Shells around red supergiants

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ph1 Universität zu Köln

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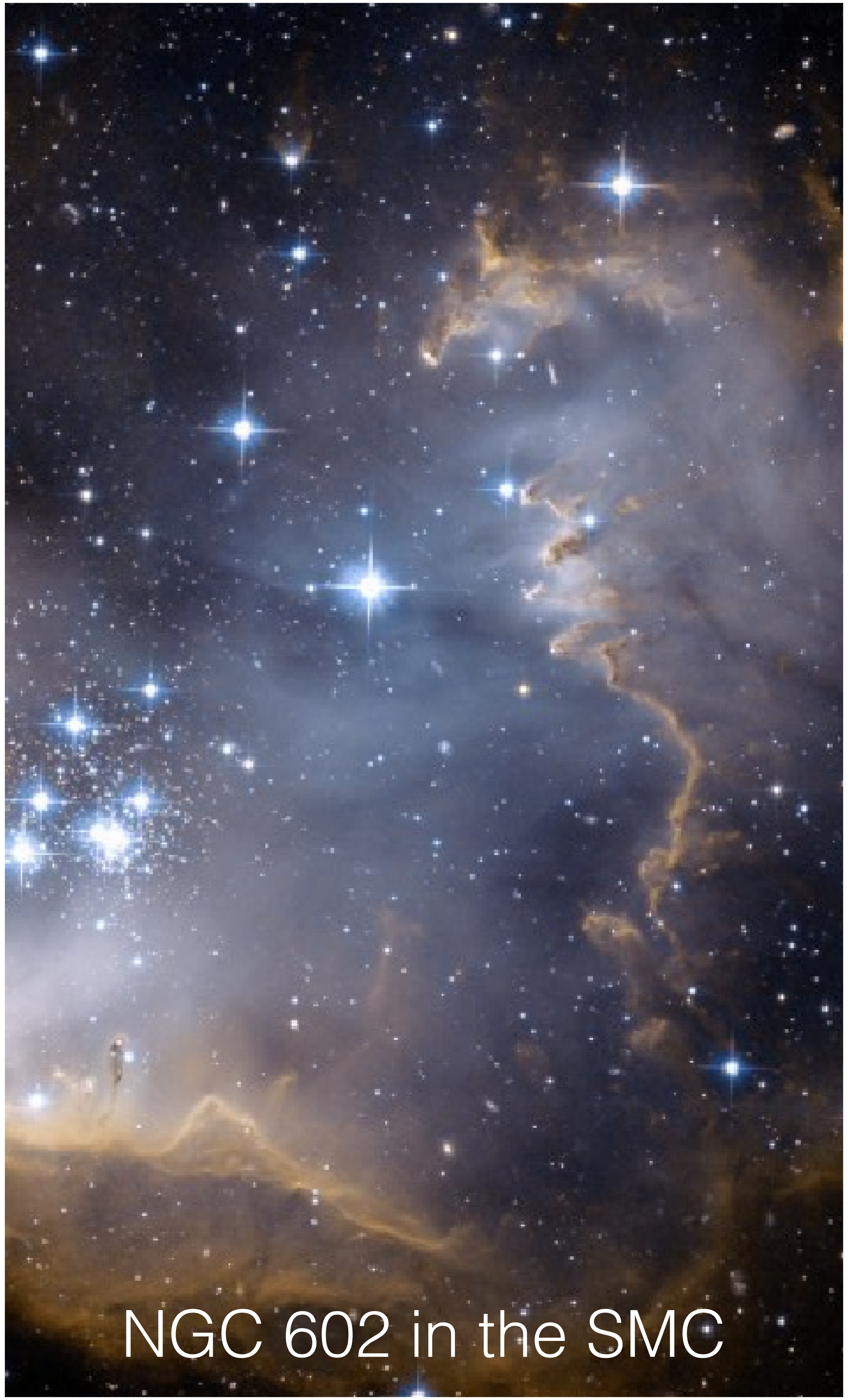
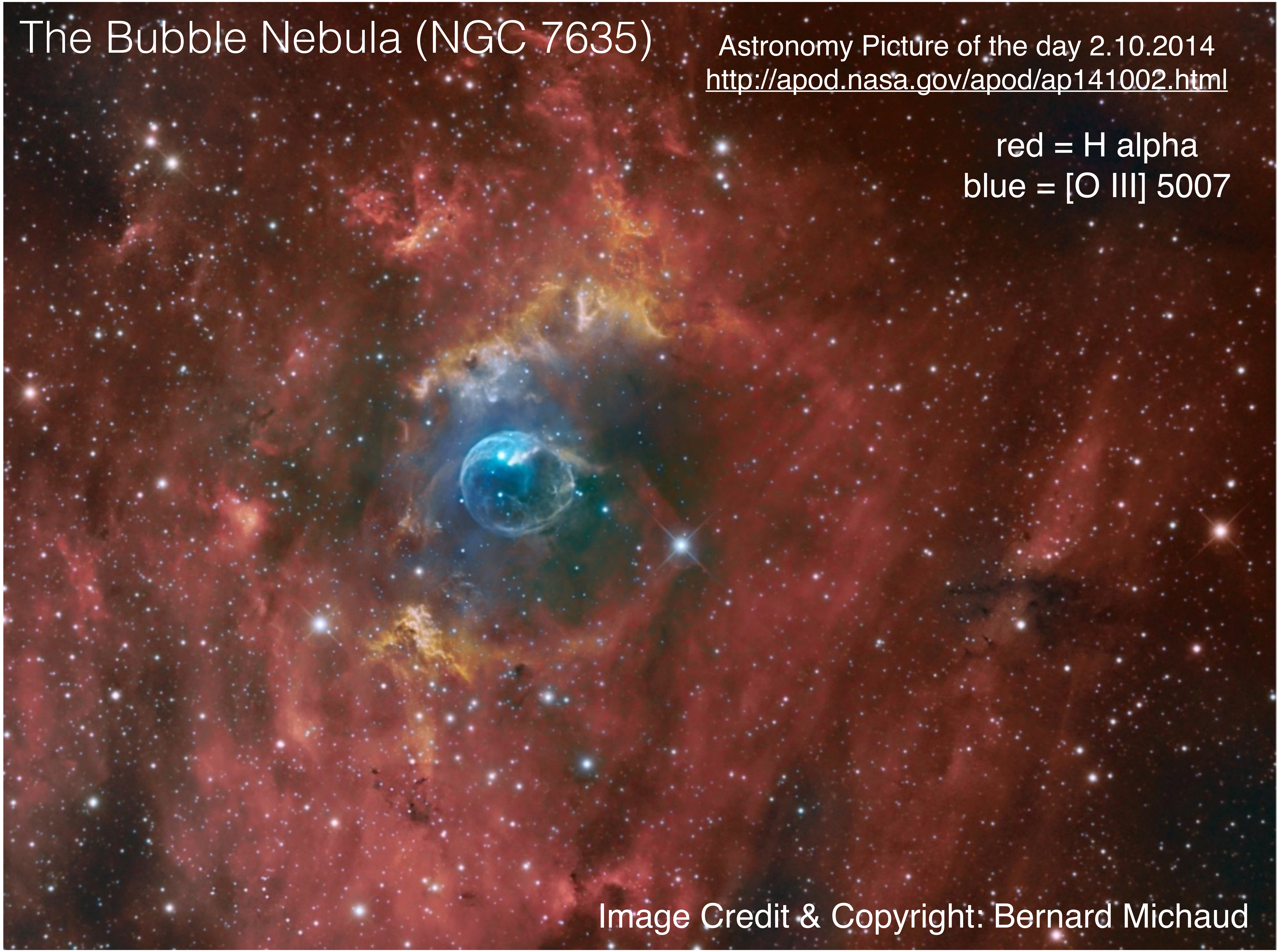
Outline

- Motivation: What can we learn from shells around evolved stars?
- Resulting from varying mass loss, or environmental effects?
- Evolved stars: the red supergiants Betelgeuse and W26.
- Betelgeuse and its 2 (or 3?) circumstellar shells.
- HI (21cm) emission from around Betelgeuse.
- Radio and nebular ([NII] and Halpha) emission from the wind of W26.

Massive Star feedback

- Massive stars drive galaxy evolution.
- Ionising radiation, stellar winds, supernova feedback, enrichment (Spitzer 1978; Weaver+1977; Mac Low & McCray 1988; Matzner 2002)
- Feedback over lifetime of stars is being simulated in less idealised situations (Mellema+2006, Arthur+2011, Rogers & Pittard,2013, Dale+2013).
- BUT, massive star evolution is not well understood.
- Late-stage feedback is important (Z; v. strong winds)
- Supernovae have to plough through CSM to get to ISM.
- —> Assigning progenitors to different types of supernova is very difficult.

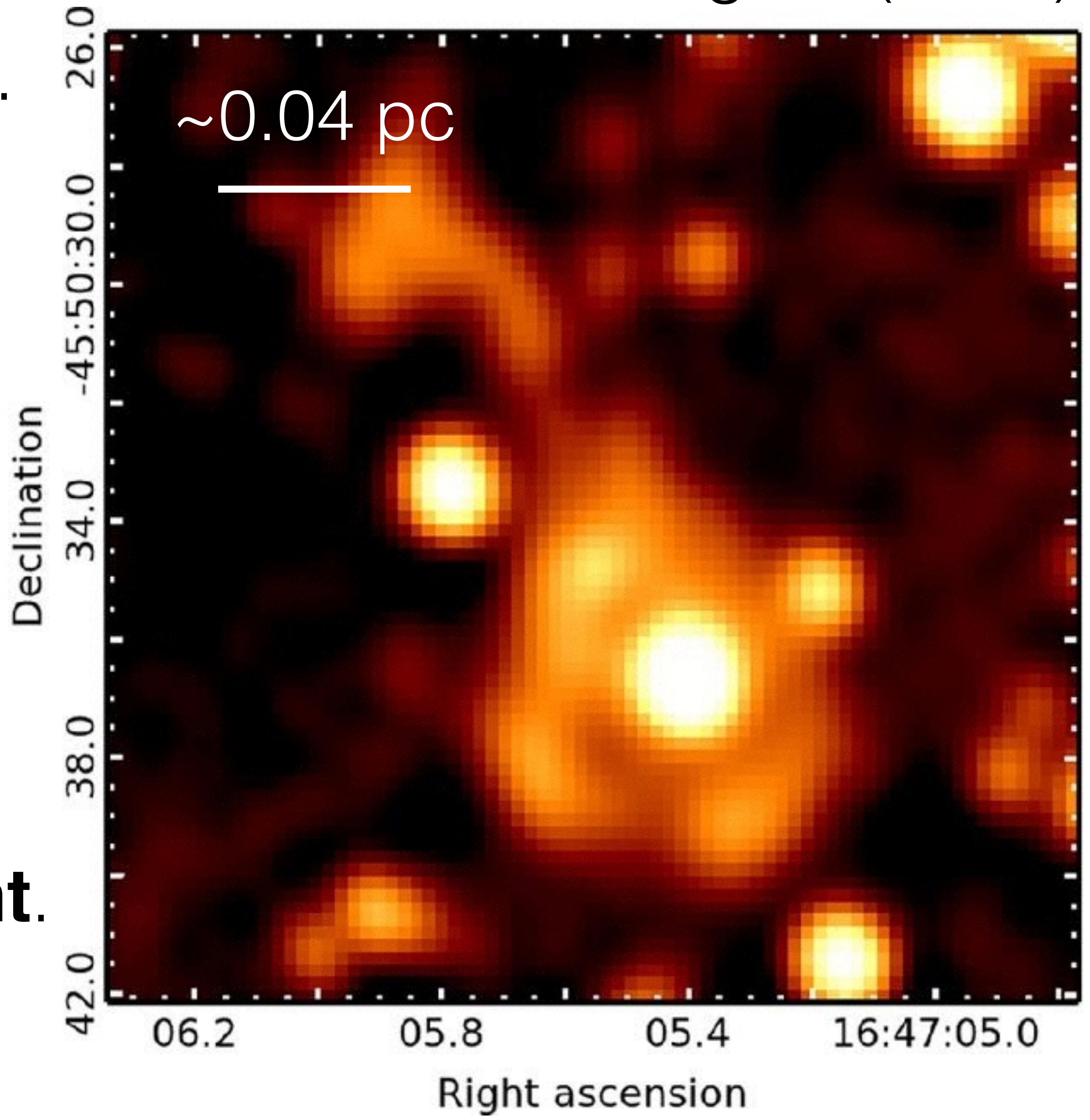



The Bubble Nebula (NGC 7635)
Astronomy Picture of the day 2.10.2014
http://apod.nasa.gov/apod/ap141002.html
red = H alpha
blue = [O III] 5007
Image Credit & Copyright: Bernard Michaud

What can wind bubbles tell us?

- **Fate** of a massive star determined by cumulative mass-loss history —> final mass.
- Will it explode?
- What kind of supernova?
- How will it look (CSM interaction)?
- How far does the free-wind region extend? 10^{15} cm, 10^{16} cm, 10^{17} cm, 10^{18} cm, more?
- How much mass is found close to the star?
- Determined by **mass loss and environment**.

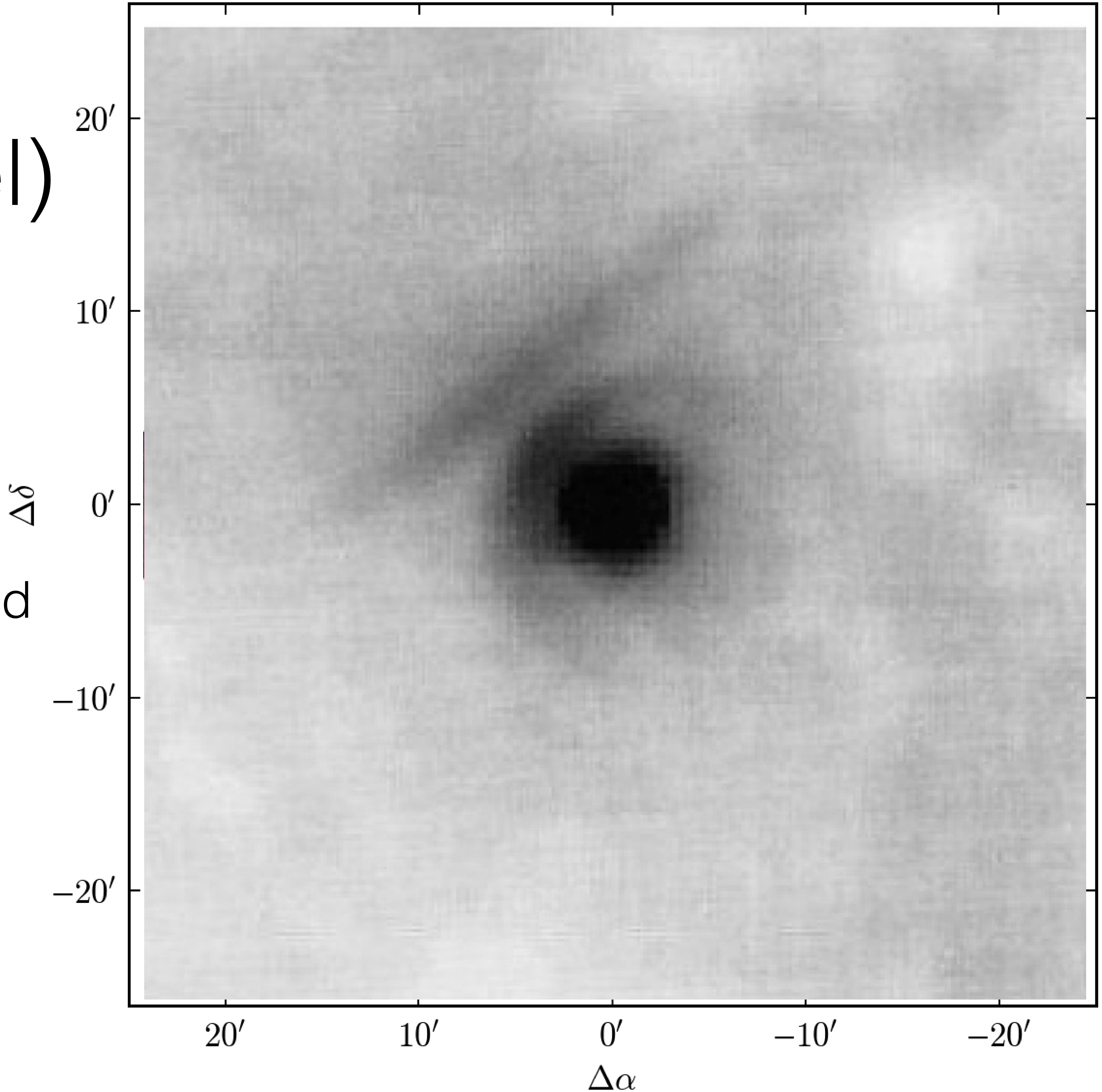
Ionized wind of W26 in Westerlund 1
Wright+ (2014)



Betelgeuse

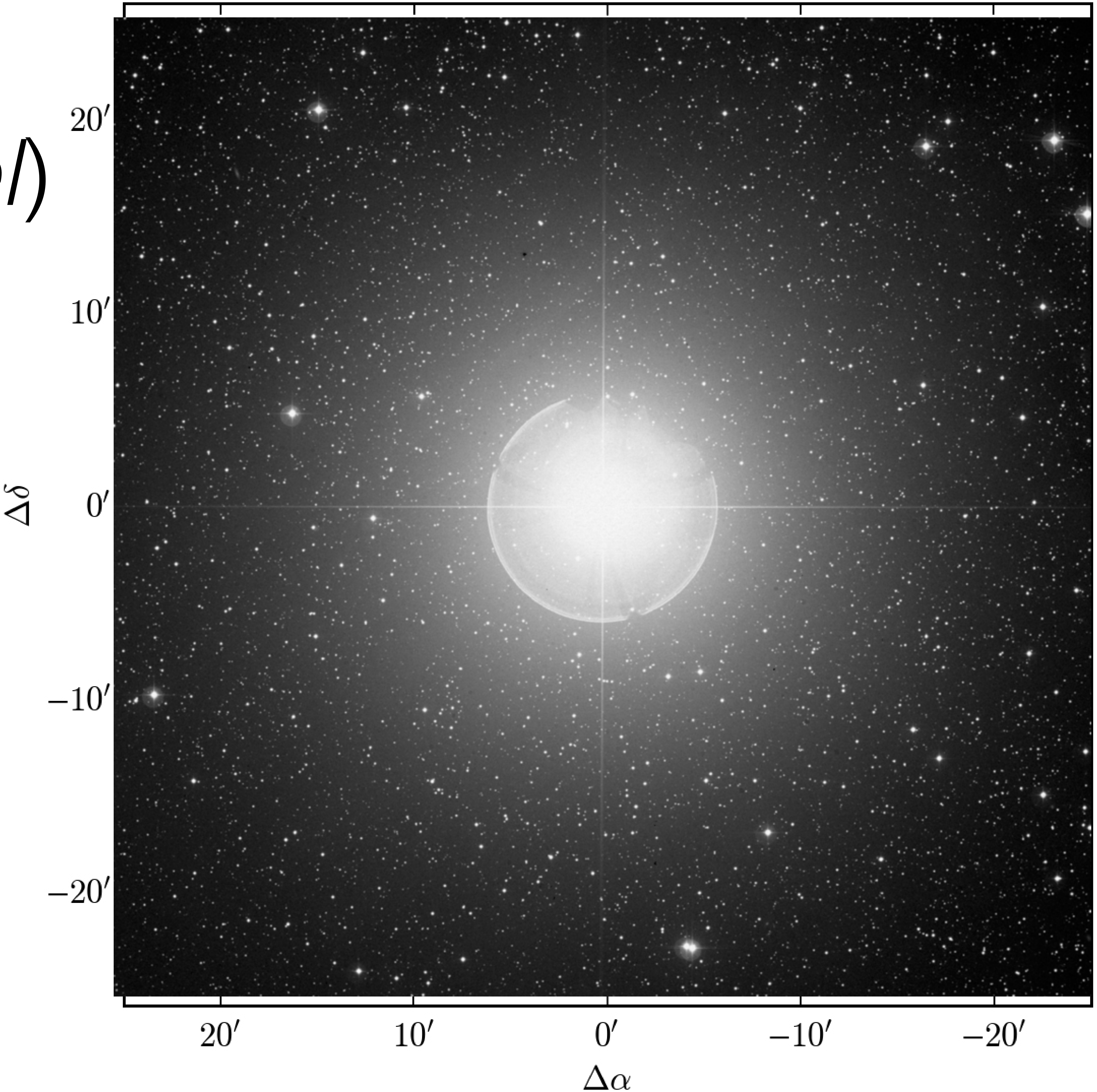
Betelgeuse (pre-Herschel)

- IRAS 60 µm image
- Noriega-Crespo et al. (1997)
- Total mass of wind and bow shock
  $M \sim 0.033\ M_\odot$
  for d=200pc.



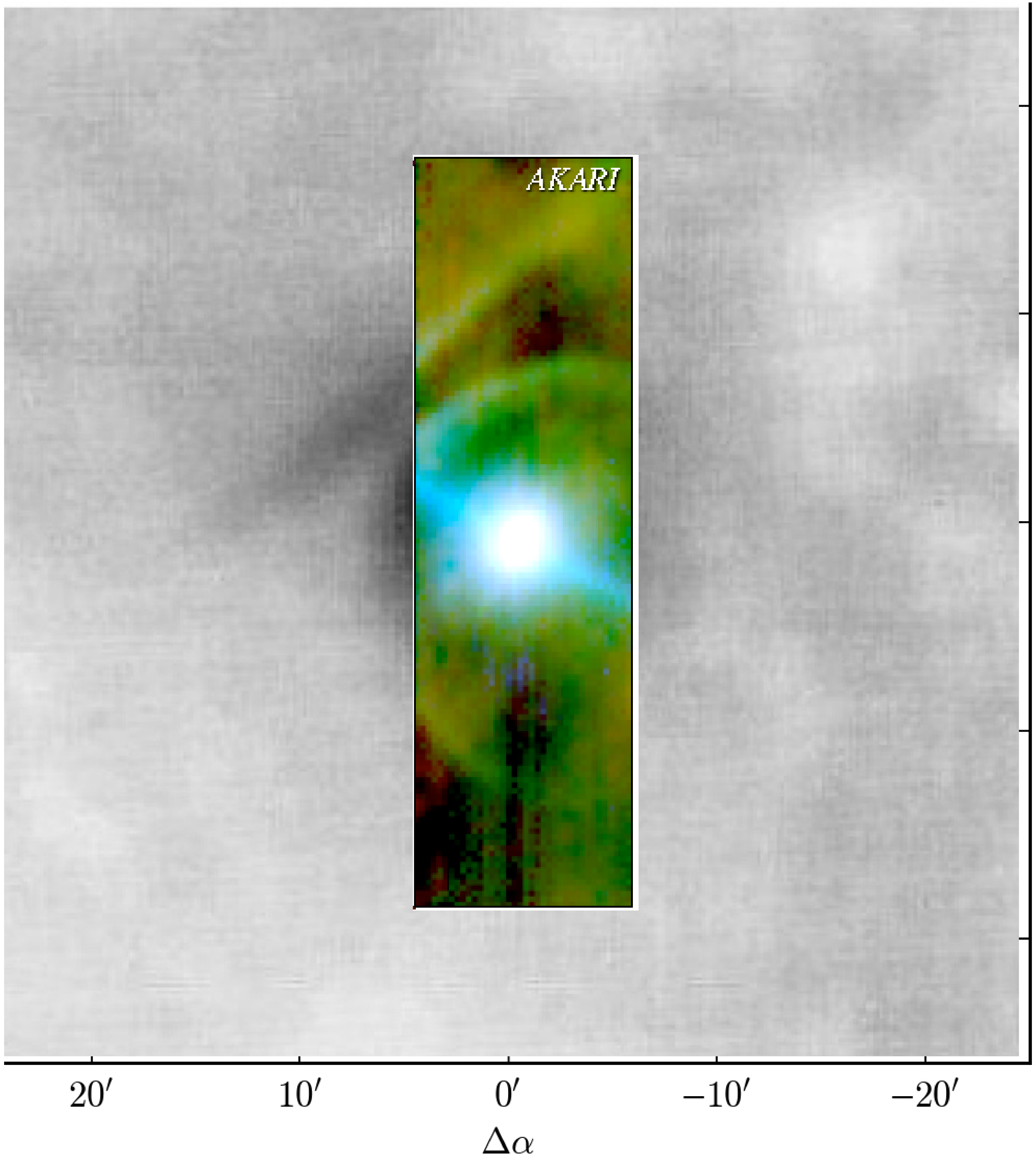
Betelgeuse (pre-*Herschel*)

- DSS POSS2 Blue image (right).
- Optical/NIR imaging is very difficult!
- CSM first discovered in far-IR data.



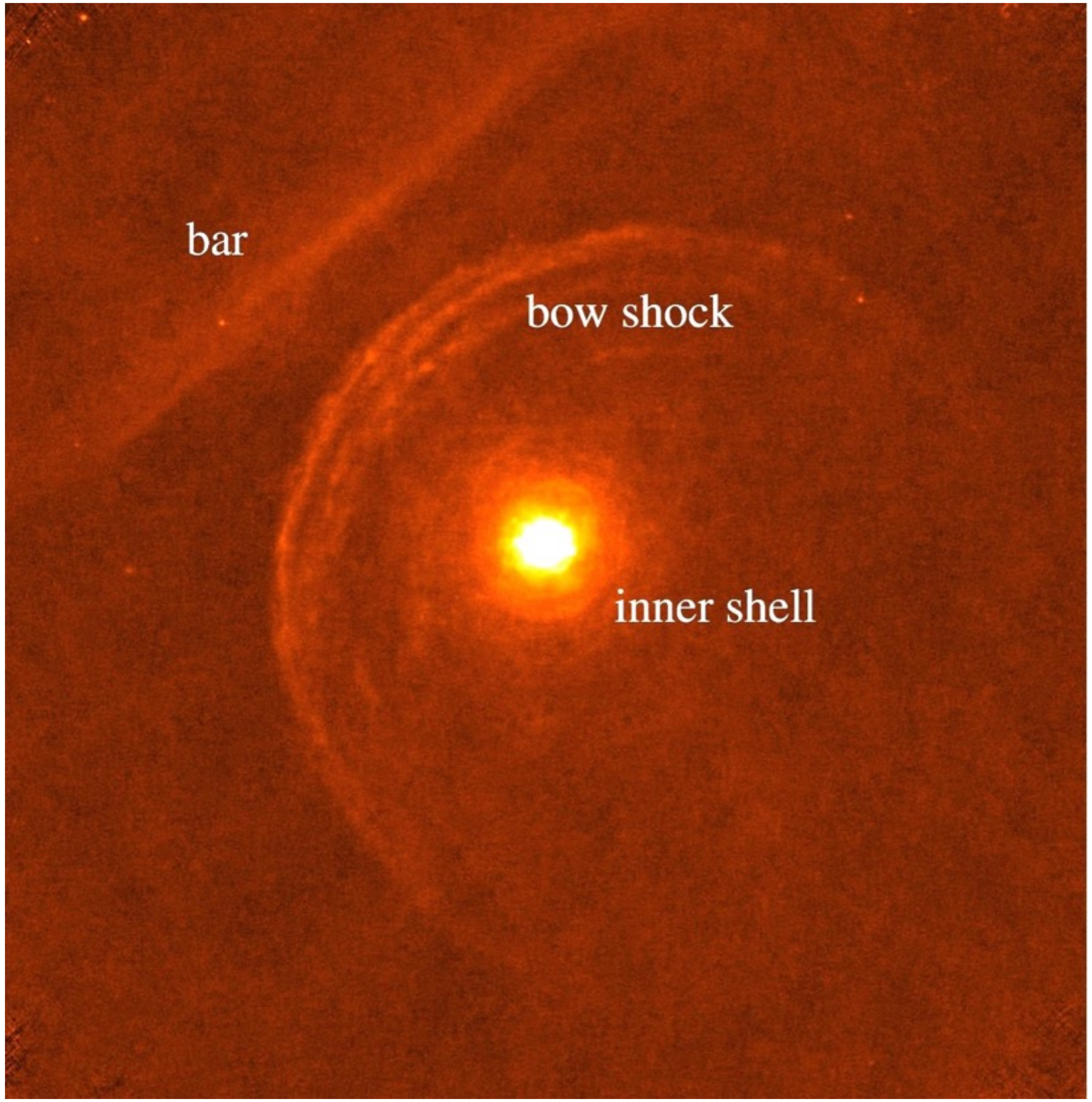
Betelgeuse (pre-*Herschel*)

- *AKARI* data (Ueta+,2008,PASJ)
- Bow-shock has
  M~0.0033 M☉,
  based on *AKARI* flux (Mohamed et al., 2012, A&A).



Herschel's view of Betelgeuse

- Far infrared emission shows dust emission from re-radiated starlight.
- The "bar" may be circumstellar (Mackey+,2012) or interstellar (Decin+,2012) in origin.
- The bow shock marks the interaction of the RSG wind with the surrounding medium (Mohamed+,2012).
- What is the inner shell? Discovered in HI 21cm obs. by Le Bertre+ (2012); confirmed with *Herschel* (Decin+,2012).



Herschel image (PACS 70 μm) of Betelgeuse's surroundings (Decin+2012)

Herschel's view of Betelgeuse

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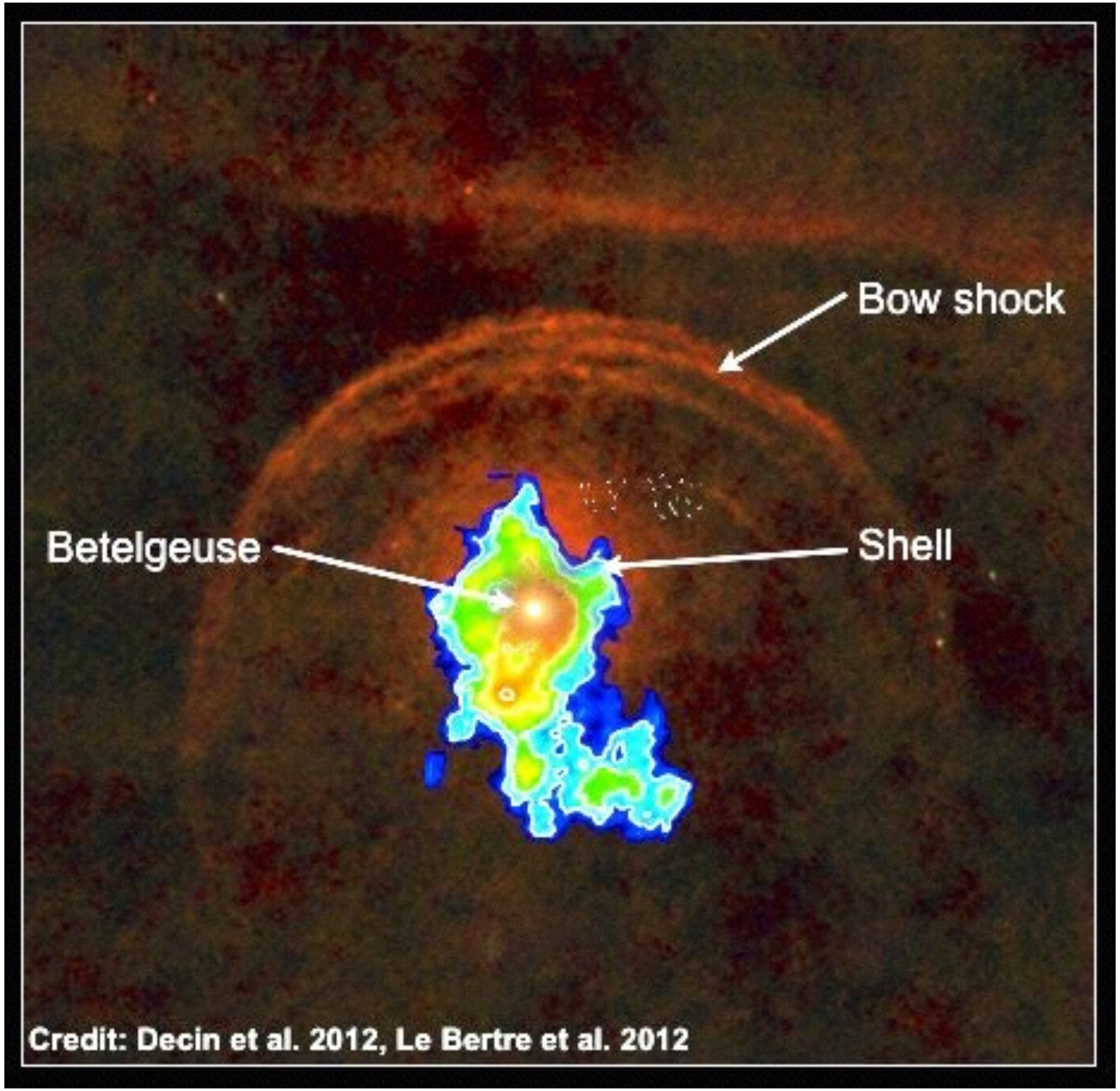


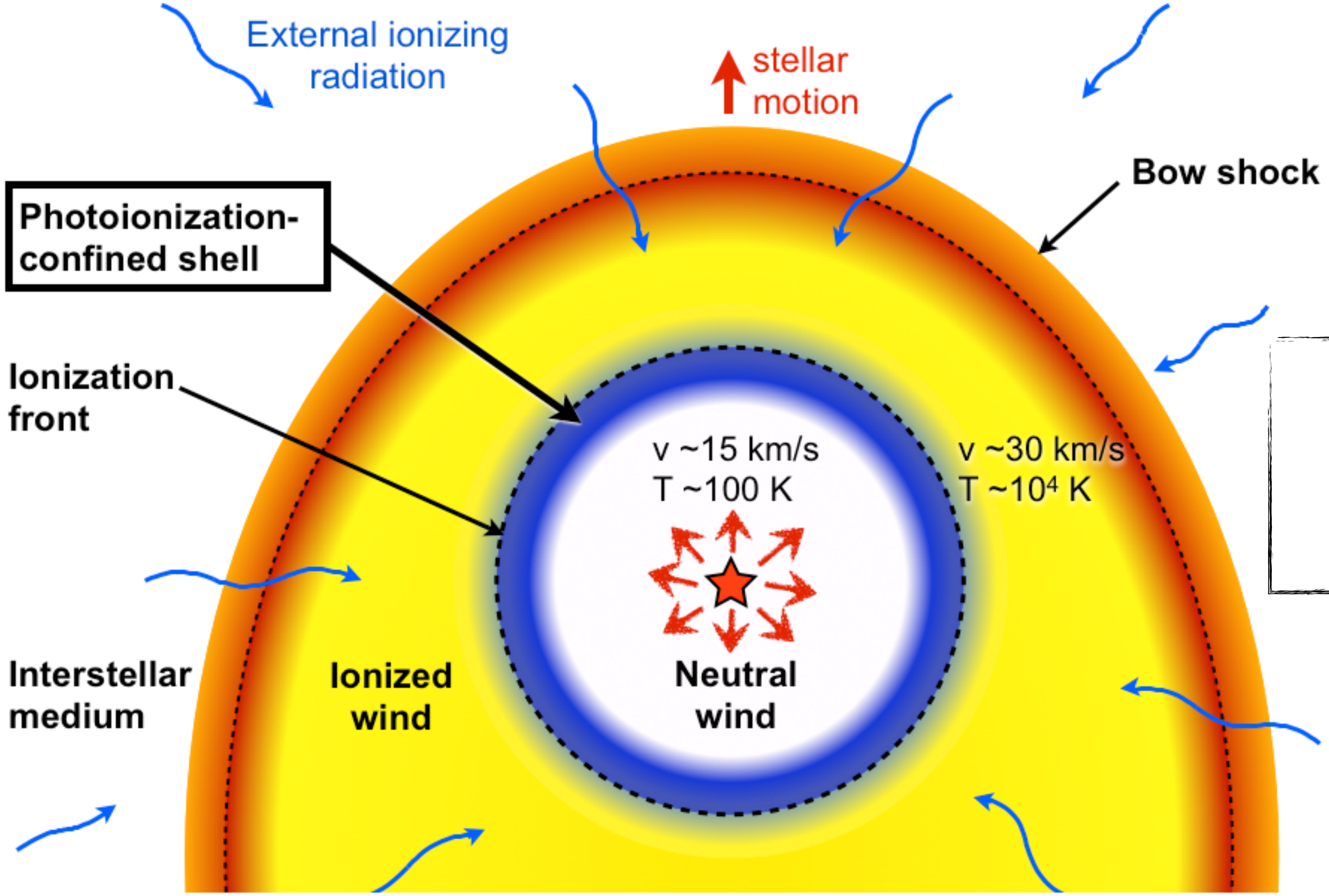
Circumstellar Medium (CSM) structures

Structure	radius	mass	interpretation
bar	0.5 pc	0.002–0.029 $M_\odot$	interstellar/circumstellar?
bow shock	0.35 pc	0.0024–0.03 $M_\odot$	wind-ISM interaction
Inner shell	0.12 pc	0.09 $M_\odot$	Photoionization-confined shell

Masses from: Decin+,2012; Mohamed+,2012; Le Bertre+,2012.

- We propose the inner shell is confined because the outer parts of the wind are photoionized by an external radiation field.
- The outer wind is hot (~10^4K), inner wind is colder (~100K).
- Pressure gradient across D-type ionization front drives a shock.
- Could also happen for AGB star winds!

Photoionization-confined shells



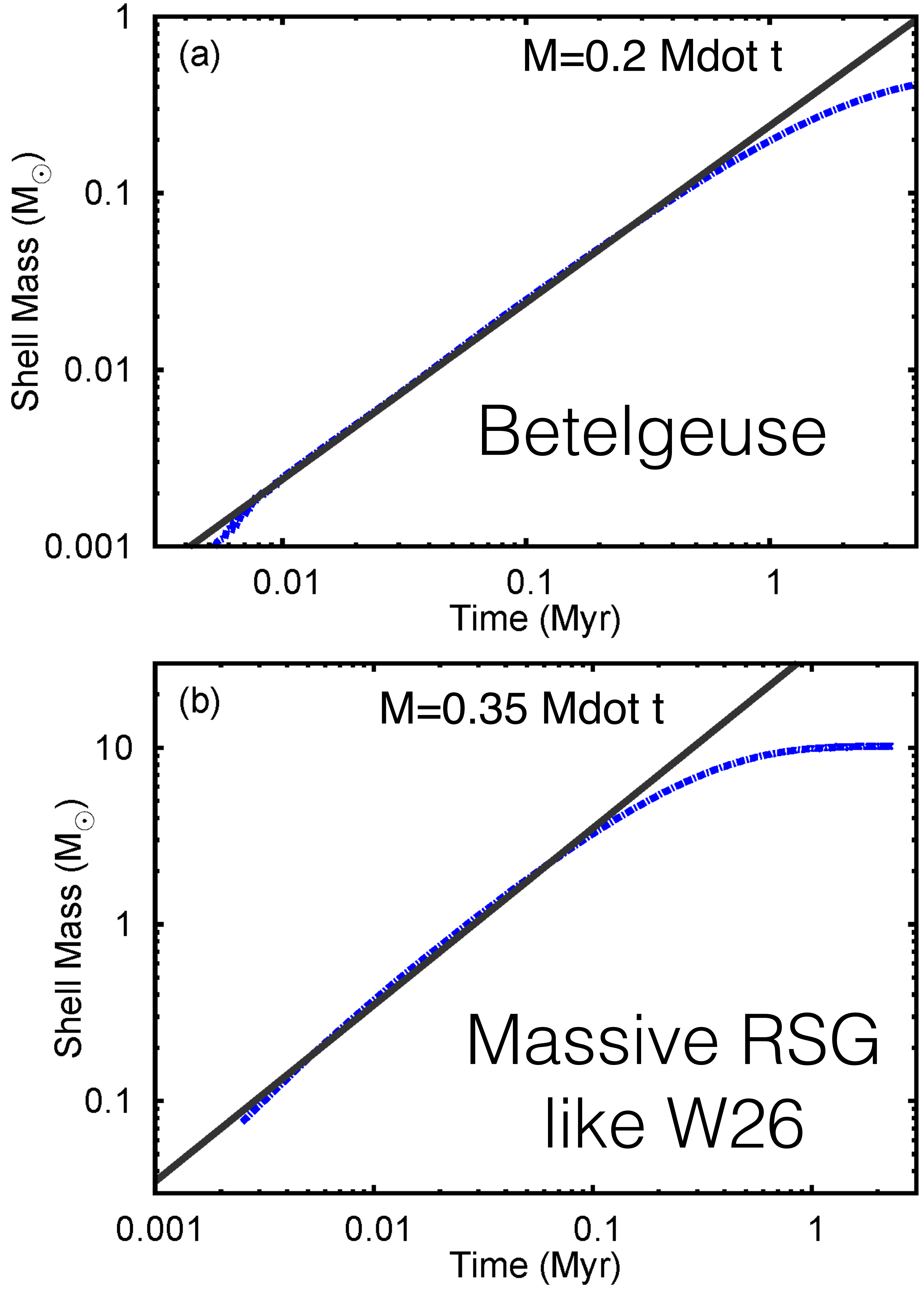
Two circumstellar shells from steady mass loss!

- Schematic diagram for Betelgeuse's bow shock and inner shell.
- inner shell is the border of an "inside-out" HII region.

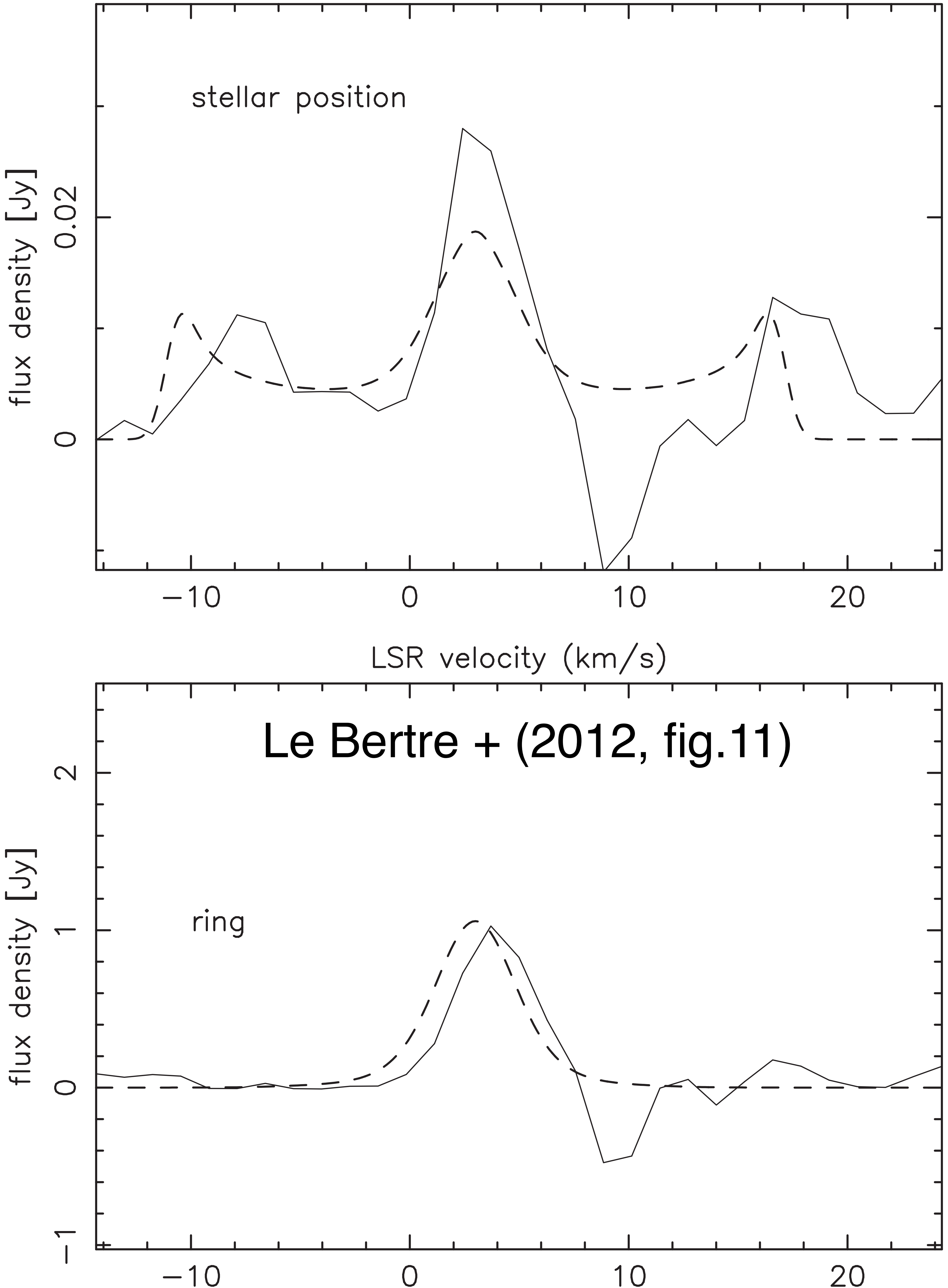
Mackey+, 2014, Nature, **522**, 282.

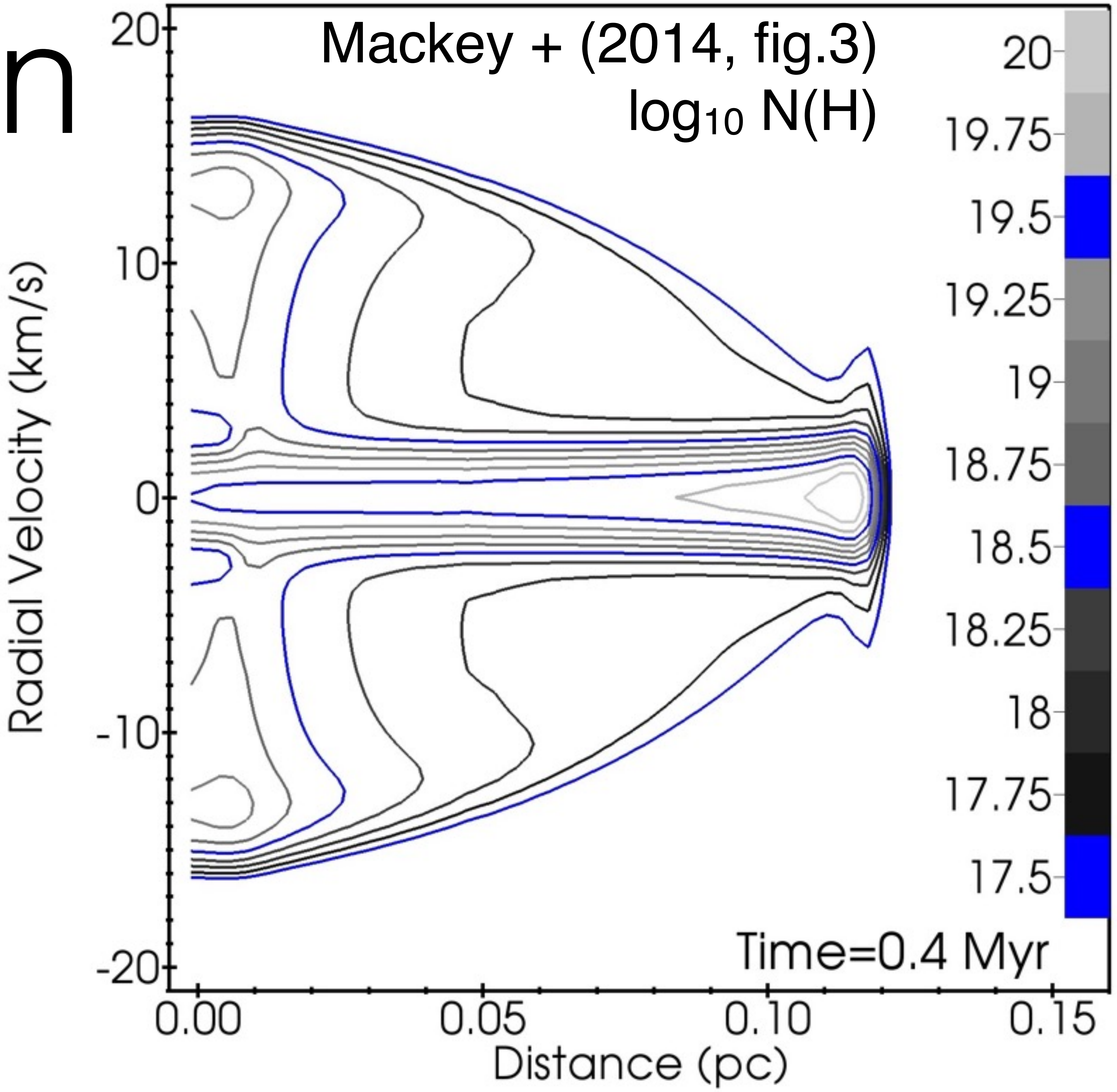
Maximum mass of shells

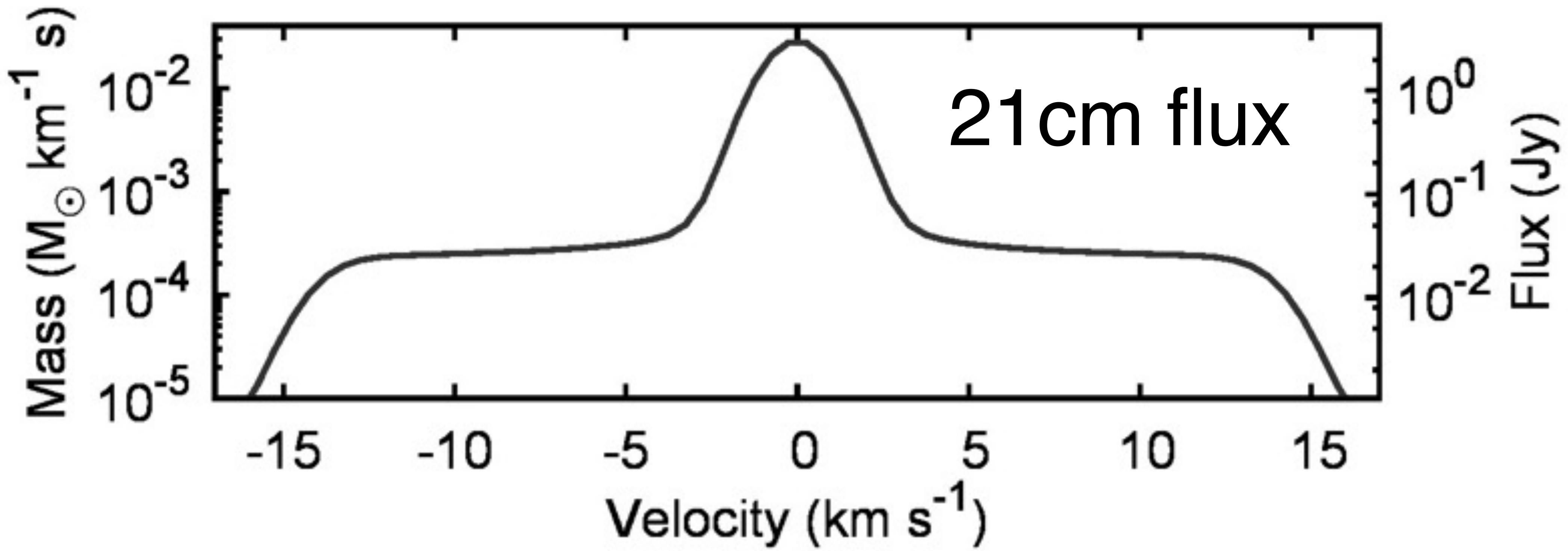
- Shell mass increases approximately linearly with time until it approaches its equilibrium mass.
- Stars like Betelgeuse can have shells with masses ~0.1-1 $M_\odot$.
- Stars like W26 (in Westerlund 1) will lose up to 20 $M_\odot$ in the RSG phase, and so can have shells with ~4-7 $M_\odot$.
- Final shell mass depends on mass-loss rate and total mass lost.



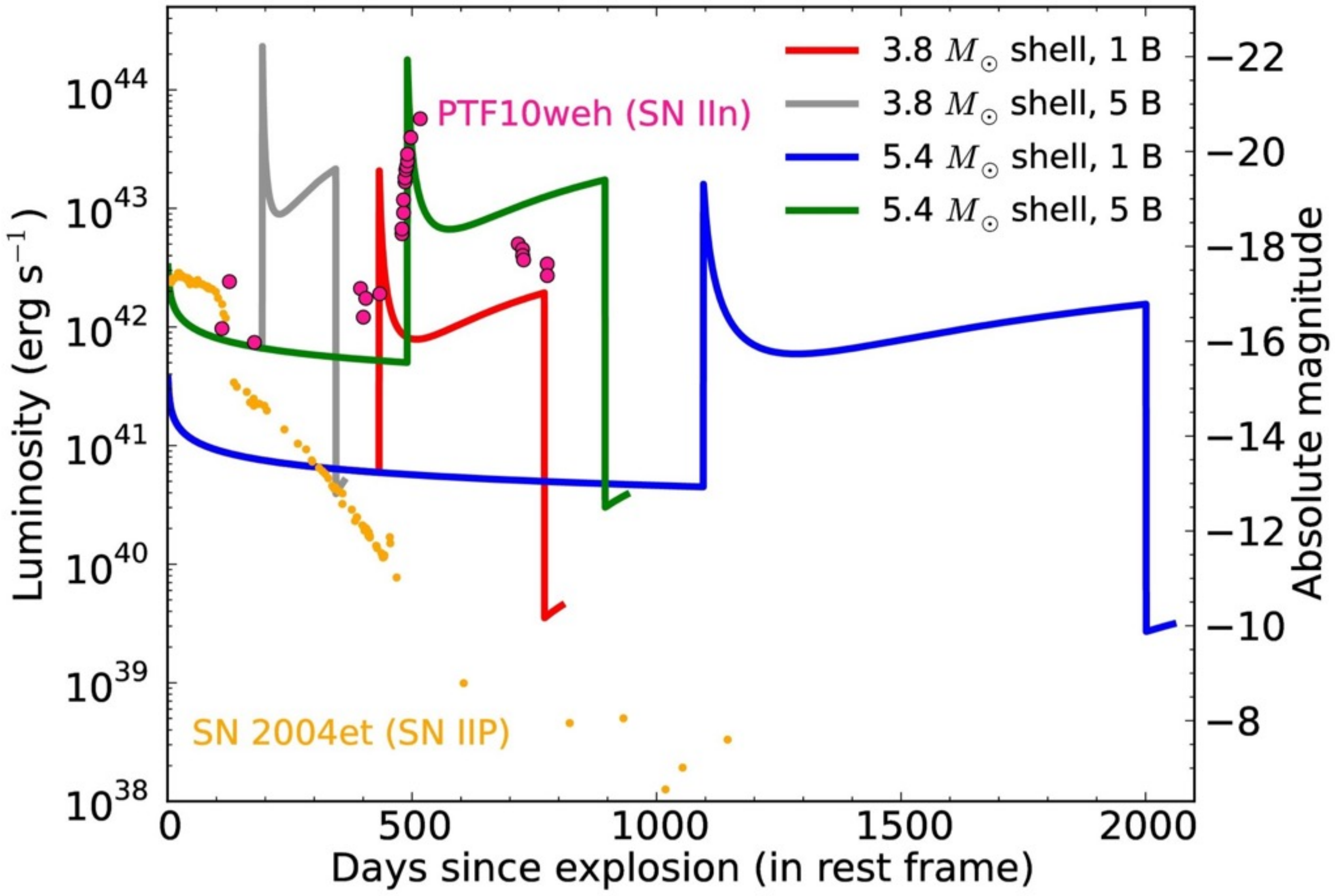
HI data and simulation







Supernova—shell interaction



- Analytic model assumes SN shock is always radiative and that 50% of kinetic energy is radiated in the postshock gas (Moriya+,2013).

- Bolometric luminosity evolution of supernovae interacting with photoionization-confined shells.
- Choose massive shells, with ionizing fluxes such that the shell is at 2×10^{16} cm (lower mass shell) and 4×10^{16} cm (higher mass shell).
- Calculations for explosions with 10^{51} and 5×10^{51} ergs (1B and 5B).
- Ejecta mass 15 $M_\odot$.
- Find strong rebrightening and long “plateau” phase, although much of this may not be optical emission.

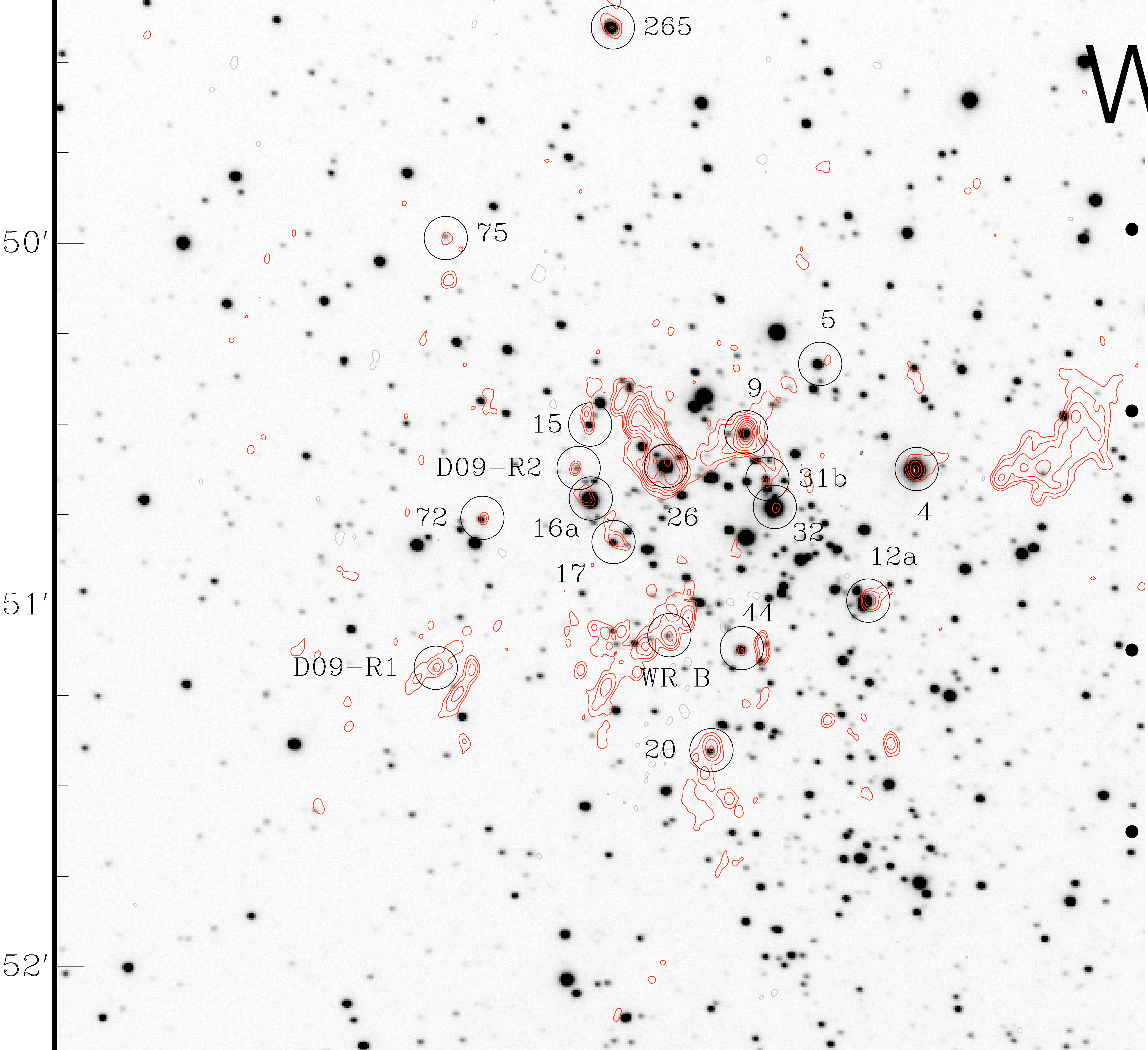
W26 in Westerlund 1

Westerlund 1

JHK image from Brandner+2008.

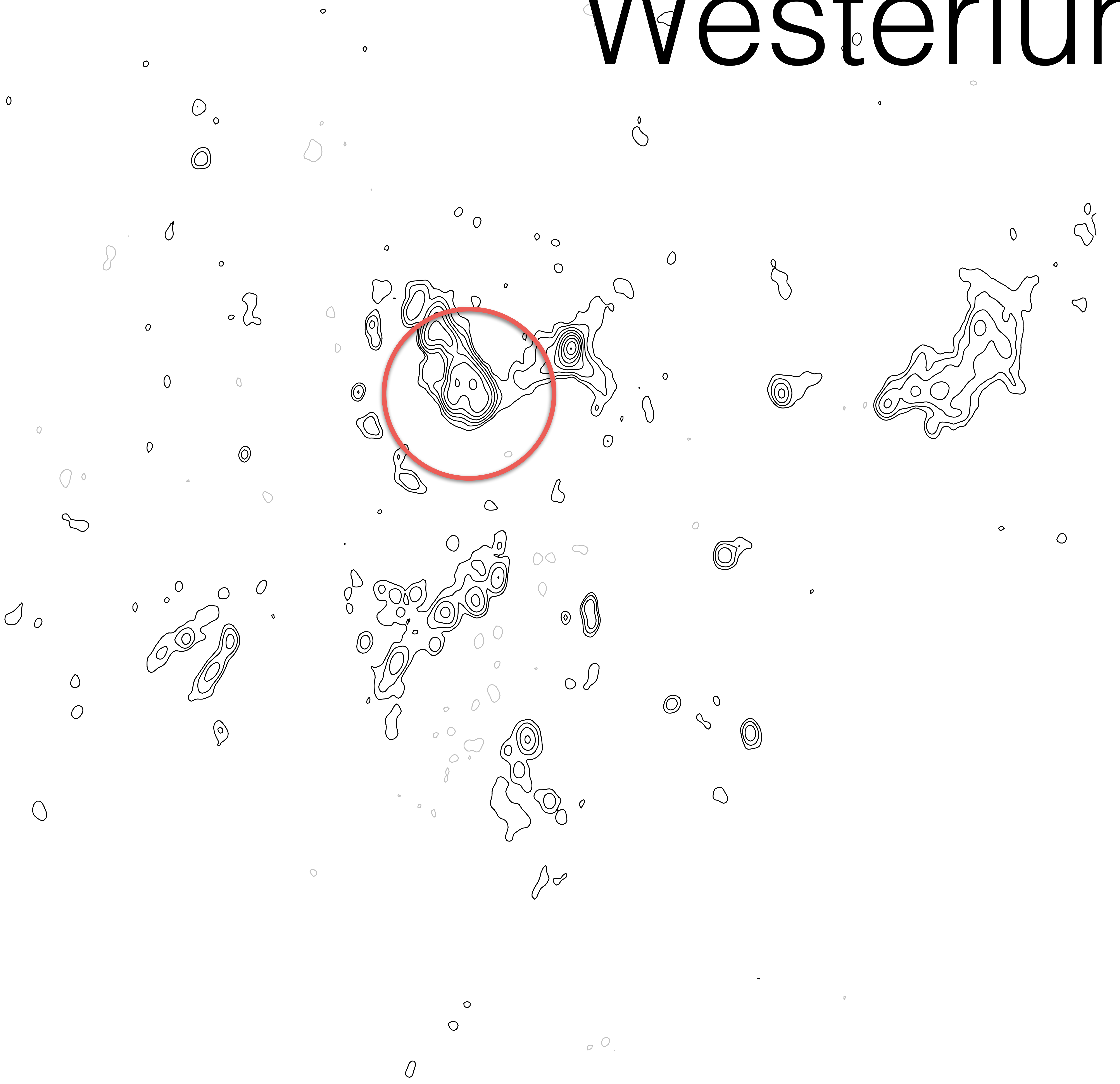
- Probably the most massive young star cluster in the Galaxy (Brandner +2008).
- Unfortunately has A_V=13.
- Age is 3-5 Myr, so that it contains both hottest (WR) and coldest (RSG) stars at the same time.
- Has largest Galactic WR star population (Crowther+,2006).
- Has >14 evolved, extreme supergiant stars (Clark+2005).
- Has a magnetar (Muno+2006).

Westerlund 1



- The evolved stars have radio-bright circumstellar nebulae (Dougherty+2010).
- This is from dense stellar winds that are ionized by the extreme environment in Wd1.
- W26 has a very bright optical nebula (Wright +2014), also W20, W237.
- Other super/hypergiants also (e.g. W9,W265,W4).

Westerlund 1



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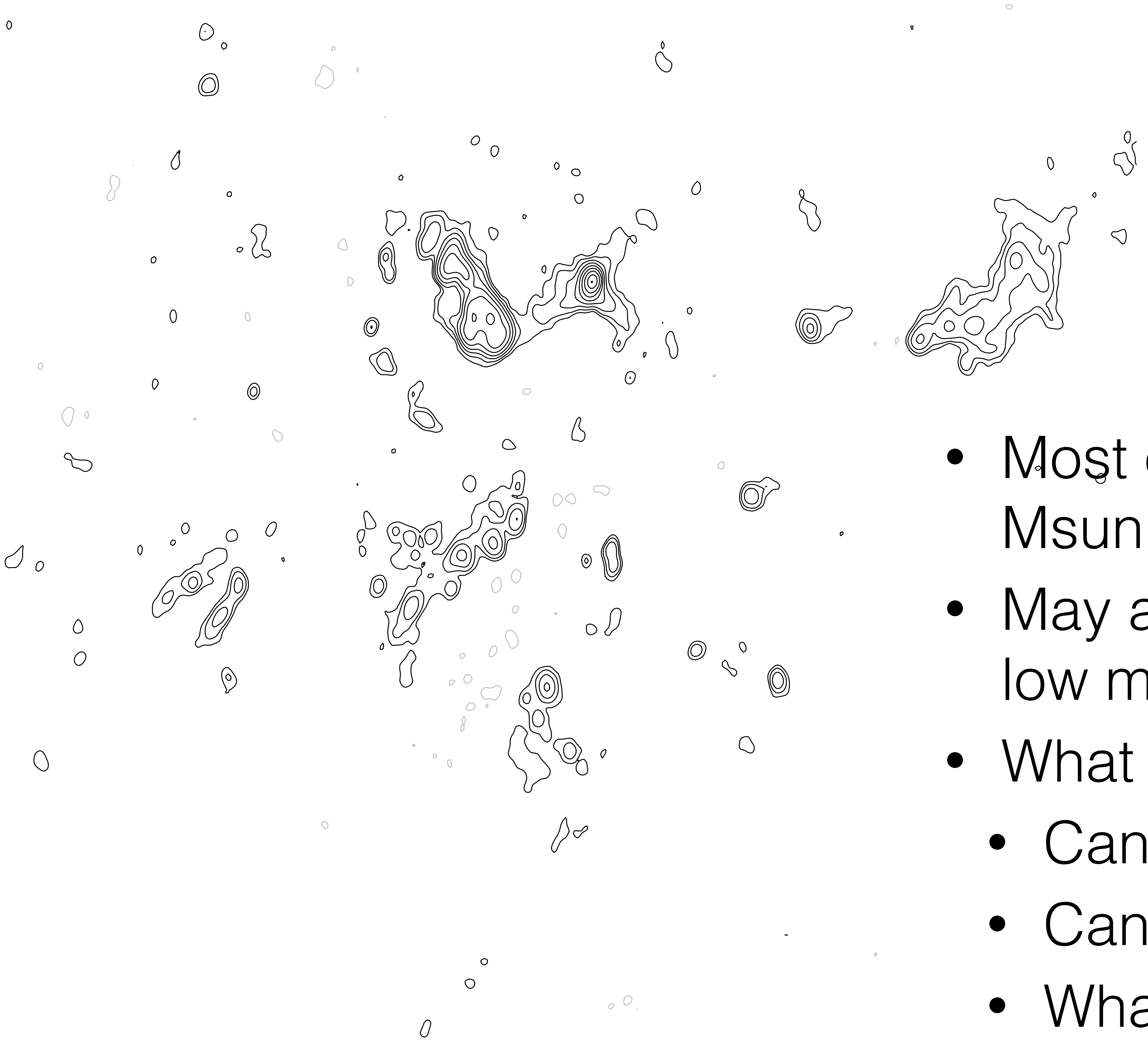
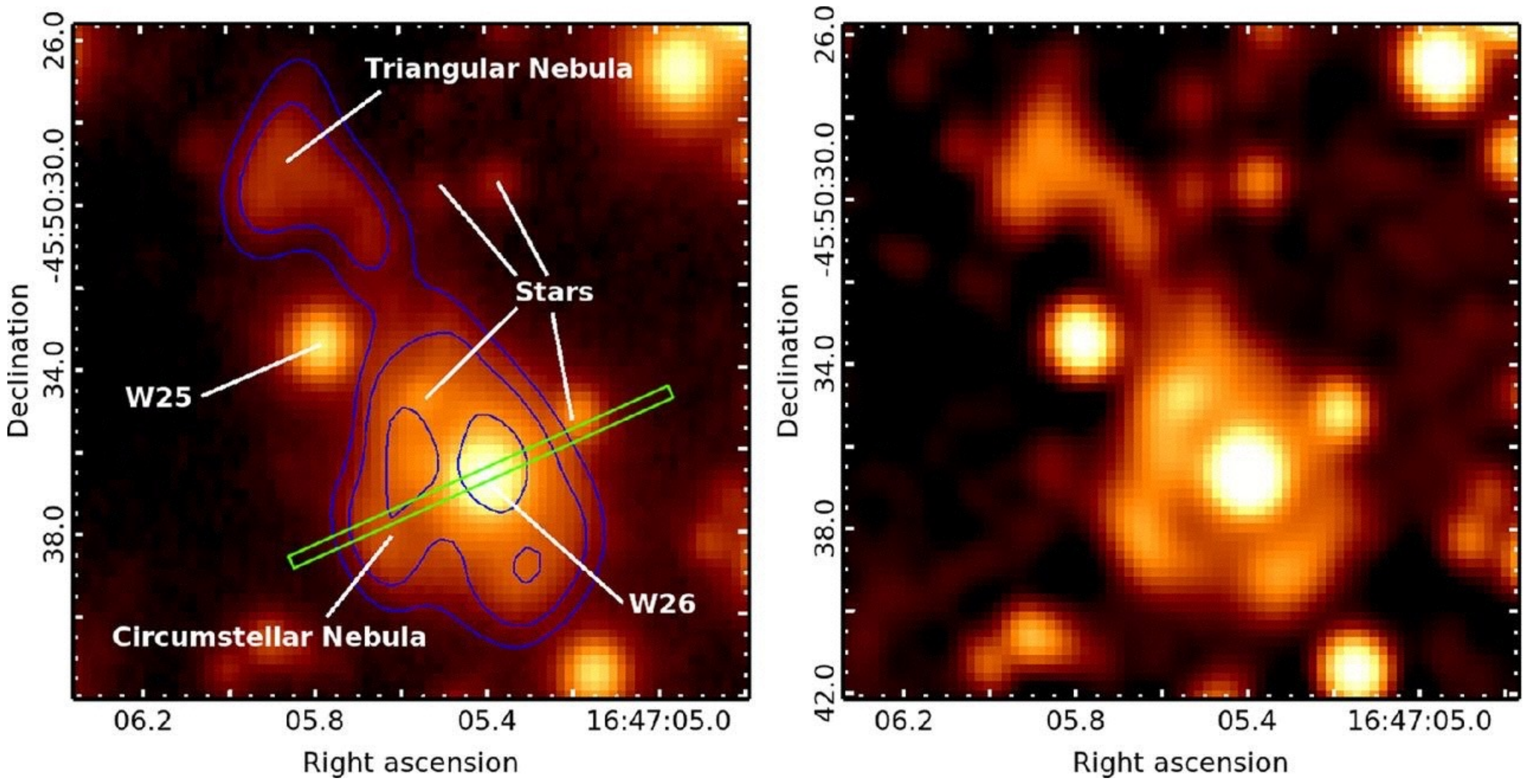
Westerlund 1



- Most of the mass lost by stars with <30 Msun is as a cold RSG, not a hot star.
- May also be true for higher mass stars at low metallicity (Yoon+2012; Szécsi+2015).
- What happens this gas?
  - Can it stay cold (neutral)?
  - Can photoionized gas remain at 10^4 K?
  - What fraction becomes hot?

Photoionized wind of W26



W26 in Westerlund 1 (Wright+,2014)

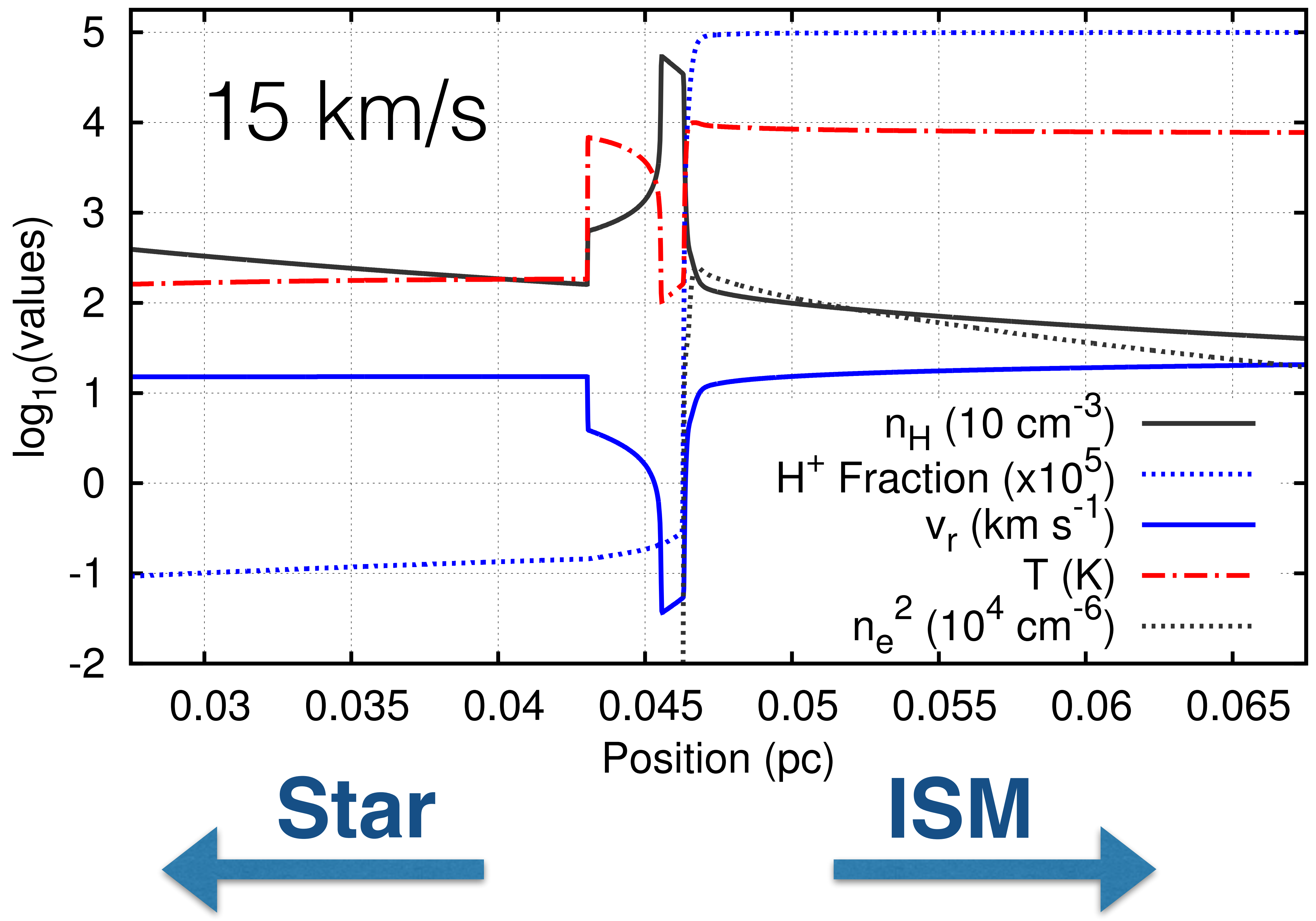
Hα+[NII] surface brightness

See also Gvaramadze+2014; Meyer+2014; for **IRC -10414**.

- Ring-shaped emission nebular about 0.03 pc from W26, a massive RSG (about 40 $M_\odot$) in Westerlund 1.
- One interpretation is that the wind is photoionized by the nearby O, B, and WR stars.
- Could also be shock ionization by wind-wind collision.
- Green box shows the FORS slit for spectral data (Wright+,2014).

Photoionized wind of W26

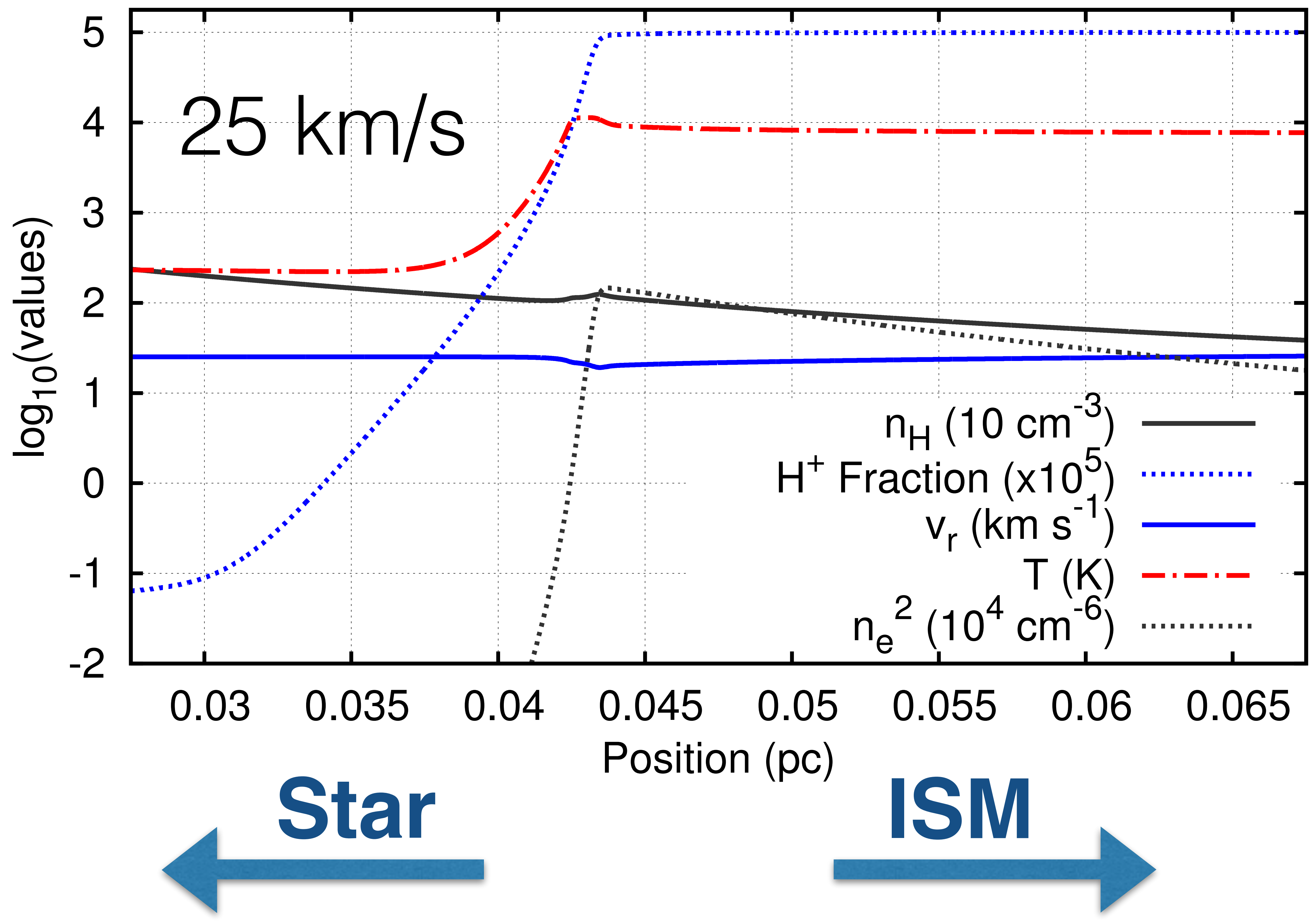
Mackey, Castro, Fossati & Langer, A&A, submitted



Ionizing flux constrained to give bright nebula at the observed radius, for given Mdot.

- Spherically symmetric simulations.
- Model with non-equilibrium heating and cooling (following Henney+2009).
- Wind velocity is unknown, so we have a slow model (15 km/s), shown at left, and a fast model (25 km/s, next page).
- Shows gas density, temperature, ionization state, as function of radius from W26.

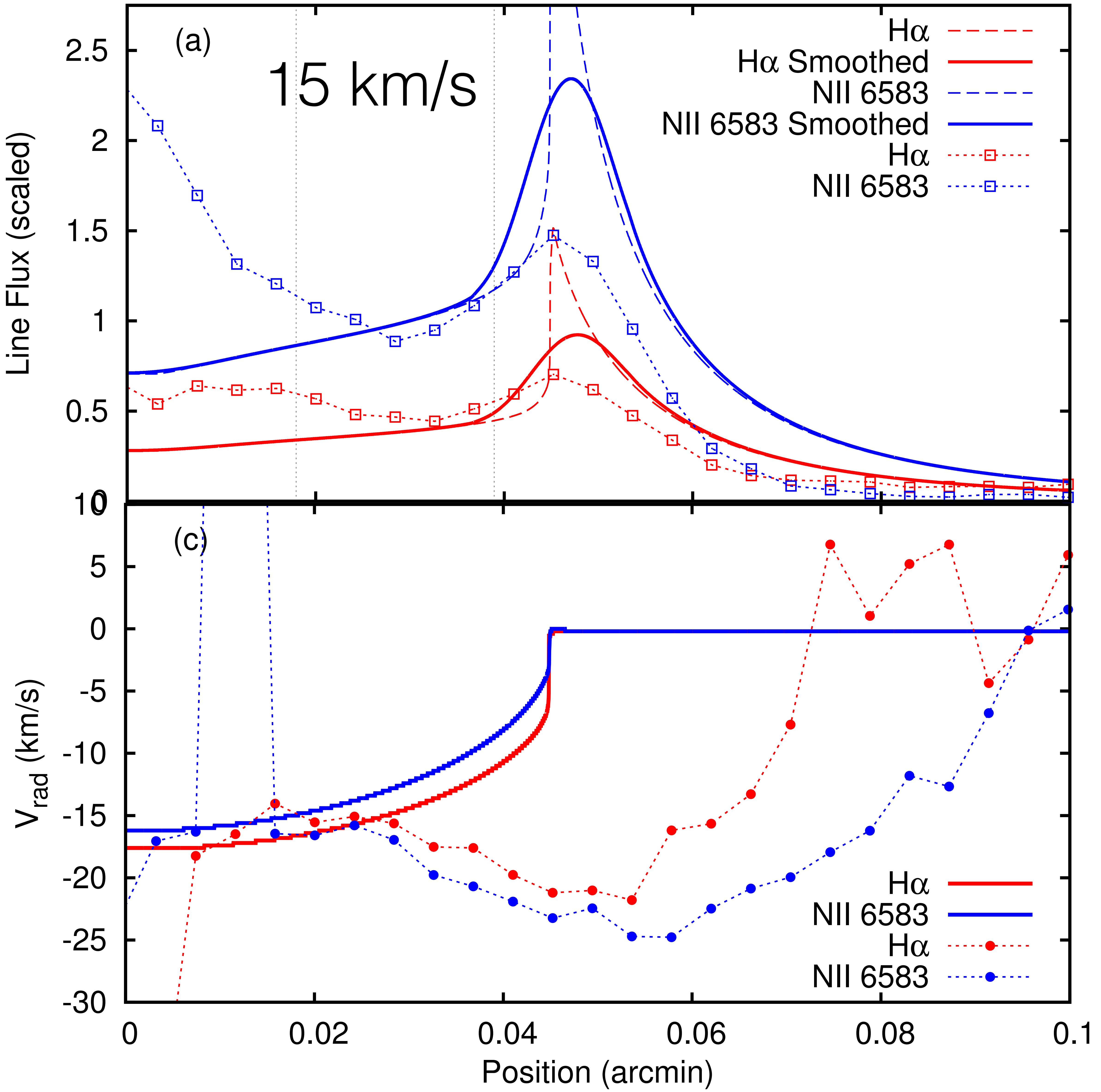
Application to W26



Ionizing flux constrained to give bright nebula at the observed radius, for given Mdot.

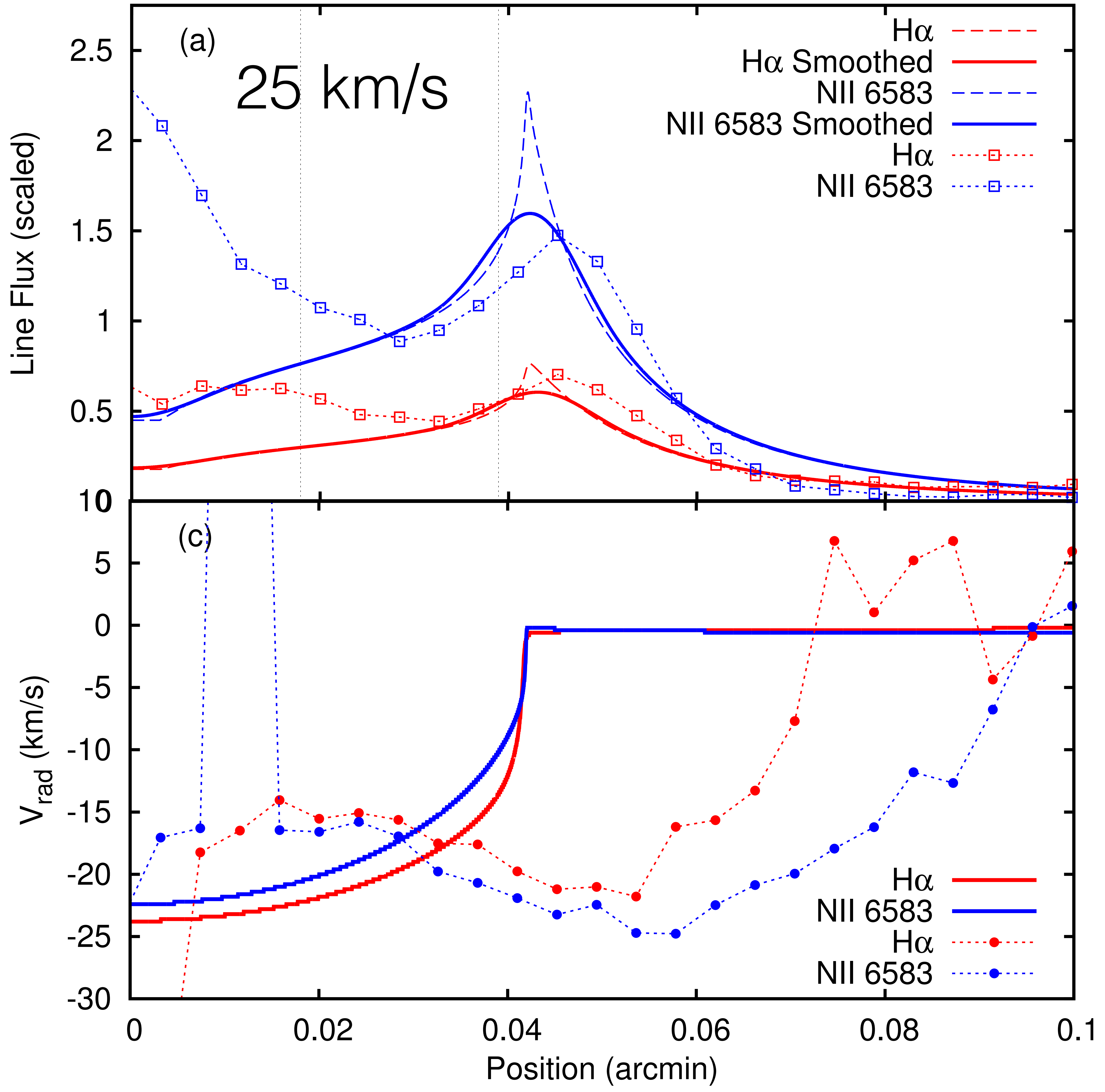
- Here the velocity is 25 km/s, so the ionization front is R-type (no shock).
- Smooth increase in ionization fraction, temperature.
- Little change in density and velocity across front.
- Less peaked electron density.

Projected line emission

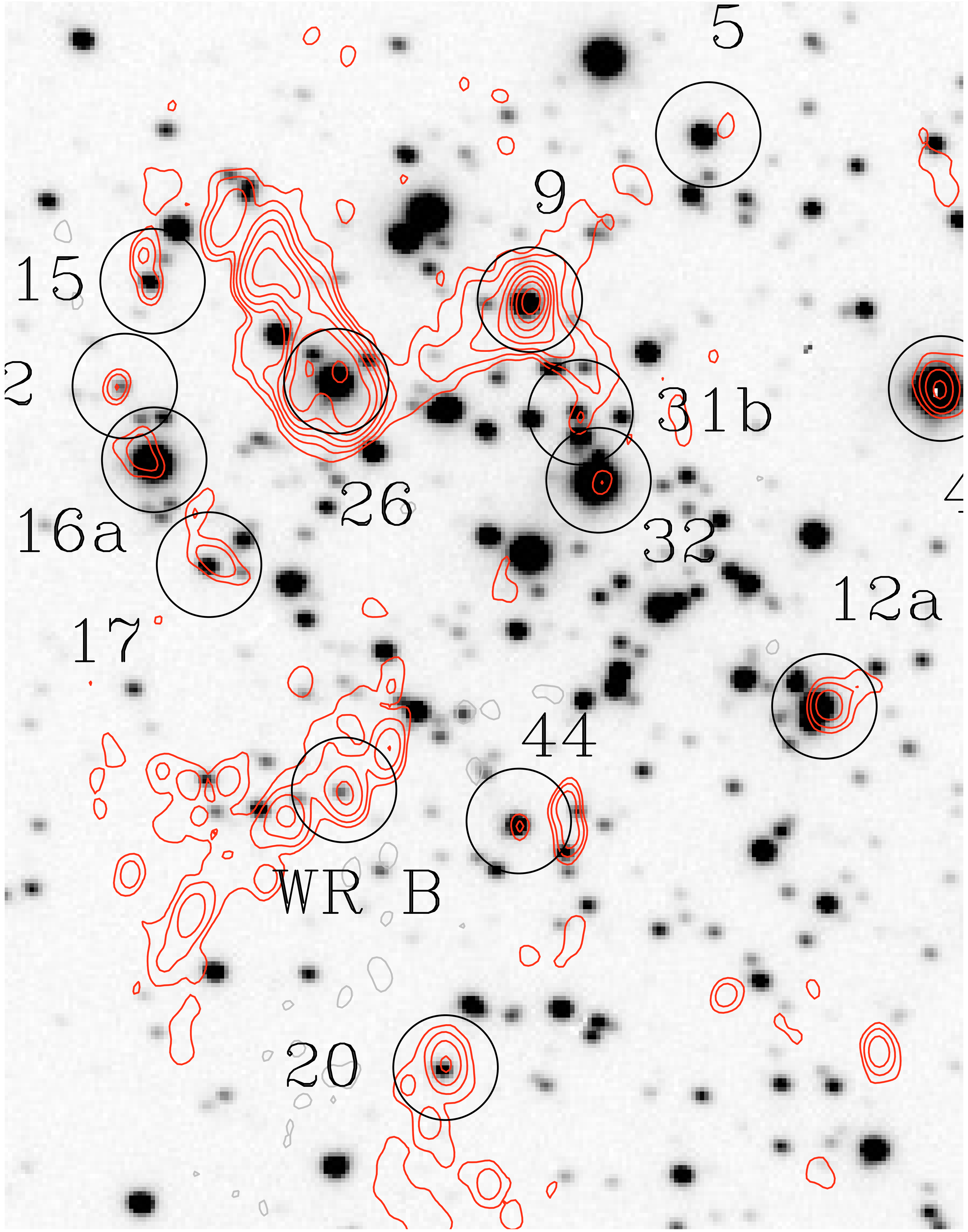


- Sharp D-type Ionization front gives very peaked [NII] and Halpha emission.
- Line ratio approx. correct.
- Simulated emission has zero rad. vel. at peak emission (limb brightening).
- Observed emission is blueshifted for the whole nebula.

Projected line emission



- R-type Ionization front gives less peaked [NII] and Halpha emission.
- Line ratio again approx. correct.
- Same problem with radial velocities.
- The whole nebula is observed to be blueshifted —>
- emission cannot be spherically symmetric.



Interpretation

- Correct line ratio —> gas is photoionized.
- N is enriched —> Wind material.
- Blueshifted nebula —> asymmetric pressure is pushing the wind of W26 towards us.
- Comparing to Betelgeuse, the observed nebula of W26 seems like a bow shock.
- There could be a photoionized shell closer to W26, with >0.1 $M_\odot$.
- W9 is 0.24pc from W26 (projected) and has a prodigious wind:
  — Mdot ≈ 3.3×10^{-4} $M_\odot$ yr^{-1} and
  — $v_\infty \approx 200$ km s^{-1} (Dougherty+2010).

Most of the cluster could be embedded in the wind of W9.

Conclusions

- Modelling circumstellar structures around massive stars is useful and important! (whether you care about stars or supernovae).
- Betelgeuse has steady mass loss, but two shells, one static with mass 0.1 $M_\odot$ —> could be a type IIn supernova? (cf. Smith+2009).
- External ionization can heat RSG winds, drive shocks, make shells.
- Shells can be much closer to the star than ISM-confined shells.
- This can happen for AGB stars too, if near hot stars…
- RSGs in clusters can have >1 $M_\odot$ shells at ~10^{16} cm.
- Cool stars lose lots of mass in hot clusters (>3 Myr old).
- It is not clear how this gas evolves thermodynamically or dynamically, but it is important for cluster evolution.