ASTEROSPHERES

Bow shocks, bow waves and dust waves around stars

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with important contributions from
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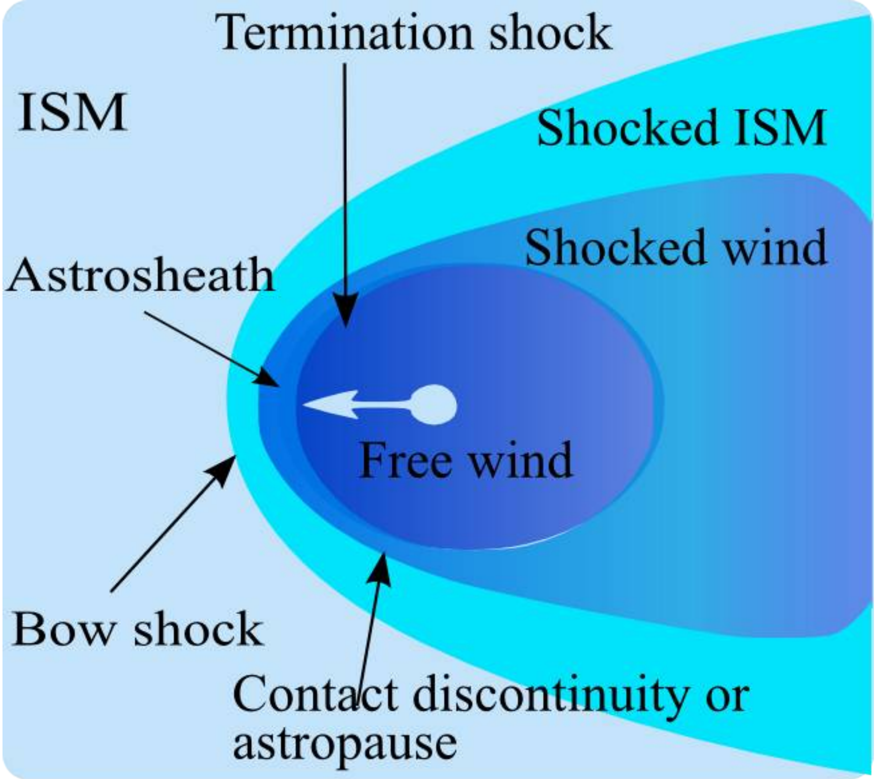
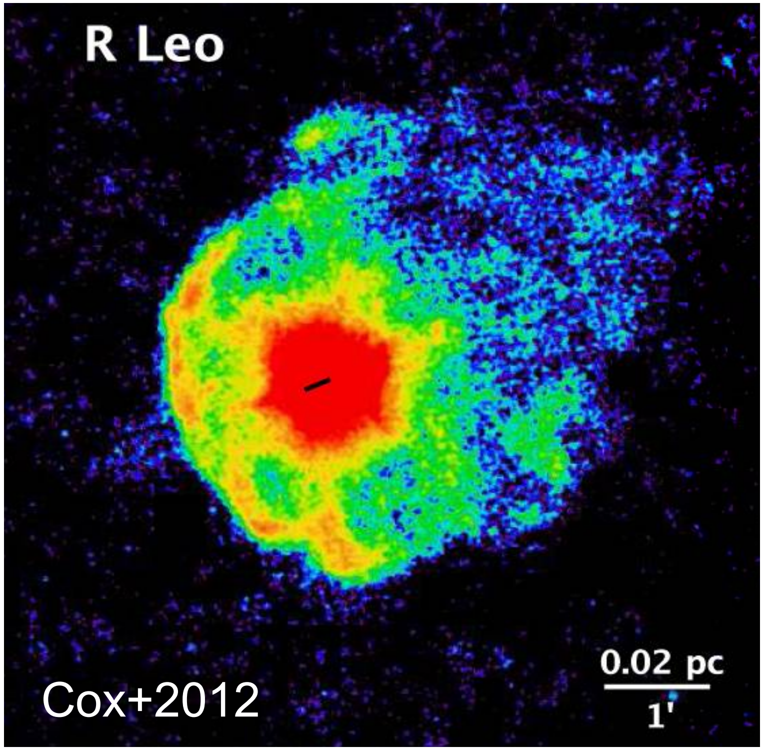
Outline

- Asterospheres: The stellar wind – ISM interaction region
- Hot stars
- Cool stars
- Conclusions and outlook

Asterospheres – bow shocks / bow waves

Basic idea: Expelled wind (gas and mass loss) interacts and sweeps up the surrounding interstellar medium. i.e. Wind-ISM interaction





Cox+2012

bow shock: where v_{ISM} goes from supersonic to subsonic values

asteropause: where $P_{ISM} = P_{CMS}$ [P=pressure] → inner (CSM) & outer (ISM) astrosheath

termination shock: place where v_{wind} goes from supersonic to subsonic values

Motivation for studying asterospheres

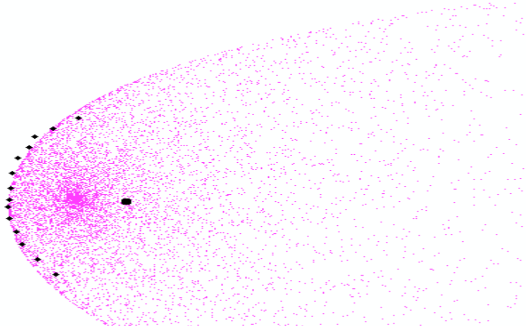
- Asterospheres can be used as proxies of the local ambient medium (i.e. density, temperature, magnetic field).
- Asterospheres can be used to identify runaways / uncover stellar motion.
- Asterospheres can provide insight on physics of dust grain-gas coupling and provide inside in dust processing in transition from CSE to ISM.
- Asterospheres offer protection to (proto-)planetary systems (i.e. similar to the heliosphere protecting the solar system).

Global size scale of asterospheres

Stand-off distance – ram pressure balance between stellar wind and ISM

$$R_0 = \sqrt{\frac{\dot{M}\, v_{wind}}{4\pi\rho_{ISM}\left(c_{ISM}^2 + v_{star}^2\right)}}$$

Wilkin 1996, Weaver 1977

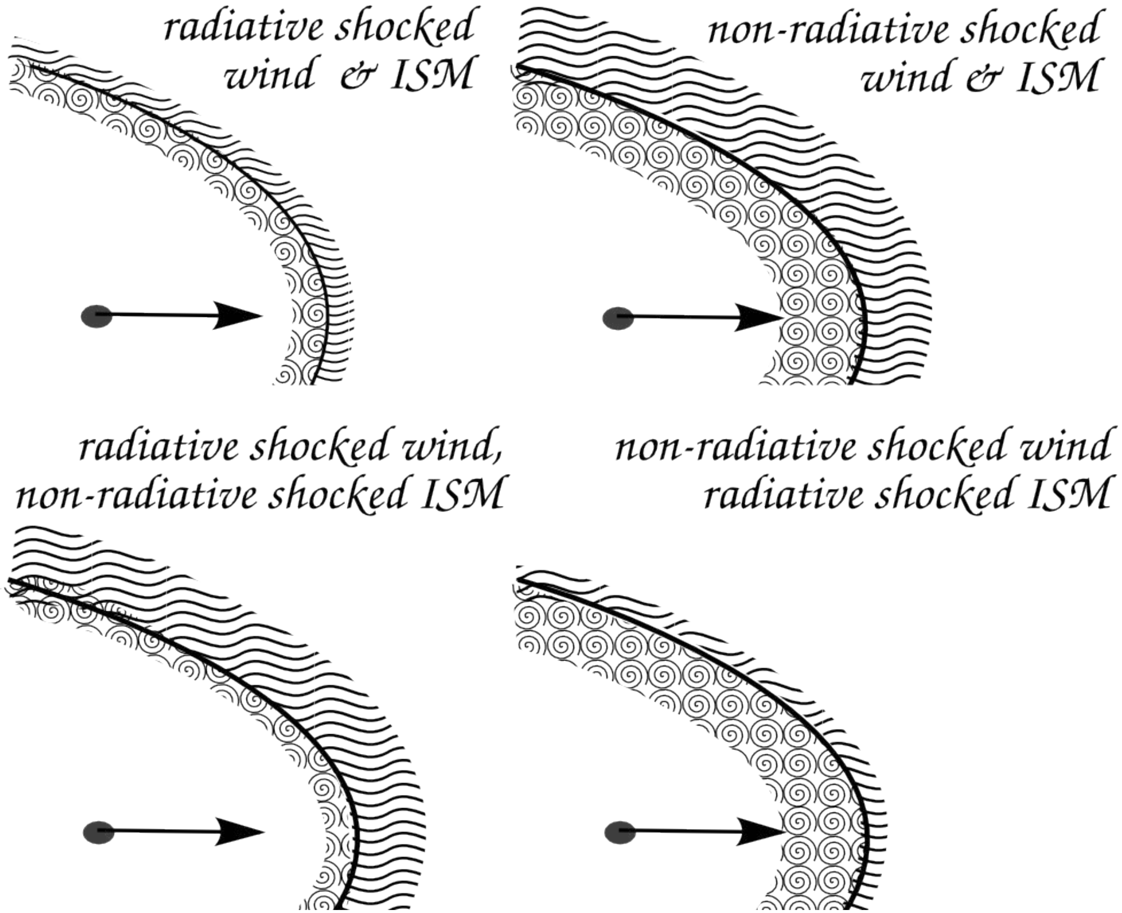


Projection of 3D 'wilkinoid' bow shock shape.

	Old cool star	Young hot star	G star (Sun)
V_{wind} (km/s)	10-30	500-2500	400 - 700
M (M_0/yr)	10^{-7} - 10^{-5}	10^{-7} - 10^{-5}	10^{-15} 10^{-13}
V_{star} (km/s)	30	30	15
$n(H)_{ISM}$ (cm^{-3})	1	1	0.01
R_0 (pc)	**~ 0.1 – 1**	**~ 0.5 – 10**	**~0.001 (200 AU)**
R_0 (arcmin)	~ 2 – 30 (@100pc)	~ 1.2 – 30 (@1kpc)	~0.2 (@10pc) **1 pc ~ 2 10^5 AU**

Note: Asterospheres are dynamical structures responding to changes in stellar parameters.

Radiative vs adiabatic shocks

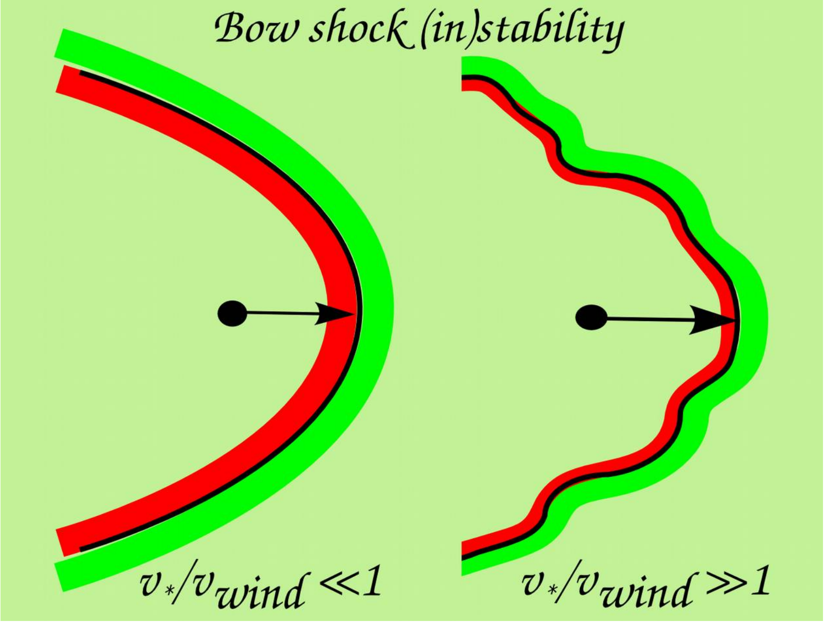


Inspired by Van Buren 1993

($M=\infty$, isothermal)

Bow shocks with
$v_*/v_w \ll 1$ → stable
$v_*/v_w \gg 1$ → unstable

Slow winds more unstable!

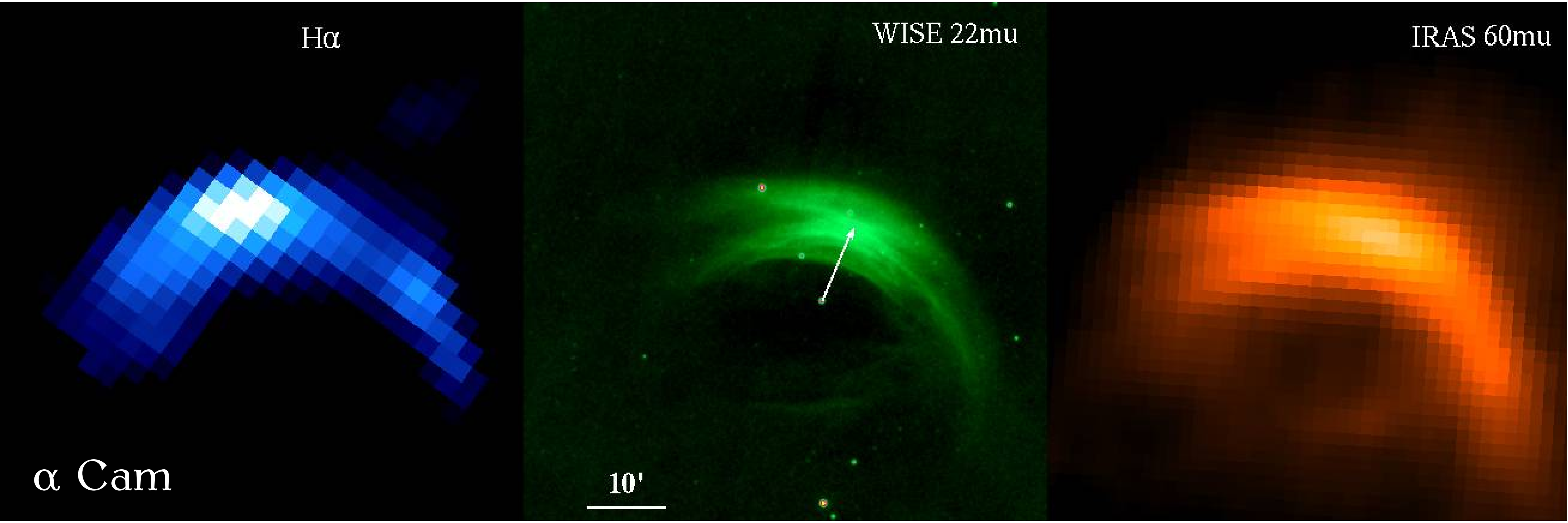


Width interaction region depends on cooling efficiency and Mach of interacting flows. Efficient (radiative) cooling → region narrows, higher gas density, ↑ with M^2. Width scales as $\sim R_0 / M^2$ (Blondin & Koerwer 1998).

Gas and dust in asterospheres of hot stars

– pre-*Herschel* –

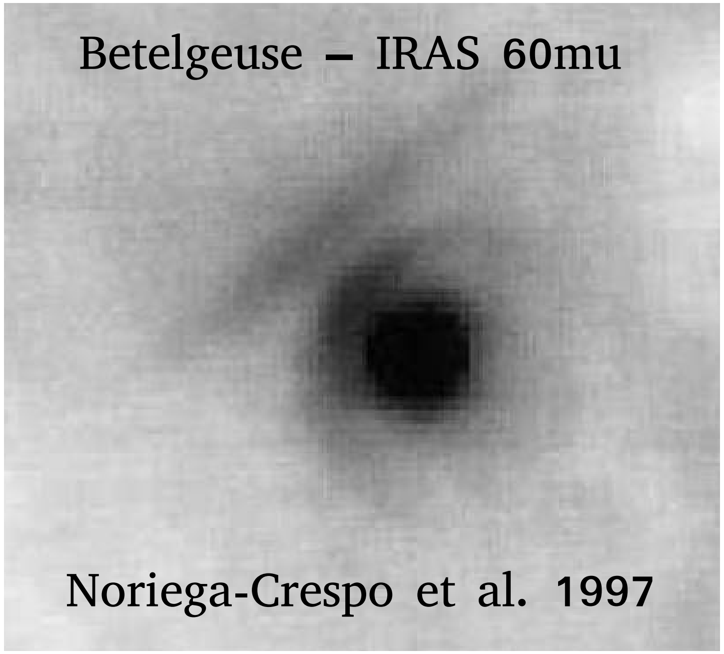
Previously infrared emission associated with hot luminous stars (ex. α Cam, ζ Oph, τ Cma) as well as the RSG α Ori



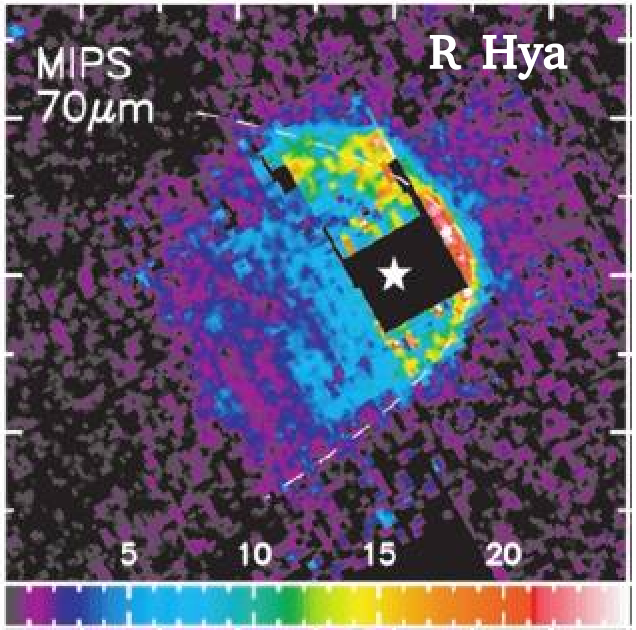
Van Buren & McCray 1998, Van Buren et al. 1995, Noriega-Crespo et al. 1997
New WISE survey of bow shocks (10-15%) runaway stars presented in Peri+2011
IRAS detected 31 bow shocks and 27 bubbles/resolved emission out of 188 runaways.

Dust & gas in asterospheres of cool, old stars

– pre-*Herschel* –

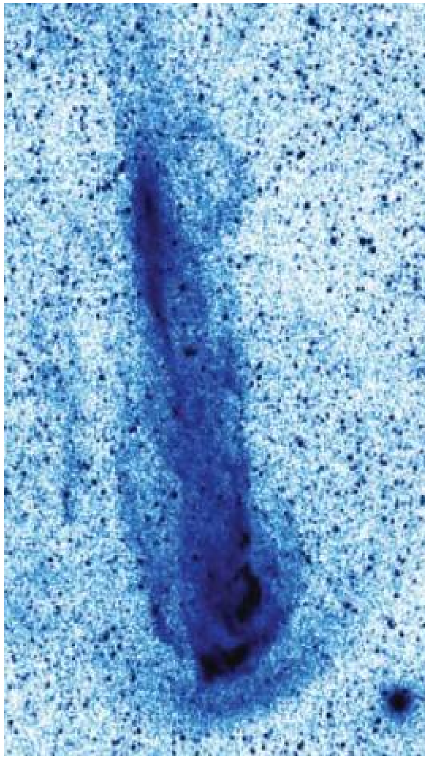

Betelgeuse – IRAS 60mu

Noriega-Crespo et al. 1997

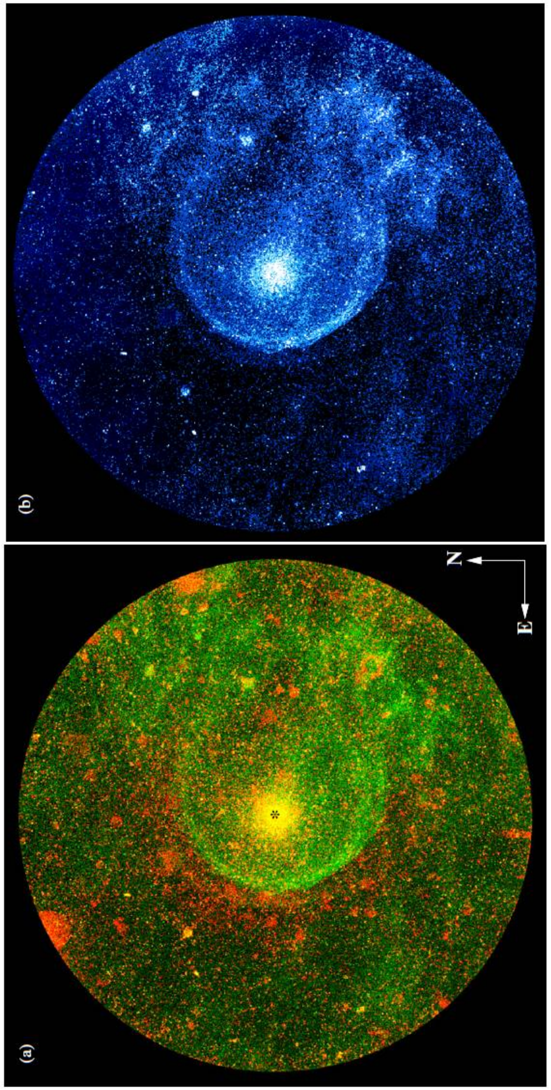


Ueta et al. 2006

MIRA – GALEX FUV


Martin et al. 2007

CW Leo – GALEX FUV



Sahai & Chronopoulos 2010

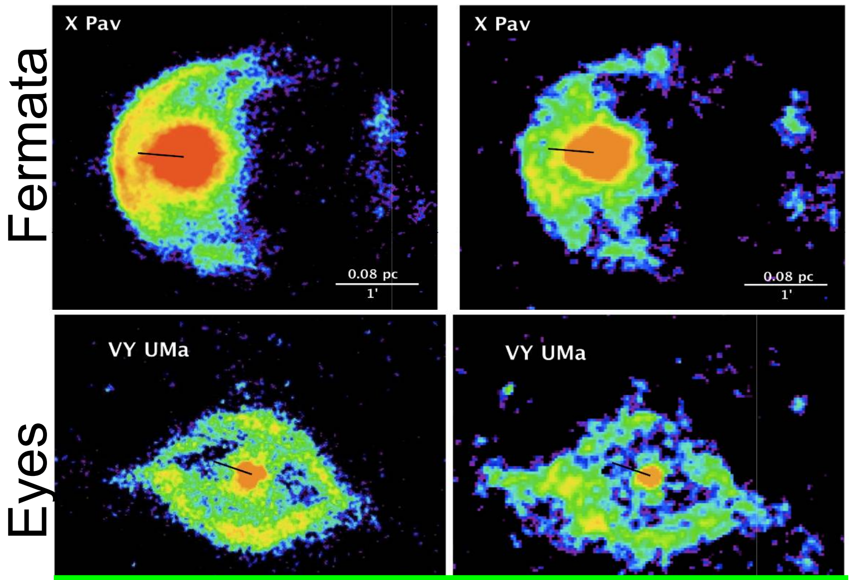
Herschel far-infrared survey of AGB/RSG

Mass-loss of **E**volved **S**tar**S**
(Groenewegen et al. 2011)

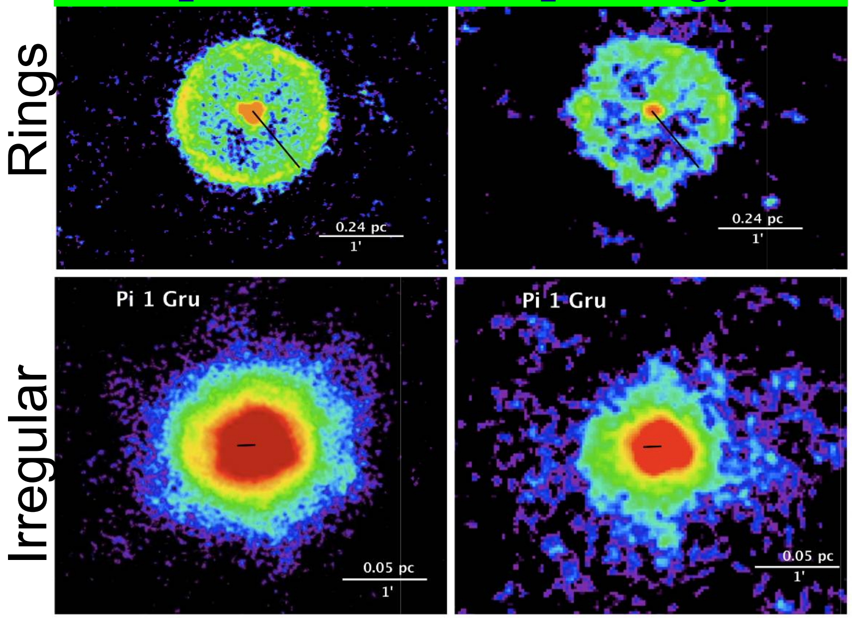
<u>IR-imaging 70 & 160 um:</u>
32 O-rich AGB/RSG, 9 S-stars, 37 C-stars

Mass loss rate: $10^{-4} – 10^{-8}$ M_o/yr,
slow winds: v_w = 5-20 km/s

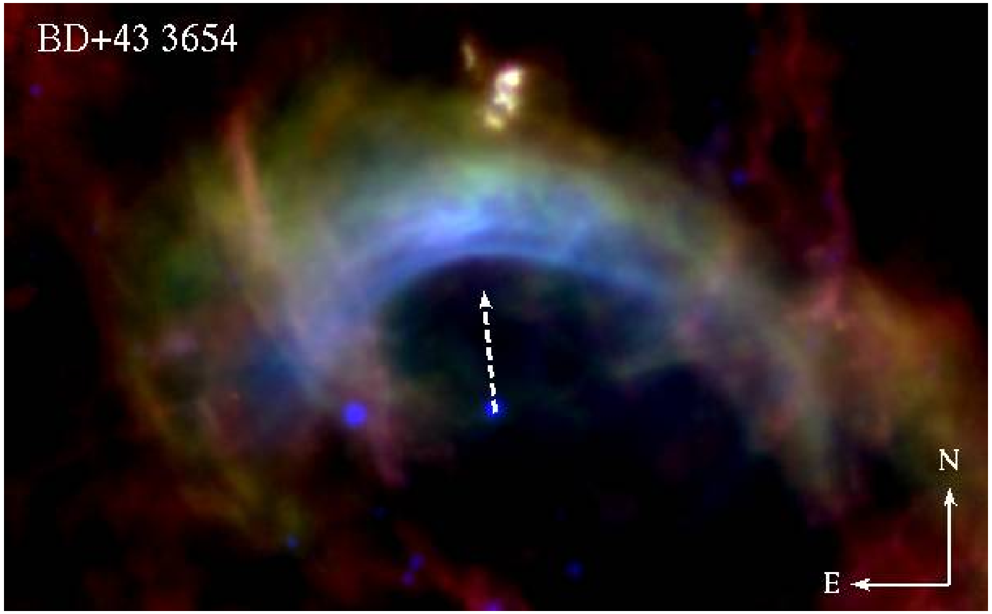
Type	N	N (d < 500 pc)
Fermata	24	22
Eye	7	7
Ring	15	13
Irregular	7	6
Point source	28 (35%)	13 (20%)
Total	81	61



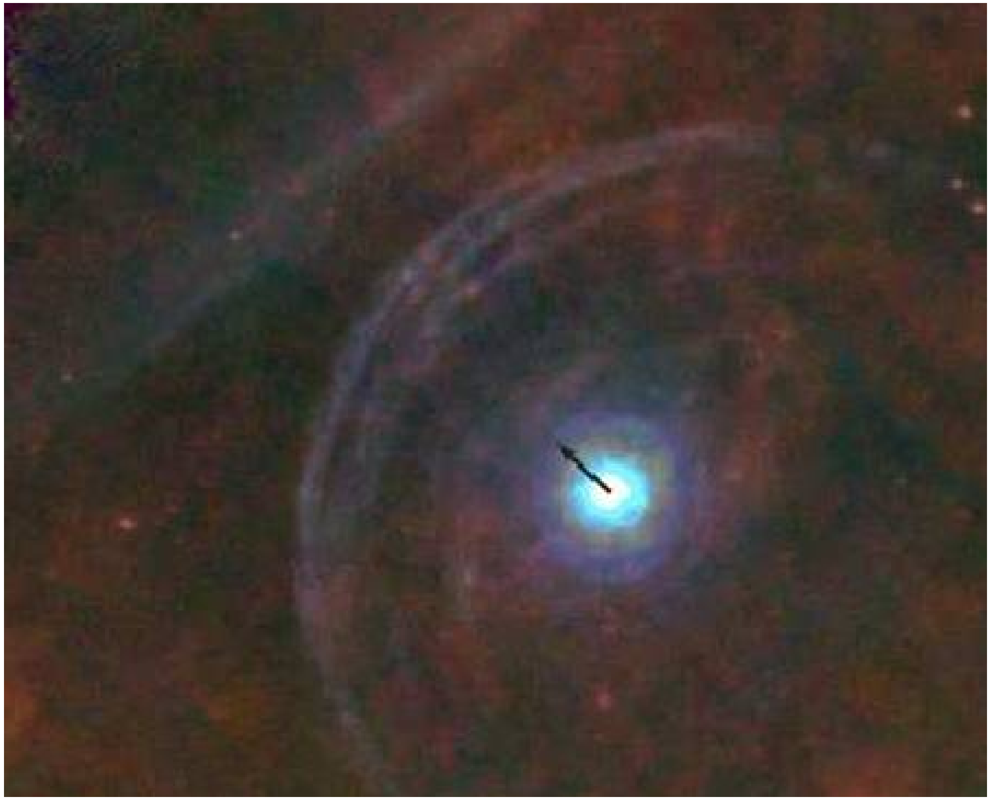
53 out of 81 objects reveal complex CSE morphology!



Herschel observations of dusty asterospheres

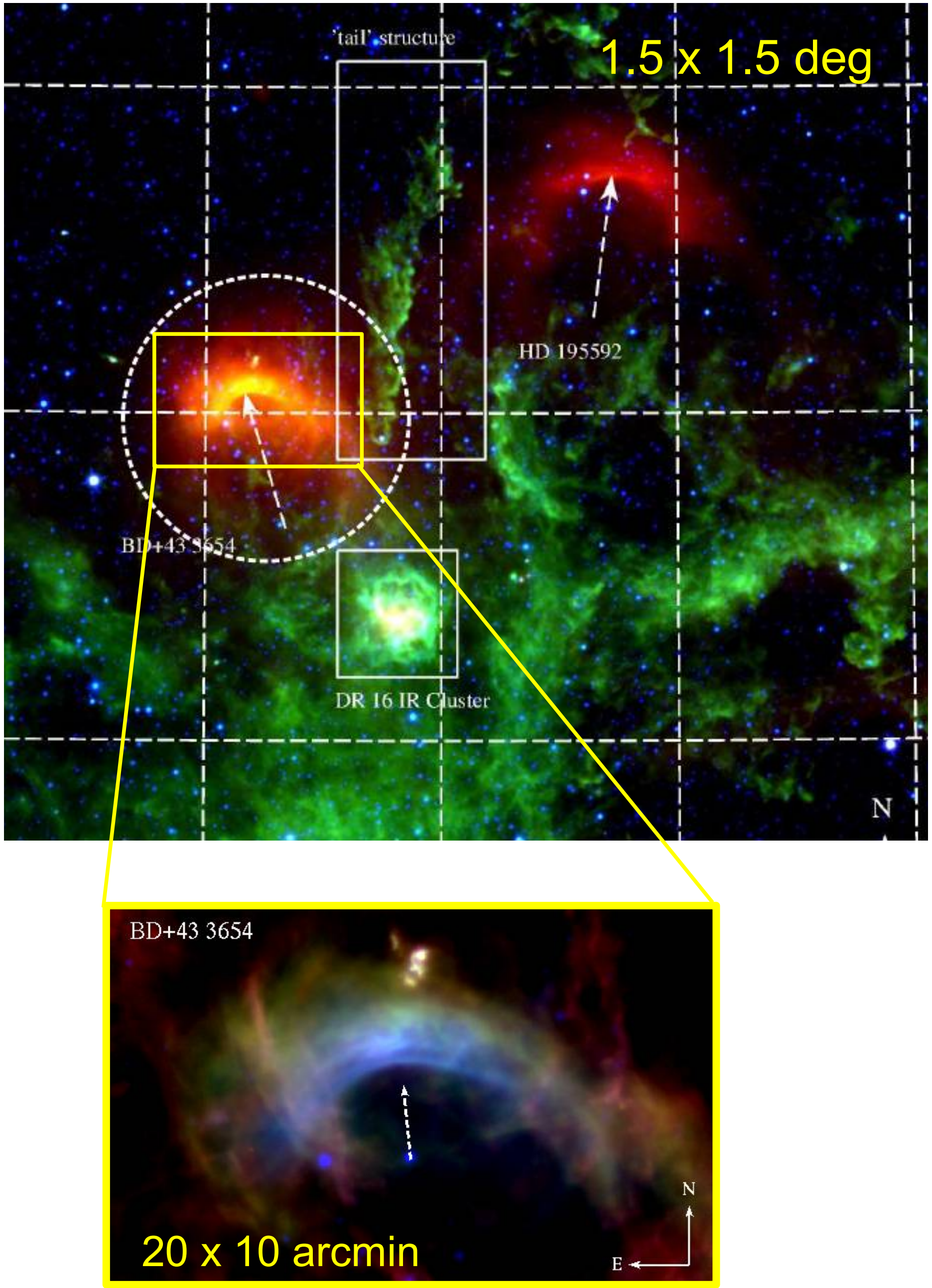


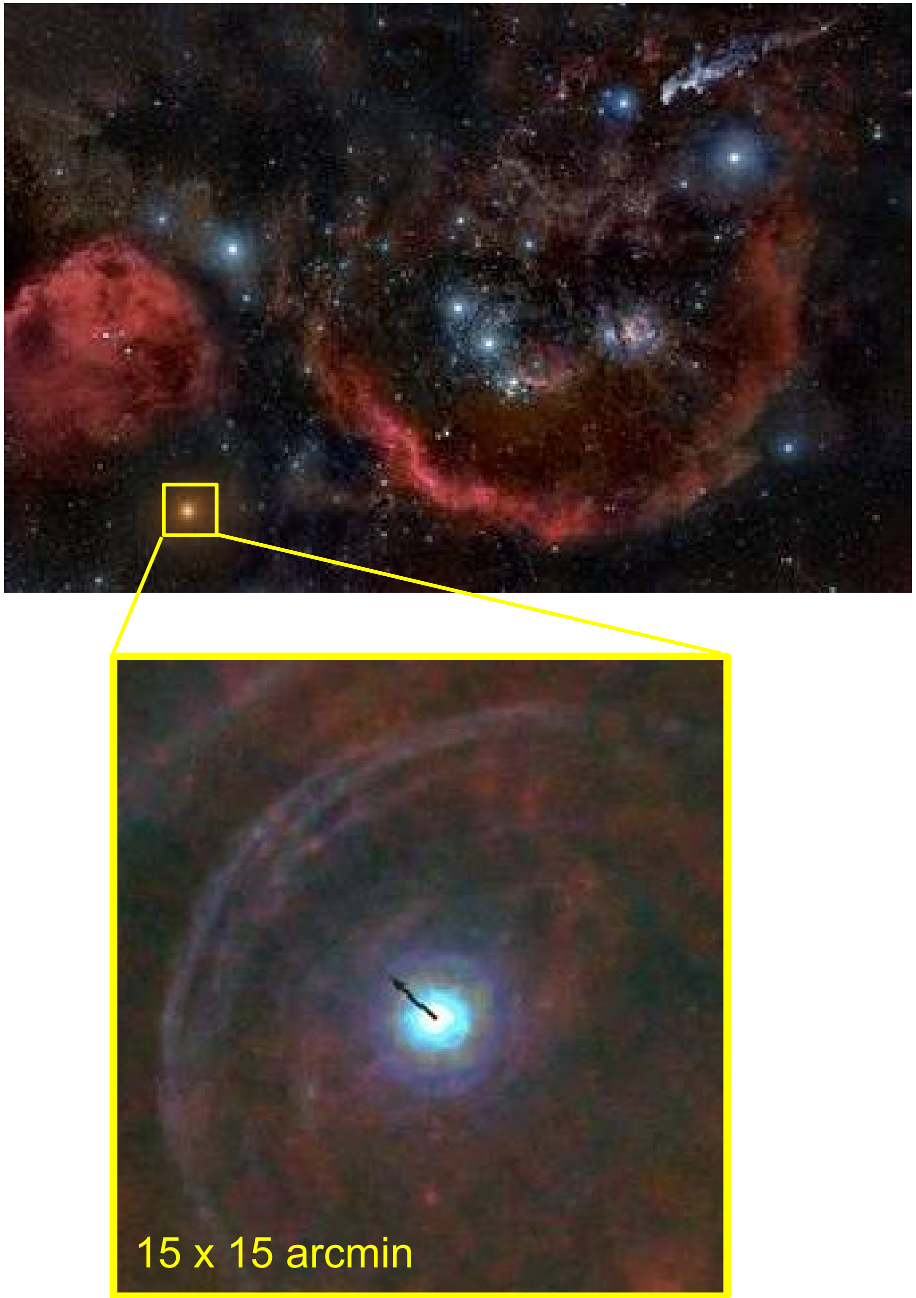
Runaway O supergiant



Red super giant

Context is important!

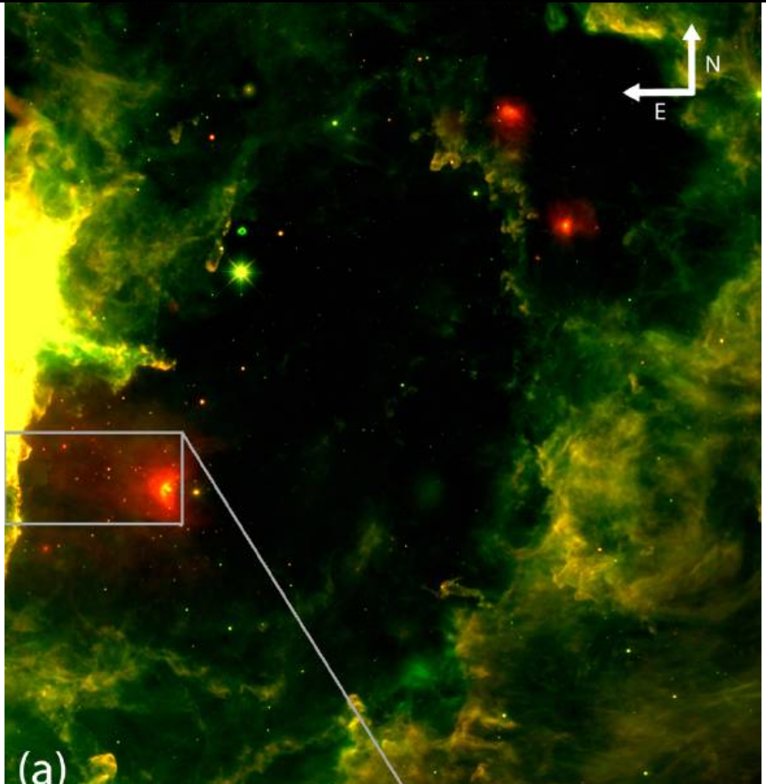


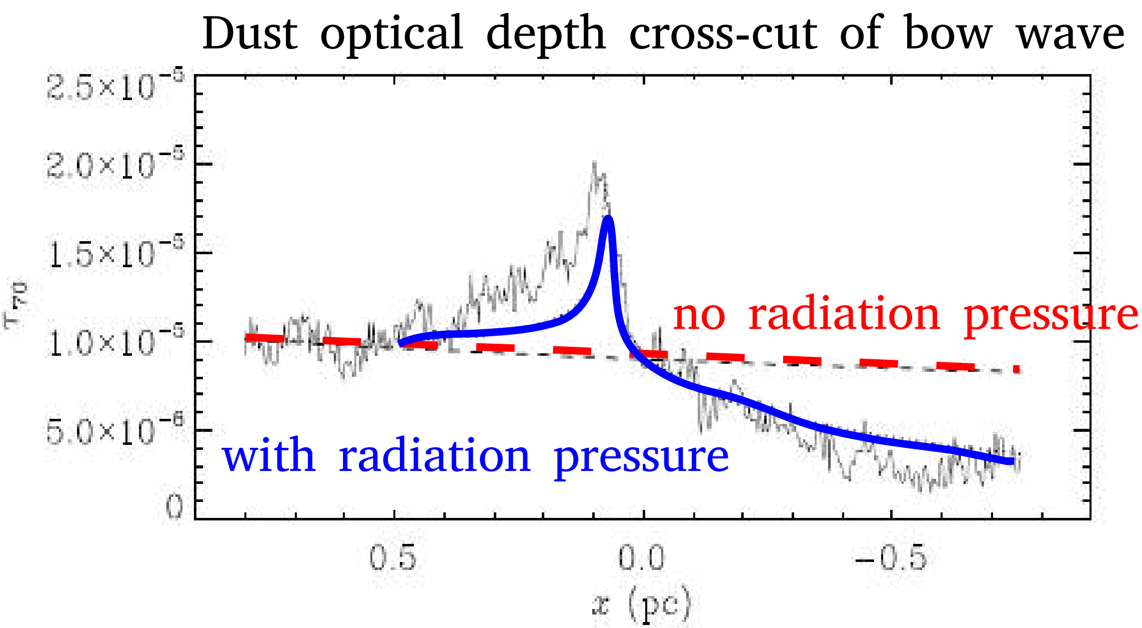


A dust wave in IC434 HII region

Orion Image Credit: ESA/Herschel/PACS, SPIRE & Herschel Gould Belt Survey Key Programme

Composite image credit: N.L.J. Cox (KU Leuven)

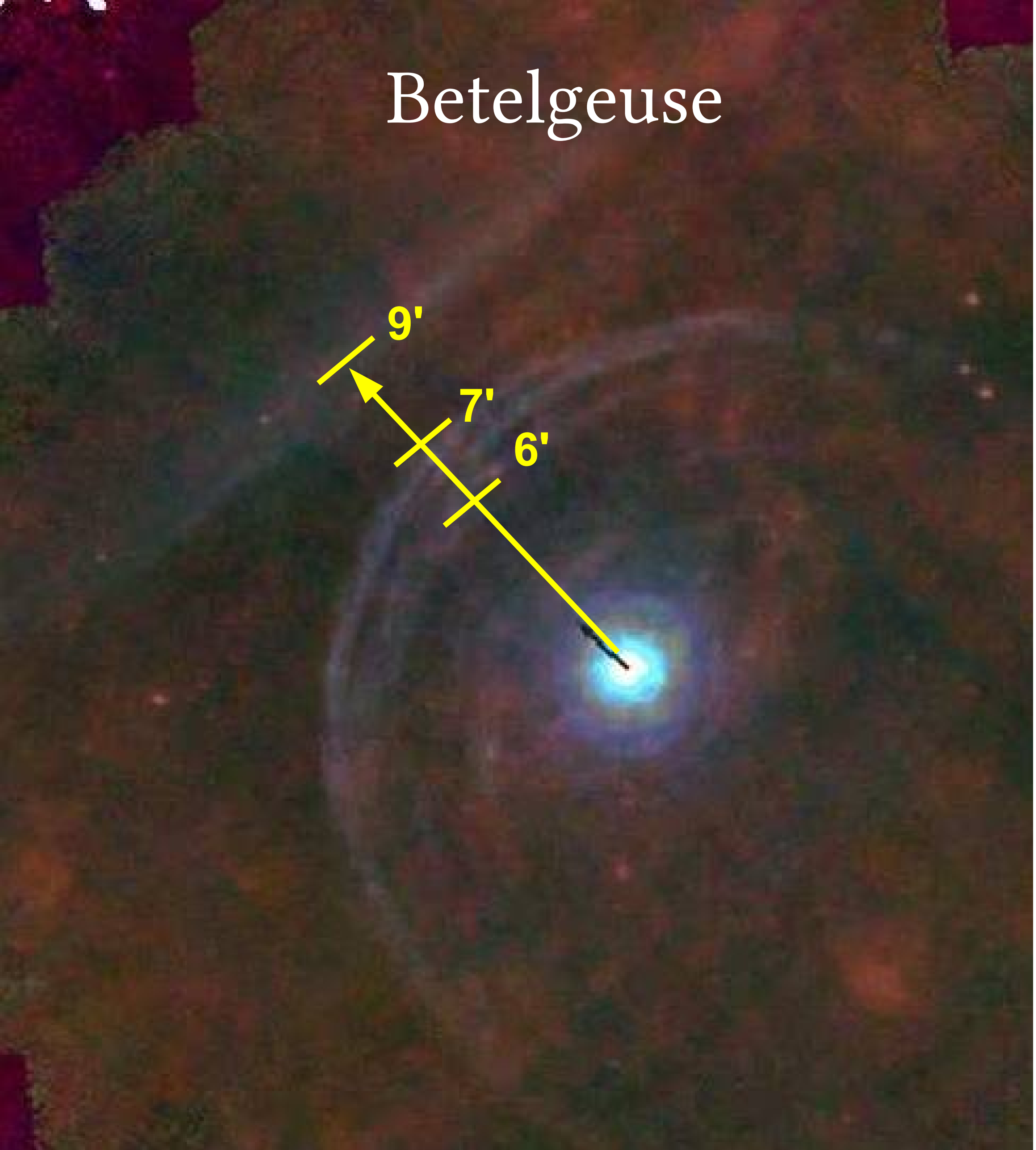




Dust optical depth cross-cut of bow wave

(Ochsendorf+2014)

Betelgeuse



$v_*/v_w > 1$
→ unstable bow shock

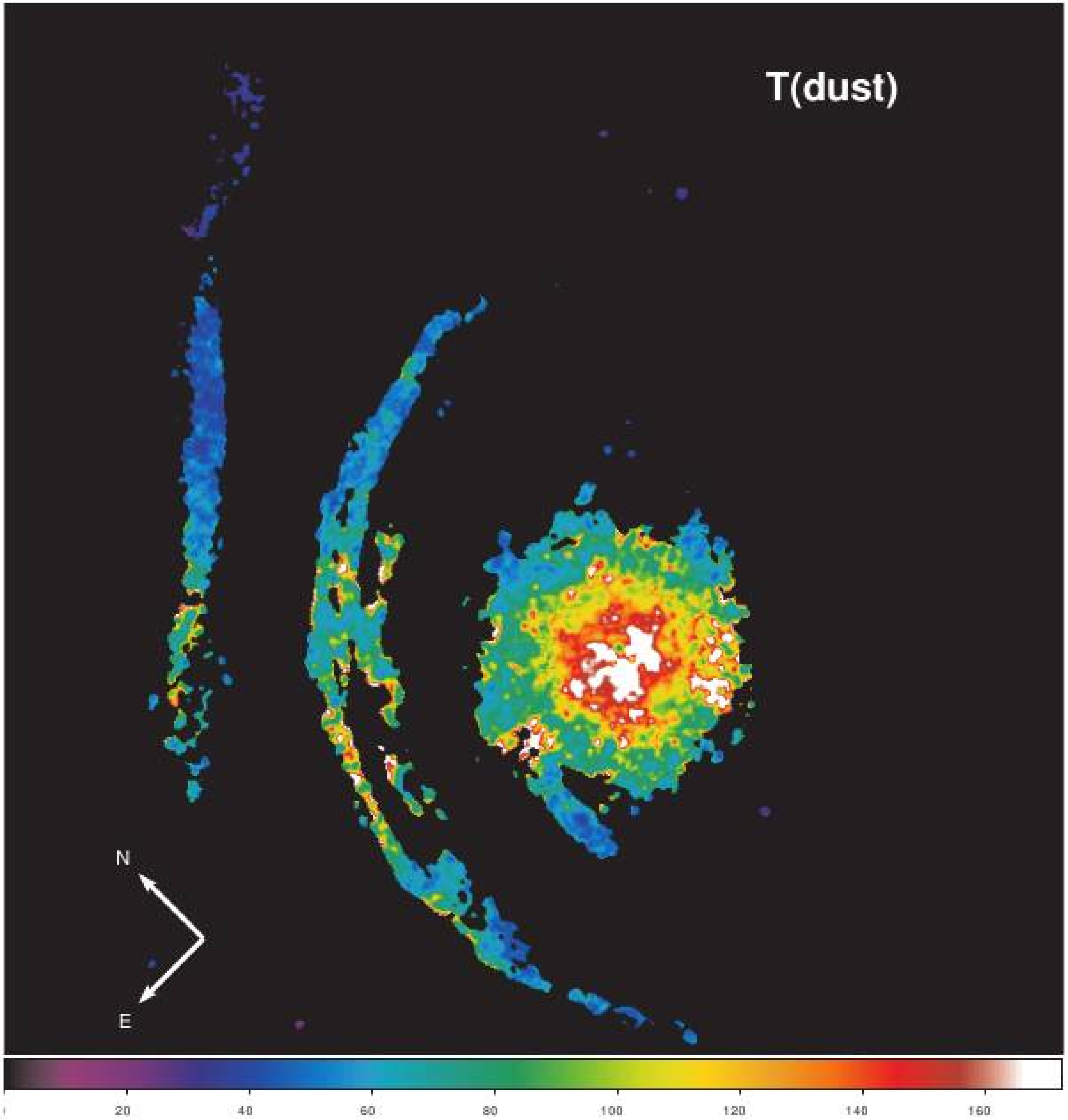
RT instabilities may fragment bow shock in direction of motion.

Magnetic field may suppress some modes but accentuate others, leading to 'RT stripes'
(Dgani & Soker 1998).

Arcs separated by 30” at distance of 330” yields
(Eq 4 in Dgani 1998).
Alven speed of pre-shock ISM of ~4 km/s.

For $n_{ISM} = 4\ cm^{-3} \rightarrow B = 3\ \mu G$.

Betelgeuse – dust temperature



Decin+2012

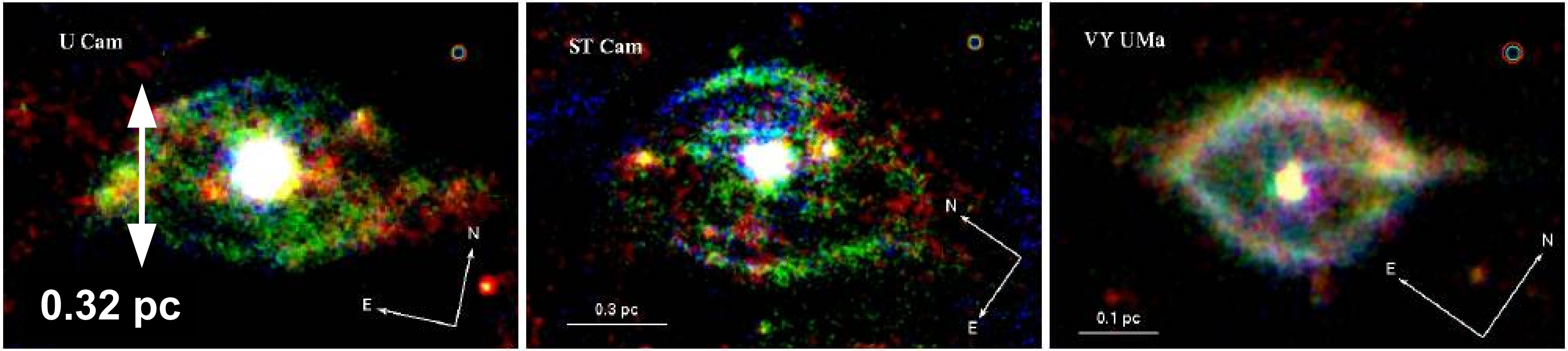
Smooth continuous outflow:

Silicate heated by the stellar radiation has temperature ~45 –60K at distance of 280–530″ from the central star.

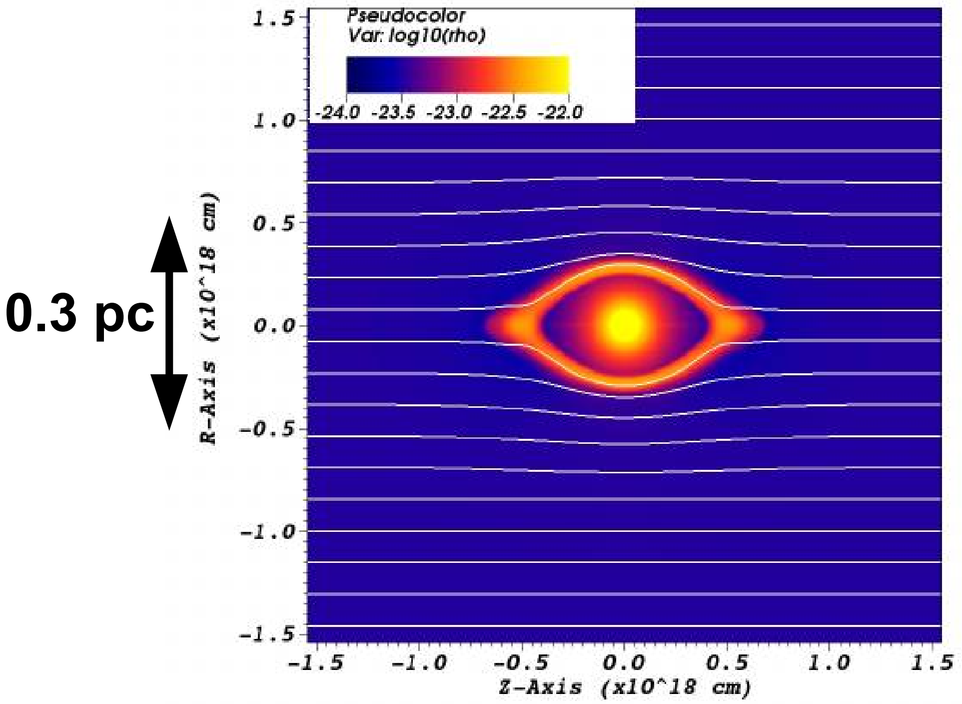
Arcs:
T_{dust} ~ 80-90 K, β~1
M_{d+g} ~ 10^{-3} M_{sun}

Bar:
T_{dust} ~ 60-70 K, β~1
M_{d+g} ~ 10^{-3} M_{sun}

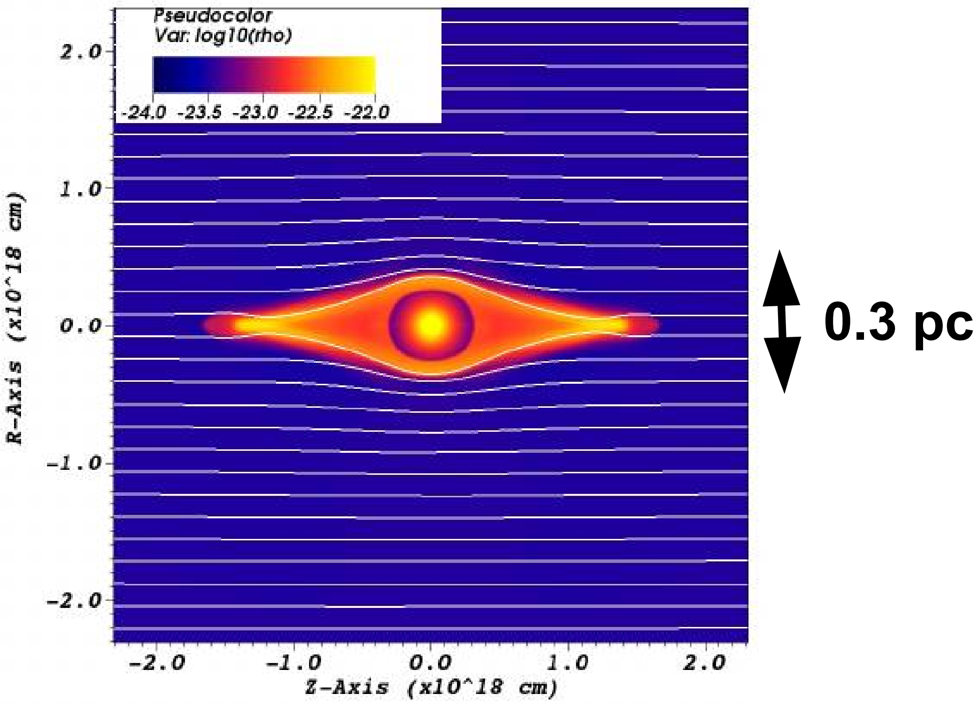
Eyes in the Sky



Van Marle, Cox & Decin (2014)



start eye-shape at 20.000 years



jets appear after 60.000 years

Mdot = 10^{-7} M_{sun}/yr, v_{wind} = 10 km/s, B = 10 μG, n_{ISM} = 2 cm^{-3}

Main conclusions & outlook

- Herschel demonstrated the ubiquitous occurrence of dusty asterospheres around AGB stars (including resolving KH and RT instabilities!)

  → Independent tools to estimate stellar and/or interstellar parameters.
  → Shape affected by binarity and magnetic field.
  → Shells related to circumstellar chemistry (thermal pulse history).
  → ISM dust mass ~1 to 25 % for evolved stars and ~100% for O/B stars.

- AGB/RSG asterospheres primarily detected via their dust (exception: CW Leo). Hot massive star asterospheres more energetic and (sometimes) visible in Hα.

- Multi-wavelength imaging AND spectroscopy of larger sample of asterospheres to understand bow shock physics, interplay gas and dust, and origin of varying morphologies.

- Work in progress: Introducing dust grains (size distribution,formation/destruction), chemistry, and magnetic fields in the hydrodynamical simulations.

- Asterospheres around later type (post-AGB/proto-PNe) or solar-type stars?