ASTROSPHERES

Bow shocks and bow waves around O/B stars, AGB stars, and red supergiants: The dusty view with *Herschel*

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Outline

- "Astrospheres": The stellar wind – ISM interaction region

- Runaway O/B stars

    Herschel Highlights: Vela X-1 & BD+43 3654

- AGB stars and red supergiants (RSG)

    Herschel Highlights: CW Leo, Betelgeuse, R Leo & W Aql

- Conclusions and outlook

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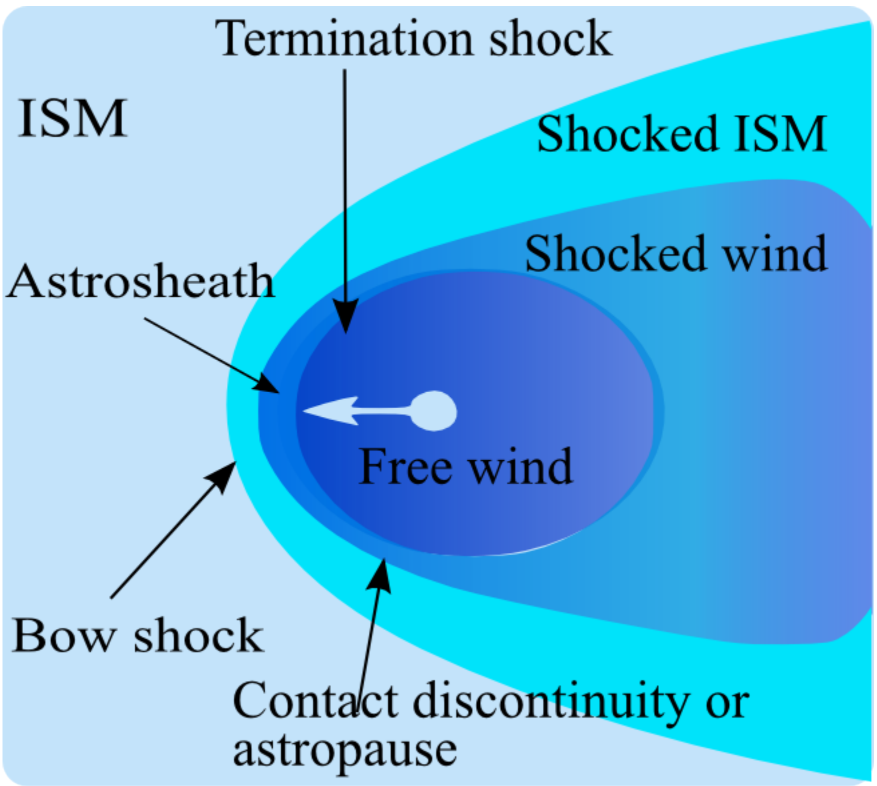
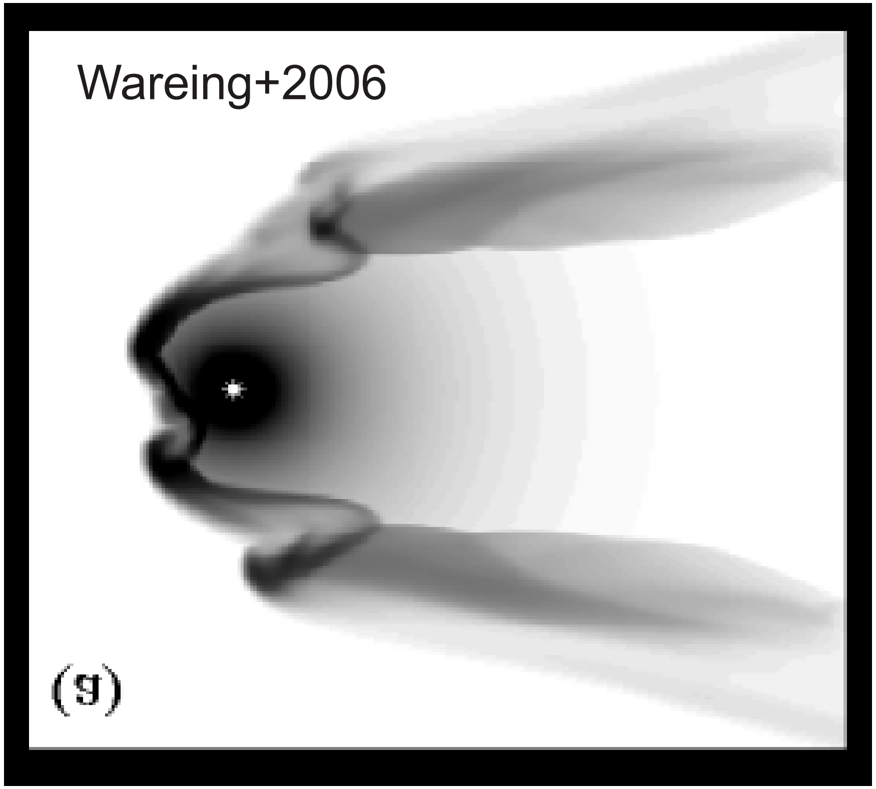
Astrospheres – bow shocks / bow waves

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



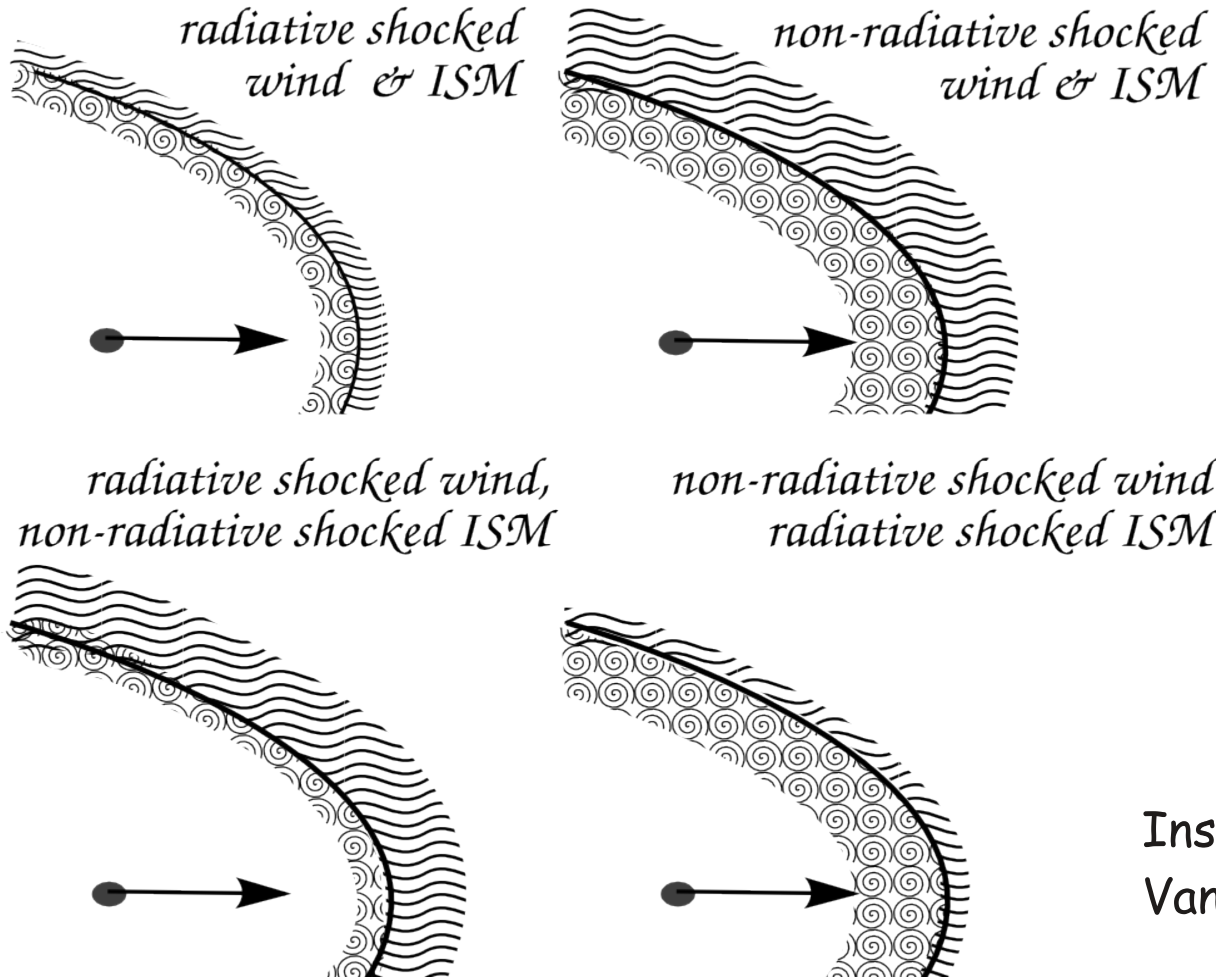


bow shock: where v_{ISM} goes from supersonic to subsonic values

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

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

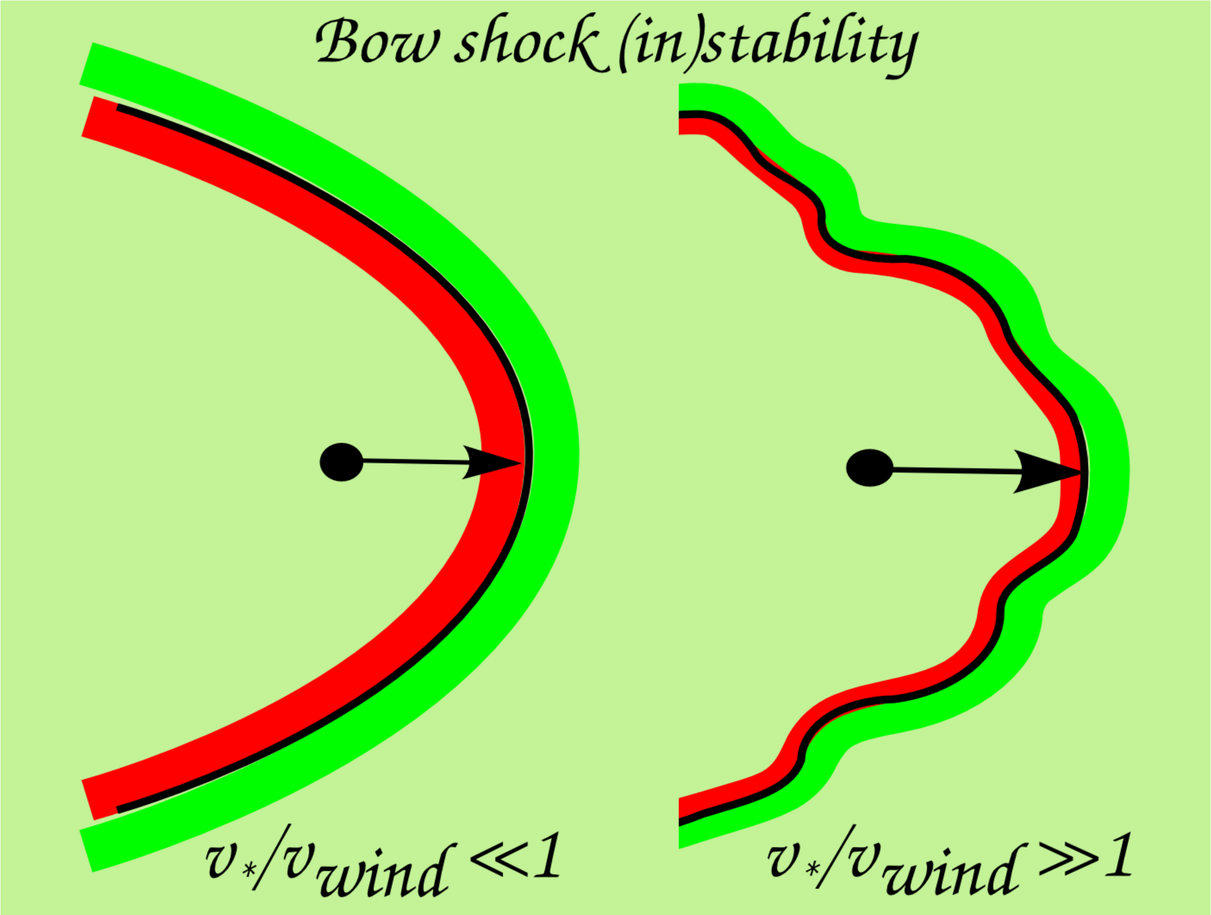
Radiative versus adiabatic shocks



Inspired by
Van Buren 1993

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 ~ R_0 / M^2 (Blondin & Koerwer 1998).

Astrospheric instabilities



(M=∞, isothermal)
Bow shocks with
$v_*/v_w \ll 1 \rightarrow$ stable
$v_*/v_w \gg 1 \rightarrow$ unstable

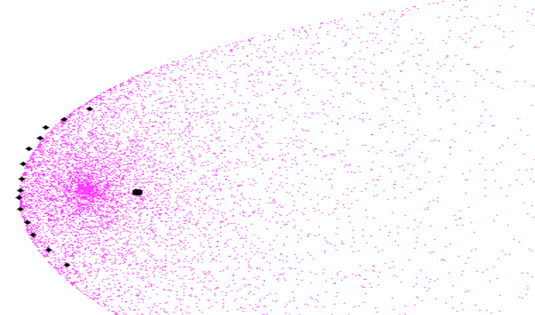
Slow winds more unstable!

Global size scale of astrospheres

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: Astrospheres are dynamical structures responding to changes in stellar parameters.

Importance of 'understanding' astrospheres?

- Astrospheres can be used as proxies of the local ambient medium (i.e. density, temperature, magnetic field).
- Astrospheres can be used to identify runaways.
- Astrospheres can provide insight on physics of dust grain-gas coupling.
- Astrospheres are potential sites for dust processing (i.e. transition from circumstellar to interstellar dust grains).
- Astrospheres are potential source of turbulence (via growth of Kelvin-Helmholtz / Rayleigh-Taylor instabilities).
- Astrospheres offer protection to planetary systems (i.e. similar to the heliosphere protecting the solar system).

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Runaway OB stars (1)

These are stars with (Blaauw 1961)

(i) **peculiar space motion ~30 – 200 km/s**, and

(ii) **origin in OB assocation**, considered runaway as they wander away.

Origin of runaway OB stars?

*** *Binary supernova scenario*** (Blaauw 1961, Zwicky 1957)
- Ejected when member of binary sheds large fraction of its mass (eg type II SN).

*** *Cluster ejection scenario*** (Poveda+1967; Gies & Bolton 1986)
- Runaways ejected during close encounters of binary systems.

However, OB stars are (on average) distant and often proper motion poorly determined. Only radial velocity can be determined reasonably accurately....

Signs of runaway OB stars → bow shocks / bow waves

Runaway OB stars (2)

REQUIRED:

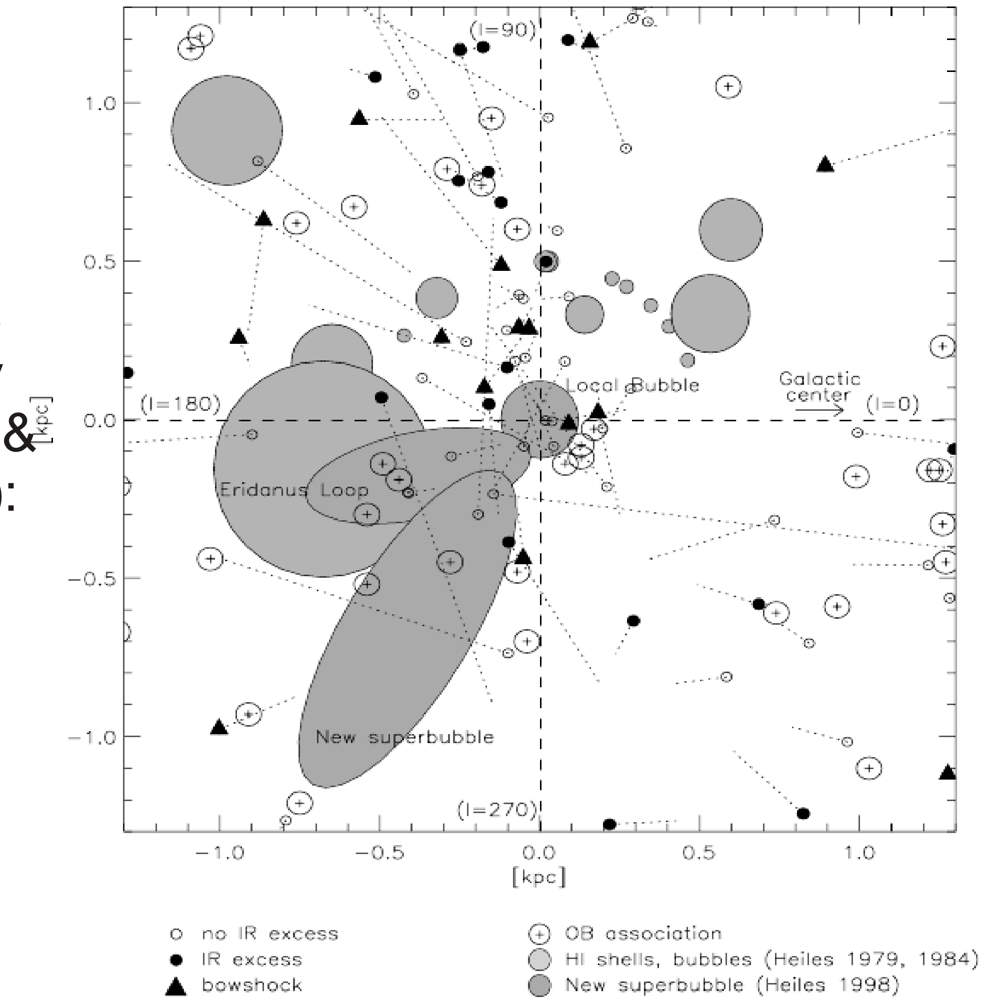
<u>supersonic</u> moving star through <u>diffuse ISM</u> (not too tenuous) with a (not too weak) stellar <u>wind</u>.

Wind bow shocks are ubiquitous → 10-20% in diffuse ISM, strong winds, high luminosity heating dust (Gull & Sofia 1979; Van Buren & McCray 1988). BUT (Huthoff & Kaper 2002):

→ ISM conditions crucial!

Filling factor of ISM with $v_{sound} \leq 10$ km/s is ~20% + 75% of O stars $v_* > 10$ km/s →
15% of O stars should have bow shocks!

Sound speed ~100 km/s in hot (10^6 K) tenuous medium → **inside super-bubbles runaway stars have subsonic velocities!**

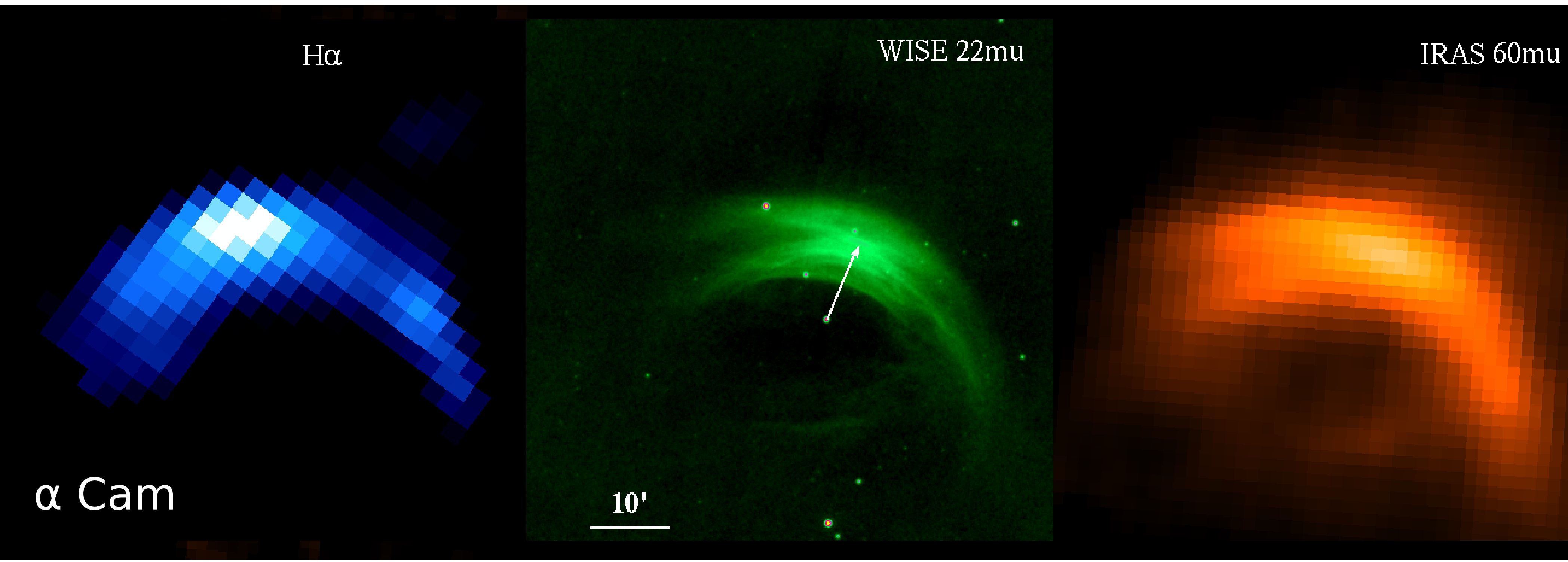


Huthoff & Kaper 2002

Gas and dust in astrospheres

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

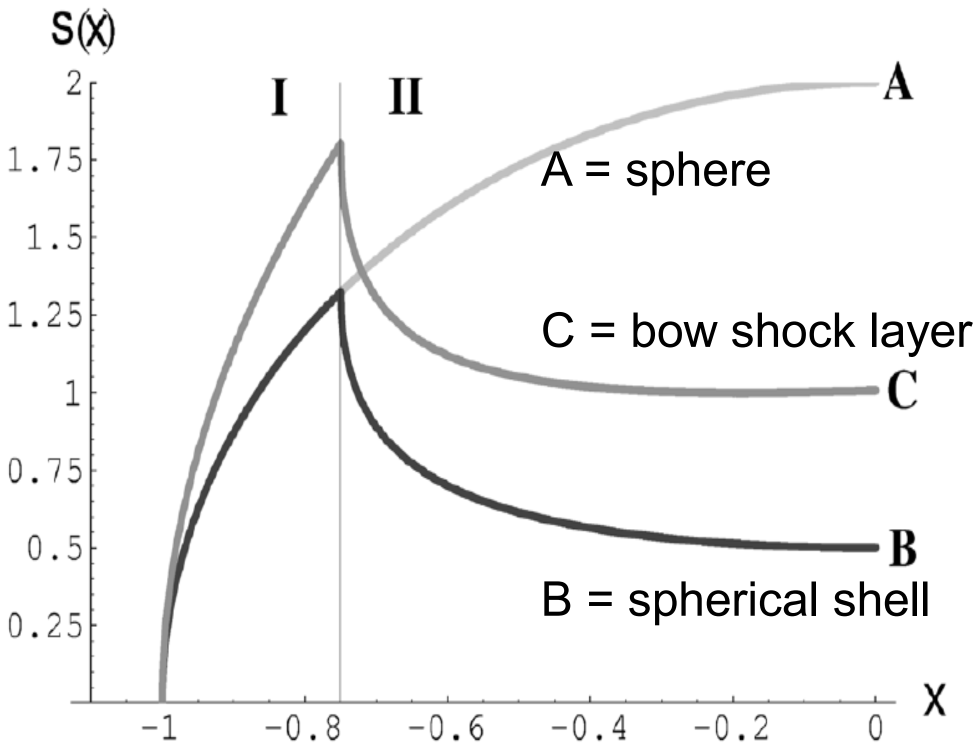


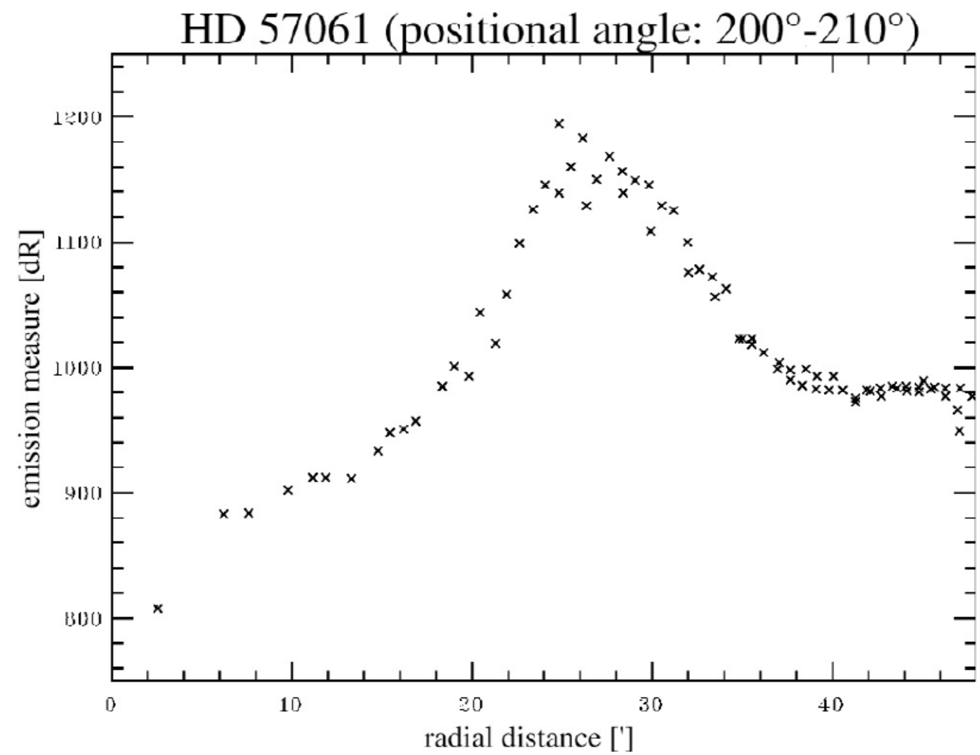
Includes stellar wind bow shocks (moving young star), wind blown bubbles/rings (stationary WR), and bow waves (radiation pressure driven). 31 bow shocks (+27 w/ bubble/resolved excess) for sample of 188 runaway stars (WR, RSG, Giants) detected with IRAS.

Hα emission from bow shocks

SHASSA/VTSS surveys (Brown & Bomans 2005)

Use thickness of bow shock layer to estimate density (~1 cm^{-3}) and maximum temperature (~10^4 K) of the ISM (warm ionised medium).





O9II at 1.9 kpc – $v_* = 56$ km/s, $R_0 \sim 25'$ / 7.6 pc, $n_{ISM}(R_0) \sim 0.1\ cm^{-3}$ / n_{ISM}(Hα width) ~ 1.5 cm^{-3}.

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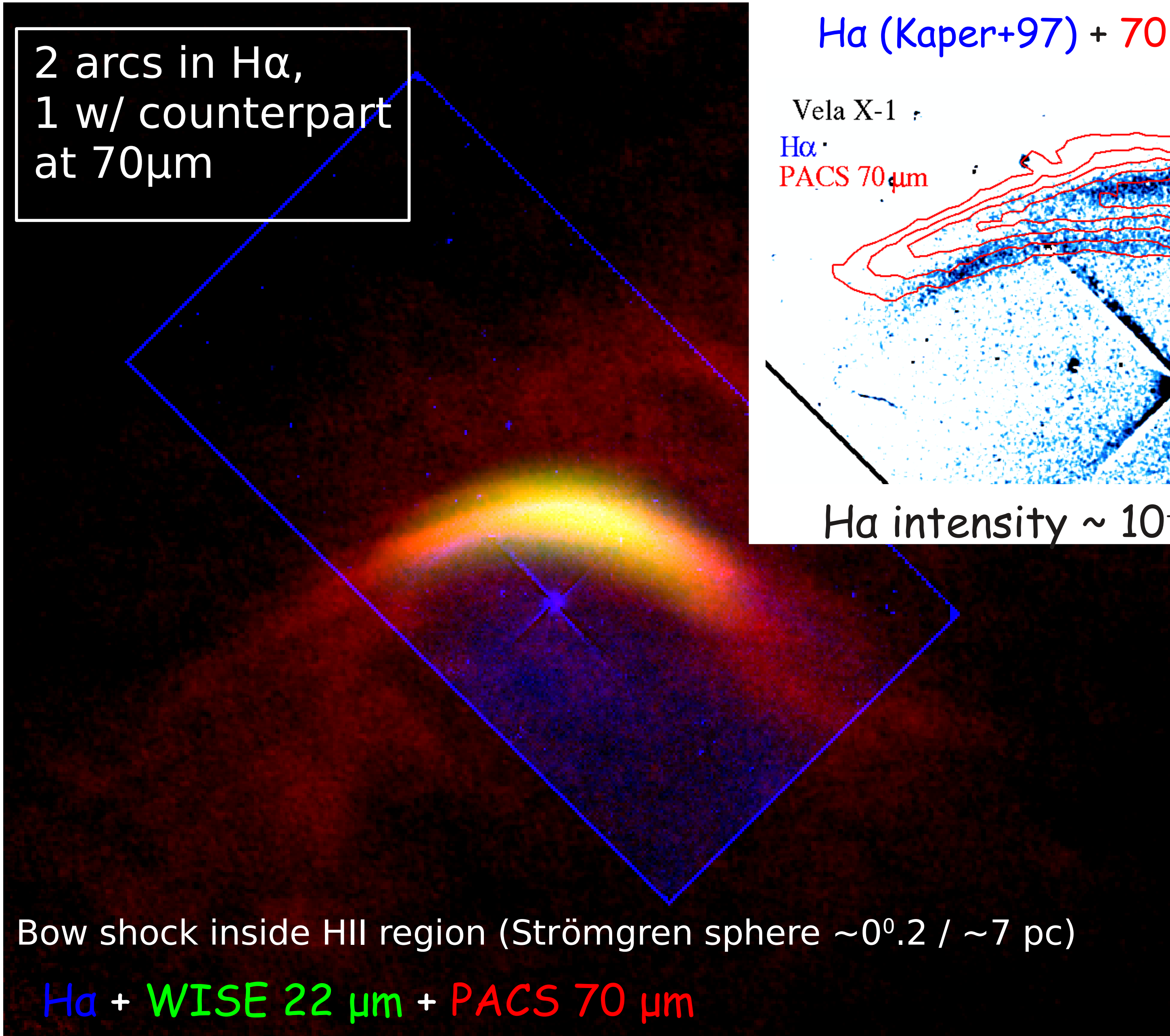
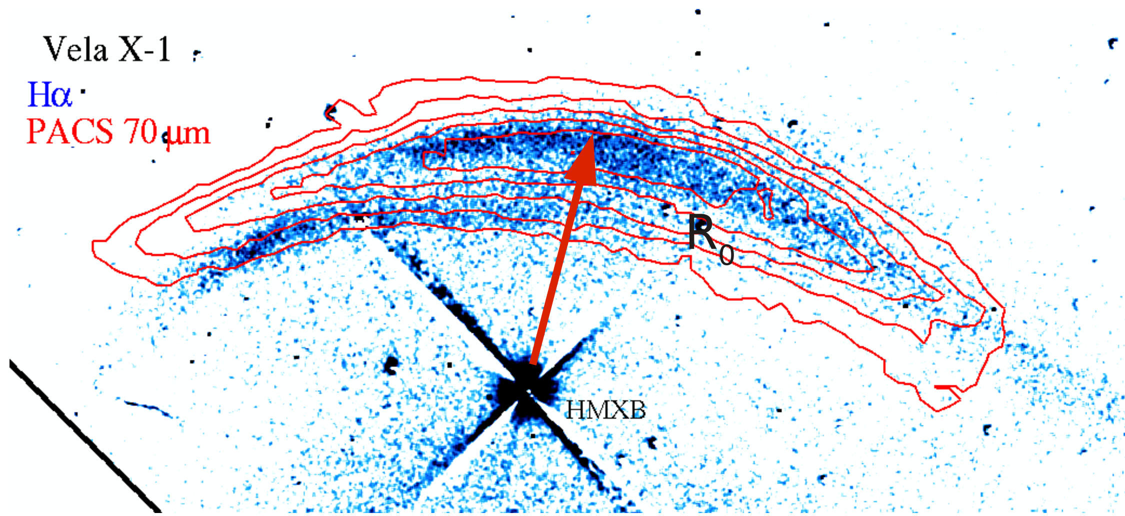
Vela X-1



Hα (Kaper+97) + 70 μm (Cox+in prep.)



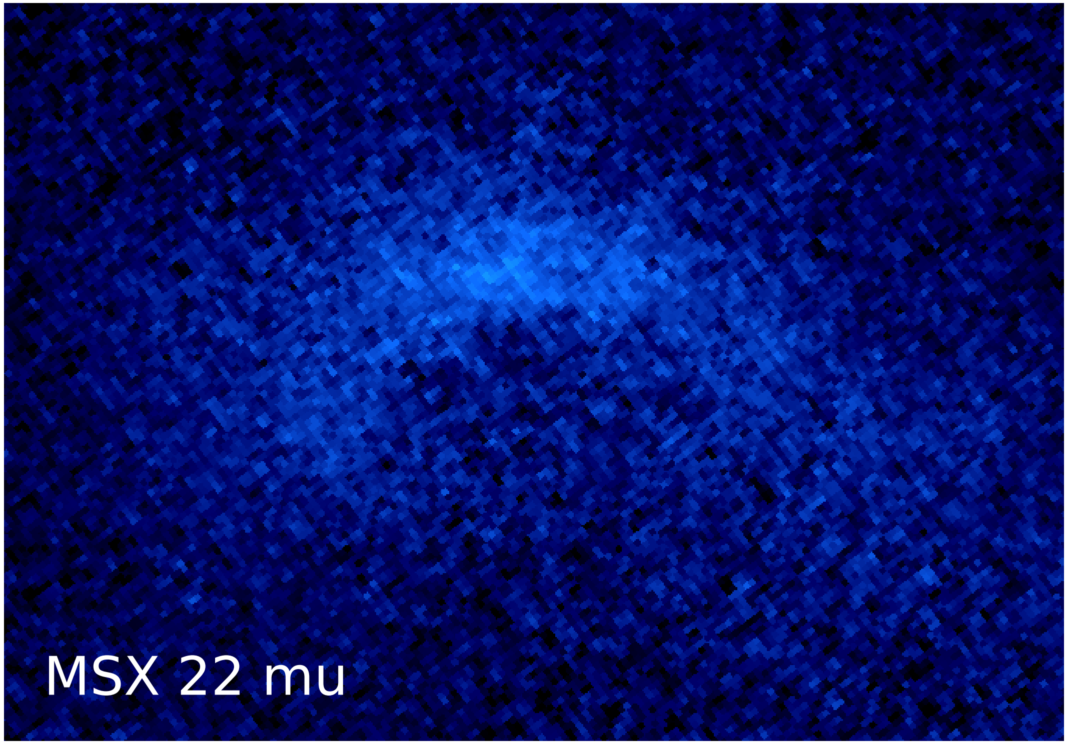
Hα intensity ~ 10^{-15} erg s^{-1} cm^{-2} $arcsec^{-2}$

R_0 = 0'.9 (0.48 pc)

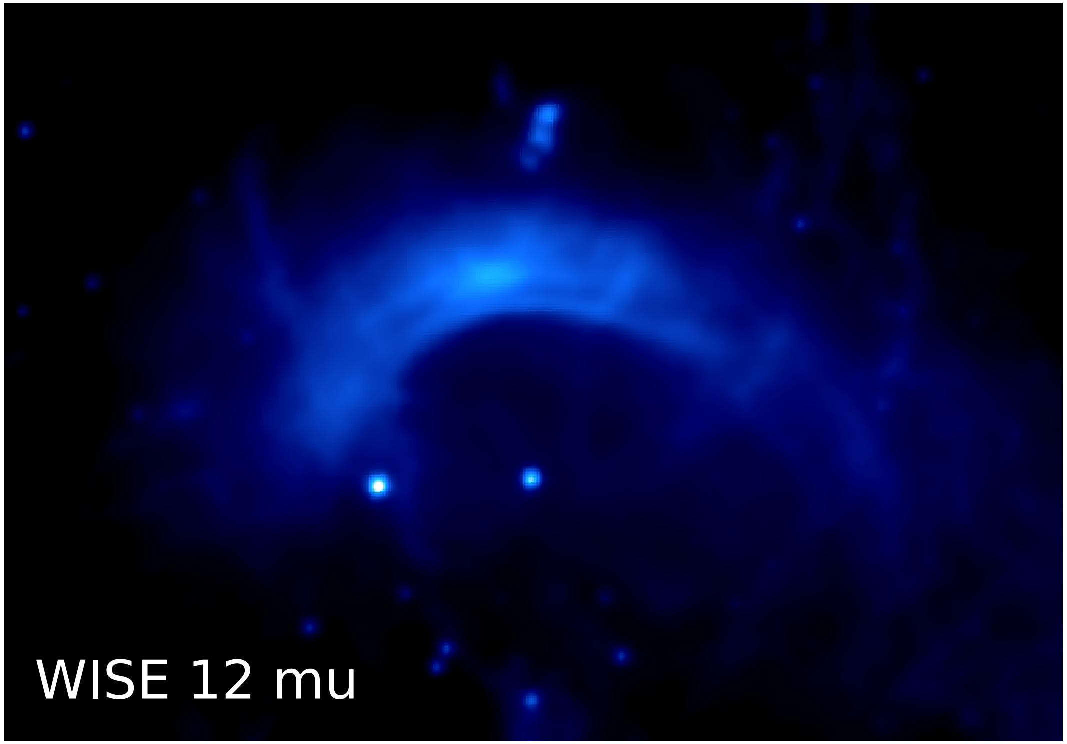
→ n_H = 1 cm^{-3}

Radiative outer shock,
Adiabatic inner shock?

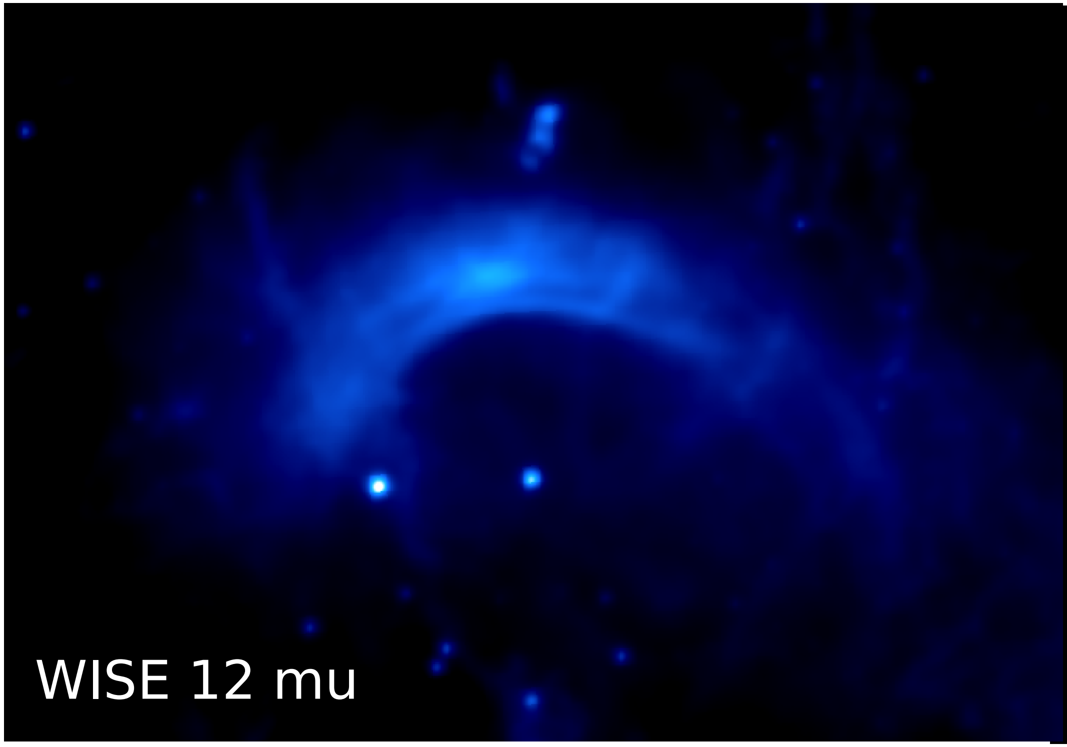
BD+43 3654: Previous w/ MSX & WISE

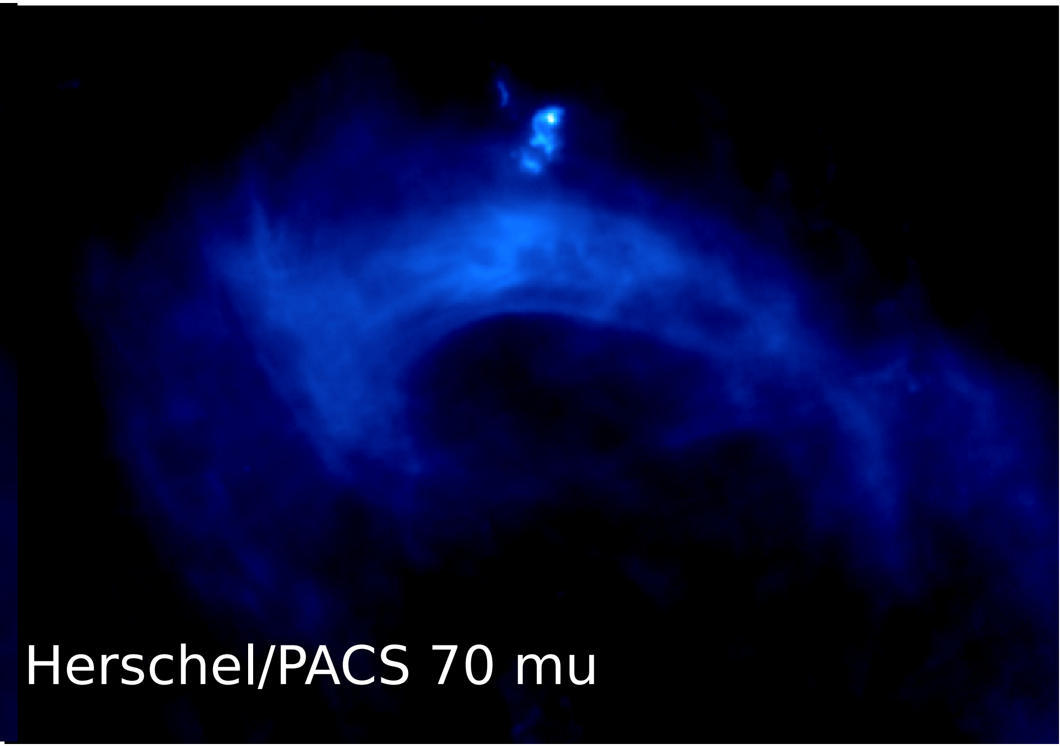


BD+43 3654: Previous w/ MSX & WISE

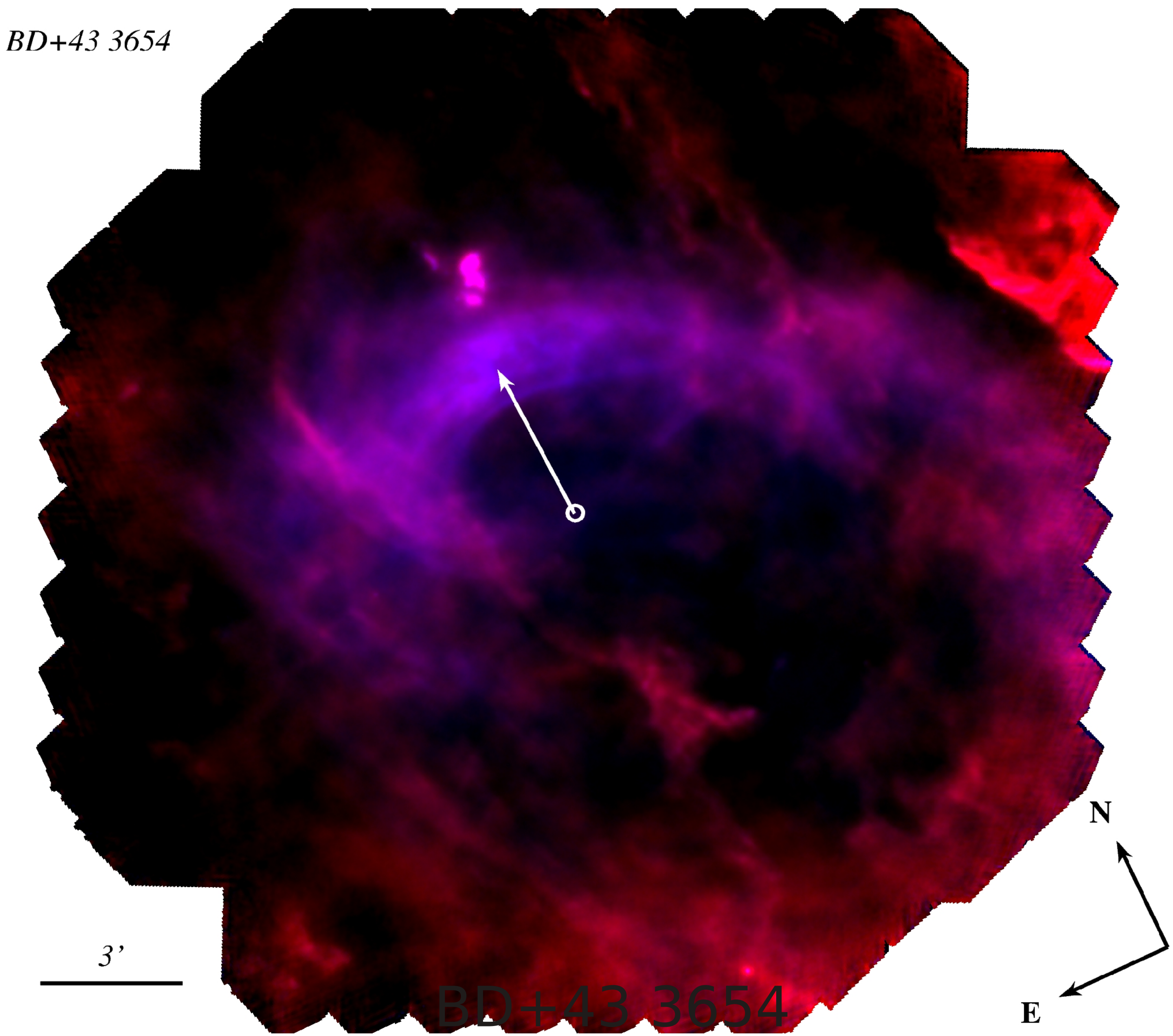


BD+43 3654: Previous w/ MSX & WISE





BD+43 3654: Herschel PACS (70 & 160 μm)



O4If

(Comeron+2002)

$L_* = 8.5\ 10^5\ L_{sun}$

(Martins+2005)

D = 1.45 kpc

$v_* = 77 \pm 10$ km/s

(Comeron & Pasqualli 2007)

$R_0 \sim 1.5$ pc (apsis)

Termination shock ~1.2 pc

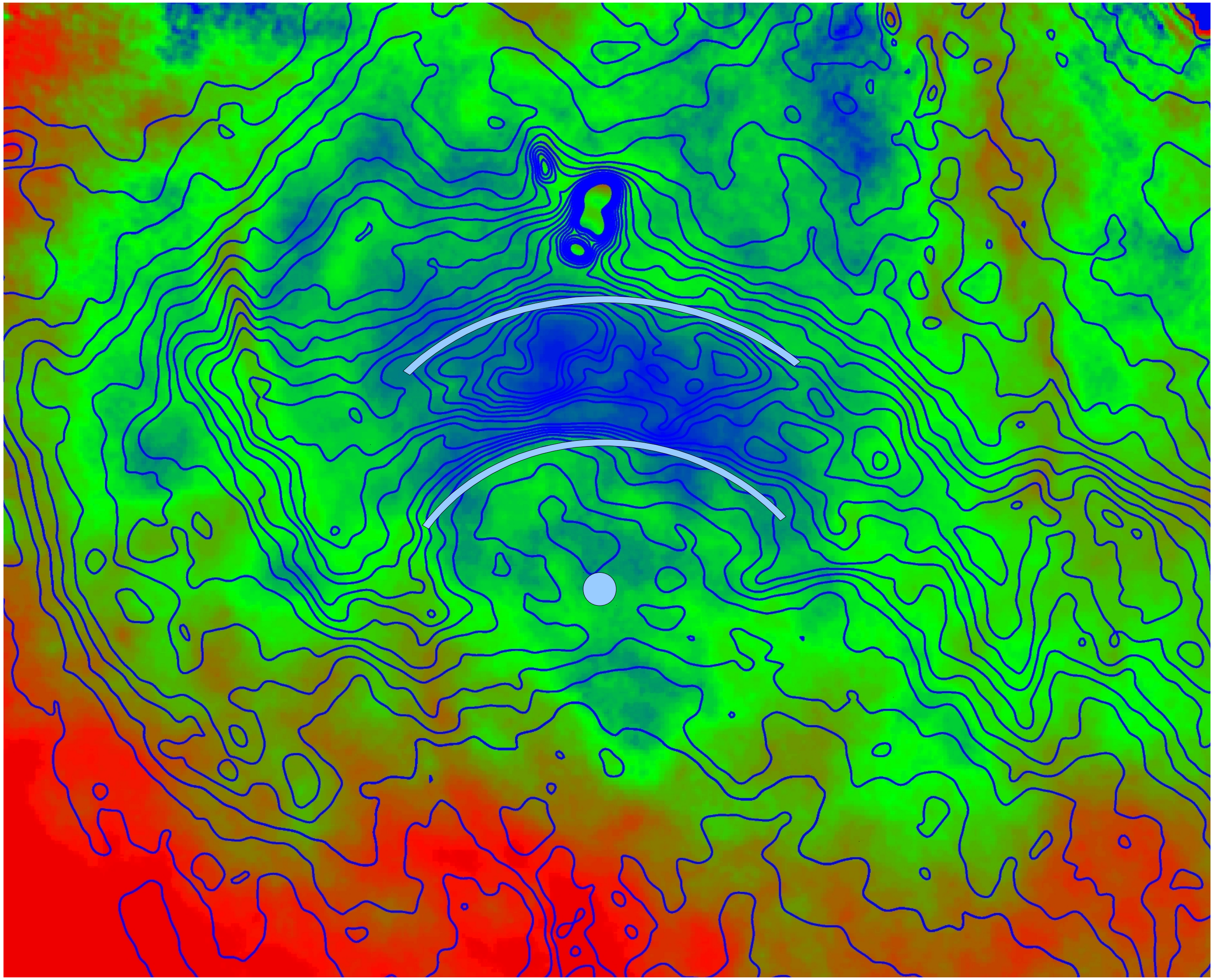
Bow shock ~2.1 pc

Assuming

$v_w \sim 2000$ km/s & $n_{ISM} = 6\ cm^{-3}$

gives $M \sim 10^{-4}\ M_{sun}/yr$

BD+43 3654



Dust colour temperature distribution map (PACS 70&160 μm)

$T_{max(obs)} \sim 45$ K

$T_{min(obs)} \sim 30$ K

Contrary to simulations, observation suggests inefficient cooling?

No Hα.

Thickness bow shock:

$\delta \sim 0.55\ M^{-2}\ R_0$

Measured: 0.9 pc

→ $M \sim 1$

→ $c_{sound} \sim v_*$

→ $T_{ISM} \sim 10^3 - 10^4$ K

$T_{dust} \sim 5.7\ (1/a)^{0.06}\ (L_*/r^2)^{1/6} \sim 50$ K [Tielens 2005]

(with grain size a = 0.1 μm)

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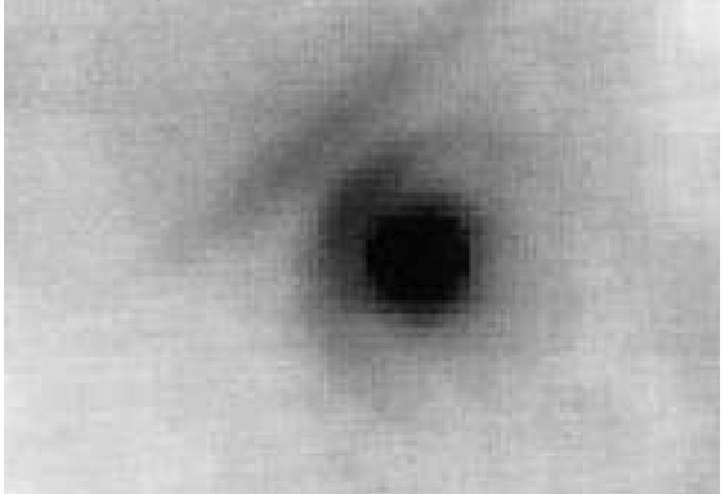
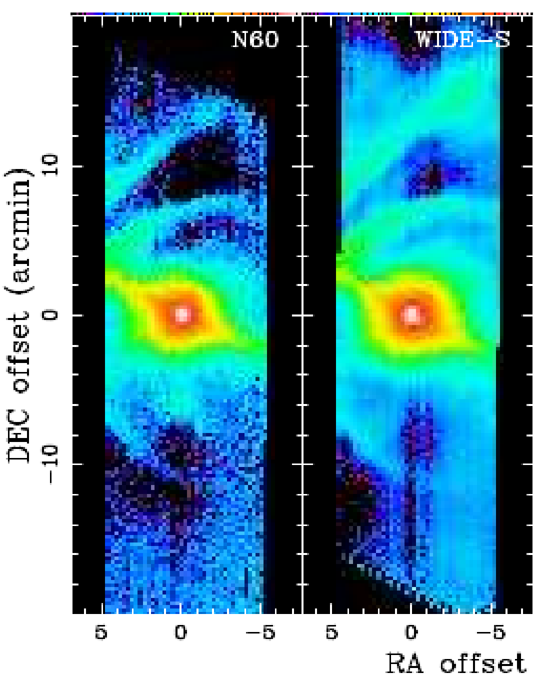
Astrospheres of cool, old stars (pre-*Herschel*)

Betelgeuse – IRAS 60mu

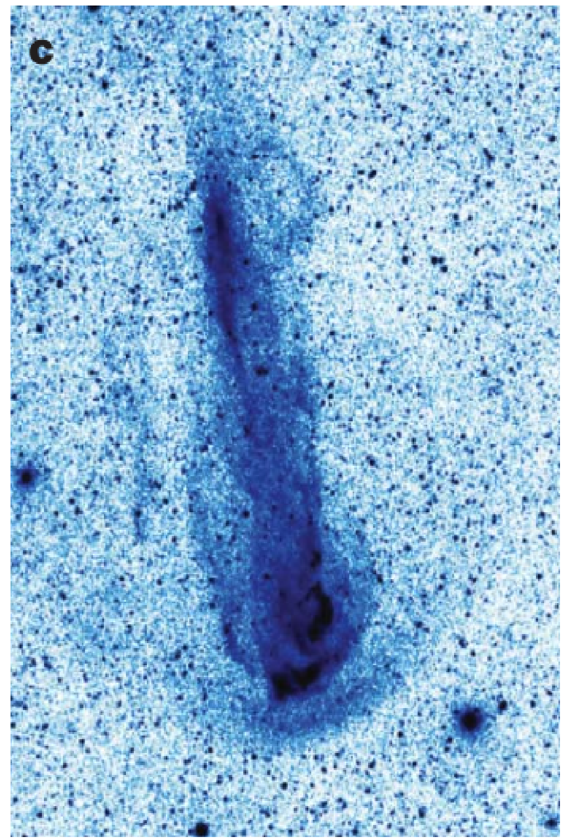


Noriega-Crespo et al. 1997



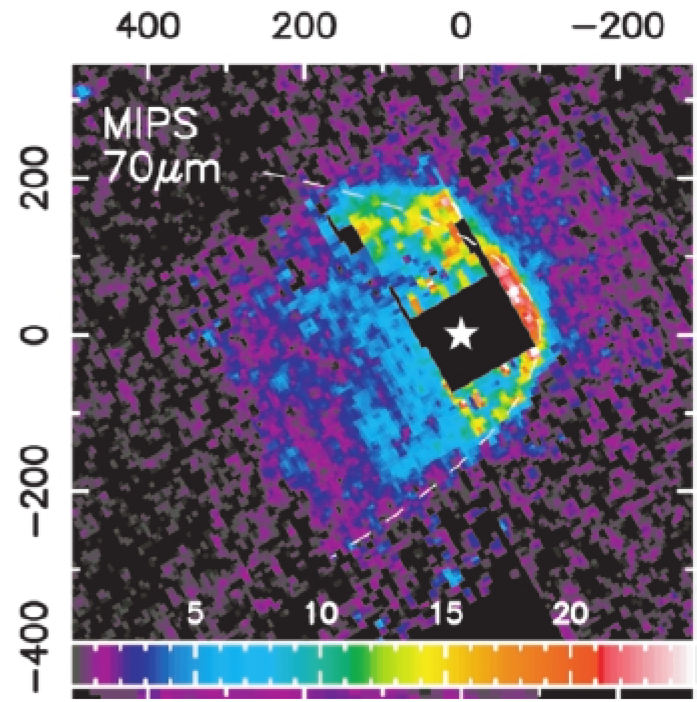
Ueta et al. 2008

MIRA – GALEX FUV



Martin et al. 2007

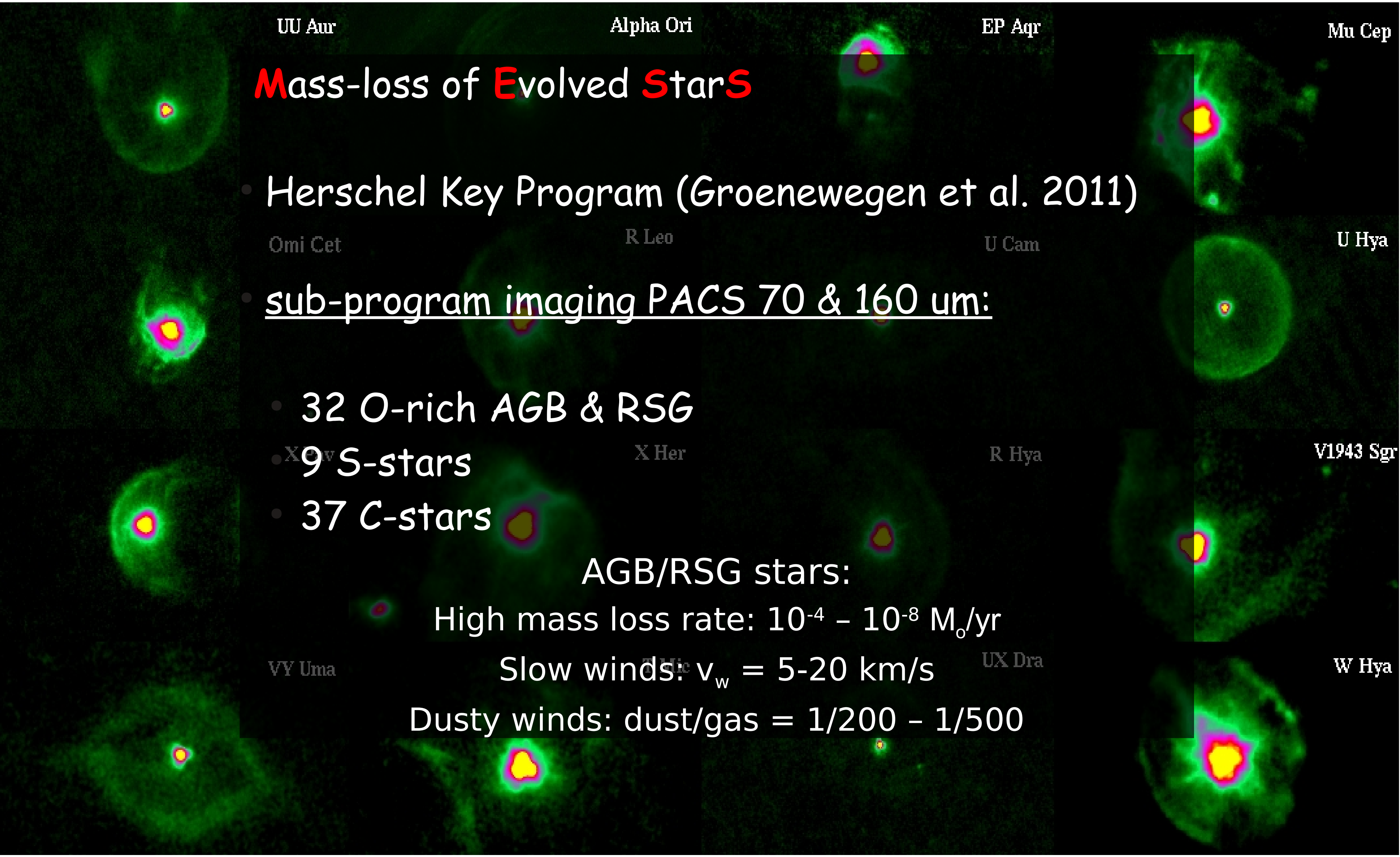
R Hya – MIPS 70mu



Ueta et al. 2006

+ some evidence for R Cas and Mira (Ueta+ 2009).

Herschel far-infrared survey of AGB/RSG



Mass-loss of **E**volved **S**tar**S**

- Herschel Key Program (Groenewegen et al. 2011)
- sub-program imaging PACS 70 & 160 um:
  - 32 O-rich AGB & RSG
  - 9 S-stars
  - 37 C-stars

AGB/RSG stars:

High mass loss rate: 10^{-4} – 10^{-8} M_o/yr

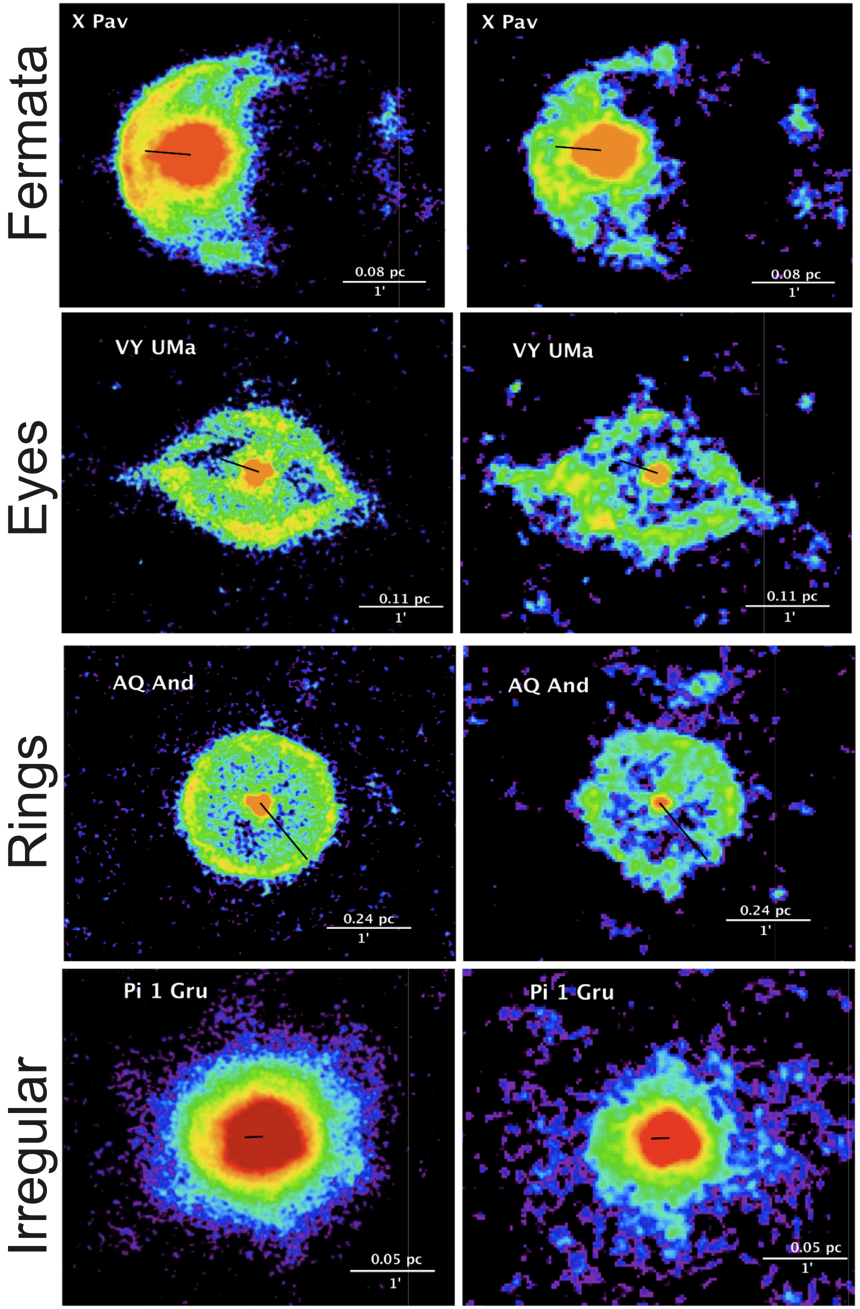
Slow winds: v_w = 5-20 km/s

Dusty winds: dust/gas = 1/200 – 1/500

Morphological - Statistics

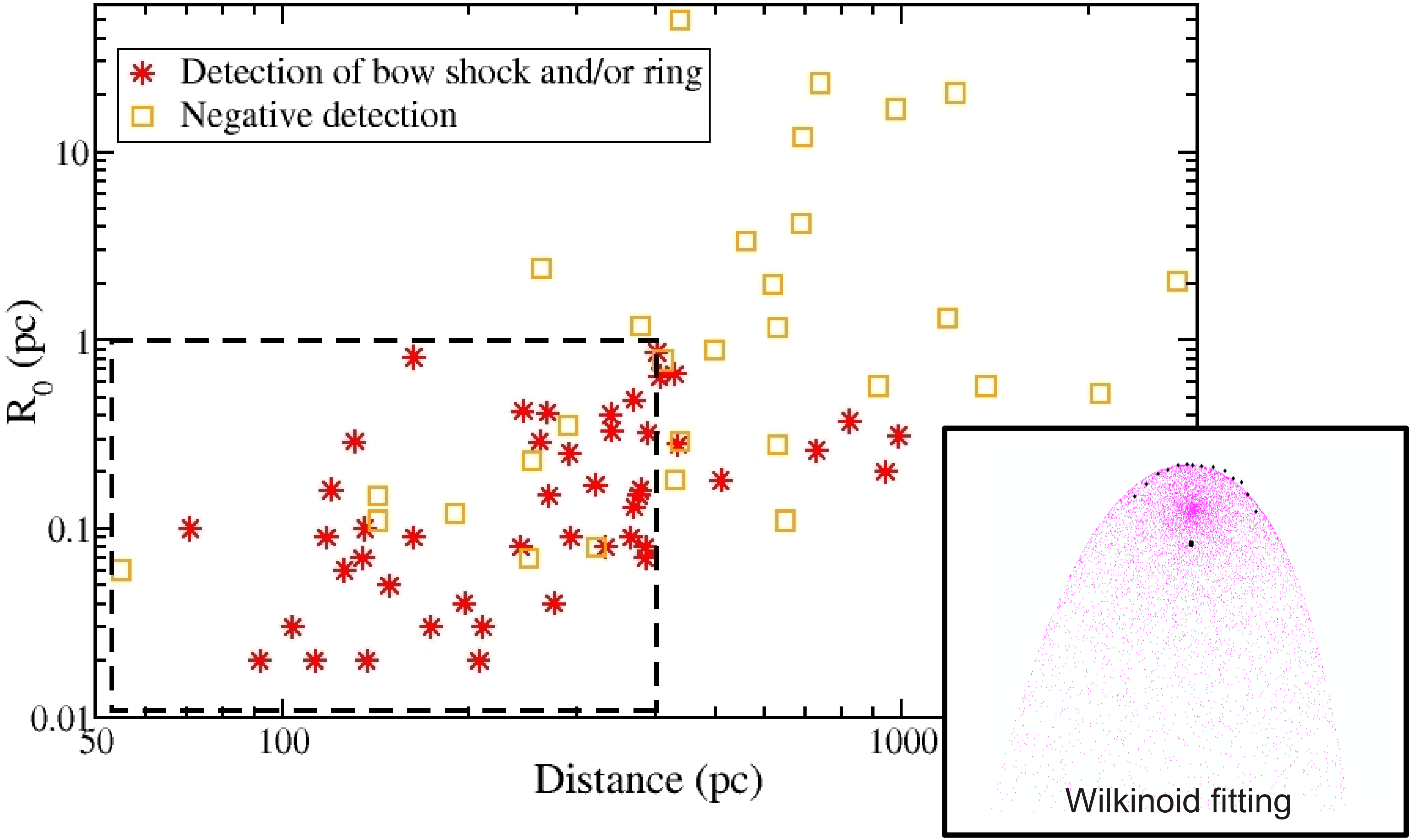
53 out of 81 objects show interaction!

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

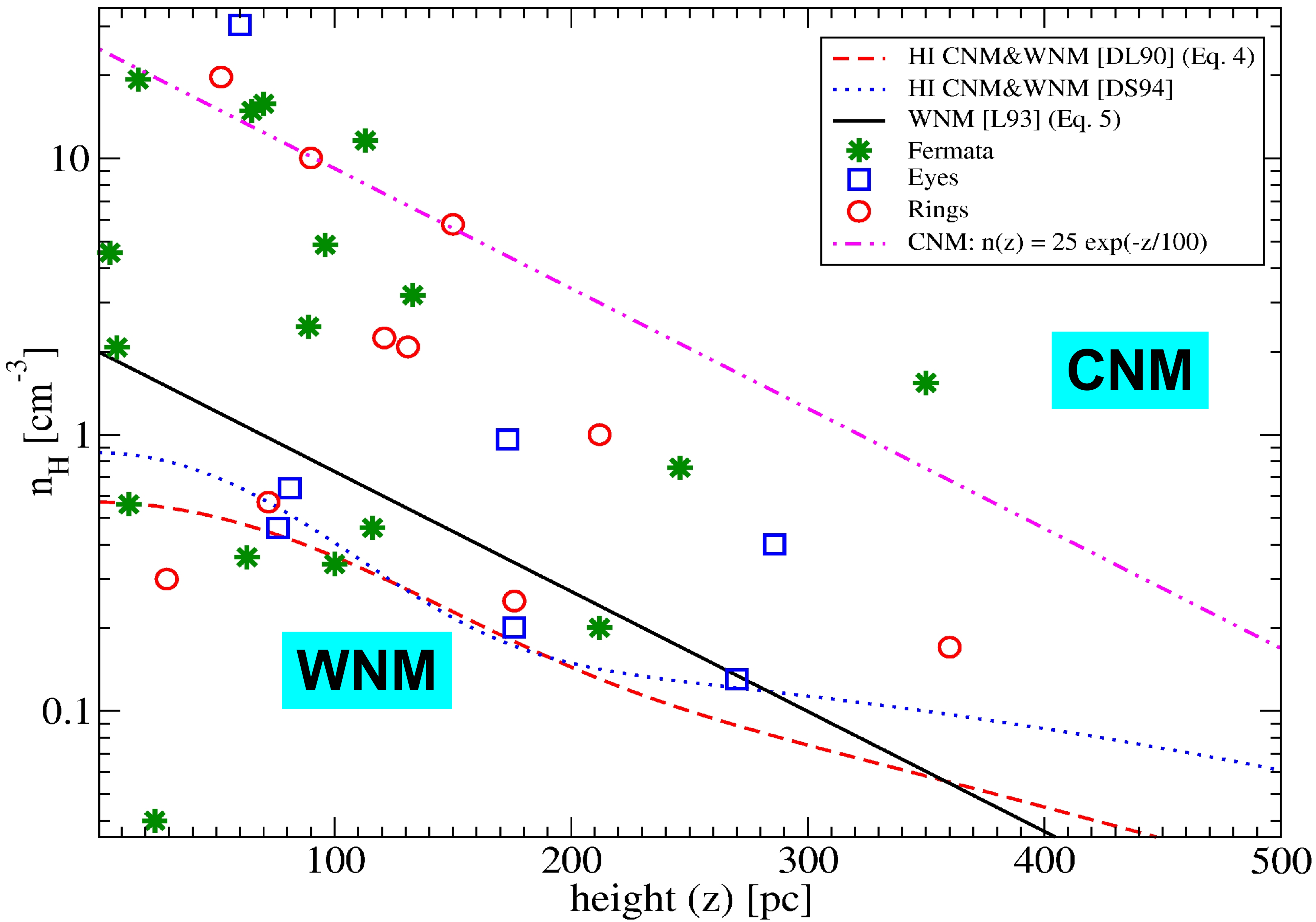


Astrospheres:

apex stand-off distance & detection bias

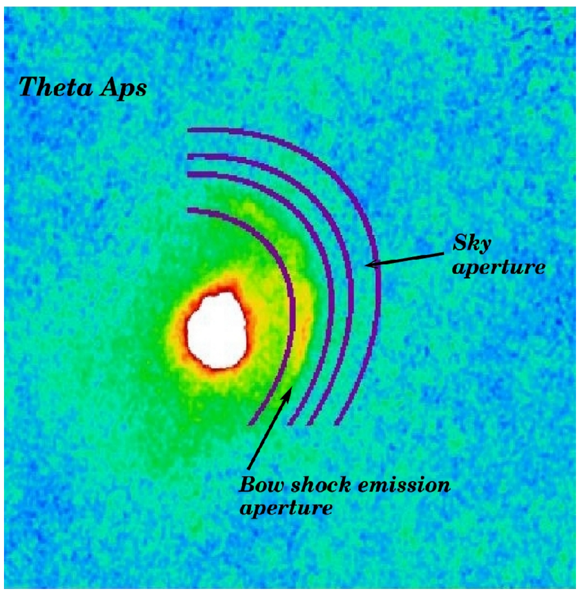


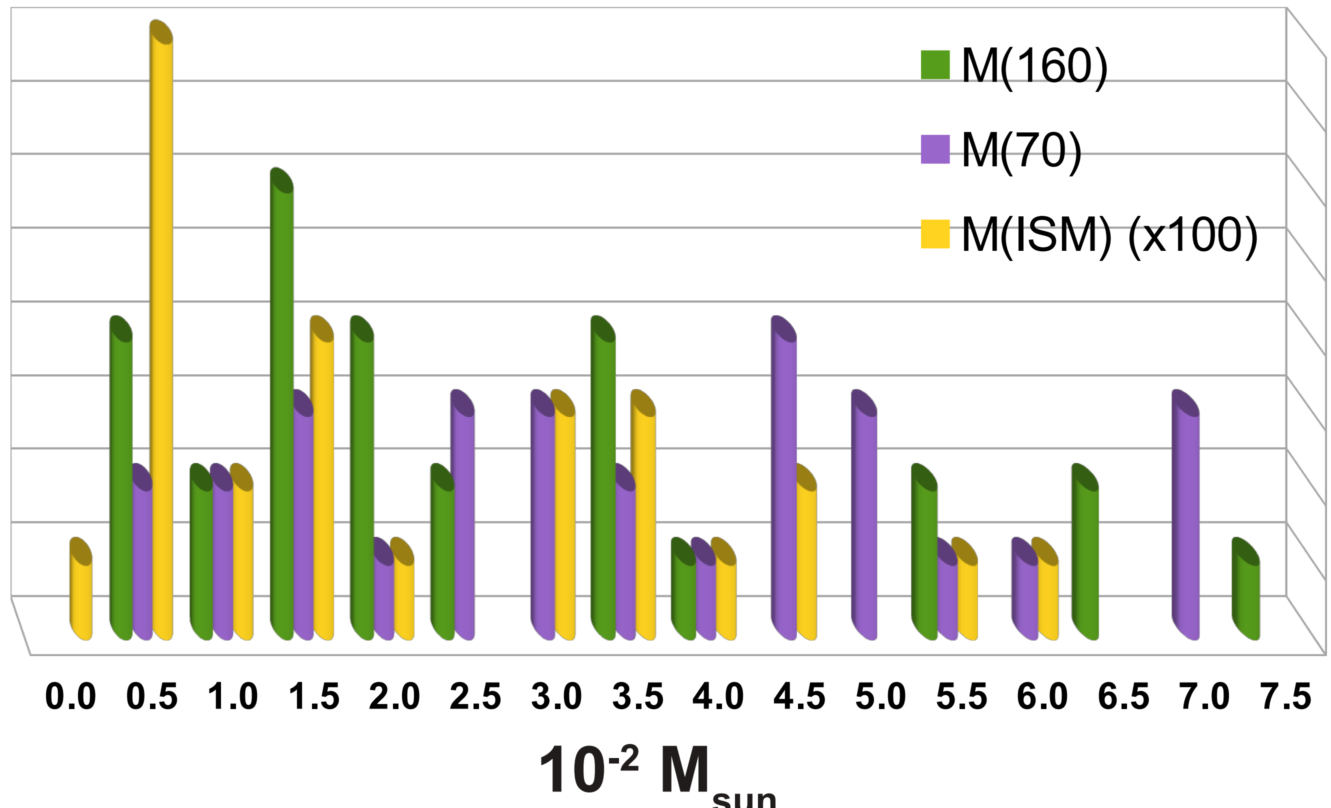
Astrospheres to probe the ISM density



Astrospheres: inferred dust & gas mass

Aperture photometry in ellipses/circles

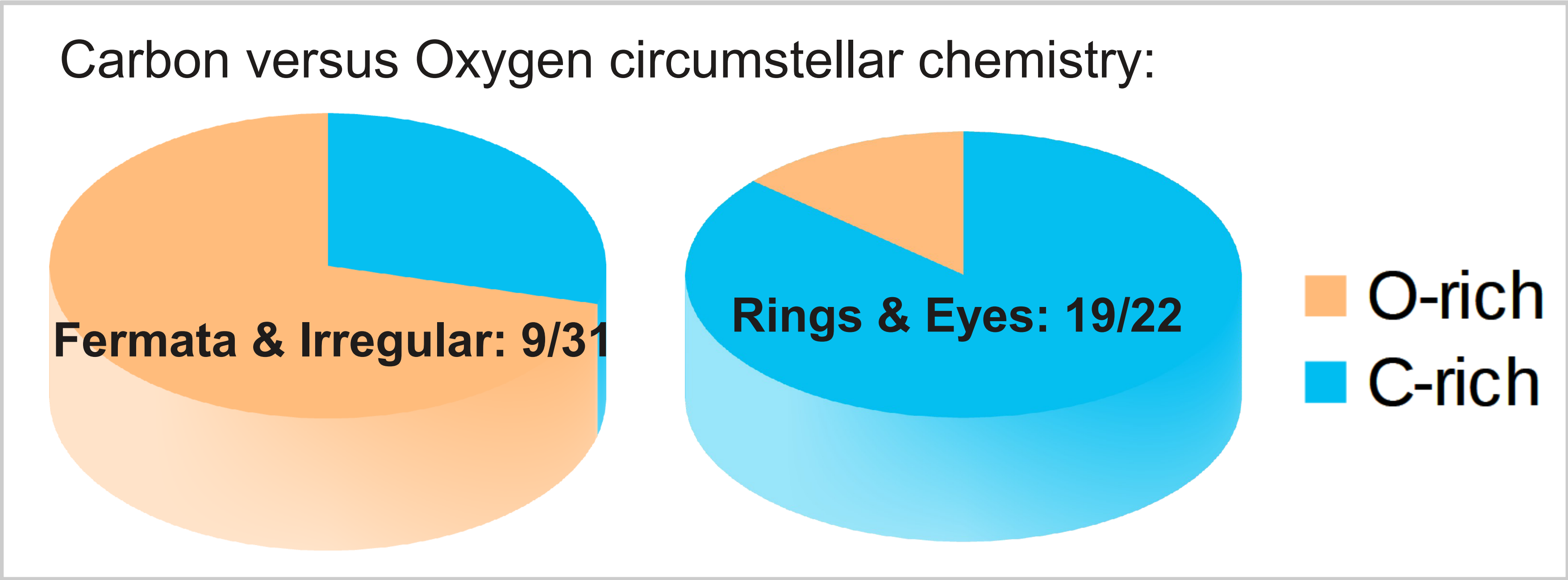




Assumed T_{dust} = 30 K.

Uncertainties due to emissivity & temperature are at least factor 2.

Circumstellar Chemistry & Morphology?



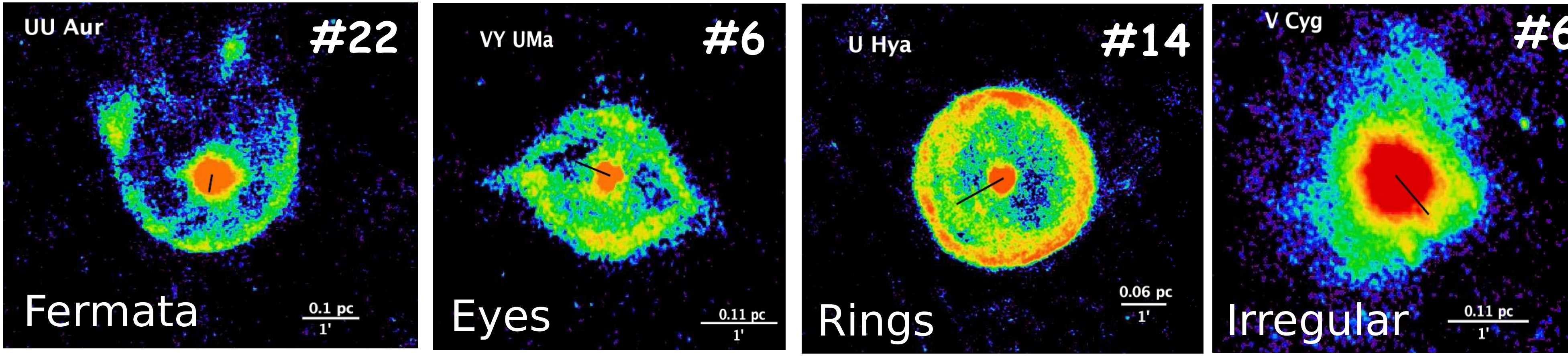
→ High fraction O-rich among Fermata & Irregulars

→ Rings: are ALL Carbon stars or Technetium enriched M super giant! (suspected for individual cases by Olofsson 2000).

Origin of detached rings? → interaction of fast wind with 'older' slow wind or dramatic change in mass loss, e.g. by thermal pulse (TP).

All Rings are TP-AGB !!

Binaries & Morphologies?



Are binaries distributed equally?

* Binary & morphology detection favoured of nearby objects
* MESS sample: 15/59 [25%] physical binaries [within 500 pc]

Fermata	Ring	Eye	Irregular	Unresolved
• *o Cet*	• *R Scl*	• VY UMa	• *o Cet*	• Y Lyn
• θ Aps		• U Cam	• π Gru	• TW Hor
• EP Aqr			• *o* Ori	• TX Cam
• W Aql			• R Aqr	• V Eri
• *R Scl*				• RW LMi
			No!	
5/23 [22%]	1/13 [8%]	2/7 [29%]	4/7 [57%]	5/15 [33%]

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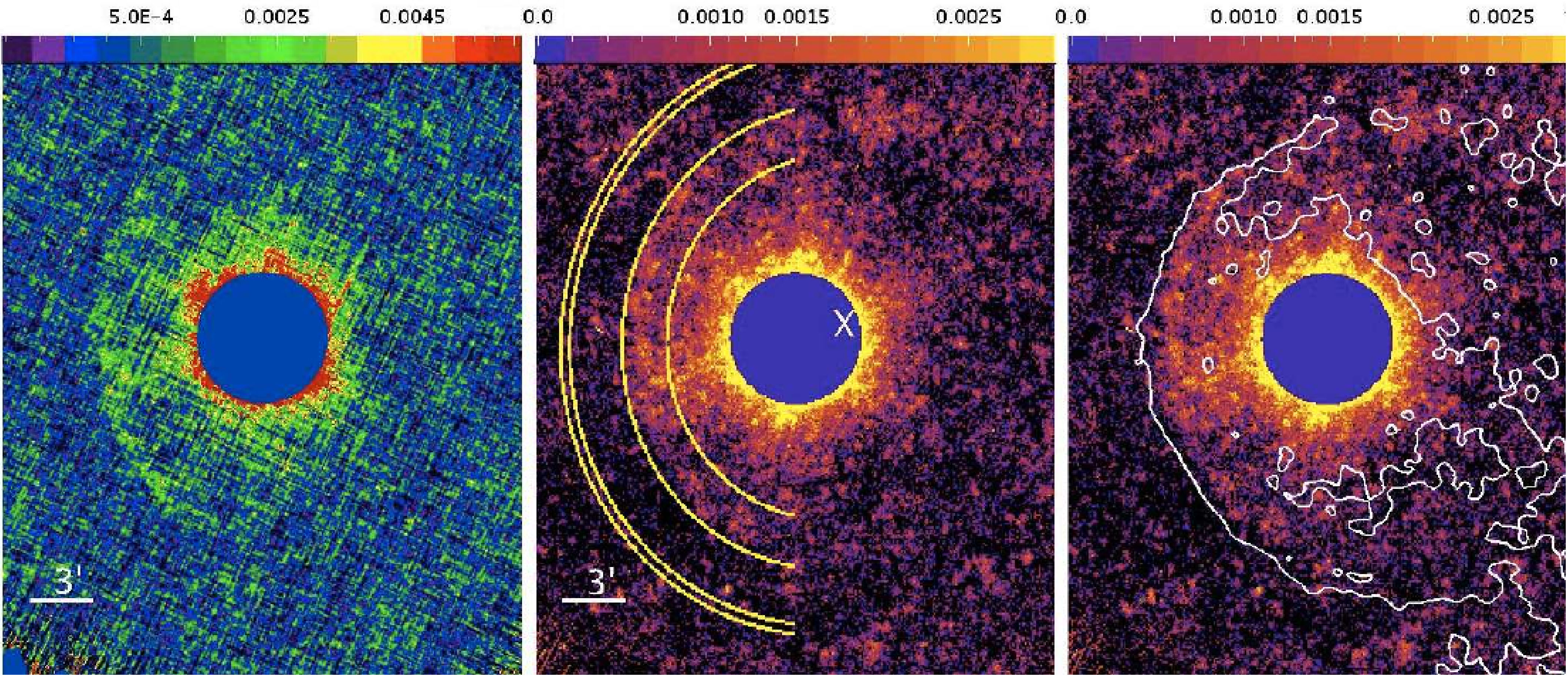
CW Leo



PACS 160 µm

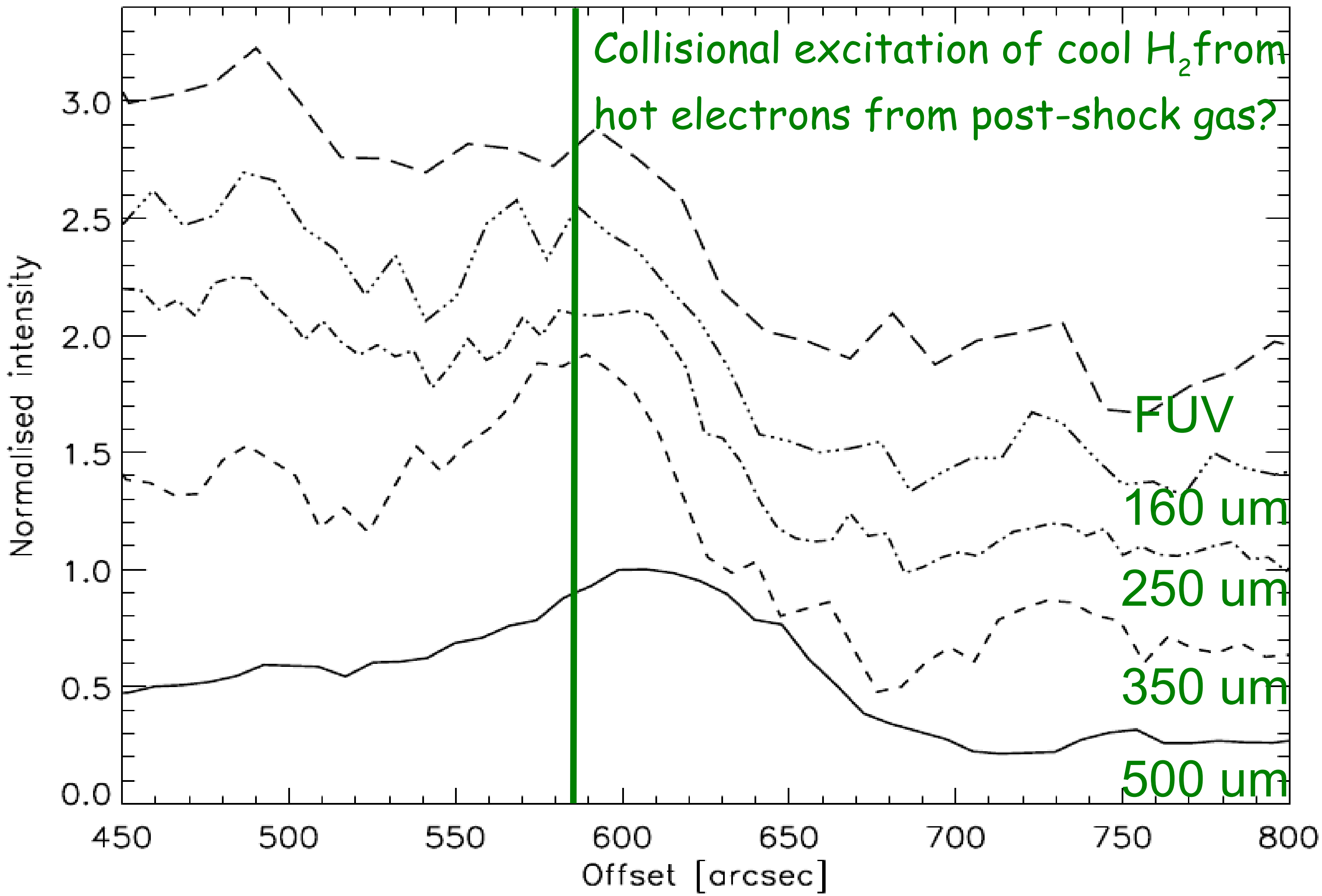
SPIRE 250 µm

SPIRE 250 µm & GALEX FUV 1528 Å

From R_0 = 0.26 pc → n_H > 2 cm^{-3} → v_* < 75 km/s

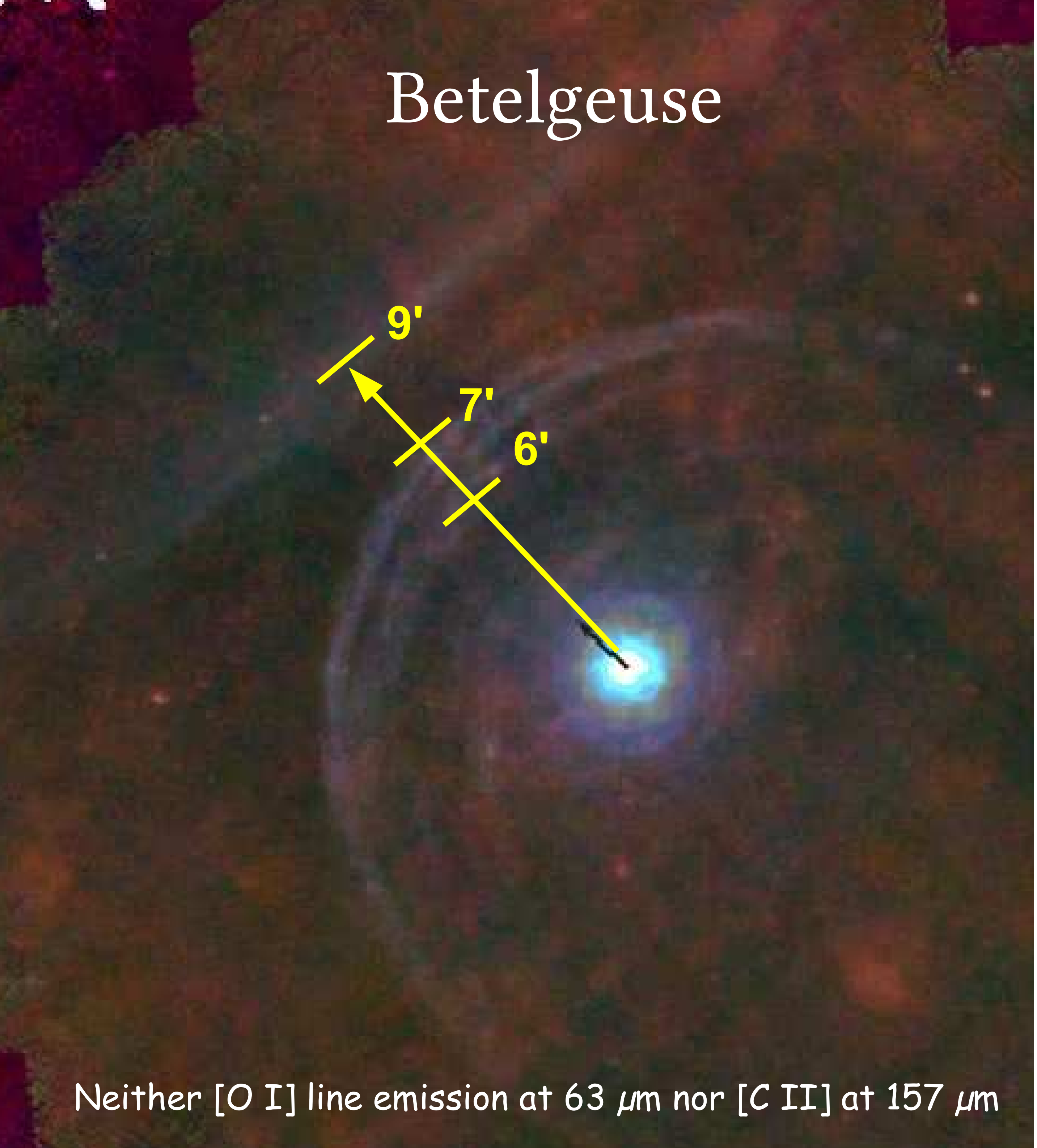
From Ladjal et al. 2010 (Herschel), *Sahai & Chronopoulos* 2010 (GALEX).

CW Leo – FIR & FUV



Intensity profiles of offset along minor axis of ellipse increasing from west to east. Normalised to intensity at 558″ (shifted for clarity) – from Ladjal et al. (2010).

Betelgeuse



Neither [O I] line emission at 63 μm nor [C II] at 157 μm

Distance of 280″ – 375″ from central star.

Width of arc ~20″

Linear length bar ~20' almost perpendicular to direction space motion

Arcs:

T_{dust} ~ 80-90 K, β~1

M_{d+g} ~ 10^{-3} M_{sun}

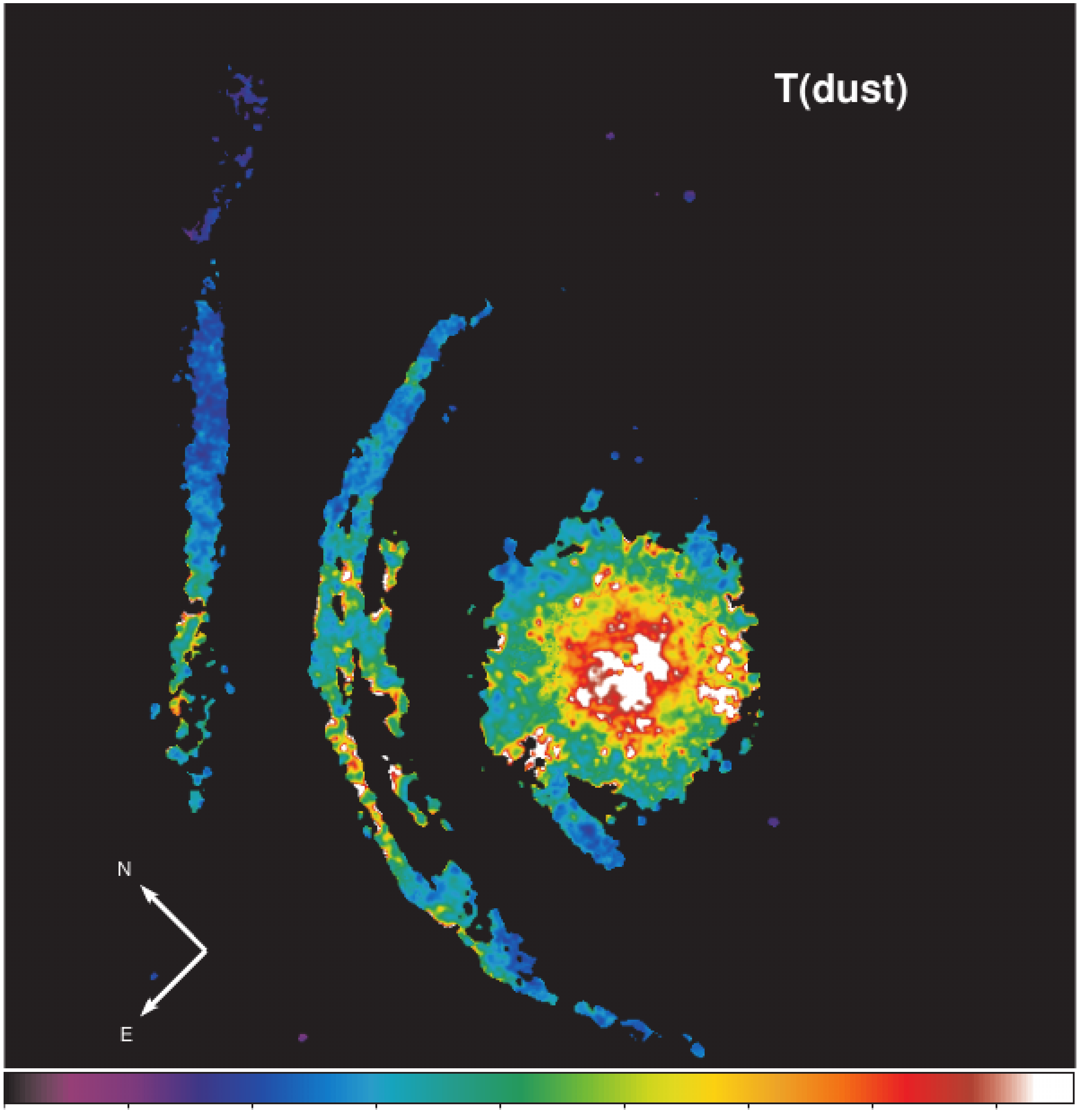
Bar:

T_{dust} ~ 60-70 K, β~1

M_{d+g} ~ 10^{-3} M_{sun}

Decin+2012

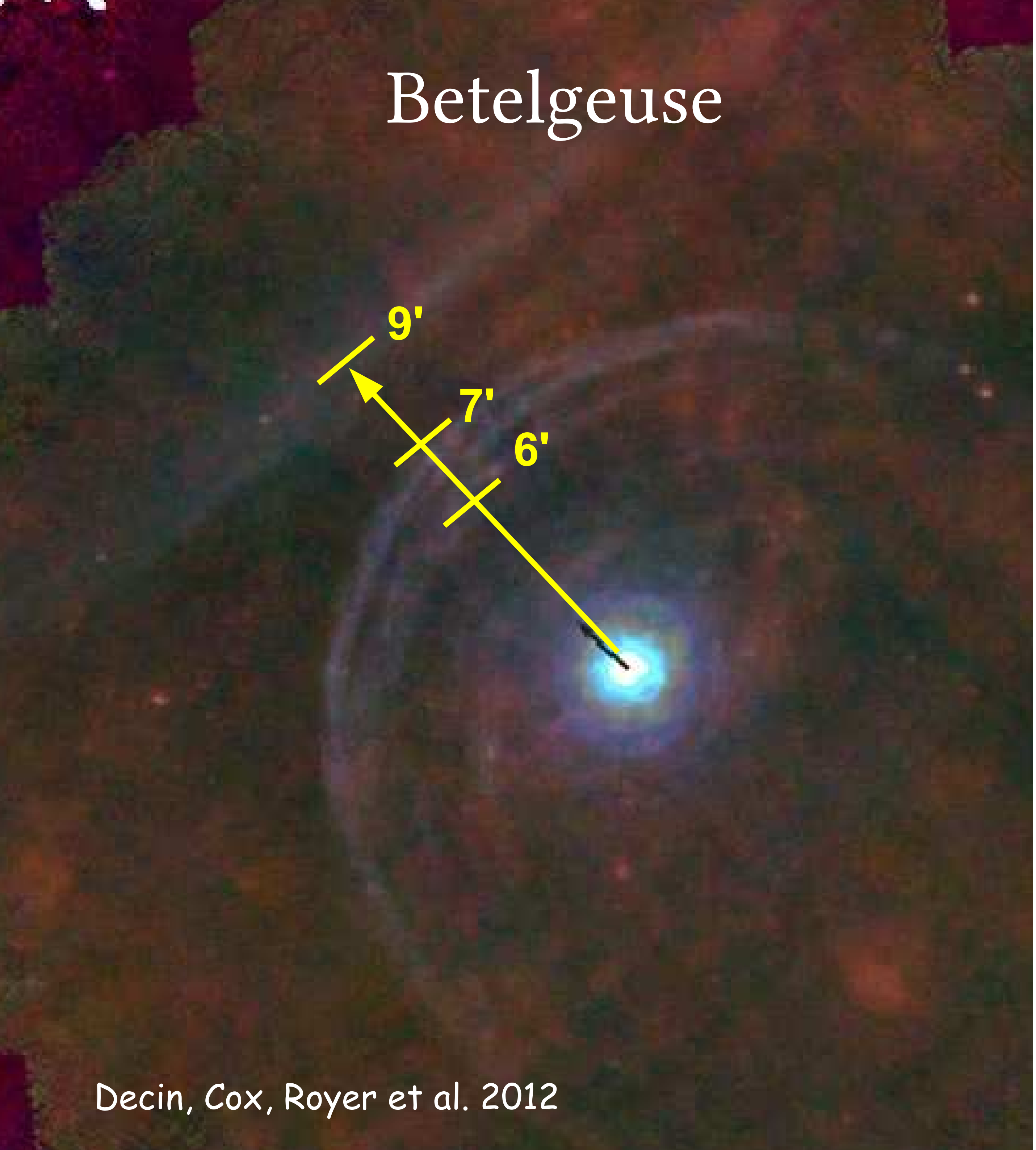
Betelgeuse – dust temperature



Decin+2012

Assuming a smooth continuous outflow, the temperature of an iron or amorphous silicate grain only heated by the stellar radiation is in the order of 45 – 60K at a distance of 280–530″ away from the central star.

Betelgeuse



Decin, Cox, Royer et al. 2012

$v_*/v_w > 1$
→ unstable bow shock

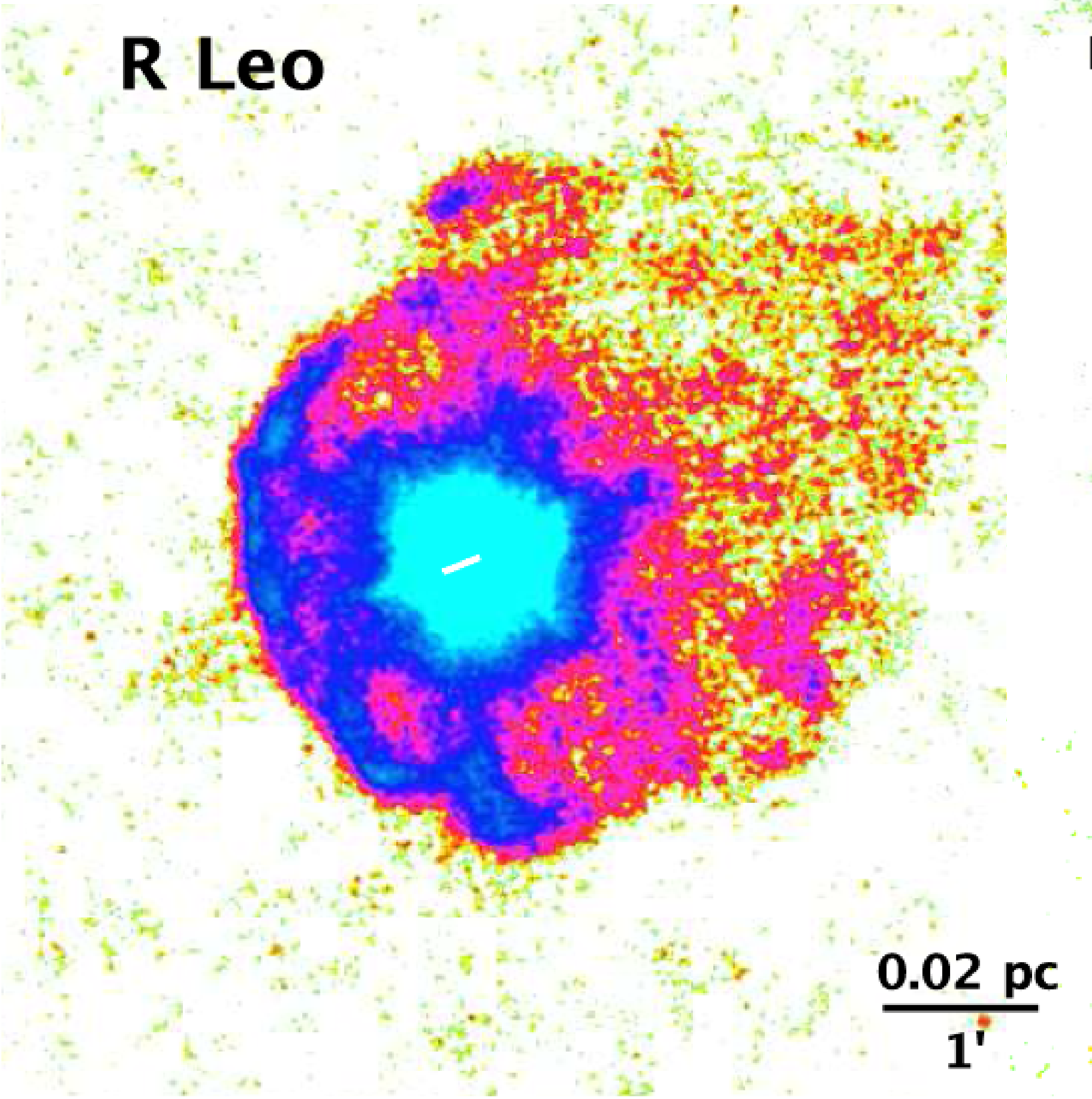
RT instabilities may fragment bow shock in direction of motion.

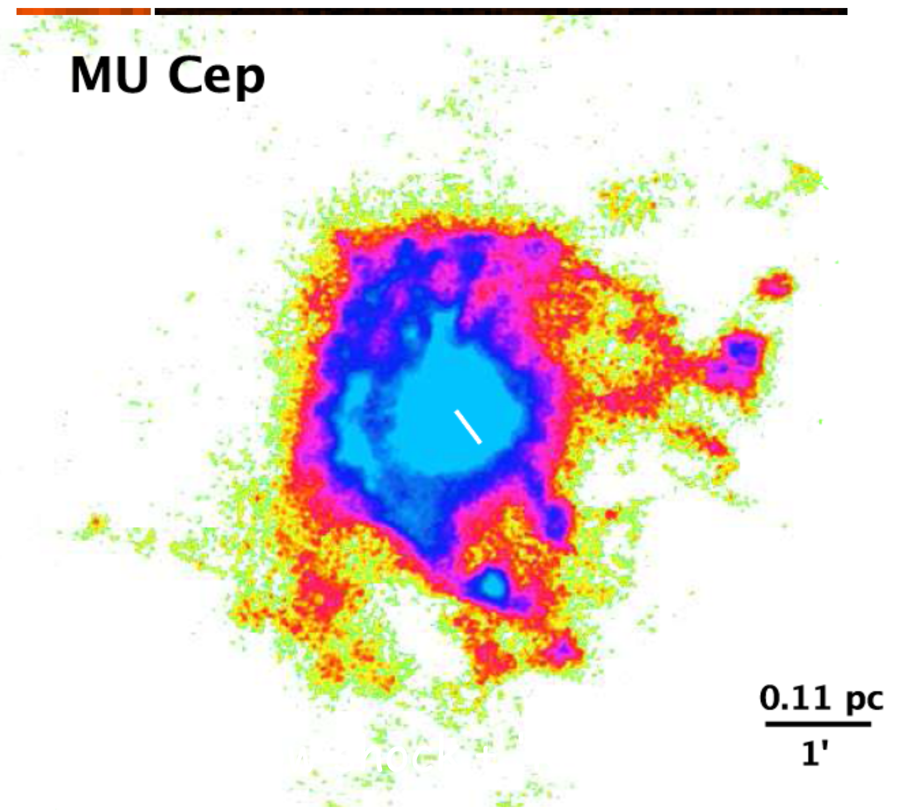
Magnetic field may suppress some modes but accentuate others, leading to 'RT stripes' (Dgani & Soker 1998).

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} →B = 3 μG.

Turbulent Instabilities (1)

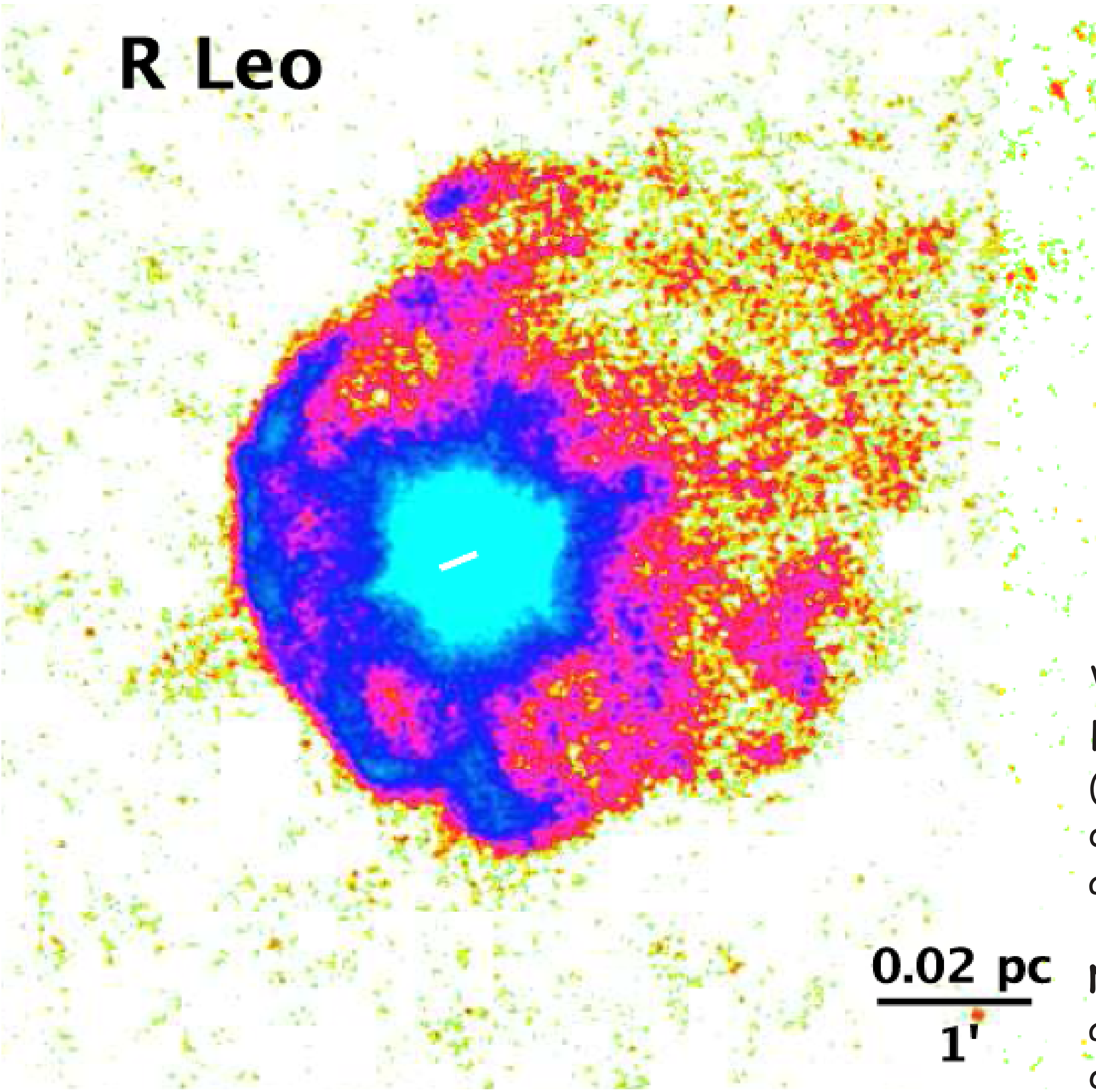


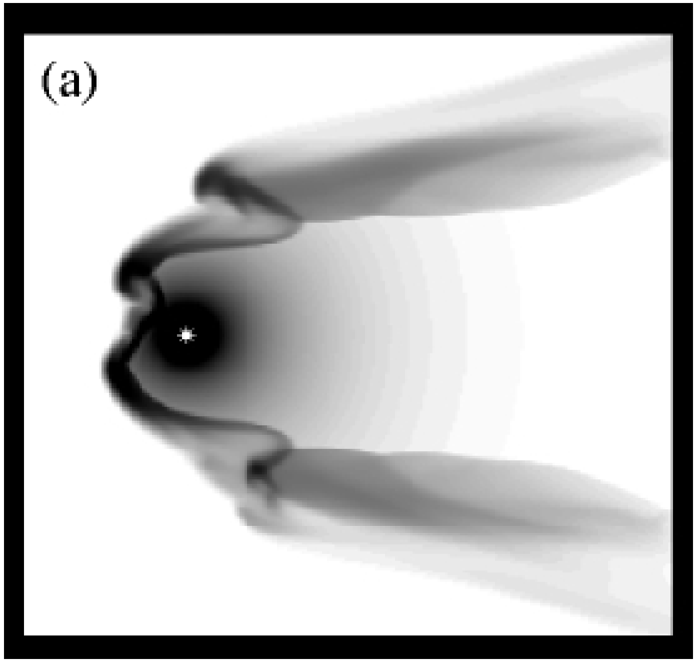


Observed 'turbulent' structure in bow shocks:

Kelvin-Helmholtz
AND
Rayleigh-Taylor instabilities

Turbulent Instabilities (2)

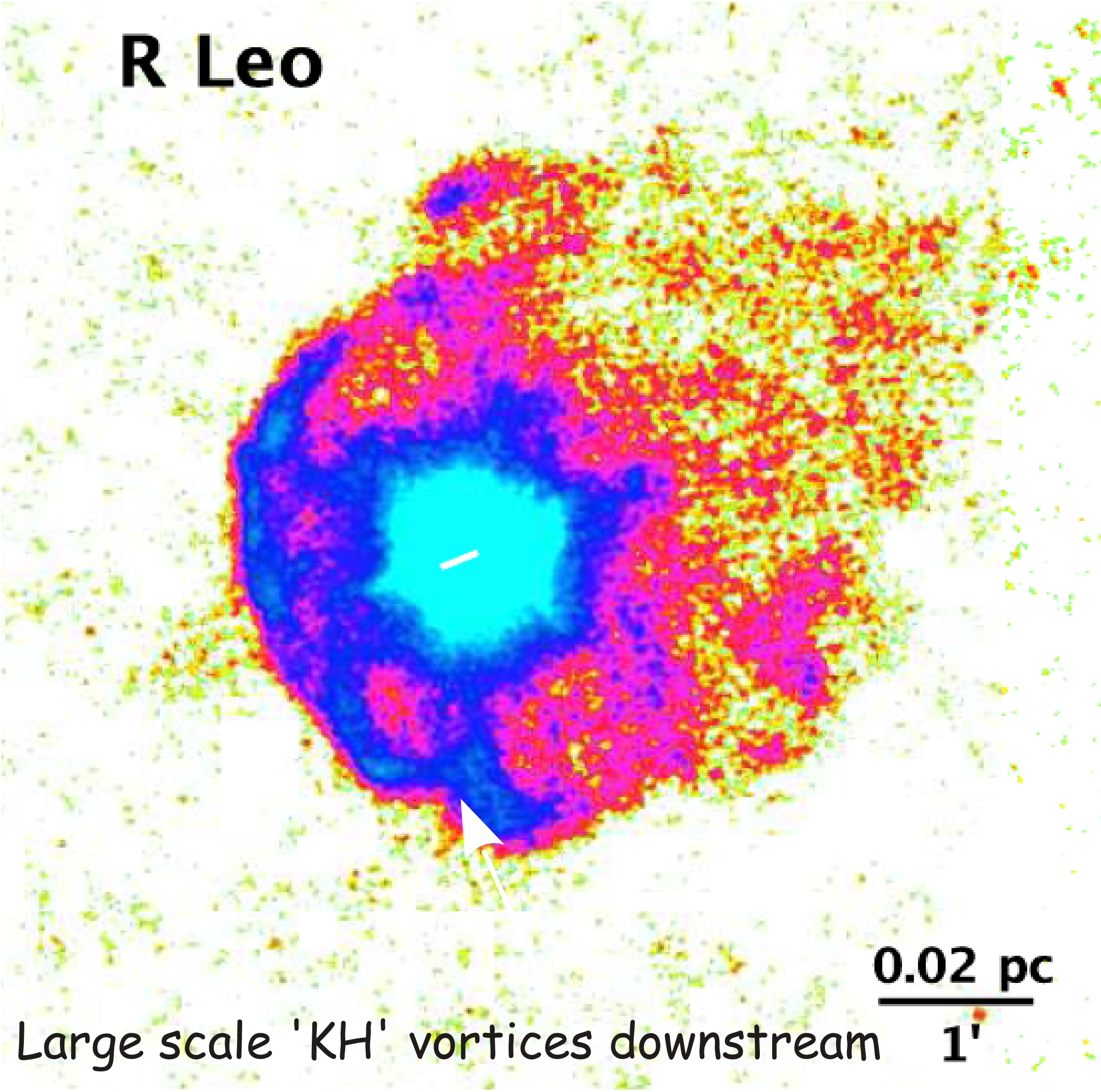


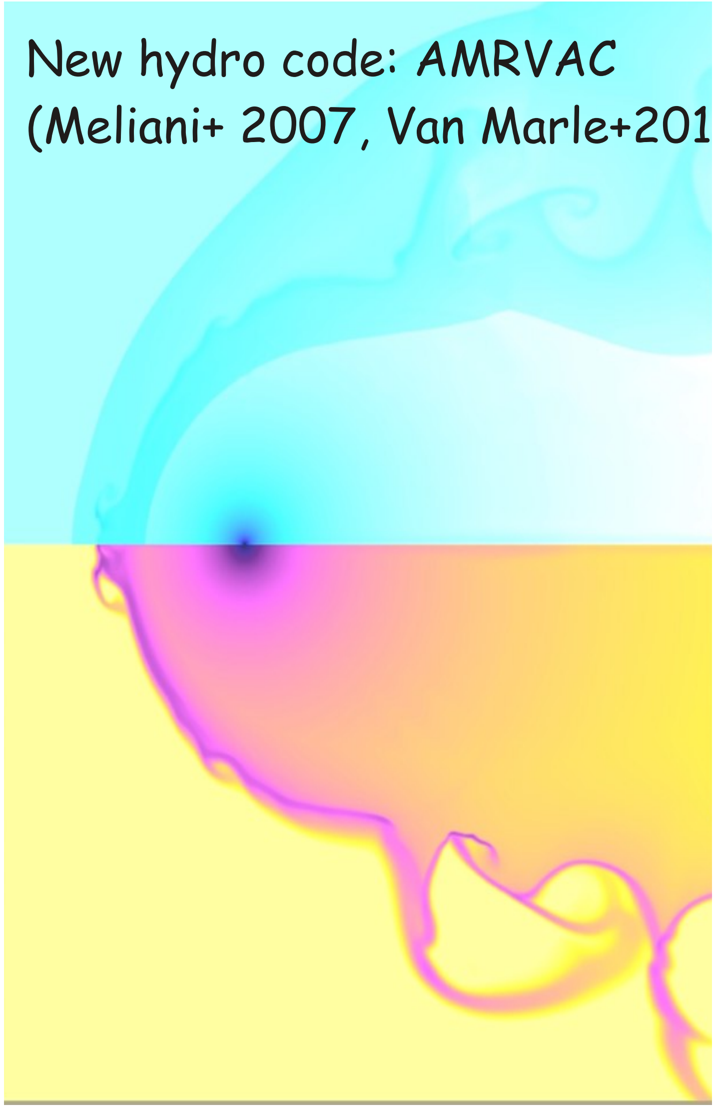


Wareing et al. 2007:
Kelvin-Helmholtz instability
(when velocity shear is present in a fluid or
or when there is sufficient velocity difference
across the interface between two fluids)

Not visible: Rayleigh-Taylor instabilities:
an instability of an interface between two fluids
of different densities, which occurs when the
lighter fluid is pushing the heavier fluid

Turbulent Instabilities (3)

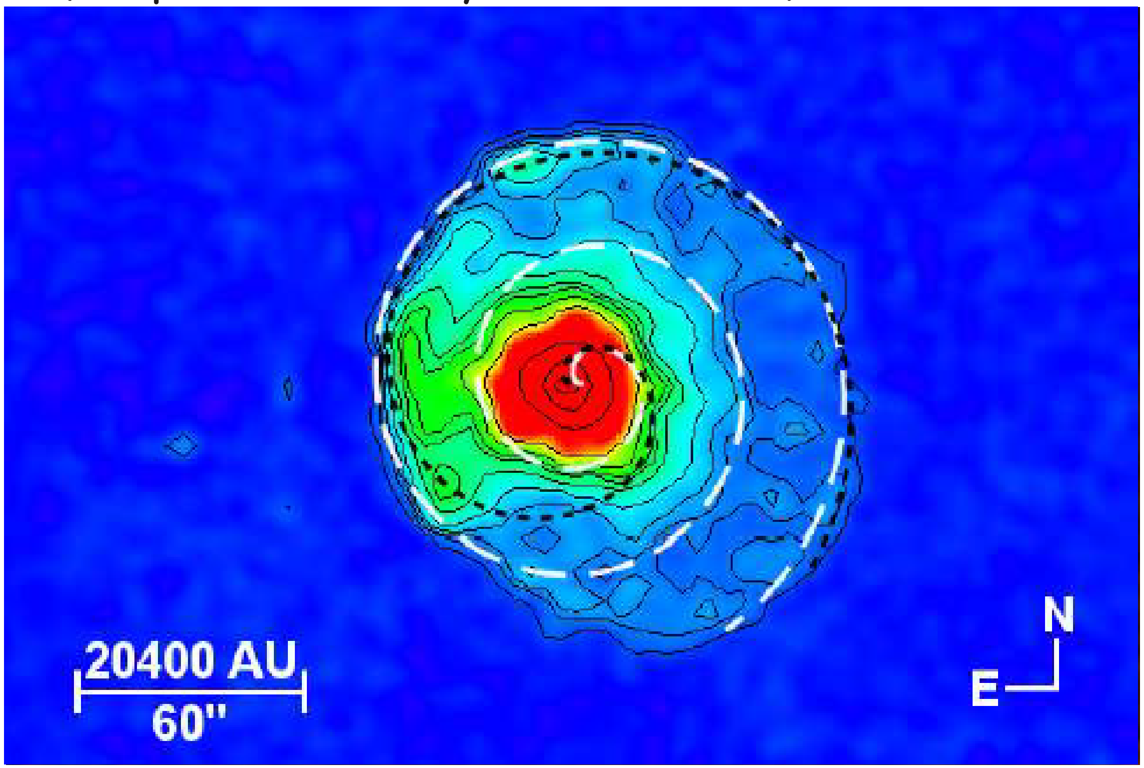




Hydrodynamical simulations: Kelvin-Helmholtz & Rayleigh-Taylor instabilities

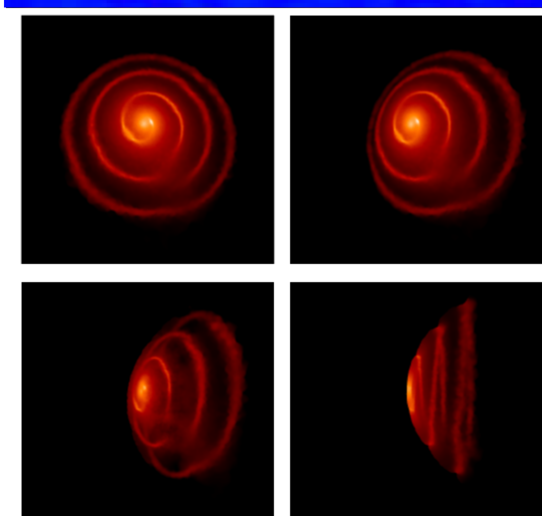
Intricate circumstellar environment of W Aql

(adapted from Mayer et al. 2013)



- Wide binary system
  - d=160 AU (Ramstedt et al. 2011)
  - AAVSO light curves: Mira + MS star, P_{orb} > 1000 yrs
- Classified as fermata but proper motion does not fit ISM, cannot shape the CSE solely!
- Archimedean spiral fits shape of CSE:
  - 2 solutions (P_{orb} = 2000 yrs & 4000 yrs)
  - But cannot explain density enhancement in east

Combination of ISM flow & motion of binary



SPH simulations (Mohamed et al. 2011).

Outline

- "Astrospheres": The stellar wind – ISM interaction region
- Runaway O/B stars

  Herschel Highlights: Vela X-1 & BD+43 3654

- AGB stars and red supergiants (RSG)

  Herschel Highlights: CW Leo, Betelgeuse, R Leo & W Aql

- Conclusions and outlook

Conclusions/Outlook (1/2)

I. Herschel has revealed – somewhat unexpectedly - the ubiquitous occurrence of astrospheres around AGB stars -> possible source of processing of circumstellar matter upon injection into the ISM.

II. Interaction of AGB winds with the surrounding ISM gives rise to interesting morphologies – shapes depend not only simply on stellar/wind velocity, mass-loss rate, BUT, also on circumstellar chemistry, binarity and possibly magnetic field.

III. All detected AGB/RSG astrospheres are smaller than 1 pc (surface brightness limit?); observed apex "stand-off" distances → estimate ISM density.

IV: KH and RT instabilities resolved for the first time, predicted by simulations.

V. Total dust+gas masses related to astrospheres range from 10^{-3} to 0.5 M_{sun}.

→ ISM contribution ~1 to 25 % for evolved stars.

→ ISM contribution ~100% for O stars.

Conclusions/Outlook (2/2)

VI. Astrospheres can be used to estimate stellar and/or interstellar parameters. Also indicate direction of stellar motion (particularly interesting for distant stars with poorly determined proper motion).

VII. Currently, most AGB/RSG astrospheres only detected via their dust component with exception of CW Leo and possibly Betelgeuse. Hot massive star astrospheres more energetic and (sometimes) visible in Hα etc.

VIII. Need multi-wavelength imaging AND spectroscopy of larger sample of astrospheres to understand bow shock physics, interplay gas and dust, and origin of varying morphologies.

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

X. Why are astrospheres not detected (yet?) around later type (post-AGB/proto-PNe) stars? Dissipated? Low surface brightness wrt cirrus?

X: Direct detection of dust/gas in astrospheres of solar-type stars?

Thank you! Questions?