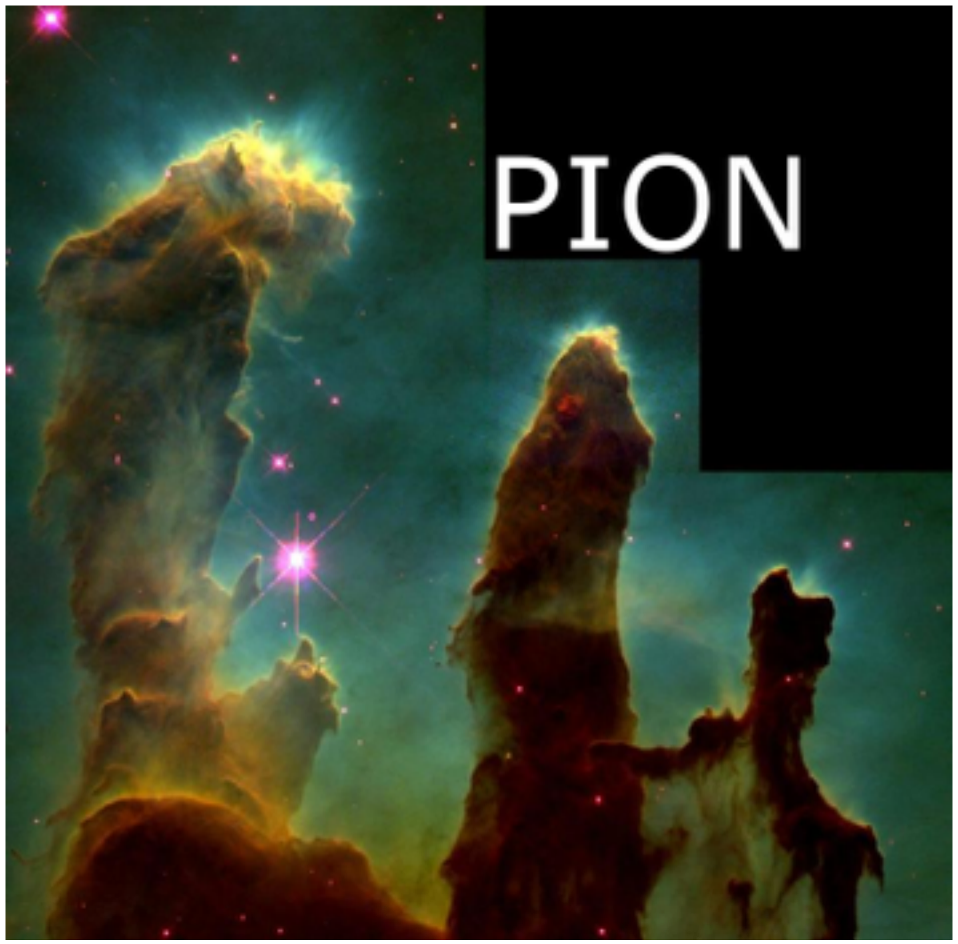
Modelling RSG winds with `PION`



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Dublin Institute for Advanced Studies (DIAS)

25 May 2017,
Evolution and Explosion of
Massive Stars Meeting, DIAS

<u>Collaborators</u>:
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DIAS
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Science Foundation Ireland sfi For what's next

Outline

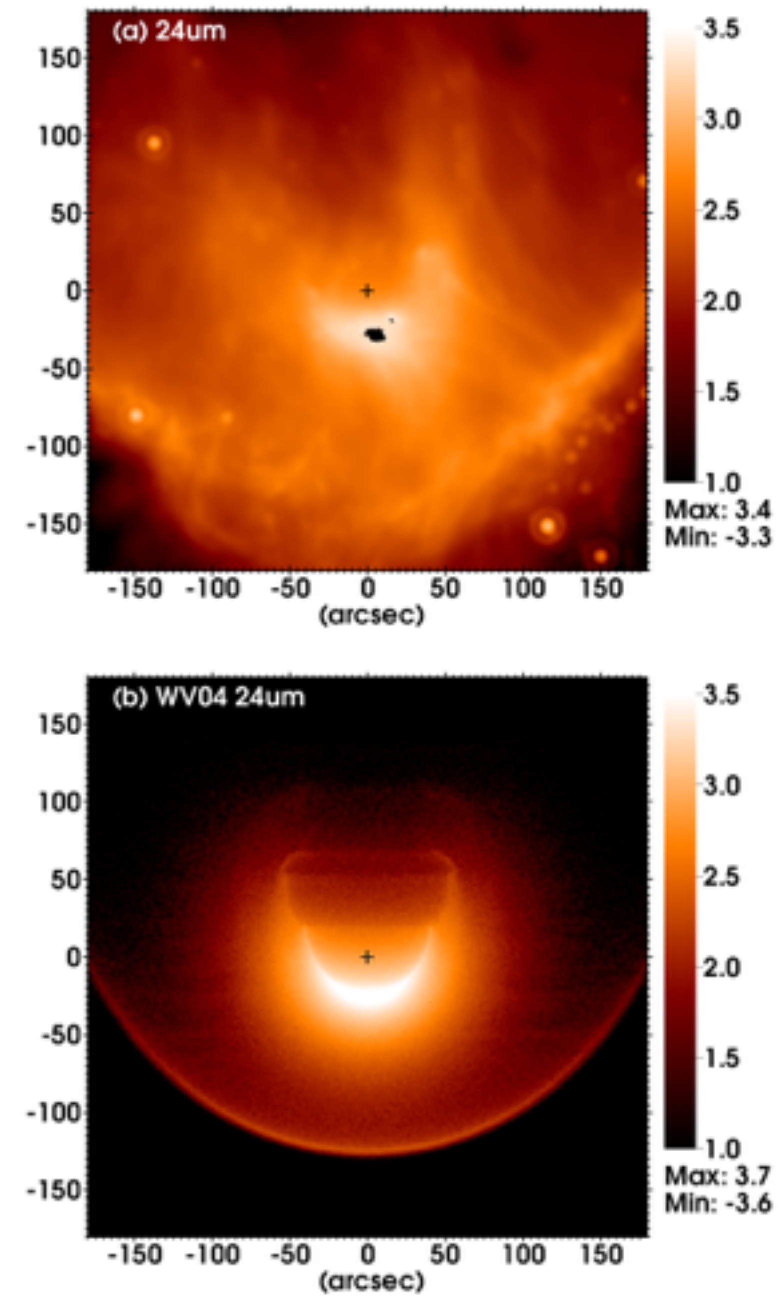
`PION`: **P**hoto**I**onization **O**f **N**ebulae

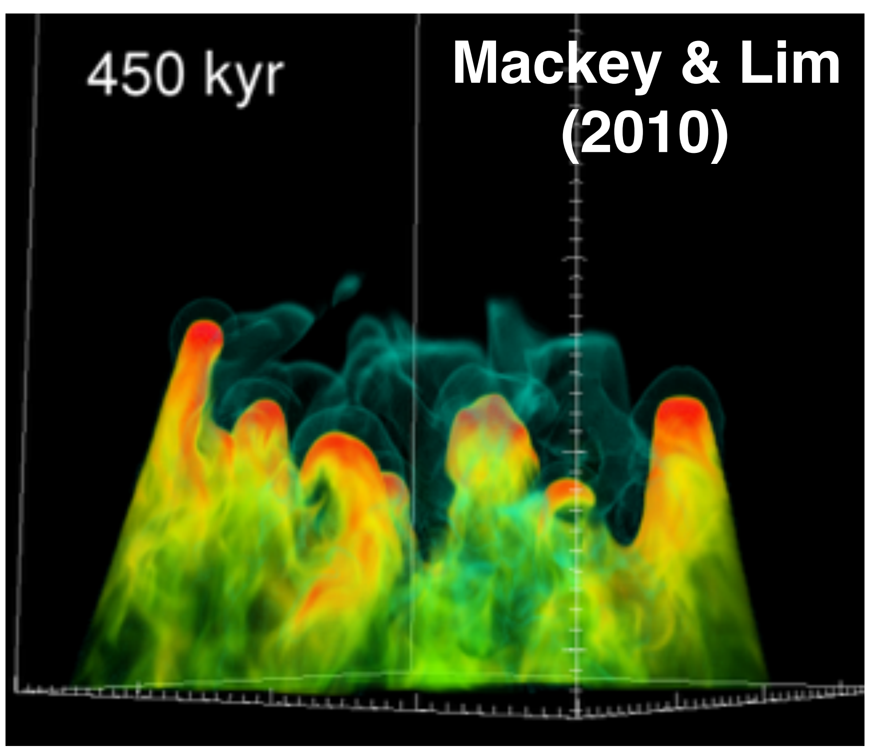
- ★ Introduction to the **`PION`** code
- ★ Betelgeuse - a normal red supergiant
- ★ Westerlund 1 - host of extreme RSGs

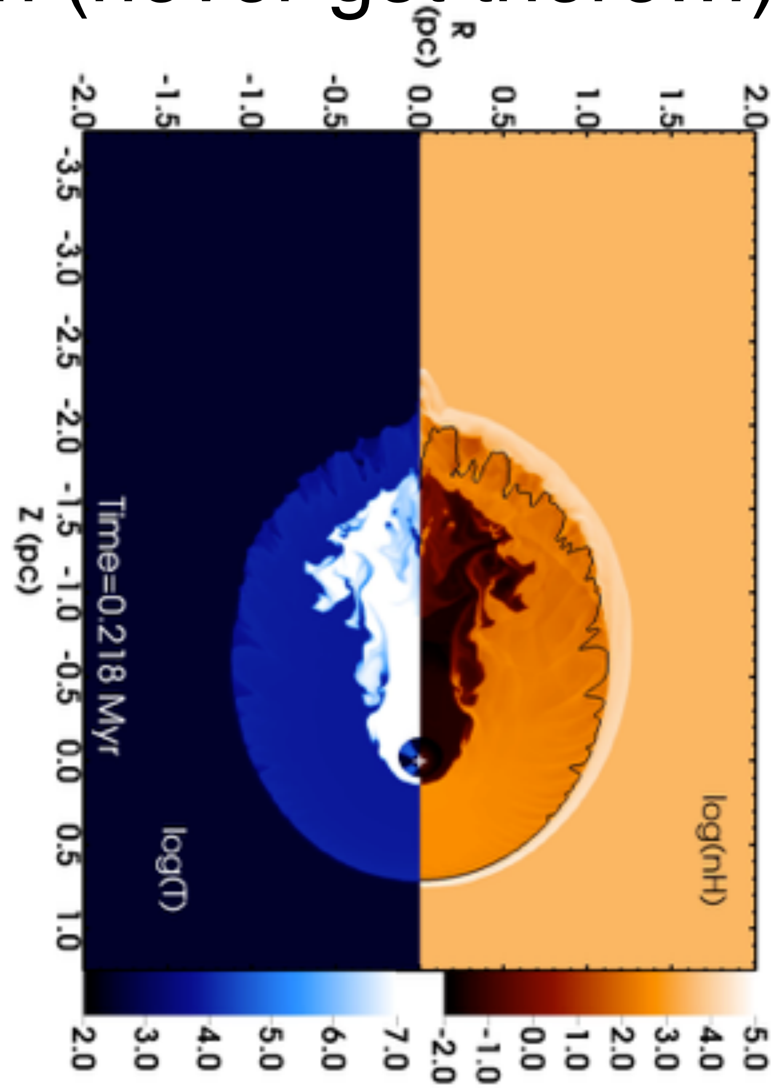
PION - Science goals

- ★ HII regions and pillars of gas/dust.
- ★ stellar wind bubbles and bow shocks, including stellar evolution.
- ★ Triggered star formation (never got there…)
- ★ supernova remnants.

Mackey, Howarth et al. 2016, A&A





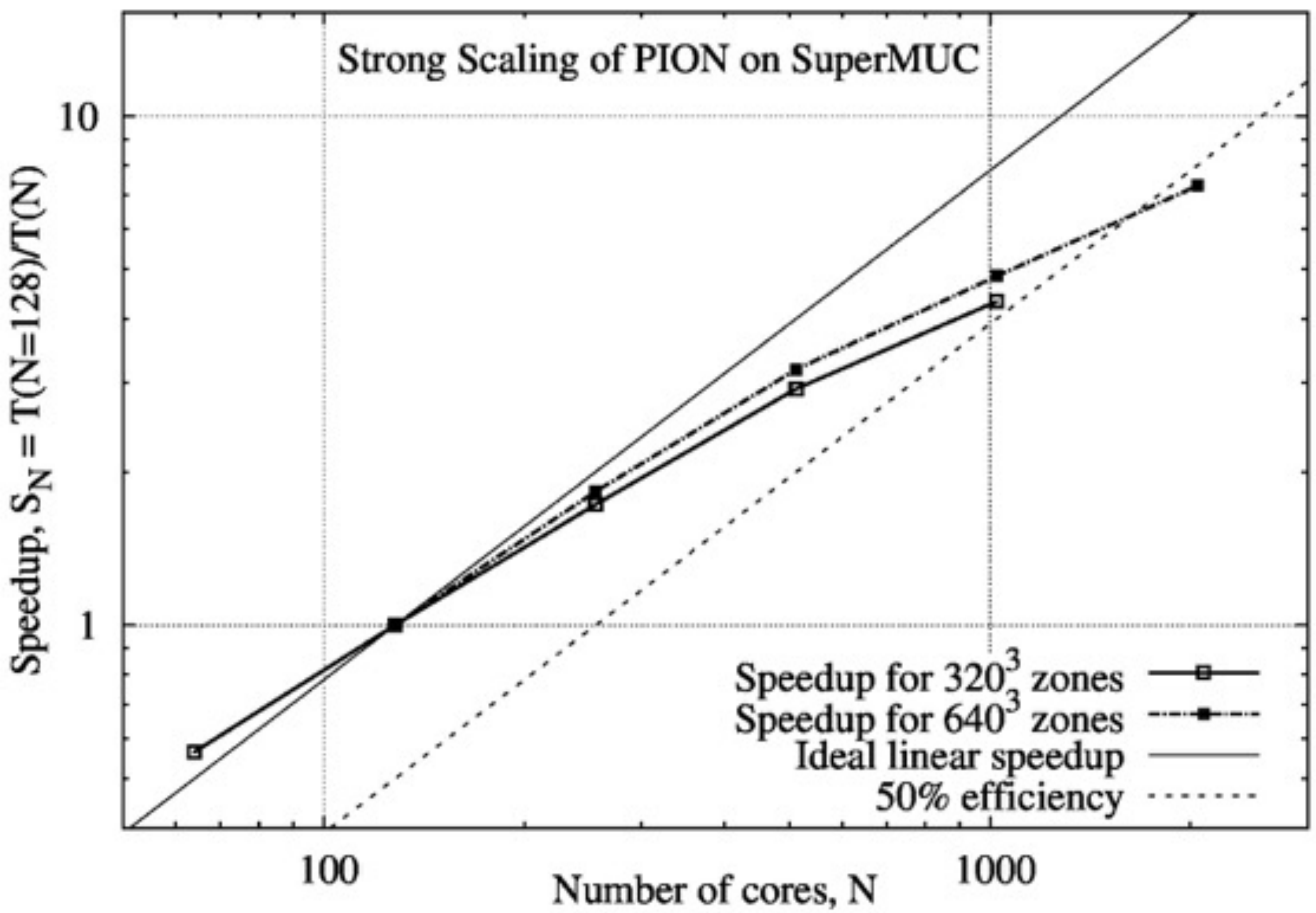


Mackey, Gvaramadze et al. 2015, A&A

Features of **PION**

- ★ Written in modular C++, with MPI parallelisation.
- ★ Grid-based code, finite-volume method.
- ★ Accurate to 2nd order in space and time.
- ★ Shock-capturing, TVD integration scheme.
- ★ Coordinate systems: spherical (1D), cylindrical (2D), Cartesian (1D,2D,3D)
- ★ Hydrodynamics and ideal MHD equations.
- ★ Many heating and cooling routines implemented.
- ★ Radiative transfer using method of short characteristics.
- ★ Coupled integration of chemistry and thermodynamics with CVODE.

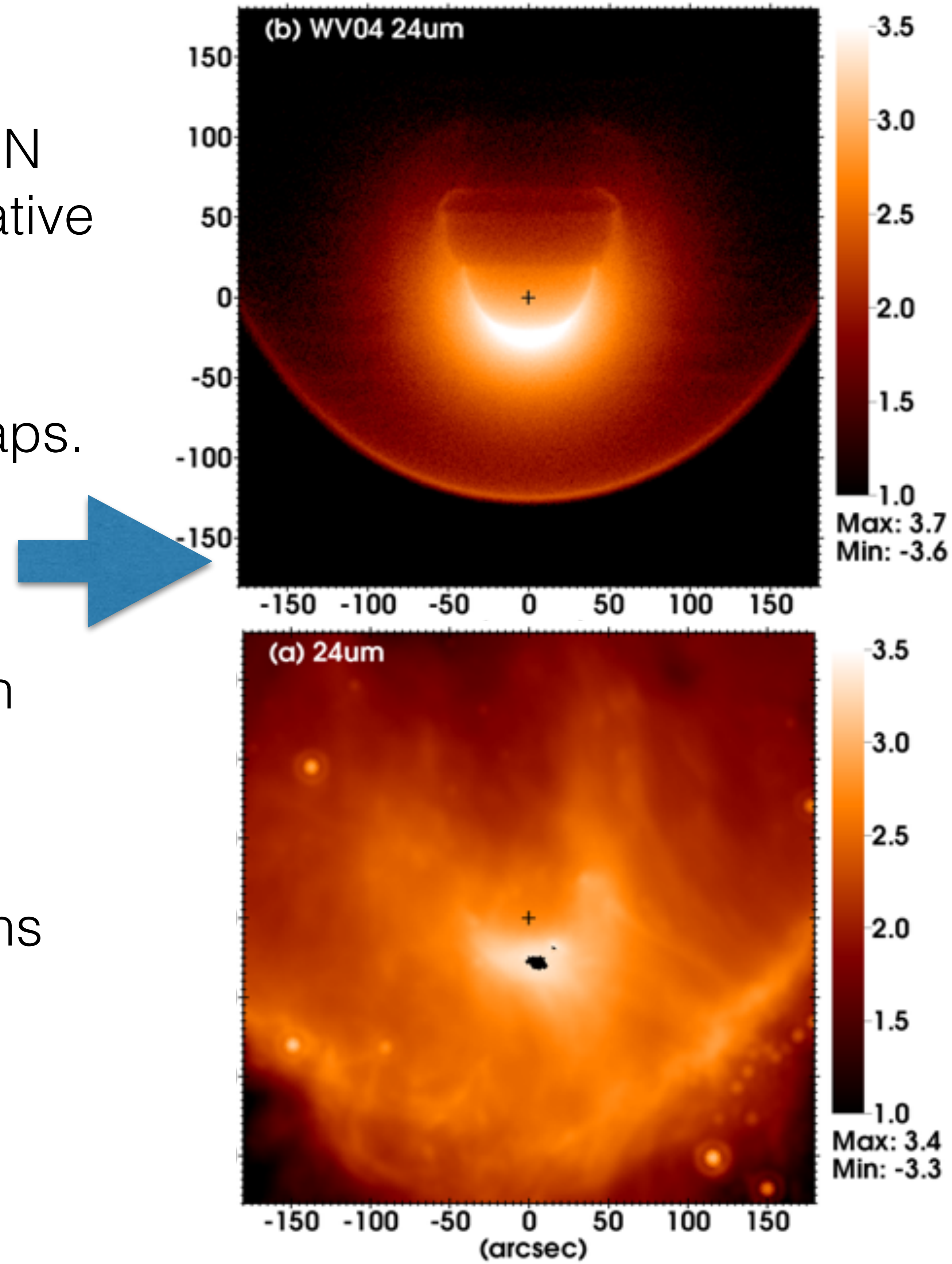
Scaling Of **PION**



- Weak scaling of PION is very good.
- Strong scaling is more difficult because raytracing involves lots of inter-process communication.
- Here is plot from 2013 on SuperMUC for a 3D radiation-hydrodynamics simulation with 320^3 or 640^3 cells.

Postprocessing **PION** Sims

- TORUS (Harries,2000) can read PION snapshots and do Monte Carlo radiative transfer.
- Simulations —> TORUS radiative transfer —> map of Tdust —> IR maps.
- From Mackey, Haworth, et al. (2016)



- Sam Green has written lots of python modules for plotting snapshots.
- Can also make synthetic observations with a number of scripts and postprocessing codes.

Future of **PIONS**

★ Public release of code in 2018.

★ Move to community development model (open).

★ Will have unrestrictive BSD-style licence, except that code can't be used for weapons research.

★ All setup files that I used for published papers will also be available for download.

★ X-ray radiative transfer module.

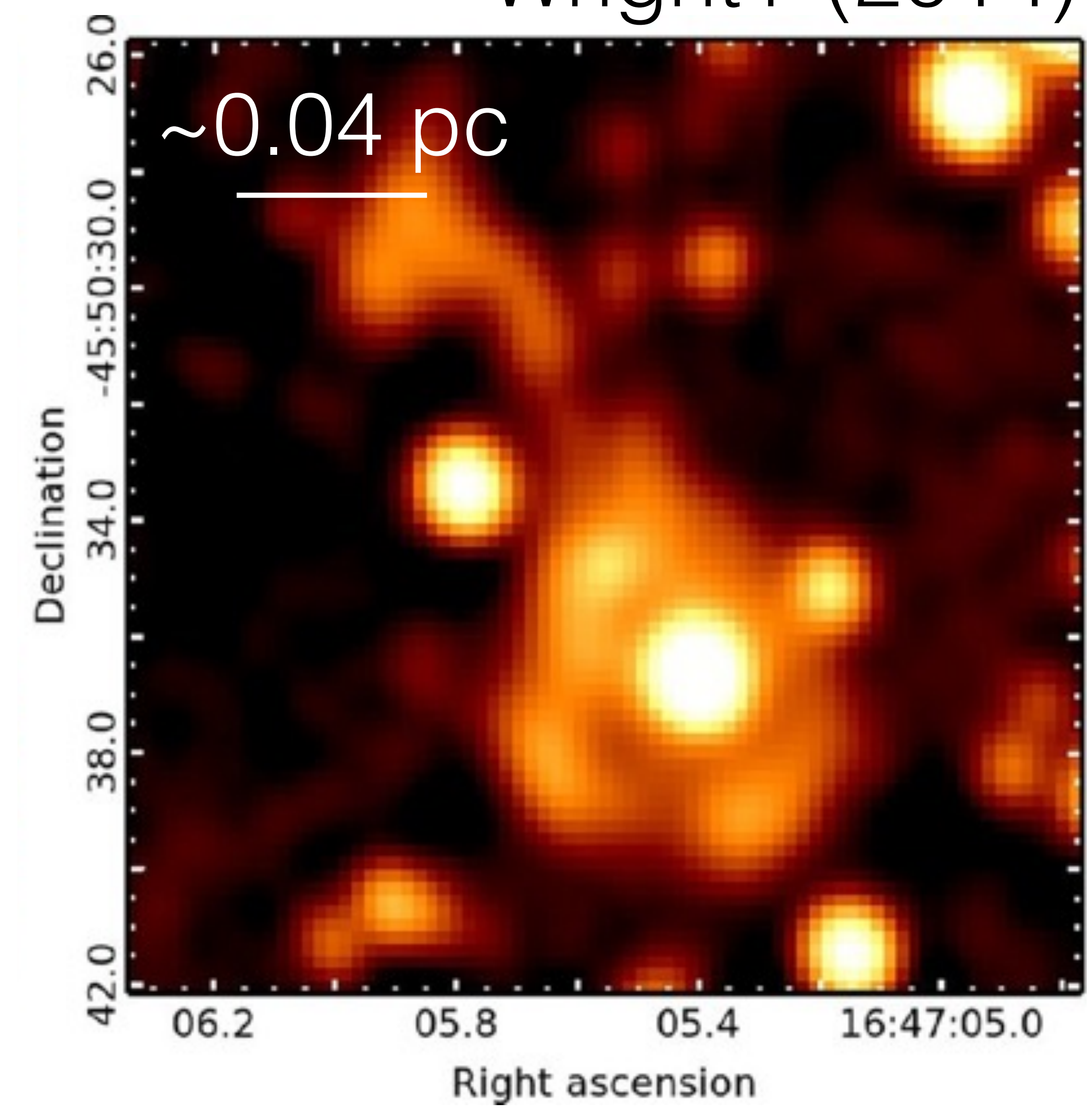
★ Multi-ion chemistry and dust modelling.

★ Non-thermal radiation postprocessing.

What can wind bubbles tell us?

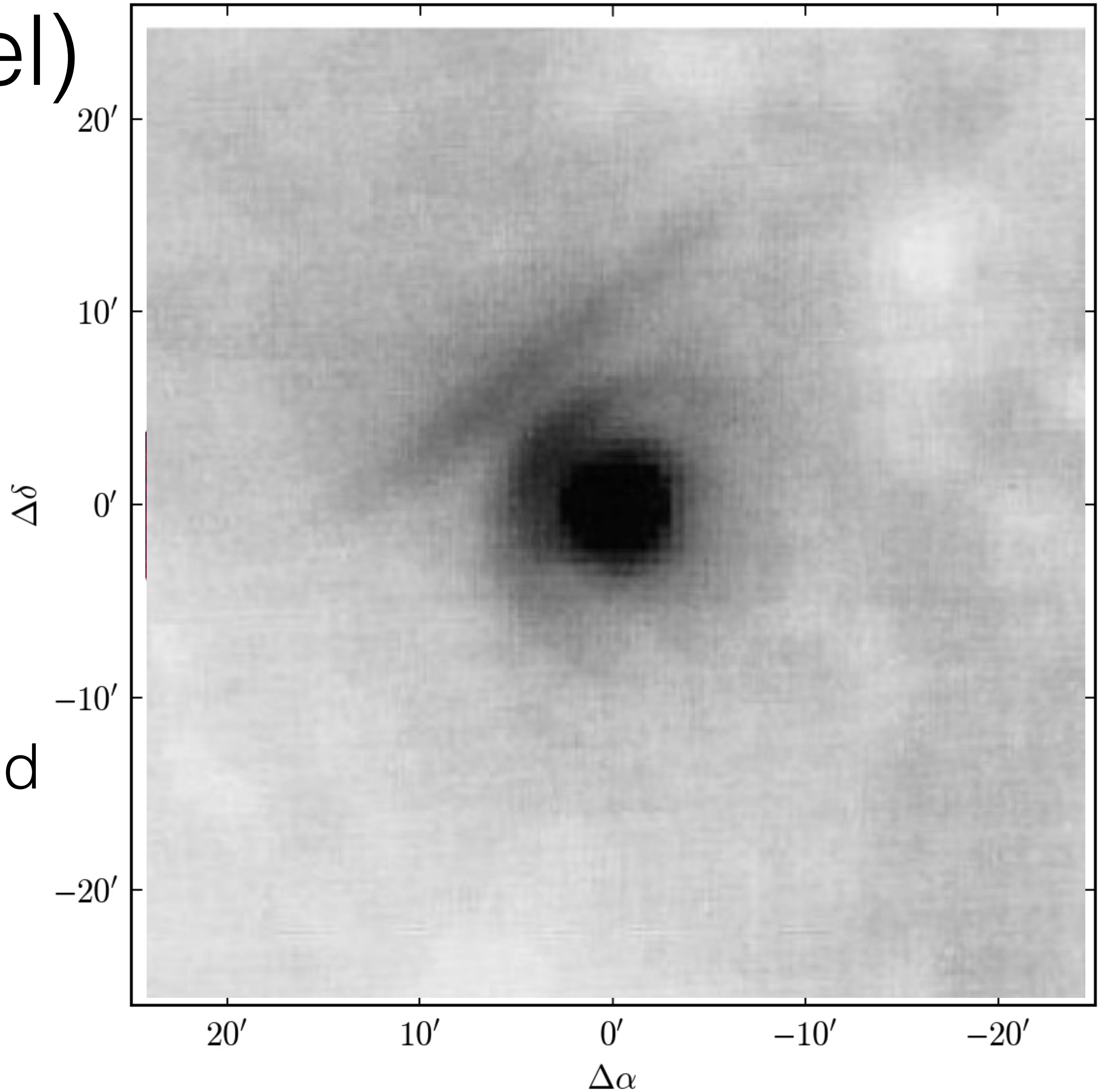
- **Fate** of a massive star determined by cumulative mass-loss history.
- Will it explode?
- What kind of supernova?
- How will it look (CSM interaction)?
- How far does the free-wind region extend?
  10^{15} cm, 10^{16} cm, 10^{17} cm, 10^{18} cm, more?
- How much mass is found close to the star?
-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

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



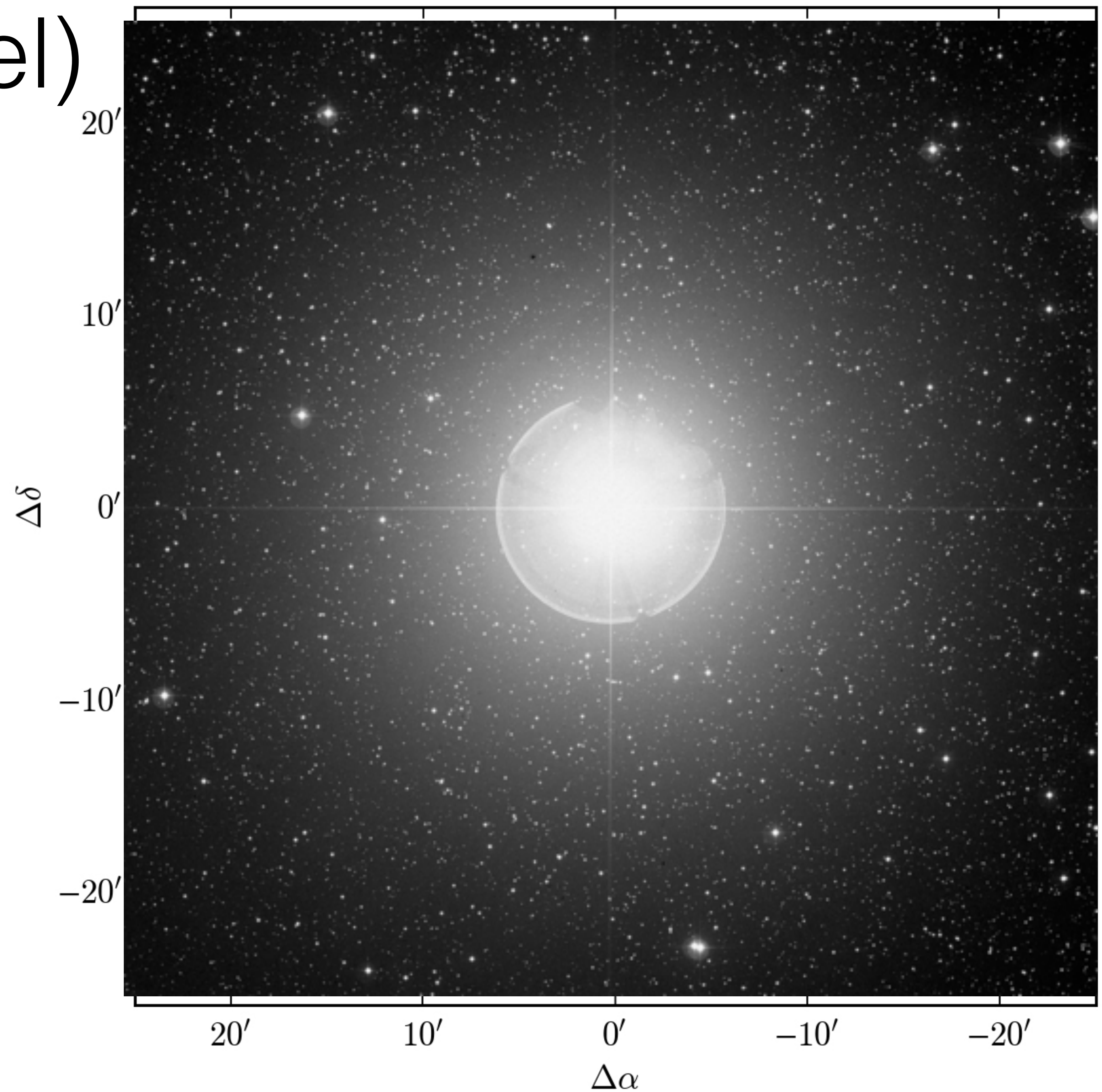
Betelgeuse (pre-Herschel)

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



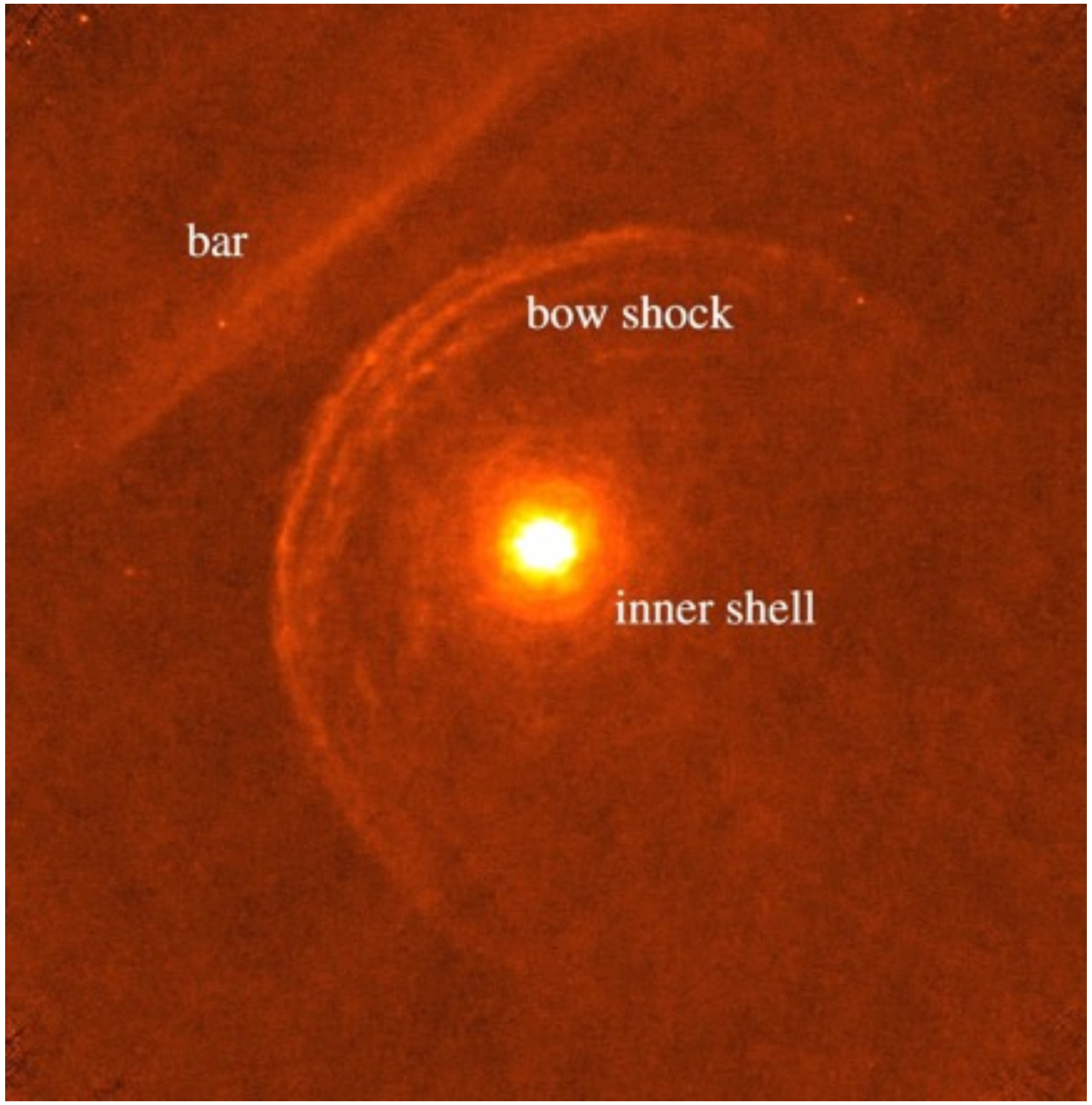
Betelgeuse (pre-Herschel)

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



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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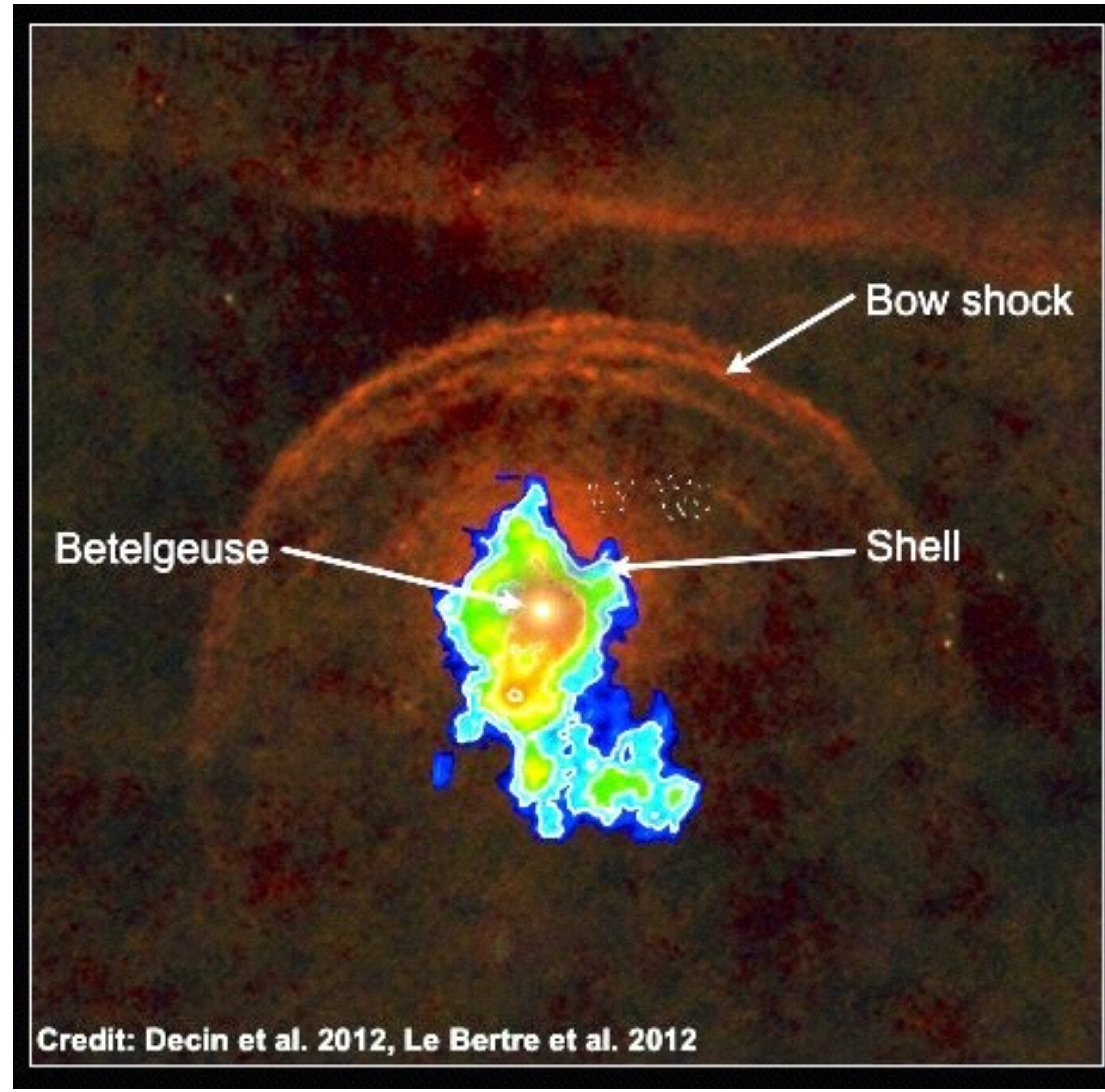


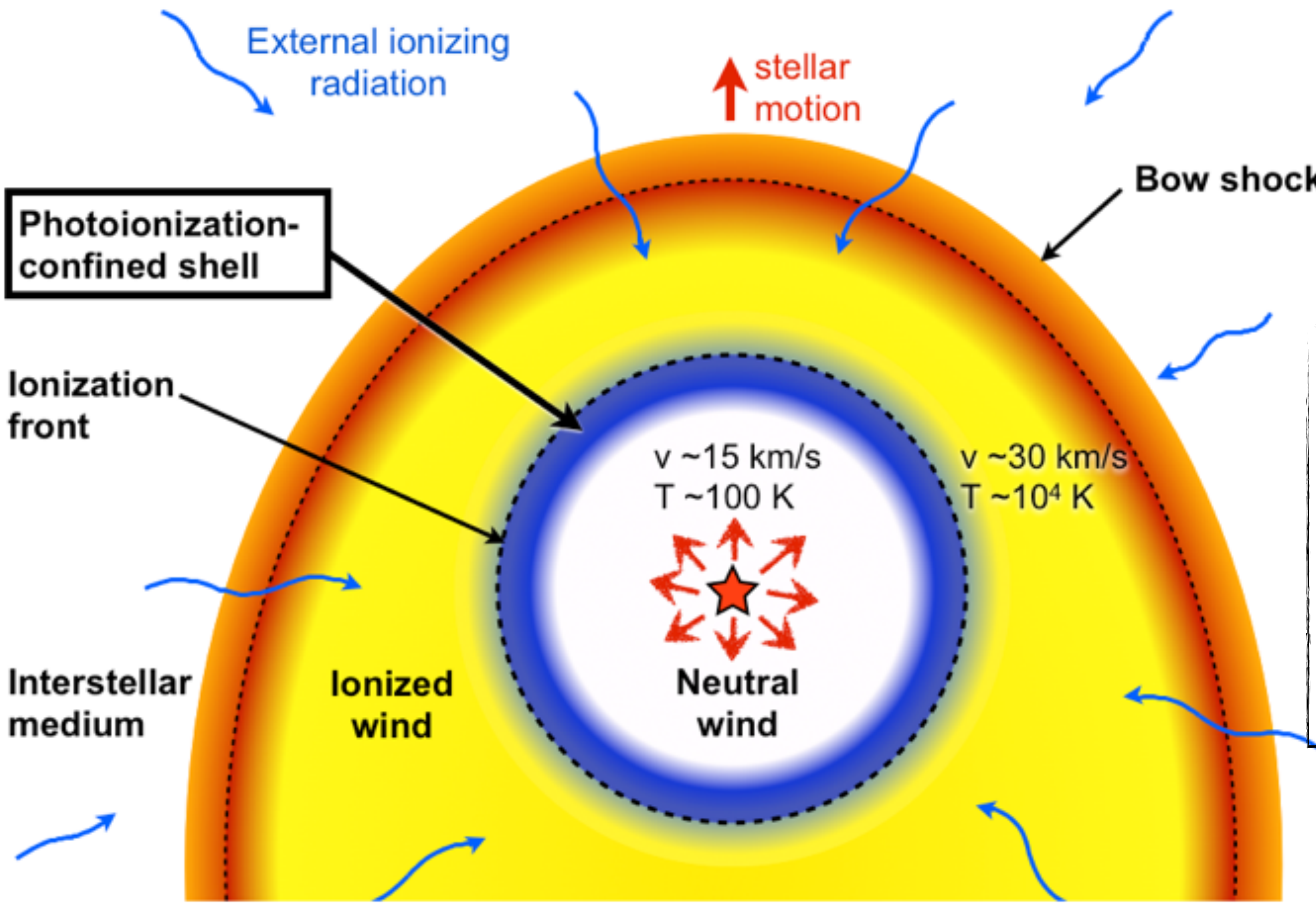
Circumstellar Medium (CSM) structures

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



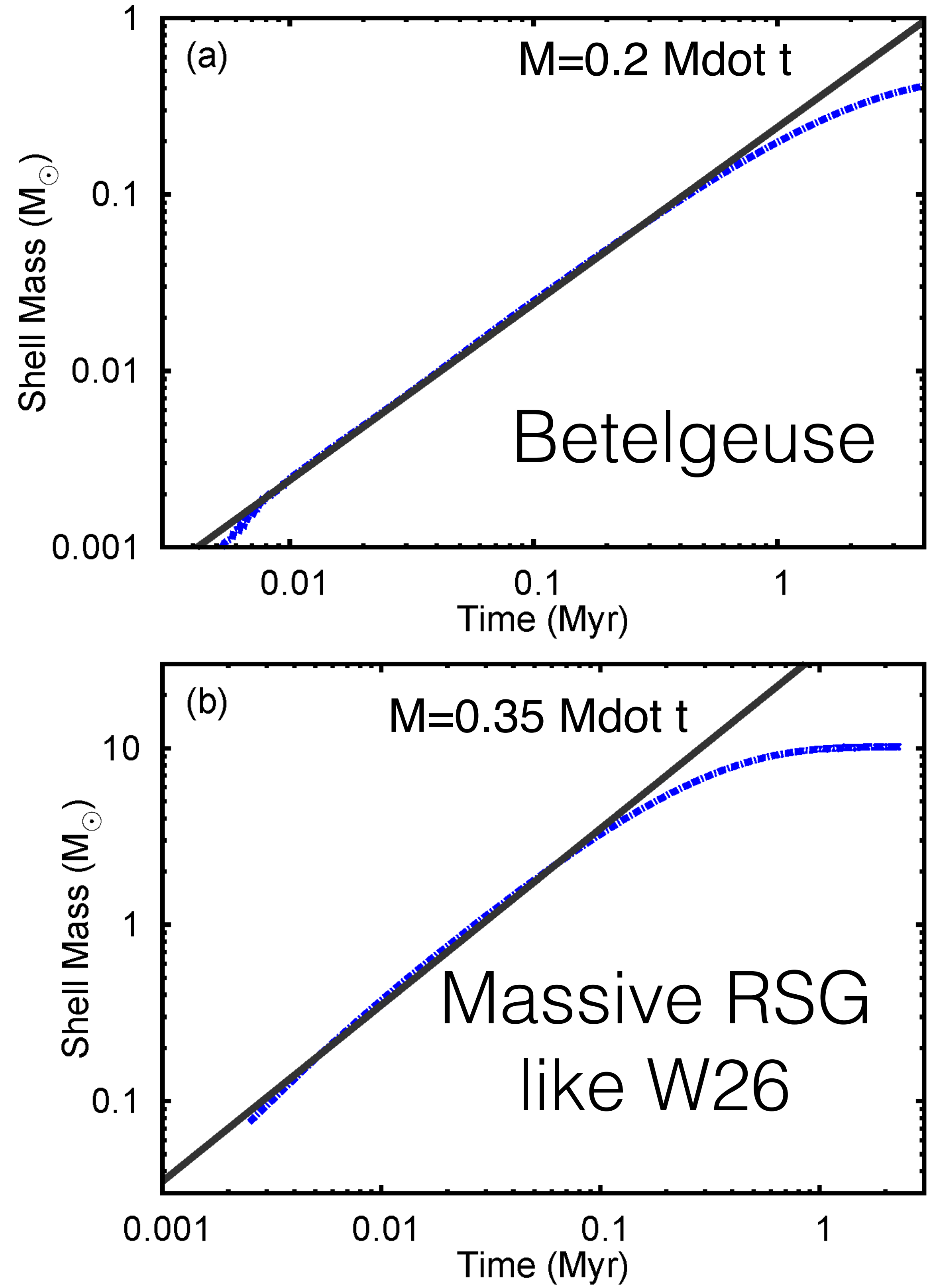
Two circumstellar shells from steady mass loss!

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

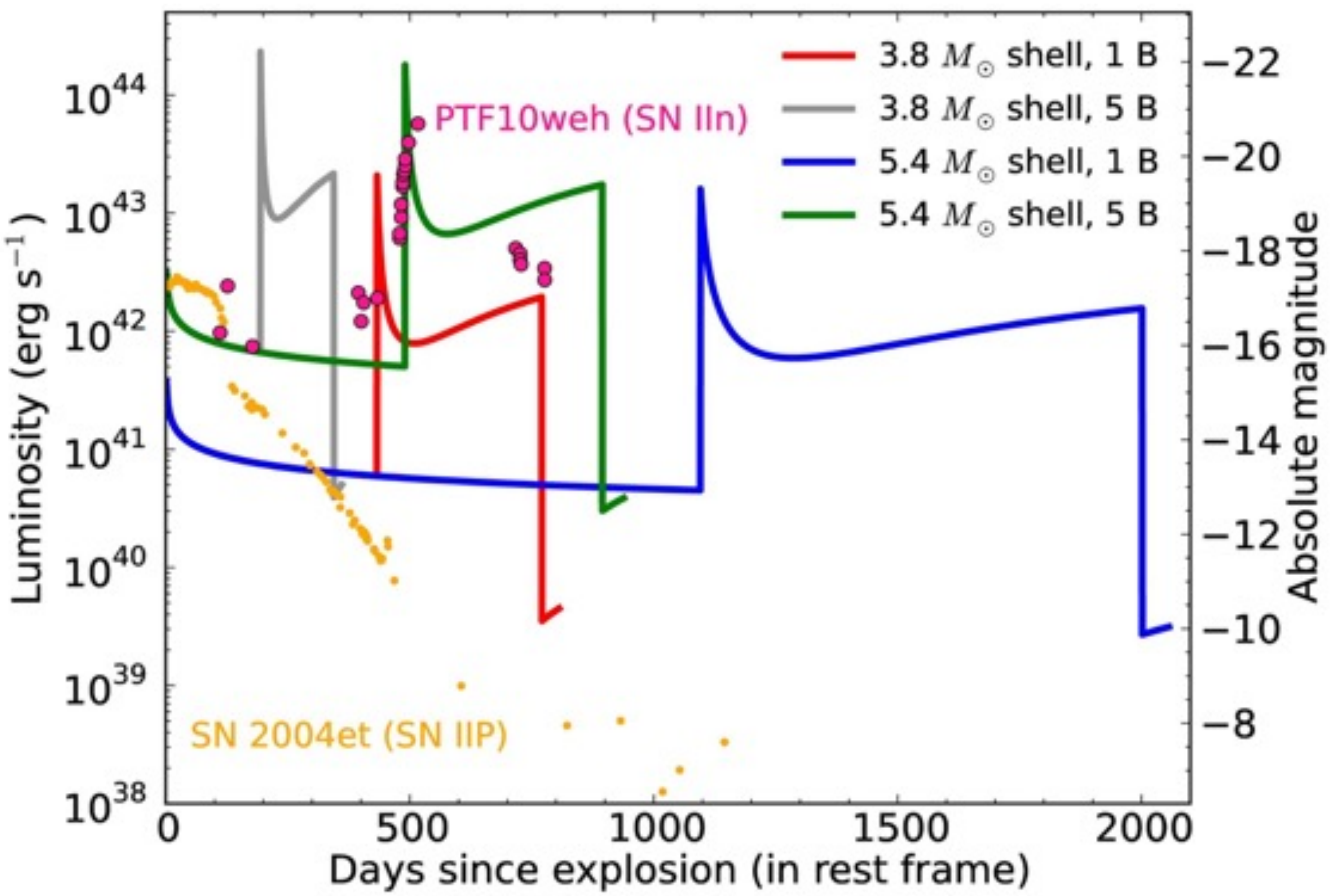
Mackey+, 2014, Nature, **522**, 282.

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.



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).

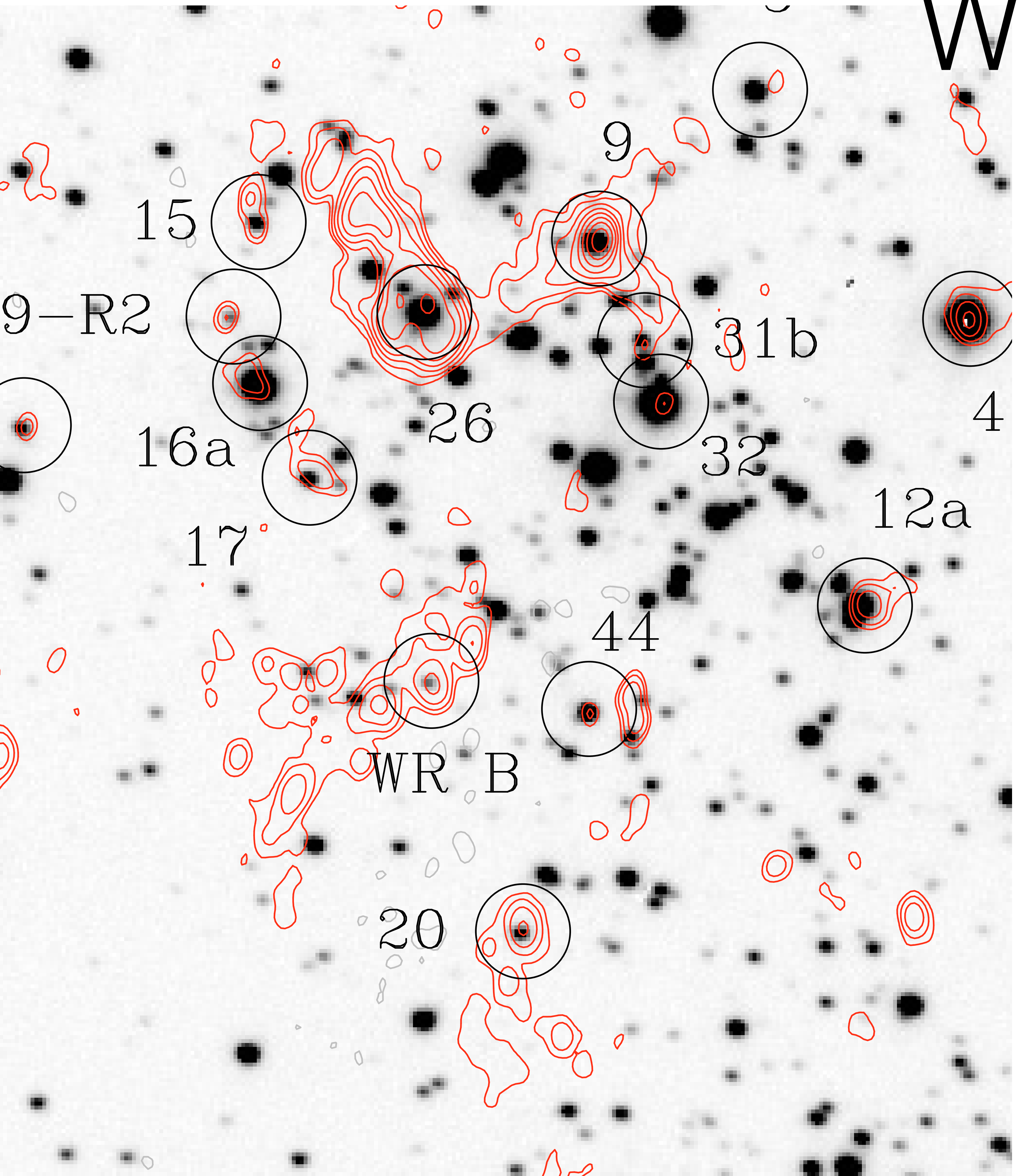
- Bolometric luminosity evolution of supernovae interacting with photoionization-confined shells.
- Choose massive shells, with ionizing fluxes such that the shell is at 2×10^{16} cm (lower mass shell) and 4×10^{16} cm (higher mass shell).
- Calculations for explosions with 10^{51} and 5×10^{51} ergs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

Westerlund 1

JHK image from Brandner+2008.

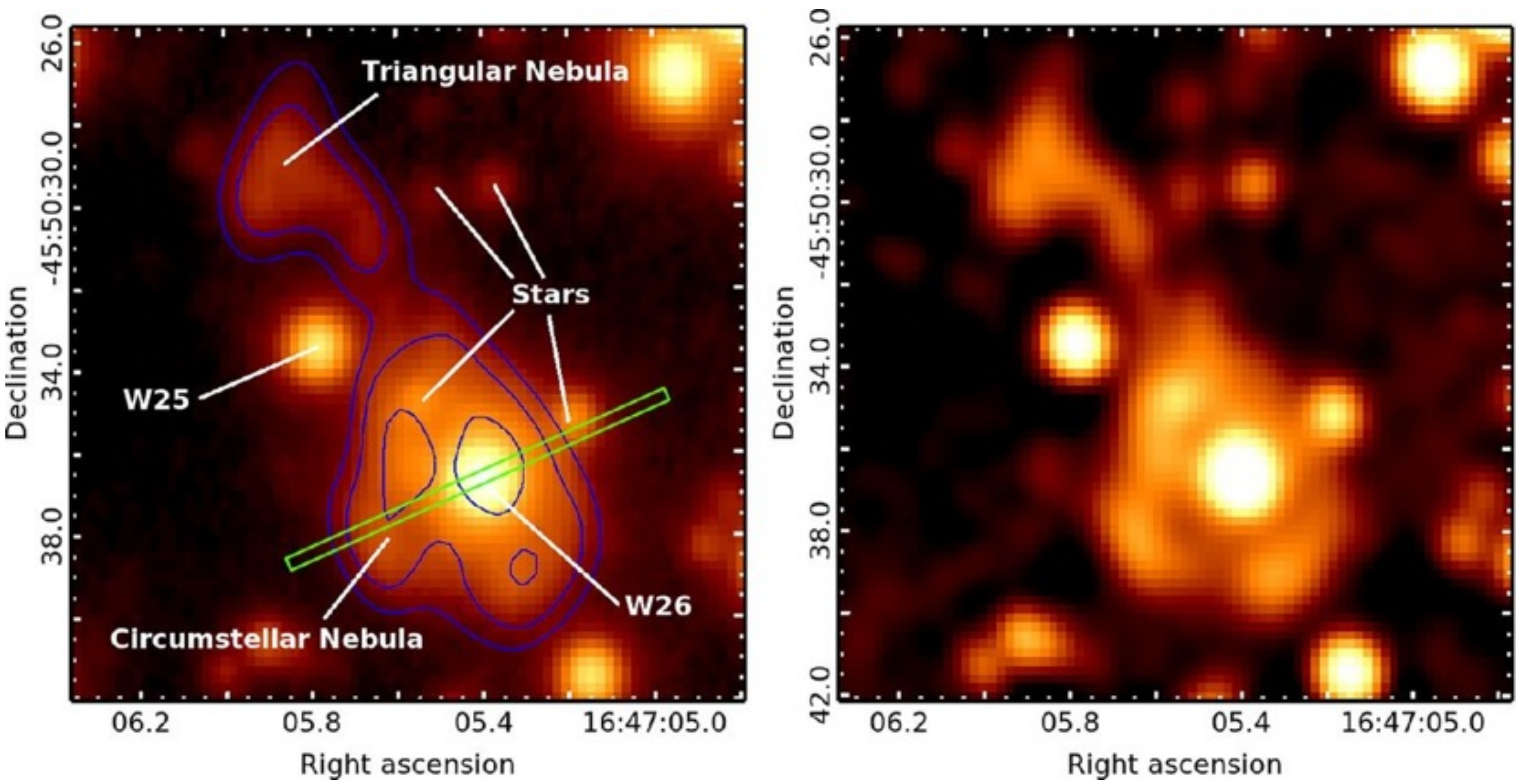
- Probably the most massive young star cluster in the Galaxy (Brandner+2008).
- Unfortunately has A_V=13.
- Age is 3-5 Myr, so that it contains both hottest (WR) and coldest (RSG) stars at the same time.
- Has largest Galactic WR star population (Crowther+,2006).
- Has >14 evolved, extreme supergiant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

Westerlund 1



- Evolved stars have radio-bright circumstellar nebulae (Dougherty+2010).
- Dense stellar winds 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).

Photoionized wind of W26



W26 in Westerlund 1 (Wright+,2014)

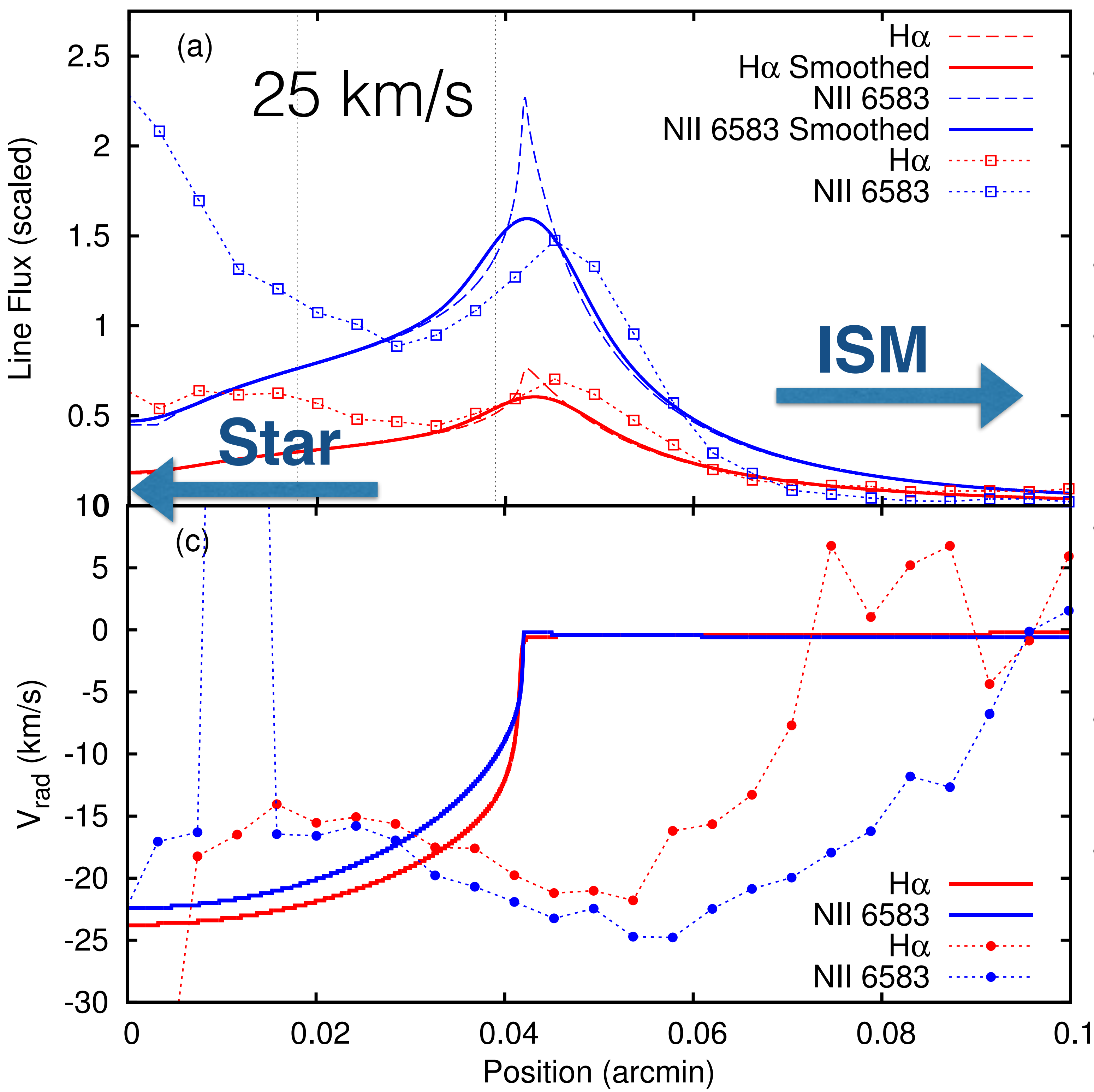
Hα+[NII] surface brightness

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).

Projected line emission

Mackey, Castro, Fossati & Langer, A&A, 2016



- R-type Ionization front gives less 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.
- The whole nebula is observed to be blueshifted —>
- emission cannot be spherically symmetric.

Conclusions

Requirements for a photoionization-confined shell:

1. a cool star with a dense and slow wind (<25 km/s).
2. located in an ionized region of space so the wind can be photoionized from outside.

RSGs are best candidates because they live near O and B stars. AGB and RG stars by chance (up to 30% of ISM is hot ionized gas), or because they have a hot binary companion.

- We explain the shell around Betelgeuse as a photoionization-confined shell, from diffuse ionizing radiation in the Orion-Eridanus superbubble.
- Predict that these shells should be common around RSGs.
- Shell mass scales with mass-loss rate, up to ~7 $M_\odot$.
- Strong influence on SN lightcurves, relating to IIn and SLSN
- Shells can be much closer to the star than ISM-confined shells.
- RSGs in clusters can have >1 $M_\odot$ shells at ~10^{16} cm.