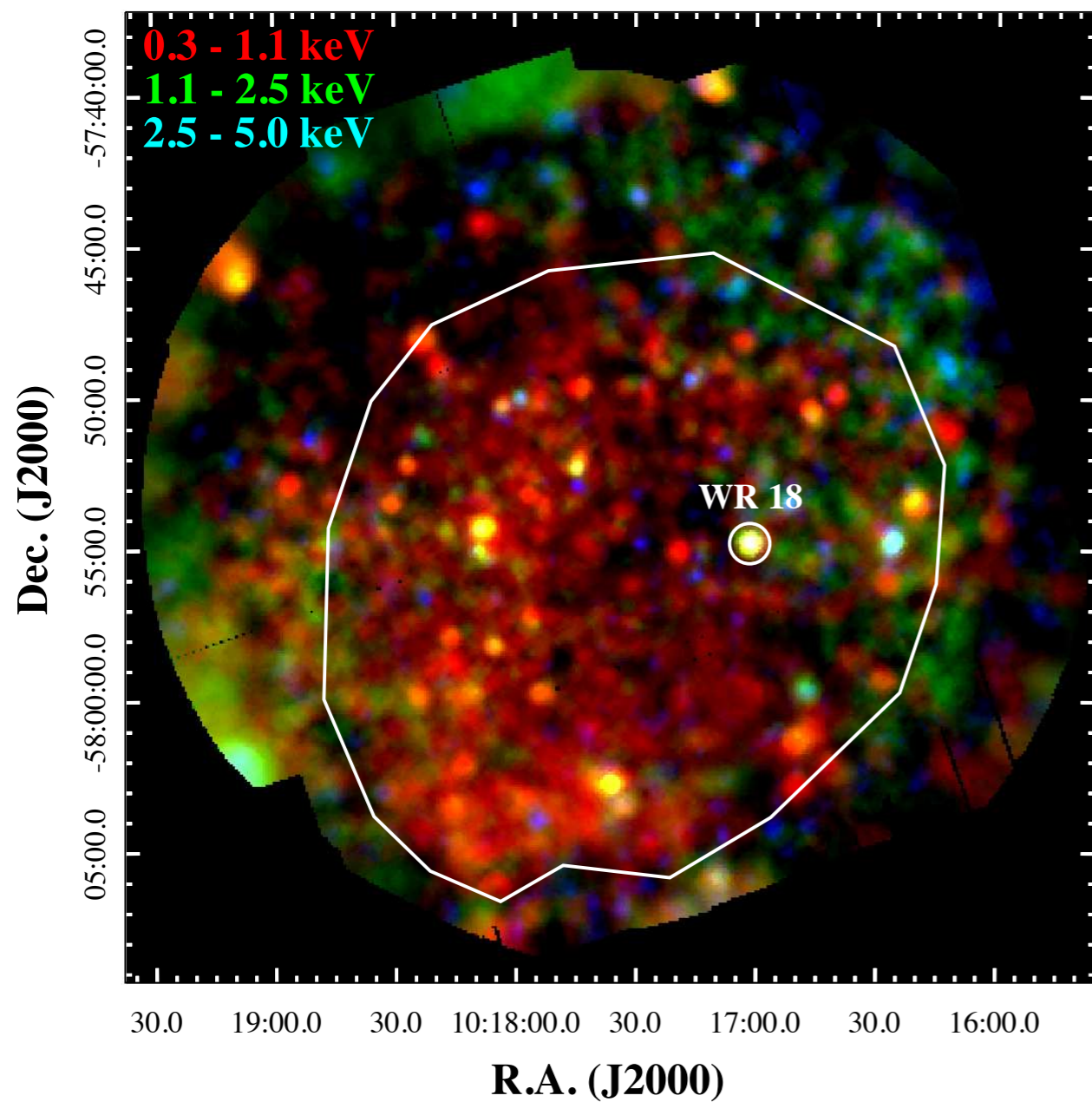
XMM-Newton

(Toalá et al. in prep.)

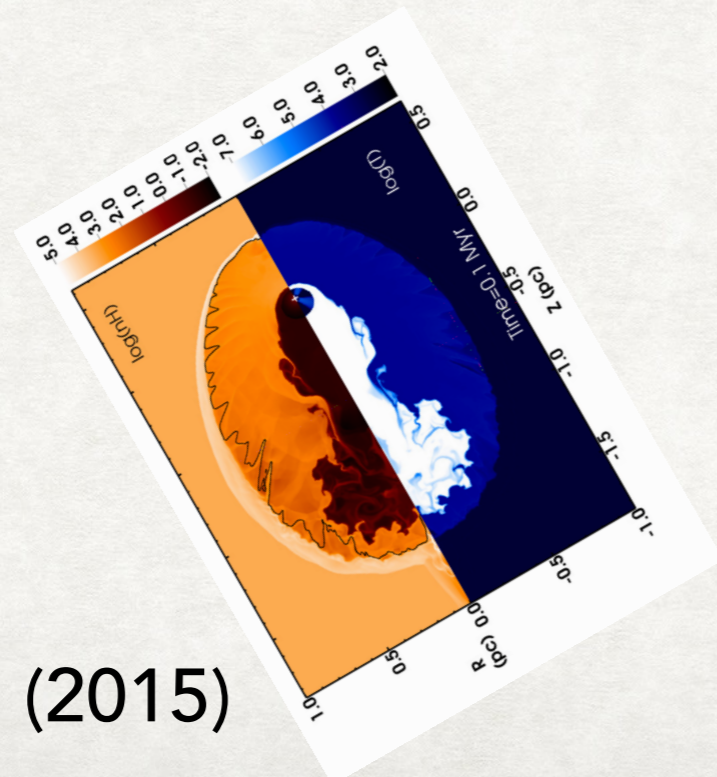
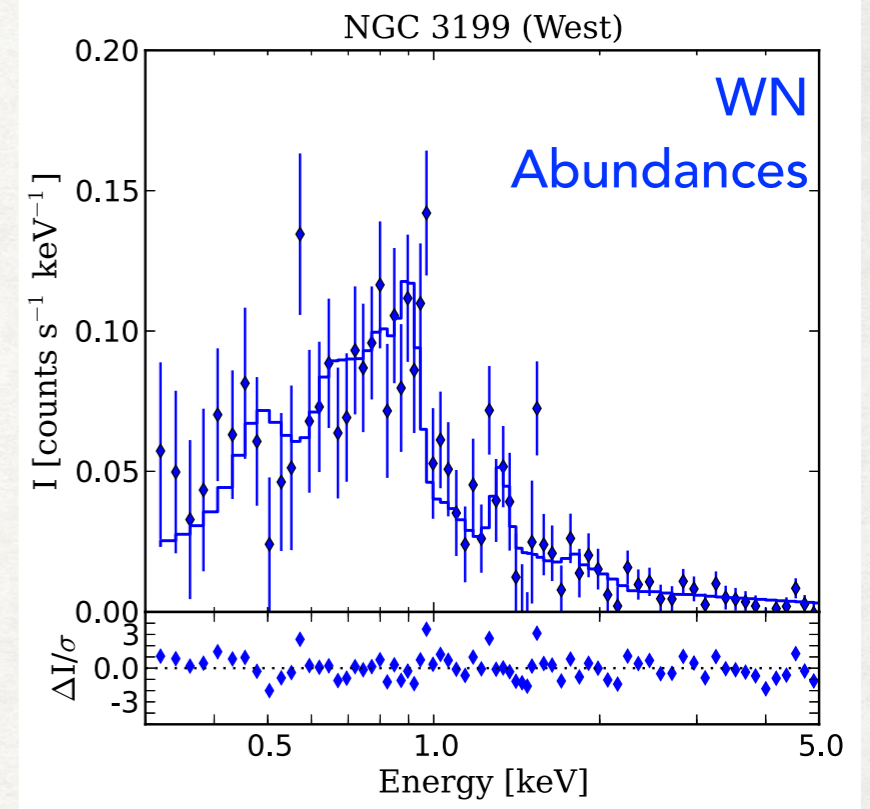
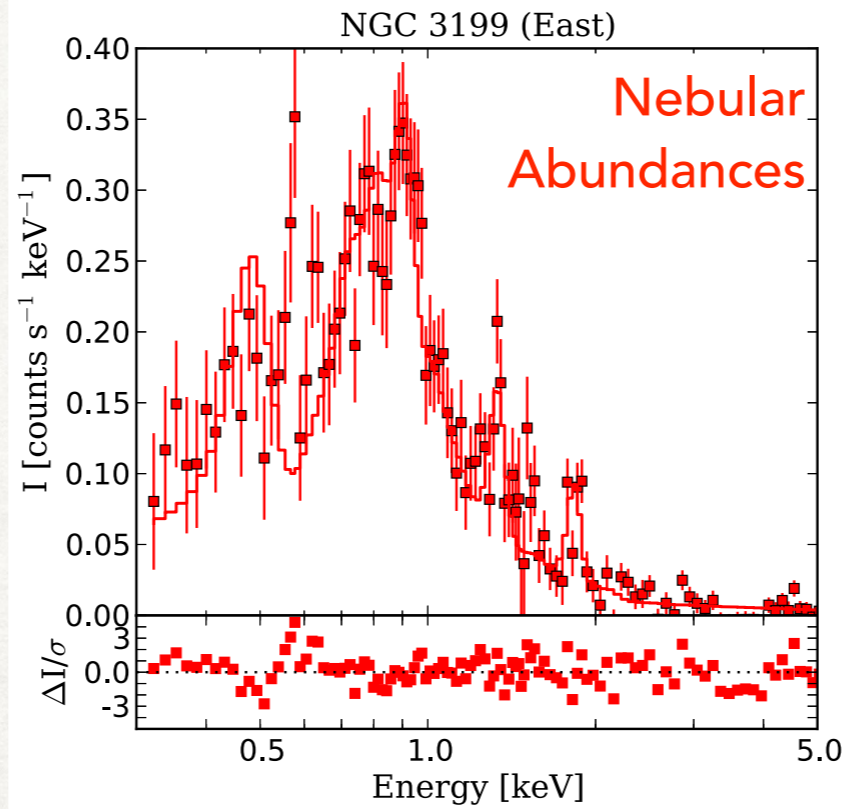
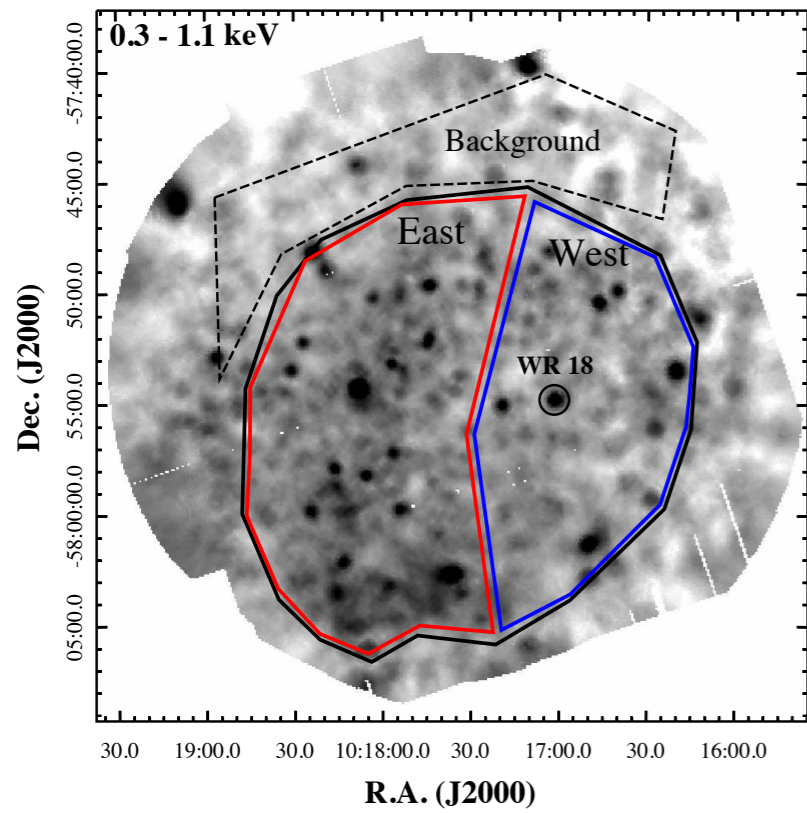
AstroDon
Don Golman



NGC 3199 (WR18)



NGC 3199 (WR18)



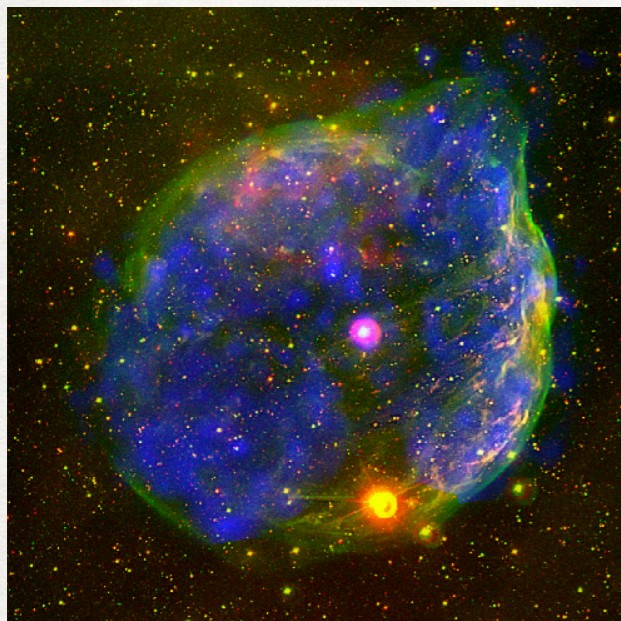
Mackey et al. (2015)

Remarks

4 WR nebulae with diffuse X-ray emission - All different origins!

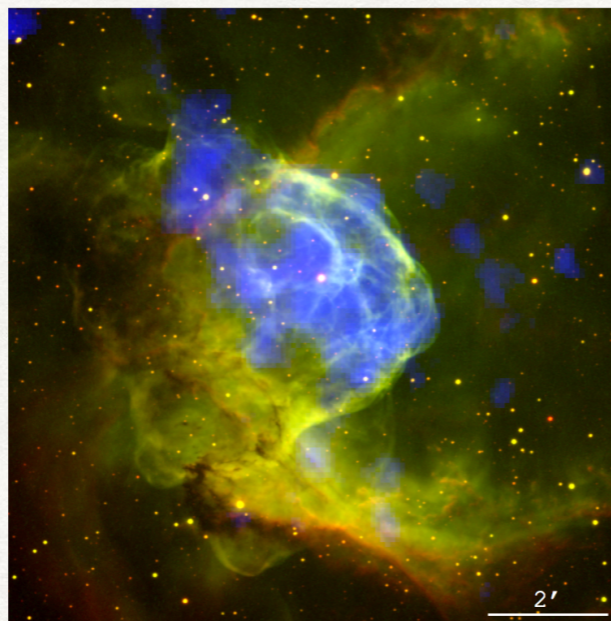
WR6

YSG



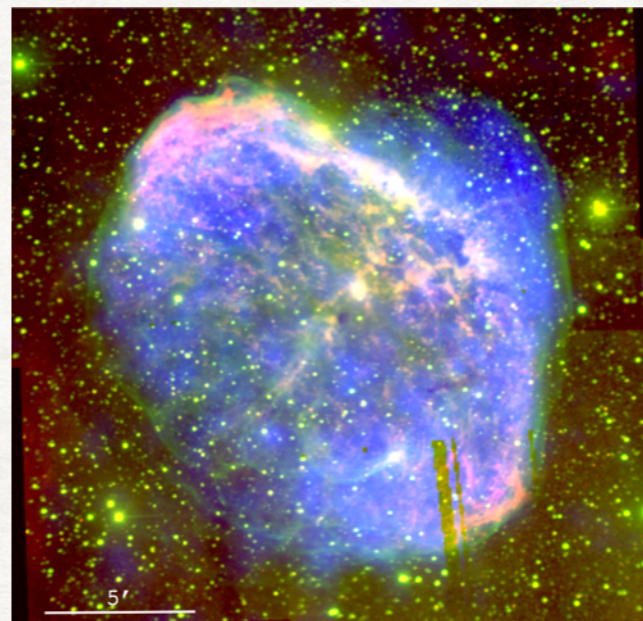
WR7

LBV



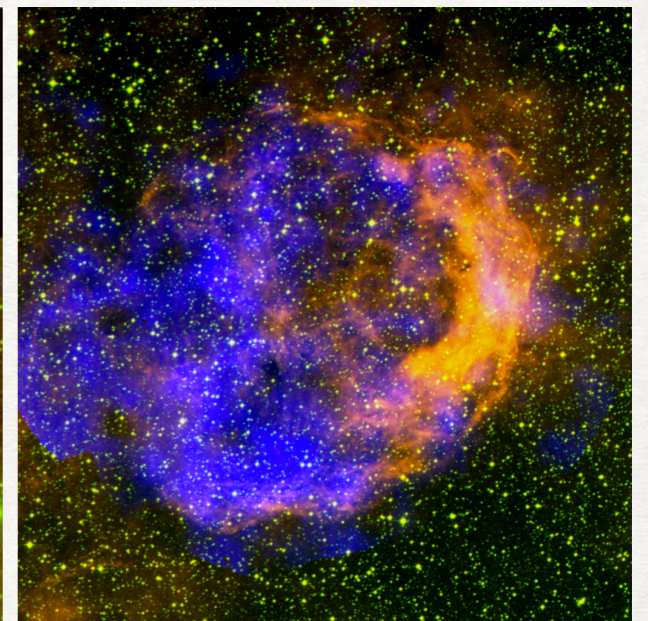
WR136

RSG/ISM interaction?

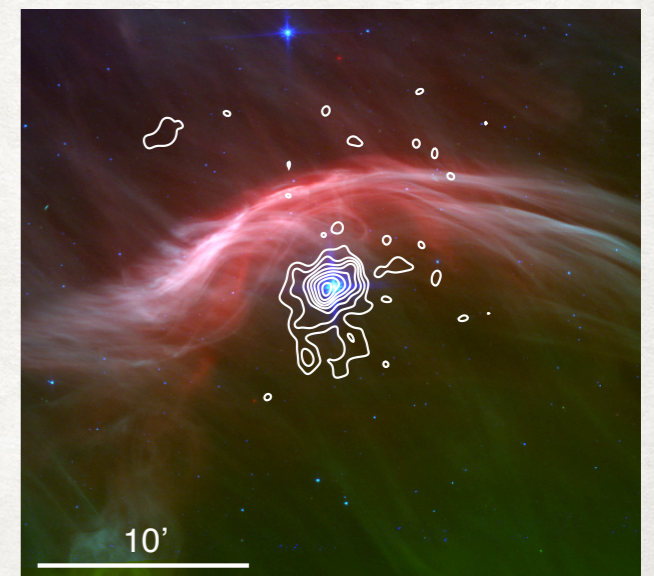


WR18

Runaway



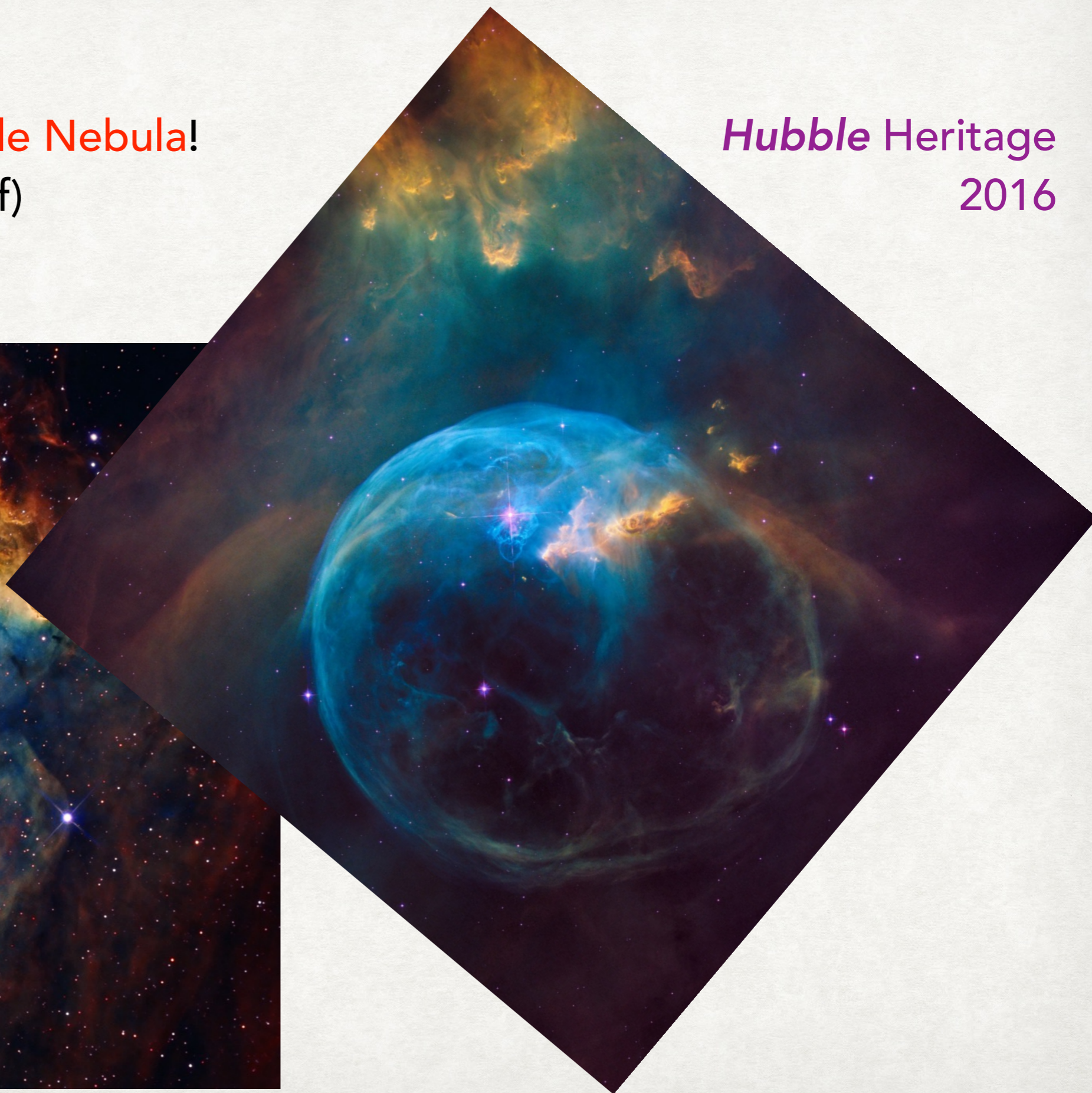
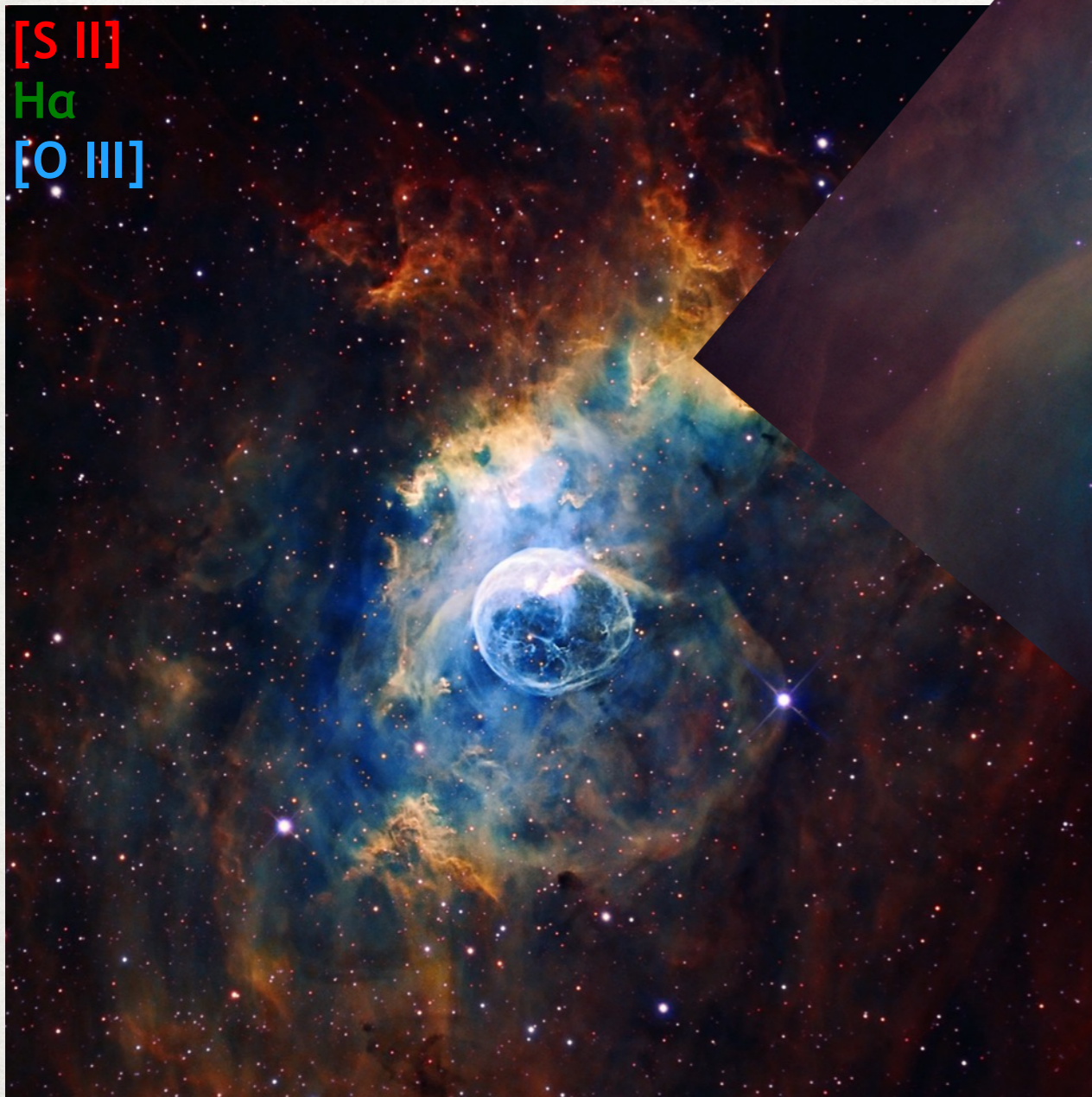
- All harbour WN4-6 stars
- X-ray-emitting gas has nebular abundances (MIXING!)
- $T_X = 1 - 2 \times 10^6$ K
- Detailed spectral analysis show abundance variations



Remarks

X-rays from the **Bubble Nebula!**
BD+60°2522 (O6.5 IIIf)

Hubble Heritage
2016

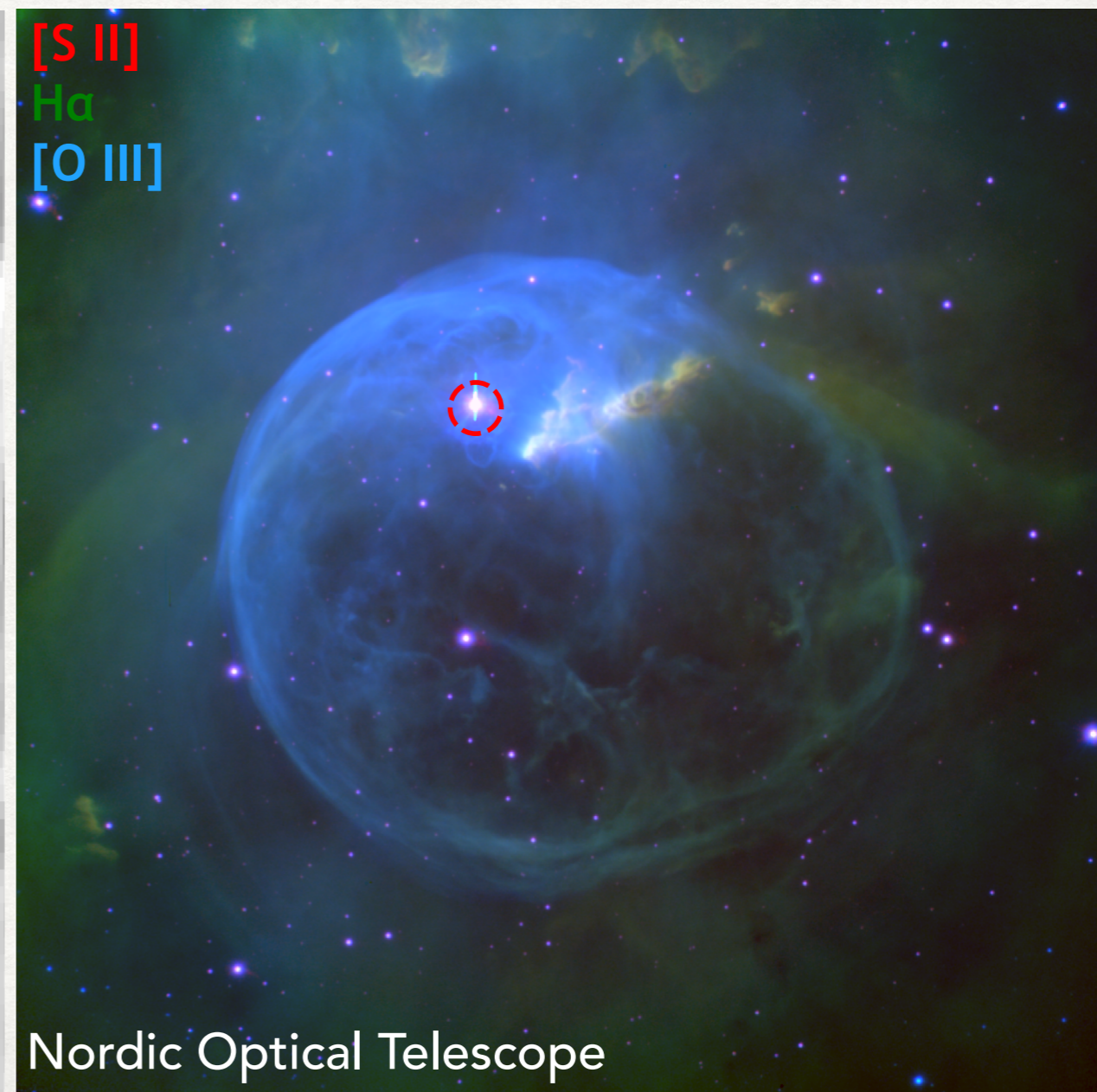
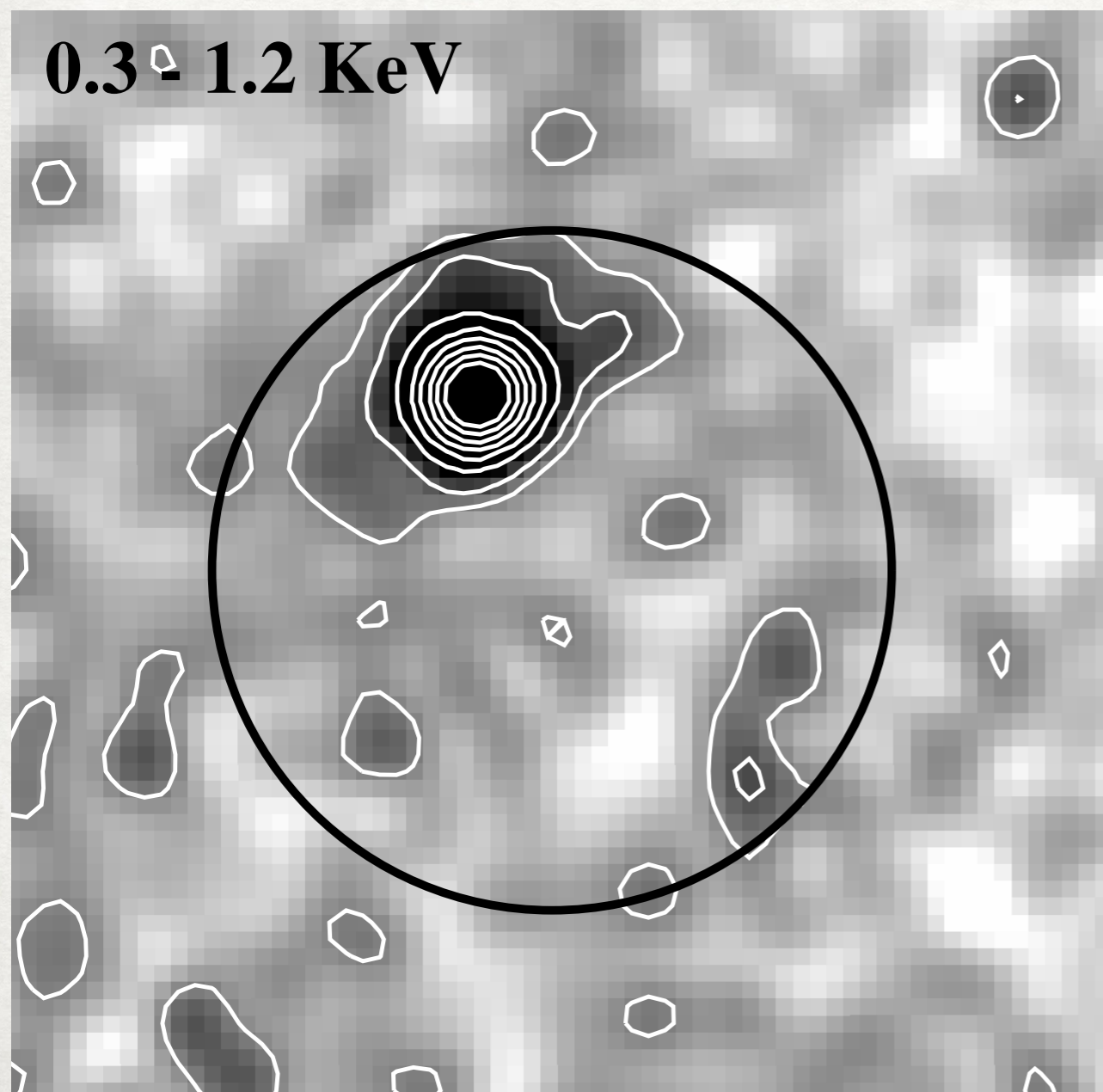


Remarks

X-rays from the **Bubble Nebula!**

Toalá et al. in prep.

XMM-Newton



THANK
YOU

