

Betelgeuse 2016

(aspects of mass loss in evolved stars and RSGs in particular)

Hot Topics

Snapshots from the recent literature
(49 papers)

Stephen Ridgway

Betelgeuse Workshop 2012

The Physics of Red Supergiants:
Recent Advances and Open Questions

Editors

P. Kervella, T. Le Bertre and G. Perrin



Introduction

[Betelgeuse – Challenging our Understanding for more than 2000 years](#)
[The past and future evolution of a star like Betelgeuse](#)

Structure and Evolution of Massive Stars

[Red supergiants and stellar evolution](#)
[How the mass-loss rates of red-supergiants determine the fate of massive stars?](#)
[The evolution of Red Supergiants at very low metallicity](#)

Atmospheric Structure and dynamics

[Atmospheric structure and dynamics: the spatial and temporal domains](#)
[The Temperatures of Red Supergiants: how cool are the coolest massive stars?](#)
[Direct ultraviolet imaging and spectroscopy of betelgeuse](#)
[Atmosphere tomography of red supergiant stars](#)
[The atmospheric structure and fundamental parameters of Red Supergiants](#)
[<3D> NLTE line formation in the atmospheres of red supergiants](#)
[NLTE water lines in Betelgeuse-like atmospheres](#)
[Spatially resolving the atmospheric dynamics over the surface of red supergiants with the Very Large Telescope Interferometer](#)
[Turbulent Structure in the Upper Chromospheres of Cool Supergiants](#)
[Global radiation-hydrodynamics simulations of red supergiant stars](#)
[3D hydrodynamical simulations to interpret observations of stellar surfaces of red supergiant stars](#)
[What is the Origin of the Water Vapour Signatures in Red Giant Stars?](#)
[Long-term spectropolarimetric monitoring of the cool supergiant betelgeuse](#)
[Exploring the water and carbon monoxide shell around Betelgeuse with VLT/AMBER](#)

Mass Loss Mechanism, dust Formation Chemistry

[The chemistry of dust formation in red supergiants](#)
[Red Supergiants and Post-Red Supergiants – the Evidence for High Mass Loss Events](#)
[Dust-forming molecules in VY Canis Majoris \(and Betelgeuse\)](#)
[Towards a coherent view at infrared wavelengths of mass loss in Betelgeuse](#)
[Mass Loss from Betelgeuse](#)
[The kinematics in the large-scale environment of Betelgeuse from radio HI-line observations](#)
[The enigmatic nature of the circumstellar envelope and bow shock surrounding Betelgeuse as revealed by Herschel](#)
[The influence of a variable mass loss rate on the dust and gas dynamics in the bow-shock of \$\alpha\$ -Orionis](#)
[3D Smoothed Particle Hydrodynamics Models of Betelgeuse's Bow Shock](#)
[Numerical models for the circumstellar medium around Betelgeuse](#)
[The SPHERE View of Betelgeuse](#)

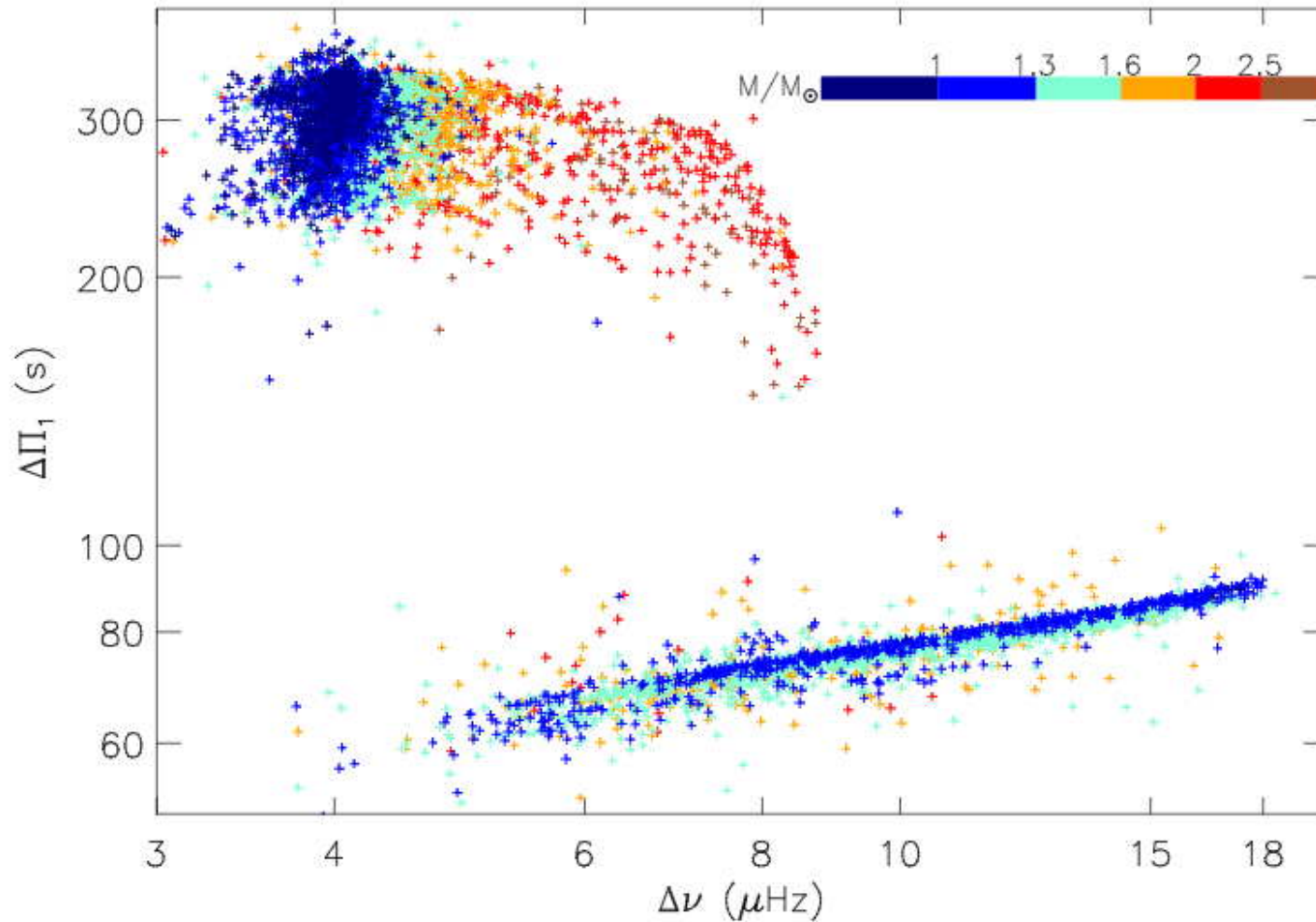
Red Supergiants in Galaxies

[Red Supergiants in the Local Group](#)
[The population of M-type supergiants in the starburst cluster Stephenson 2](#)
[Red Supergiants as Cosmic Abundance Probes](#)
[A large population of red supergiants in the super star cluster NGC 1705-1](#)
[Spectral classification of very late luminous stars in the Gaia region](#)

Summary

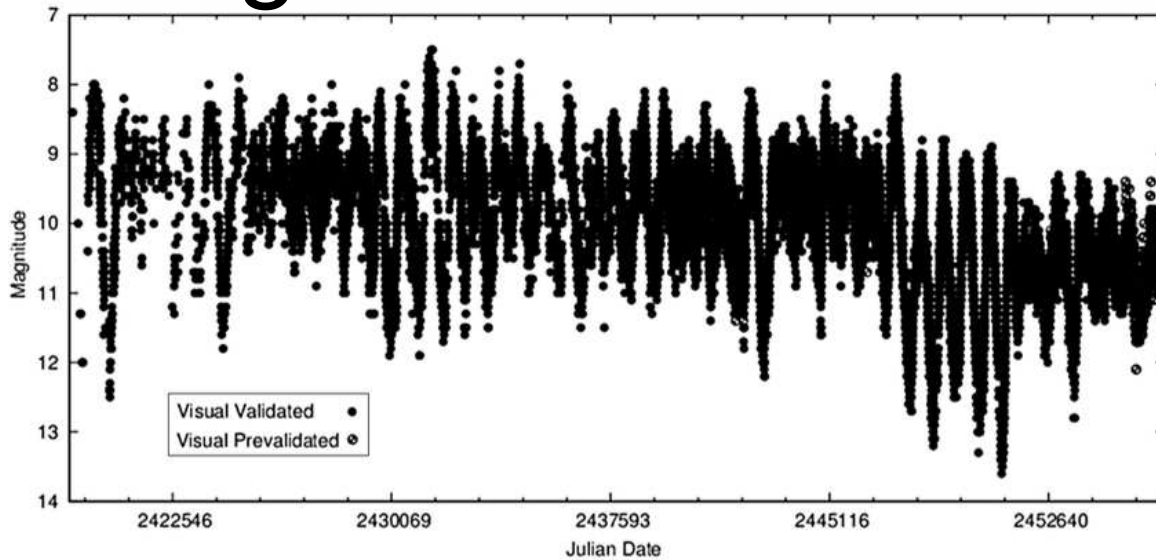
[Betelgeuse and the Red Supergiants](#)

Masses, Radii, Internal Structure for 12,900 RGB Stars

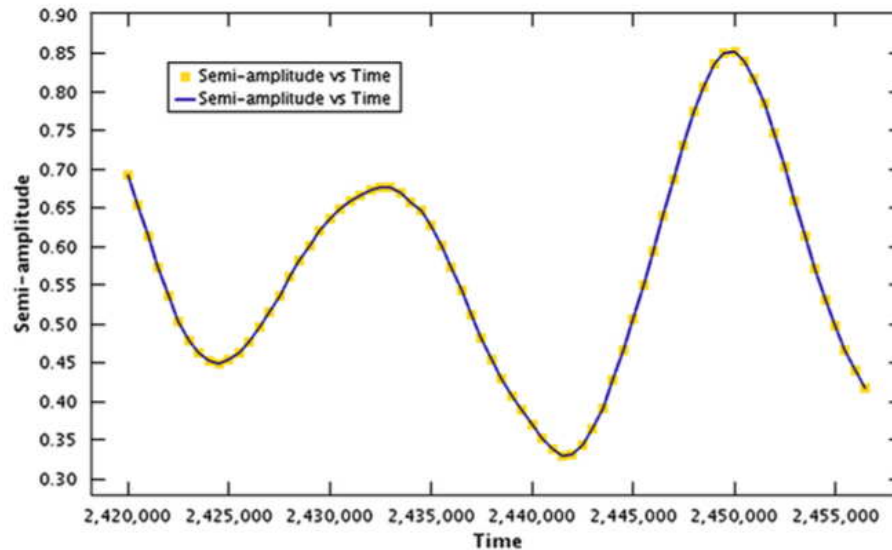


Period spacings in red giants II. Automated measurement, M. Vrad, **Benoît Mosser**, R. Samadi, A&A 588, A87 (2016)

Long Duration Photometric Series



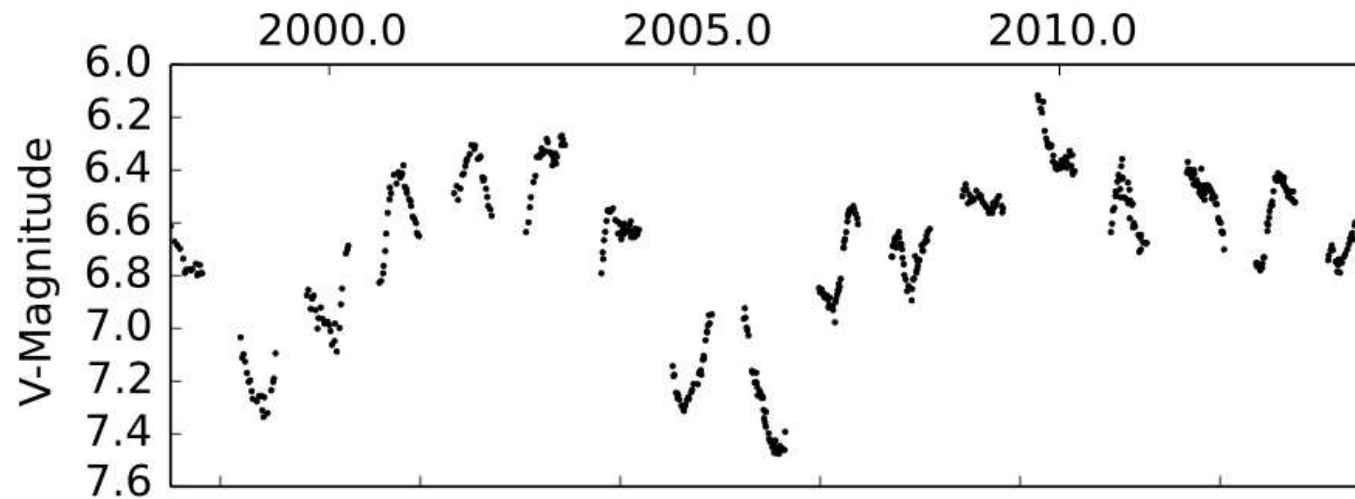
S Per Magnitude



S Per Variability Amplitude

Amplitude Variations in Pulsating Red Supergiants, J.R. Percy & V.C.Khatu, JAAVSO 42, 1 (2014)

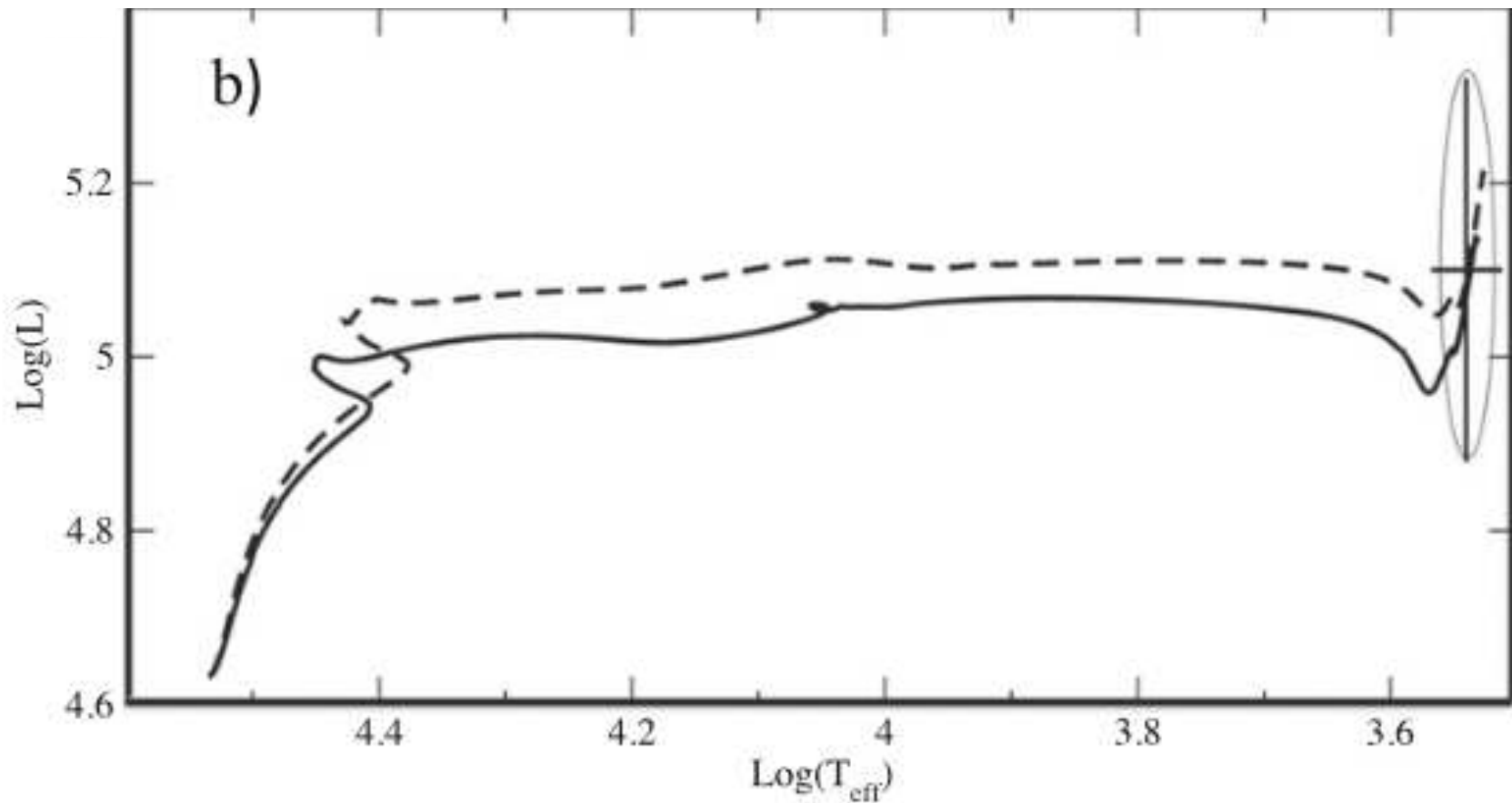
Precision Photometric Series



V-Band, Near-IR, and TiO Photometry of the Semi-Regular Red Supergiant TV Geminorum: Long-Term Quasi-Periodic Changes in Temperature, Radius, and Luminosity, R.P Wasatonic, E.G.Guinan & A.J. Durbin, PASP 127,1010 (2015)

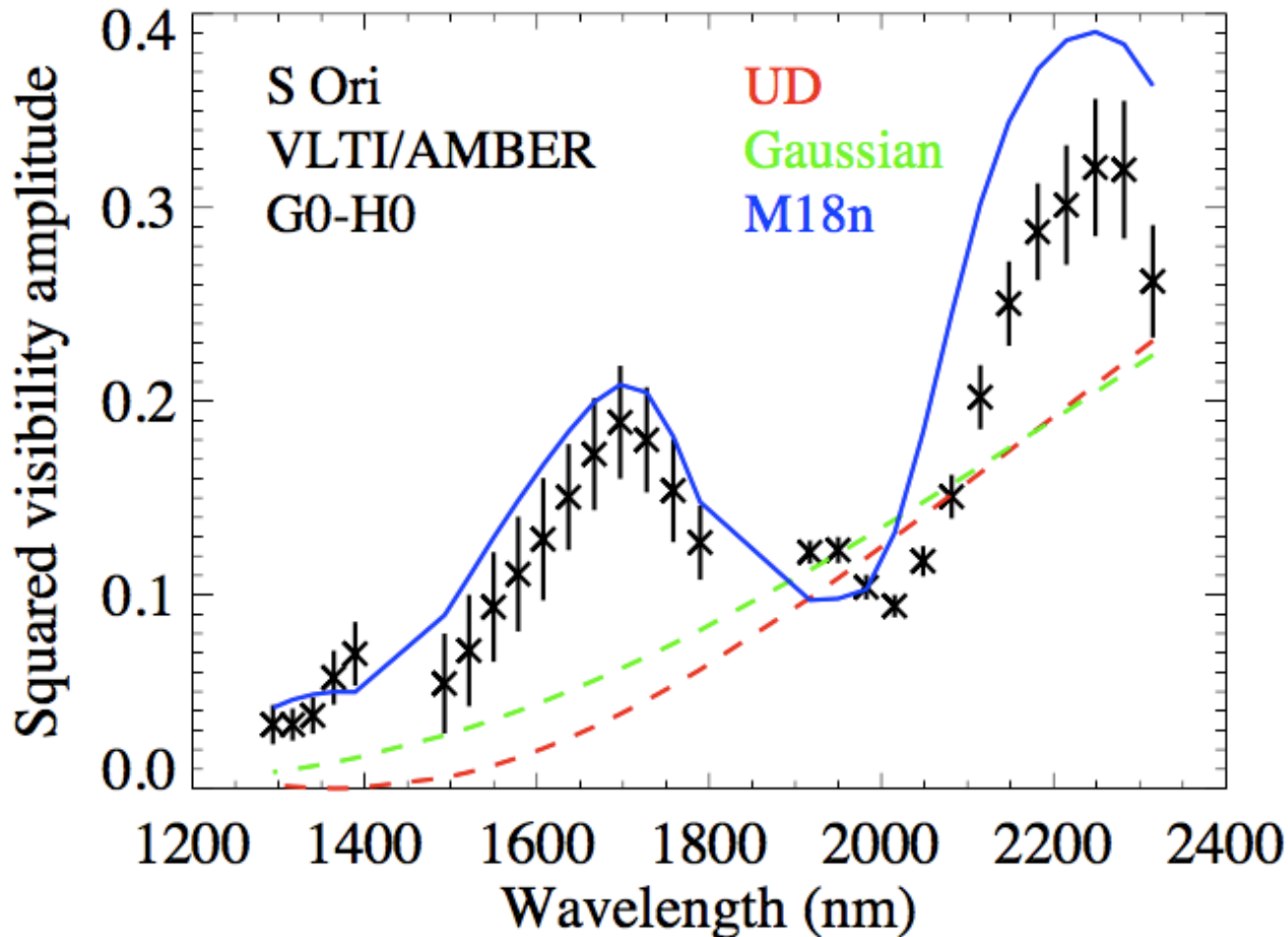
Feature	Periods (days)	Relative intensity
V- and A-band magnitudes	3137 ± 95	145
	411 ± 3	87
	320 ± 3	42
	1120 ± 20	22
B-band magnitude	3250 ± 89	147
	407 ± 3	79
	320 ± 3	40
	1081 ± 18	30
C-band magnitude (L_*/L_\odot)	3355 ± 102	115
	407 ± 4	70
	1104 ± 27	47
	547 ± 5	45
T_{eff}	2966 ± 82	139
	411 ± 3	76
	320 ± 3	49
	1184 ± 24	21
(R_*/R_\odot)	1128 ± 23	59
	447 ± 3	55
	536 ± 7	52
	2298 ± 233	28

Variability and Models



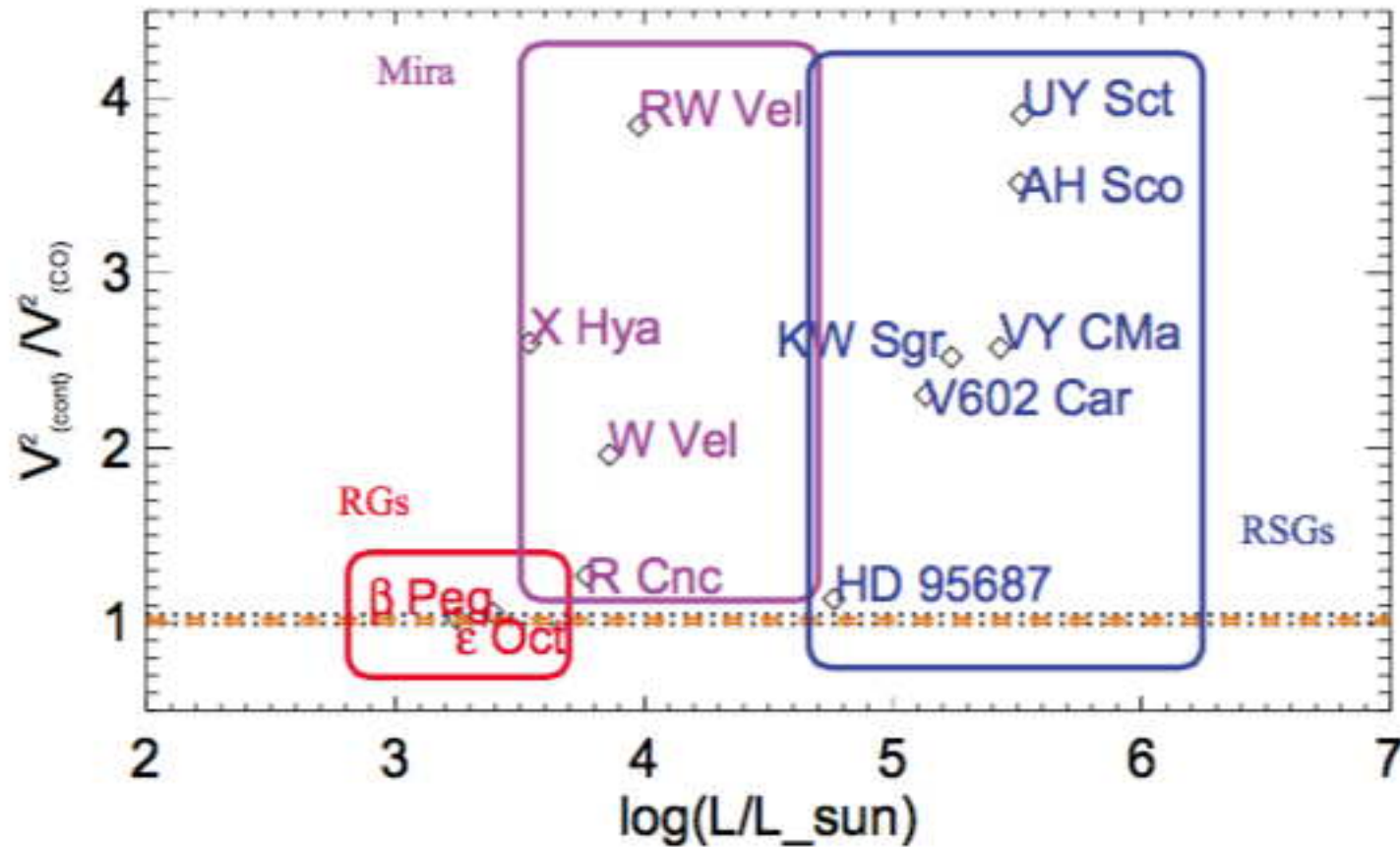
Evolutionary Tracks for Betelgeuse, M.M.Dolan et al., ApJ 819:7 (2016)

S Ori Wavelength dependence of apparent diameter



From The Atmosphere To The Circumstellar Environment In Cool Evolved Stars,
Marcus Wittkowski & Claudia Paladini, arXiv:1501.05825v1

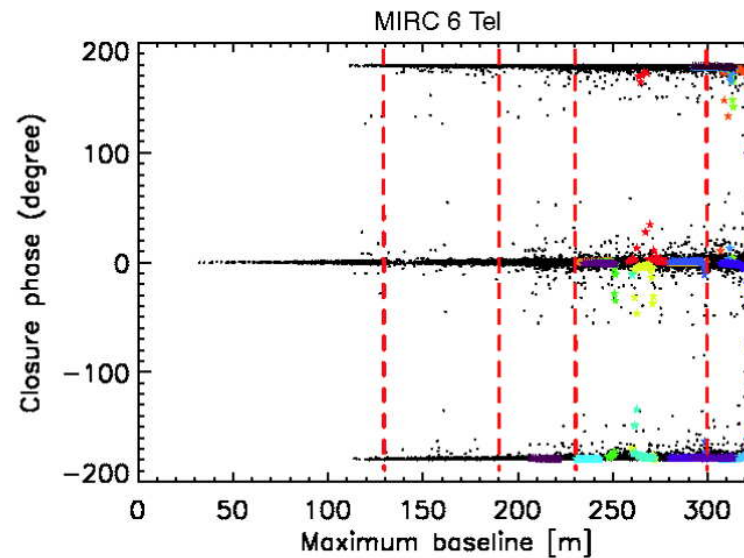
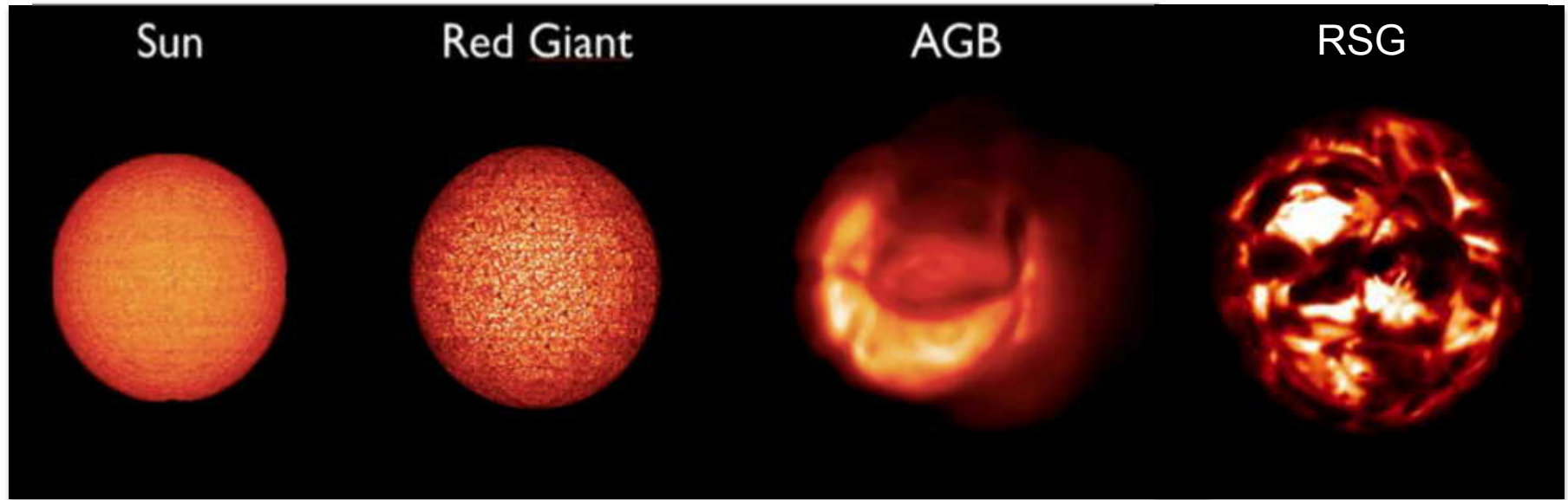
Atmospheric Extension



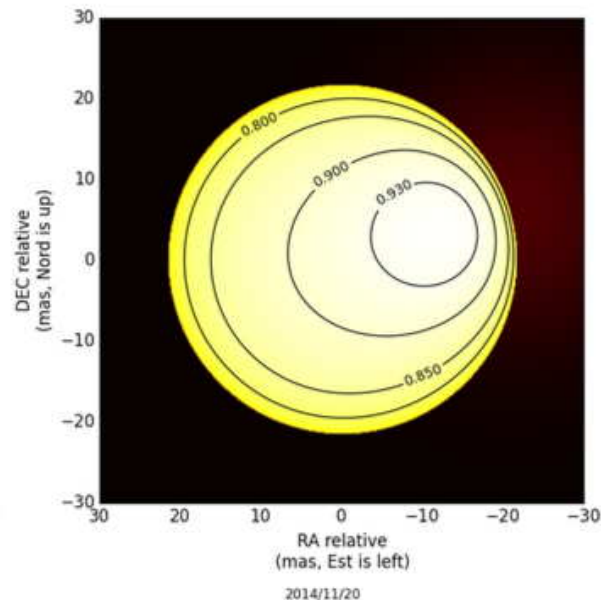
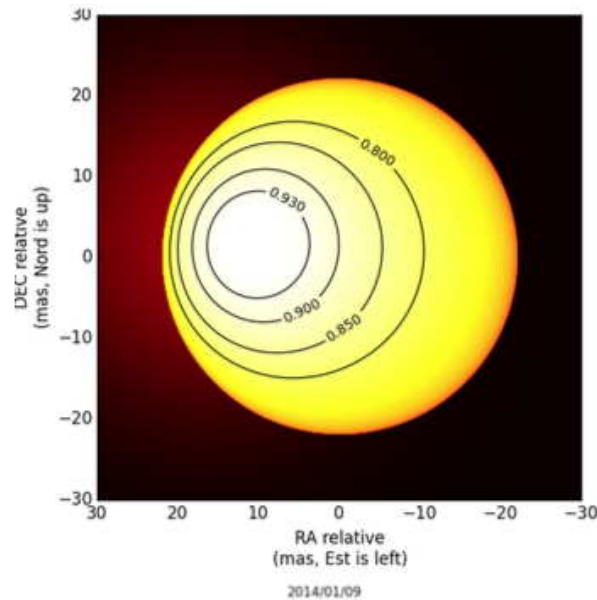
What causes the large extensions of red supergiant atmospheres?

B. Arroyo-Torres, **Marcus Wittkowski**, **Andrea Chiavassa**, et al., A&A 575, A50 (2015)

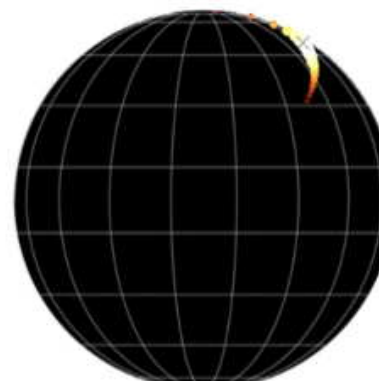
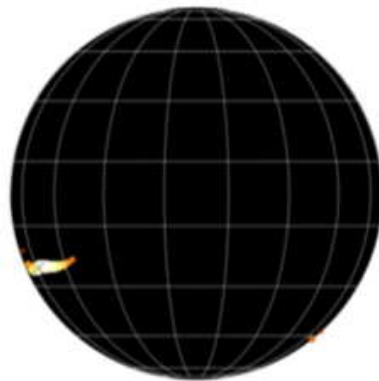
Modeling – Emergent Intensity from RHD simulations



Mapping the Surface - Betelgeuse



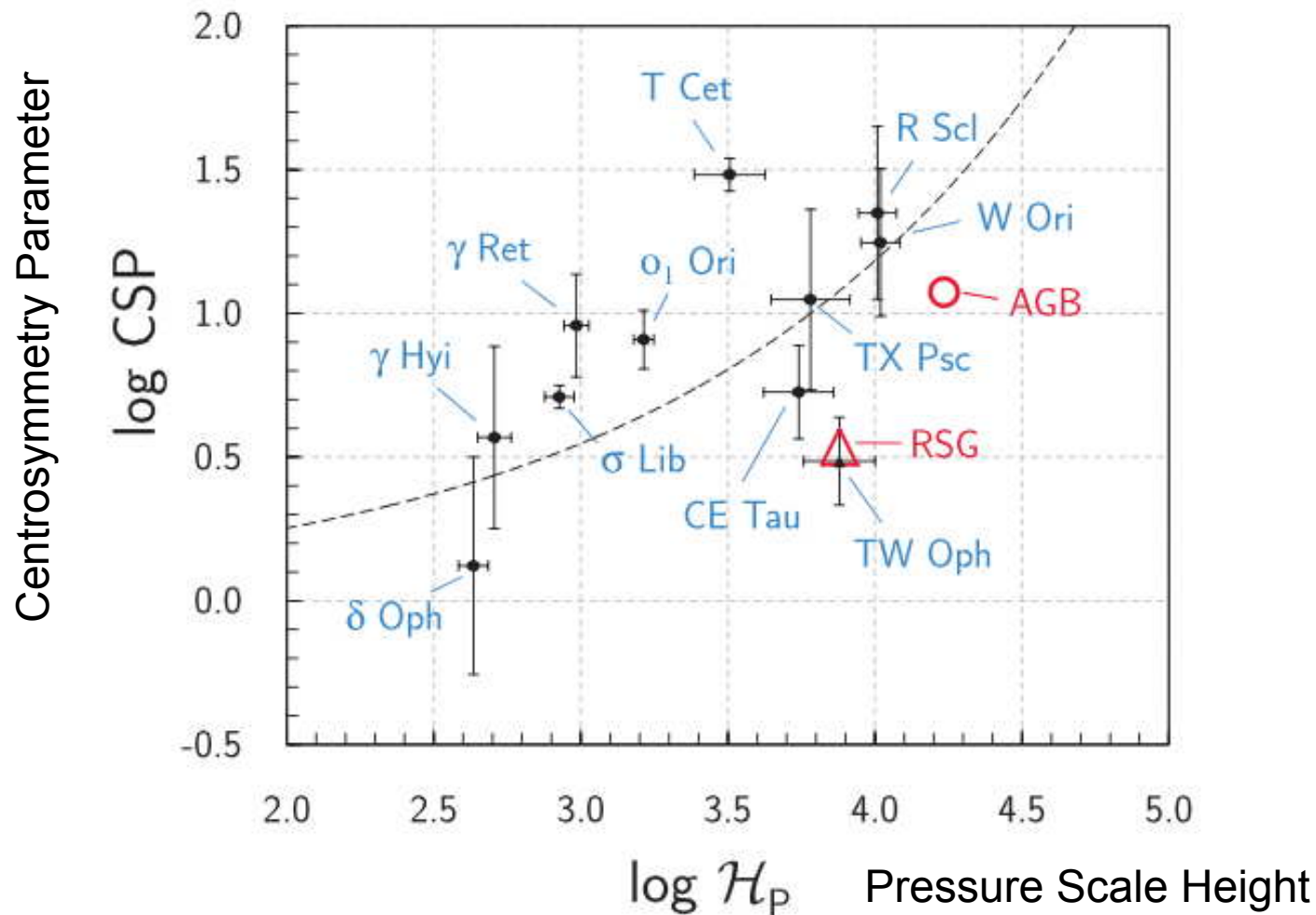
Infrared interferometry



Visible Polarimetry

Discovery of a complex linearly polarized spectrum of Betelgeuse dominated by depolarization of the continuum, M. Auriere, **Arturo López Ariste**, **Agnès Lèbre**, **Miguel Montargès**, **Andrea Chiavassa**, et al. A&A 591, A119 (2016)

Brightness Asymmetries



Departure from centrosymmetry of red giants and supergiants measured with VLT/AMBER, P. Cruzalebes, **Andrea Chiavassa**, **Claudia Paladini**, et al., MNRAS 446, 3277

How to Characterize Different Surface Regions?

- Example – two-stream model
- Spectral lines are asymmetric
- Line bisectors reflect velocity, temperature structure, and fractional cell area

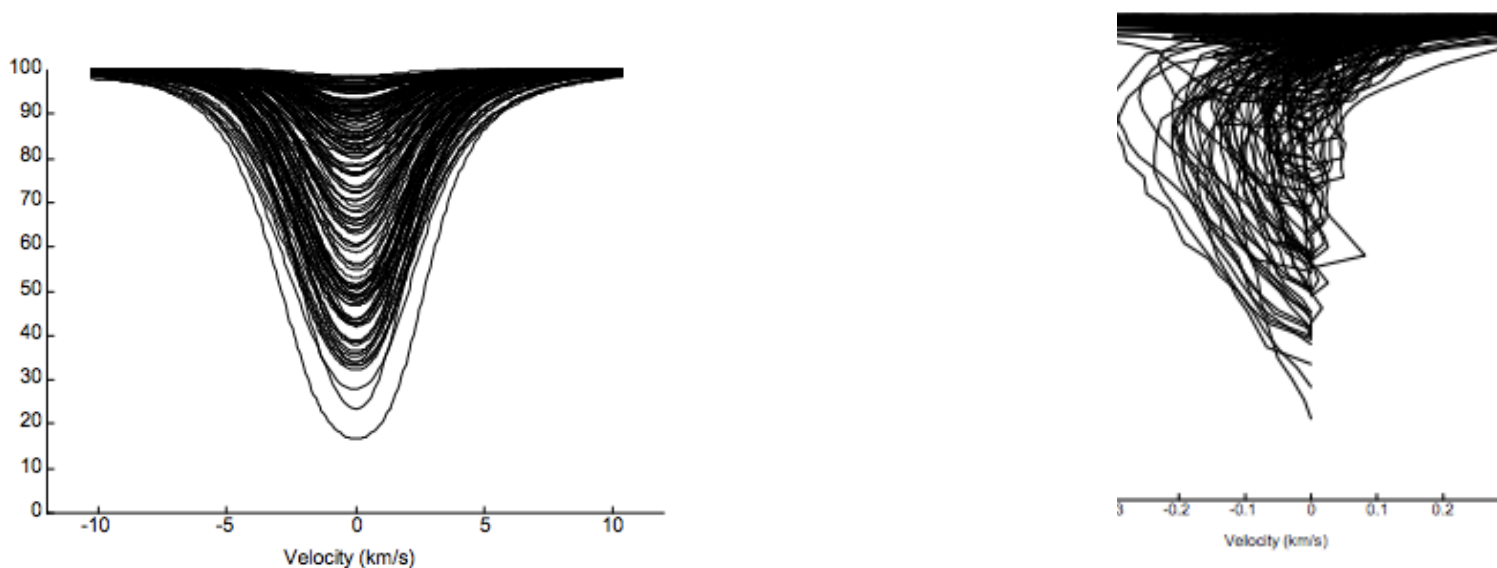
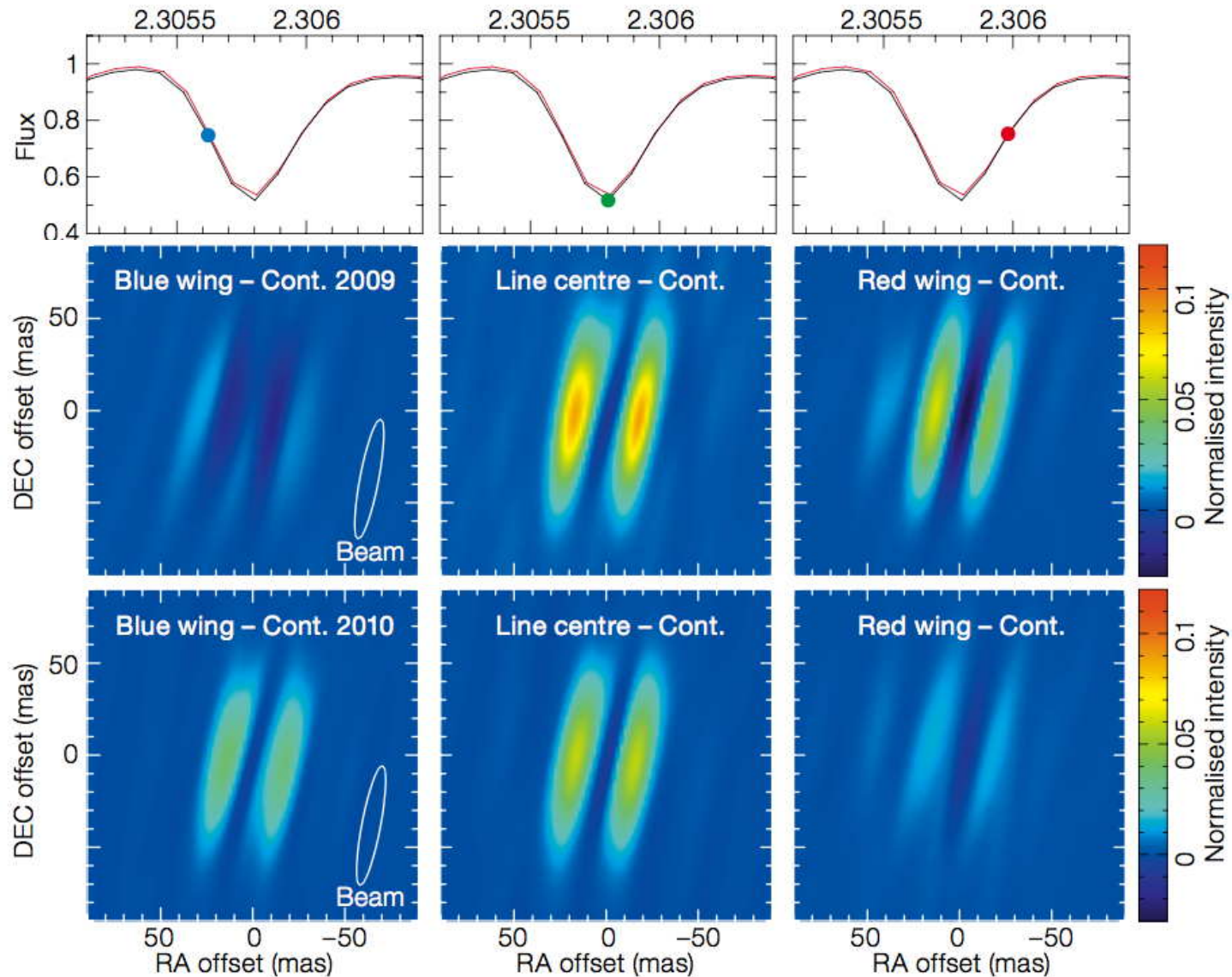


Figure 1-9: Profiles (velocity)

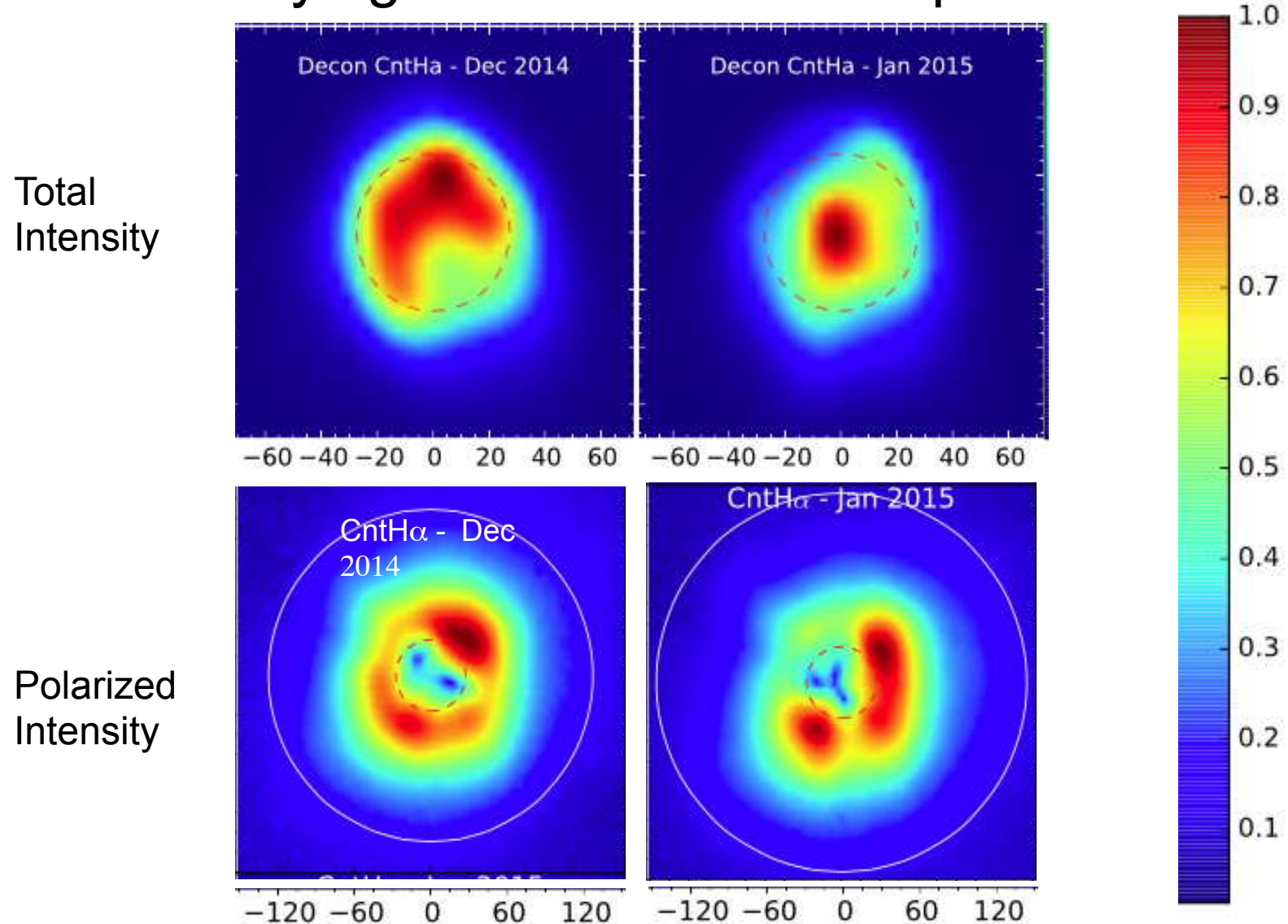
The Asymmetry of Photospheric Absorption Lines, M. Kasi & C.J. Durrant, AA 116, 332 (1982)

Spatially Resolved Line Profile Analysis



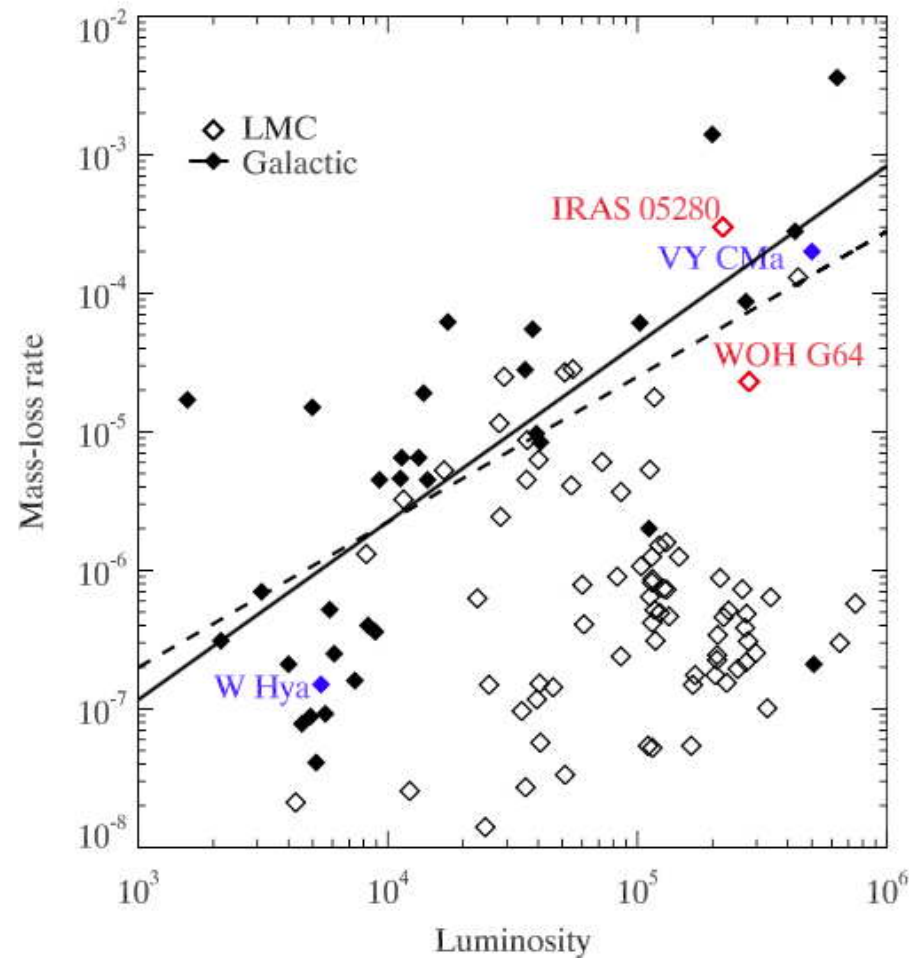
Revealing the Complex Dynamics of the Atmospheres of Red Supergiants with the Very Large Telescope Interferometer, K. Ohnaka et al., MNRAS 462, 46 (2015)

Time Varying Surface and Atmosphere – R Dor



Study of the inner dust envelope and stellar photosphere of the AGB star R Doradus using SPHERE/ZIMPOL, T. Khouri, **Pierre Kervella**, **Leen Decin**, **Eamon O’Gorman**, **Eric Lagadec**, et al. A&A 591, A70 (2016)

RSG Mass Loss Rate Depends on Luminosity, Not on Dust



The mass-loss rates of red supergiants at low metallicity: detection of rotational CO emission from two red supergiants in the Large Magellanic Cloud. M. Matsuura, **Leen Decin**, et al., MNRAS 462, 2995 (2016)

RG Mass Loss Depends on Pulsation, Not on Dust – EU Del

Table 2. Wind parameters of EU Del from APEX observations

Parameter	Unit	$^{12}\text{CO } J=2-1$	$^{12}\text{CO } J=3-2$	$^{13}\text{CO } J=3-2$	Global
Frequency	GHz	230.538	345.796	330.587	–
Resolution	km s^{-1}	0.099	0.066	0.069	–
Noise	K	0.023	0.062	0.022	–
Intensity	K km s^{-1}	1.96 ± 0.04	3.57 ± 0.08	0.26 ± 0.12	–
Amplitude	K	0.1031 ± 0.0017	0.187 ± 0.004	0.013 ± 0.005	–
	Jy	4.02 ± 0.07	7.69 ± 0.16	0.54 ± 0.21	–
Half-width	km s^{-1}	9.492 ± 0.015	9.522 ± 0.019	9.86 ± 0.65	9.505 ± 0.021
Centre	km s^{-1}	-51.93 ± 0.04	-51.77 ± 0.04	-51.94 ± 0.60	-51.85 ± 0.10
Boxcar χ_{red}^2	–	1.087	1.322	1.224	–
$\dot{M}_{\text{Ramstedt}}$	$M_{\odot} \text{ yr}^{-1}$	$5.1^{+7.5}_{-3.8} \times 10^{-8}$	$3.4^{+7.8}_{-3.2} \times 10^{-8}$	–	$4.7^{+5.3}_{-3.7} \times 10^{-8}$

Notes. Velocities are in the v_{LSR} frame, temperatures are antenna temperatures. The global mass-loss rate was produced by the logarithmic averaging of the $^{12}\text{CO } J=3-2$ and $2-1$ lines.

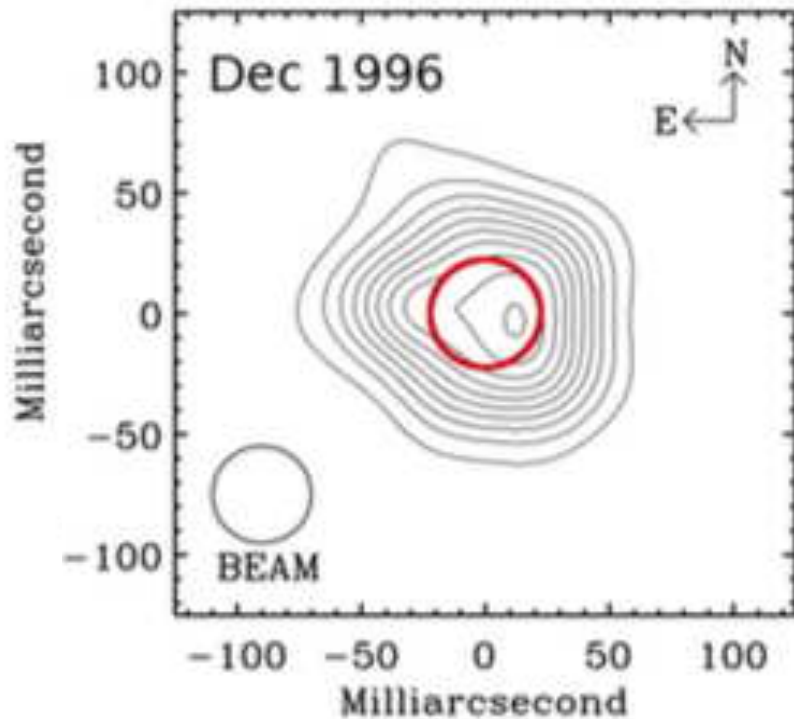
EU Del: exploring the onset of pulsation-driven winds in giant stars,
Ian McDonald, Eric Lagadec, et al., MNRAS 456, 4542 (2016)

Mass Loss – Don't Forget Magnetism

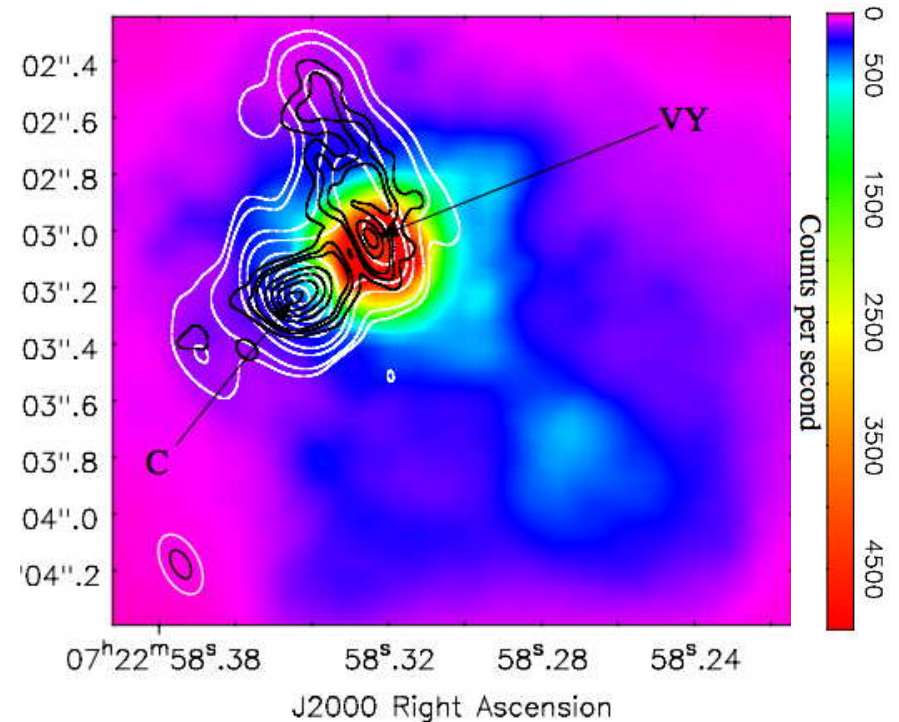
- Surface magnetic fields
- Possibly originating in convective dynamo

Search for surface magnetic fields in Mira stars - First detection in χ Cygni,
Agnès Lèbre et al., A&A 561, A85 (2014)

Envelopes

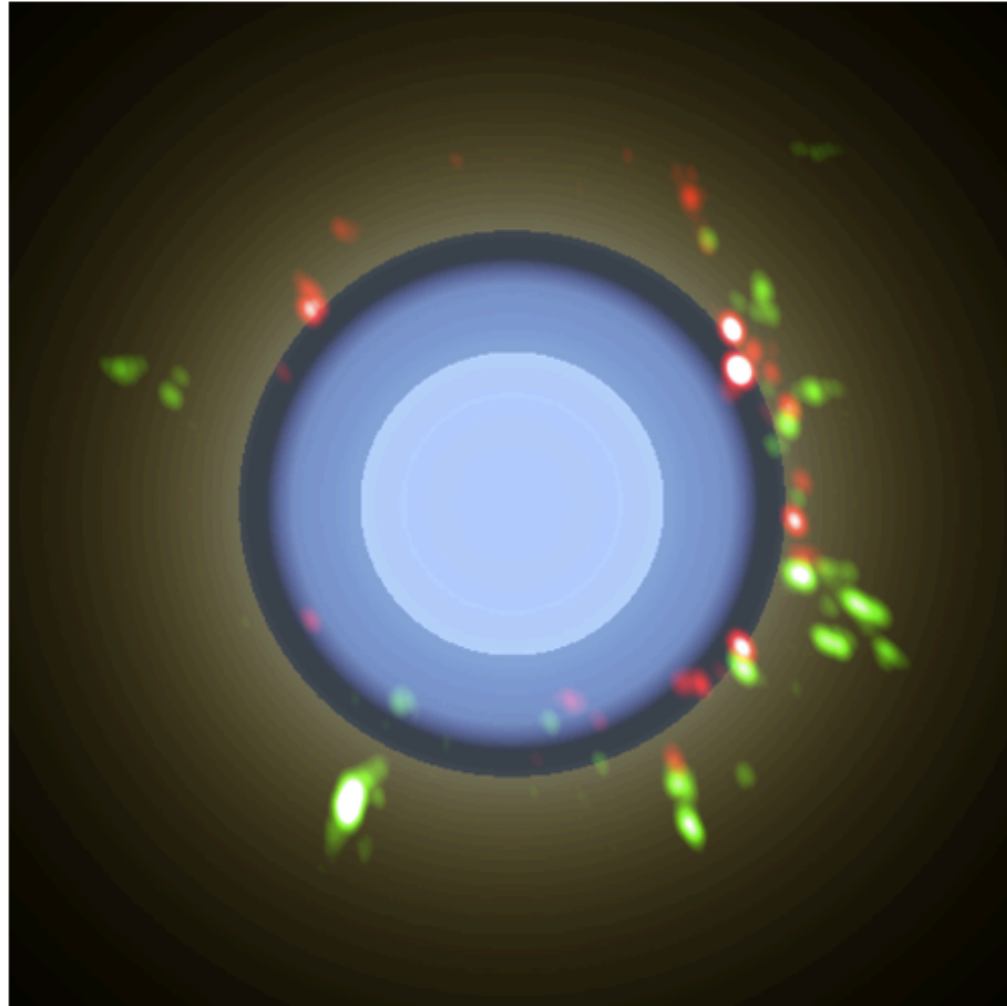


Temporal evolution of the size and temperature of Betelgeuse's extended atmosphere,
Eamon O'Gorman, Anita Richards,
et al., A&A 580, A101 (2015)



ALMA observations of anisotropic dust mass loss in the inner circumstellar environment of the red supergiant VY Canis Majoris,
Eamon O'Gorman, Anita Richards,
Leen Decin, Elizabeth Humphreys, et al., A&A 573, L1 (2015)

S Ori Structural Model + maser emission



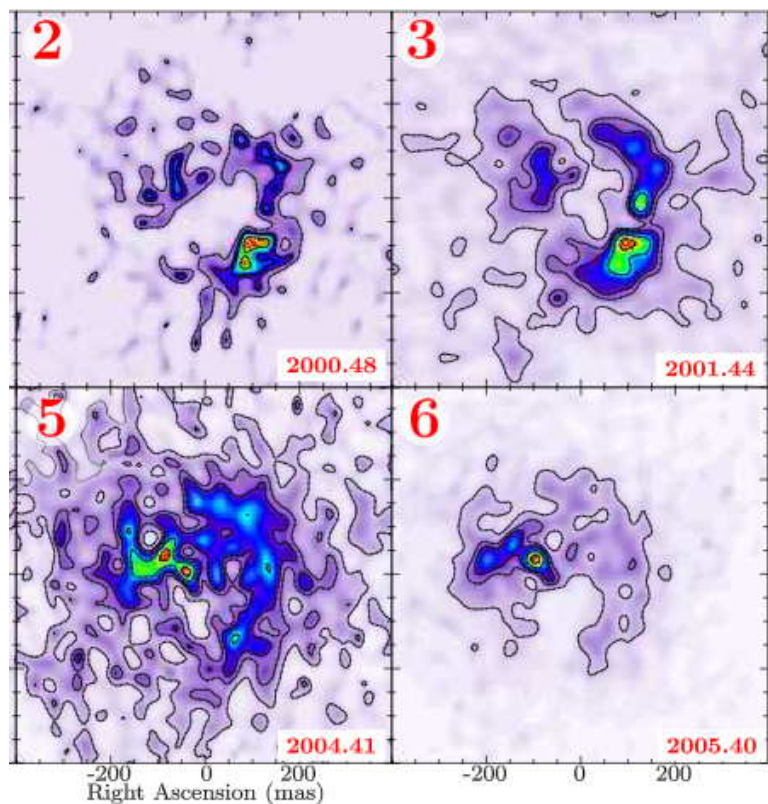
From The Atmosphere To The Circumstellar Environment In Cool Evolved Stars,
Marcus Wittkowski & Claudia Paladini, arXiv:1501.05825v1

Interferometric Measurements of O-rich Mira Stars Consistent with Multiple Scenarios for Dust Grain Growth

- Al_2O_3 grains only (seed particles)
- Warm silicates only
- Both

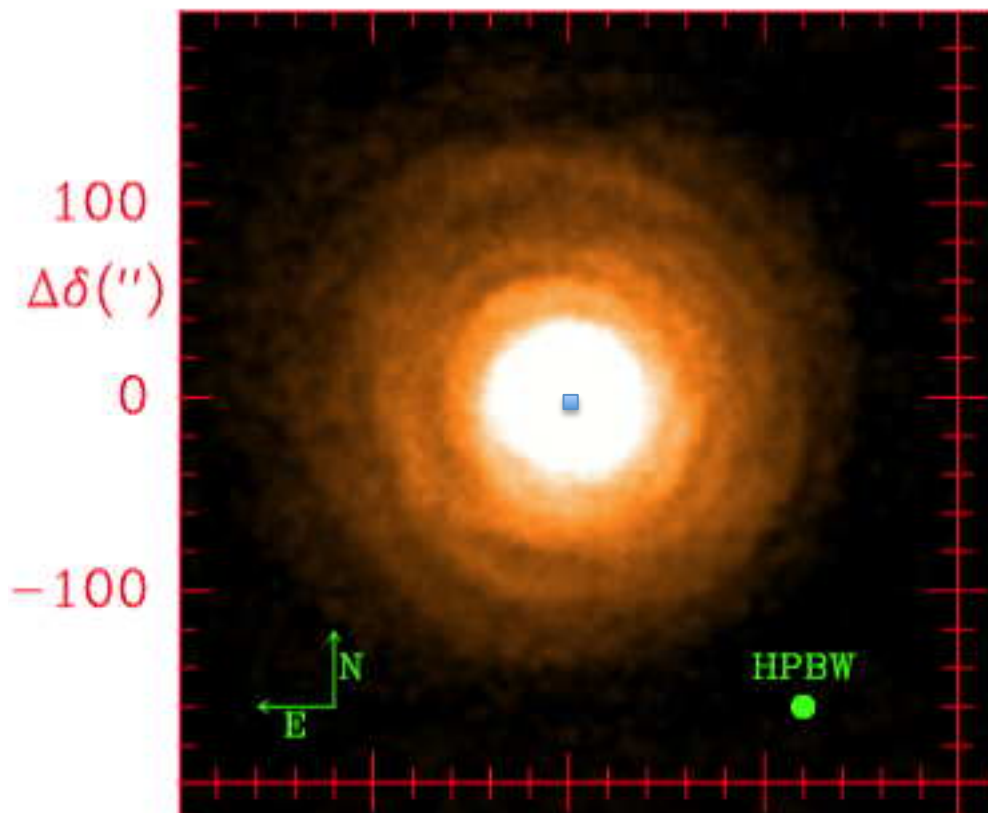
Interferometric Constraints on Molecule and Dust Formation in Oxygen-rich Mira stars, **Marcus Wittkowski** et al., ASPC 497, 327 (2015)

Mass Loss History from Envelopes



$\lambda = 2.27 \mu\text{m}$

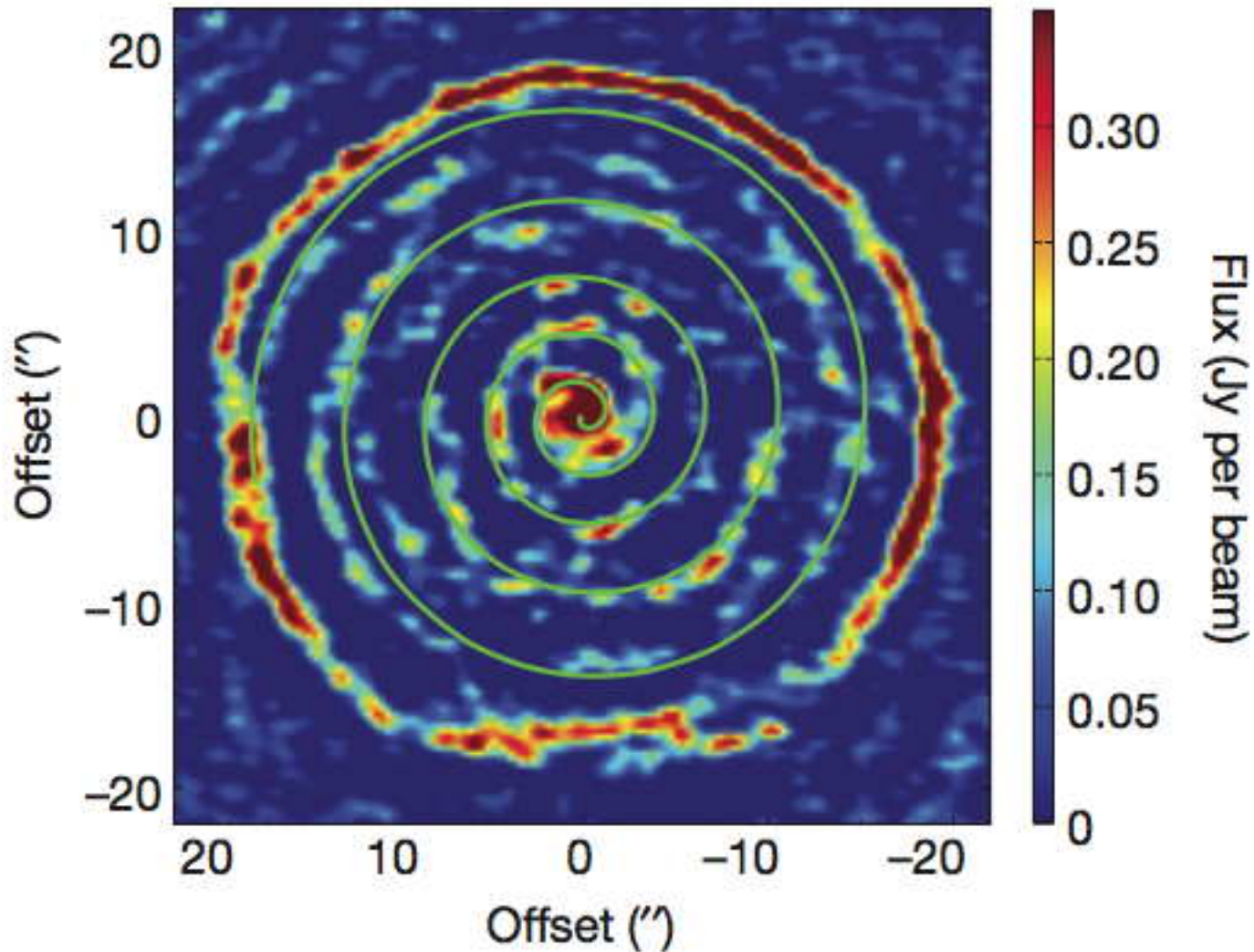
The weather report from IRC 10216: evolving irregular clouds envelope carbon star, P.N. Stewart et al., MNRAS 455, 3102 (2016)



velocity-integrated CO ($J = 2-1$)

Molecular shells in IRC+10216: tracing the mass loss history, J. Cernicharo et al., A&A 575, A91 (2015)

Mass Loss History from Envelopes



Unexpectedly large mass loss during the thermal pulse cycle of the red giant star R Sculptoris, M. Maercker, **Elizabeth Humphreys** et al., Nature 490, 232 (2012)

Spiral Structure in the Wind of CW Leo

- The molecular emission lines trace different regions in the wind acceleration region and suggest that the wind velocity increases rapidly from about $5 R_*$ almost reaching the terminal velocity at $11 R_*$
- From modeling the ALMA data, we deduce that the potential orbital axis for the binary system lies at a position angle of $10\text{--}20^\circ$ to the North-East and that the spiral structure is seen almost edge-on. We infer an orbital period of 55 yr and a binary separation of 25 au (or $8.2 R_*$). We tentatively estimate that the companion is an unevolved low-mass main-sequence star.

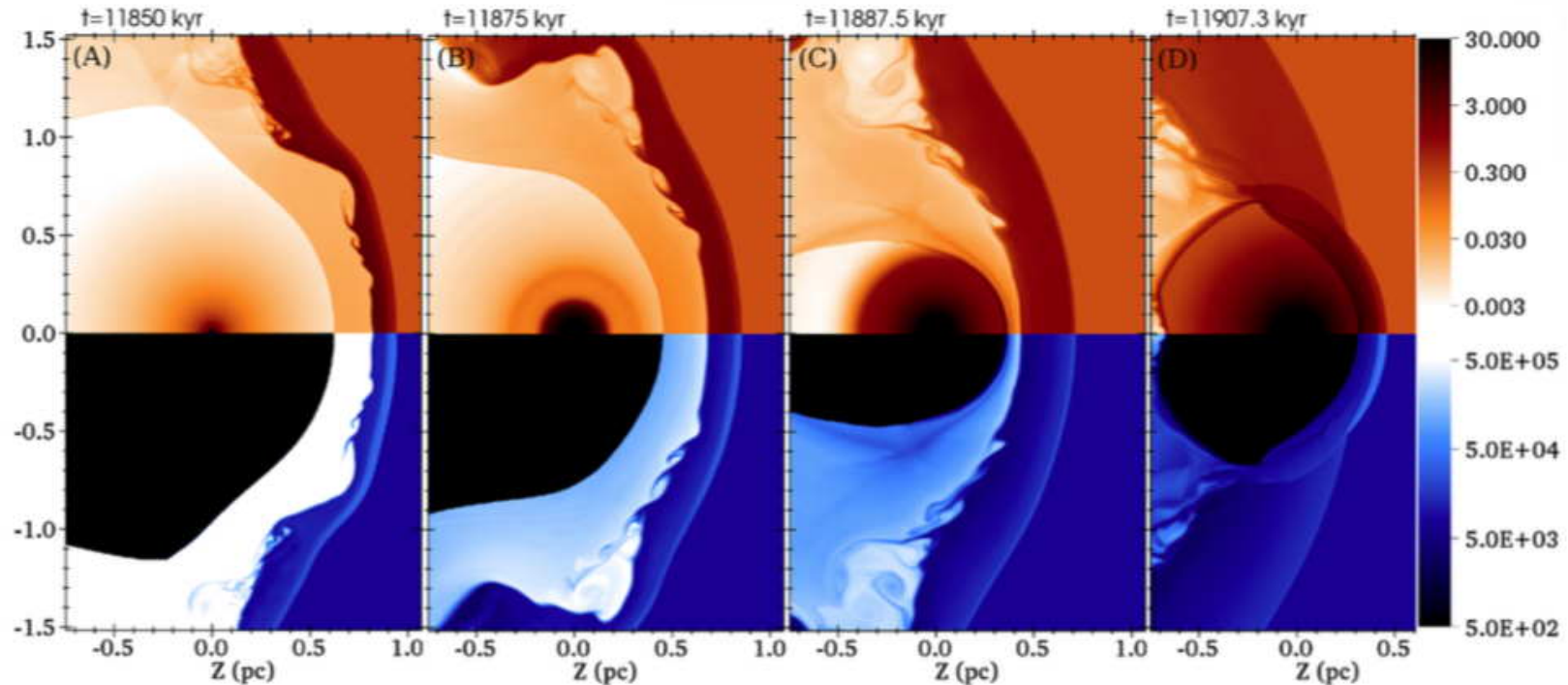
ALMA data suggest the presence of a spiral structure in the inner wind of CW Leo, **Leen Decin et al.**, A&A 574, A5 (2015)

How do AGB Shells Relate to PN?

- Approximately 80% of a sample of PN show asymmetry, commonly attributed to binarity*.
- Do most AGB stars show evidence of shell asymmetry or binarity? Difficulty of distinguishing random clumping from systematic structure.
- (But, PN statistics are based on ~3000 objects out of an expected 25,000.)

* Searching for Faint Planetary Nebulae Using the Digital Sky Survey, G.H. Jacoby et al., PASA 27, 156 (2010)

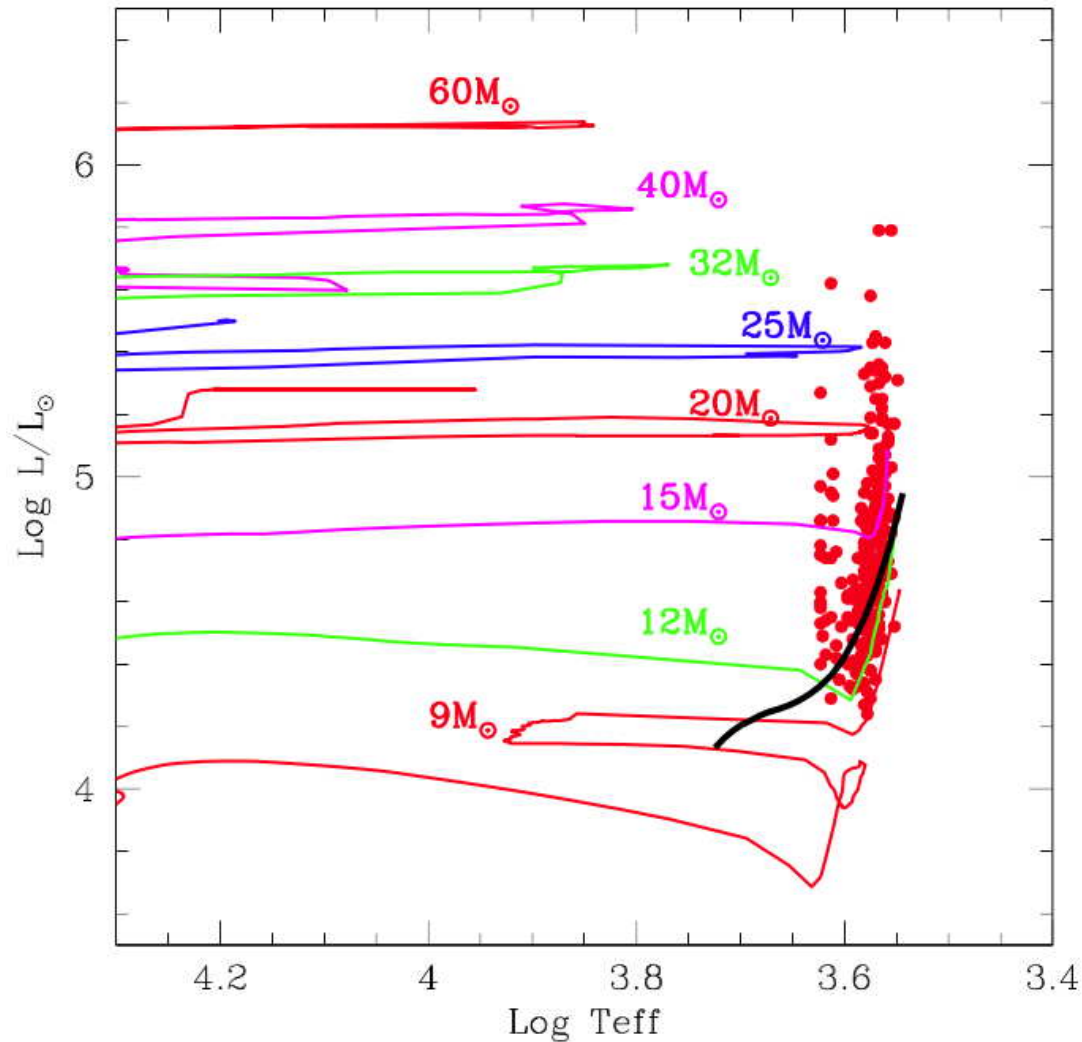
Betelgeuse Recently Evolved from Blue Supergiant Phase (<25K years)?



The Circumstellar Medium of Massive Stars in Motion, J. Mackey et al.,
arXiv:1406.0878v1 (2014)

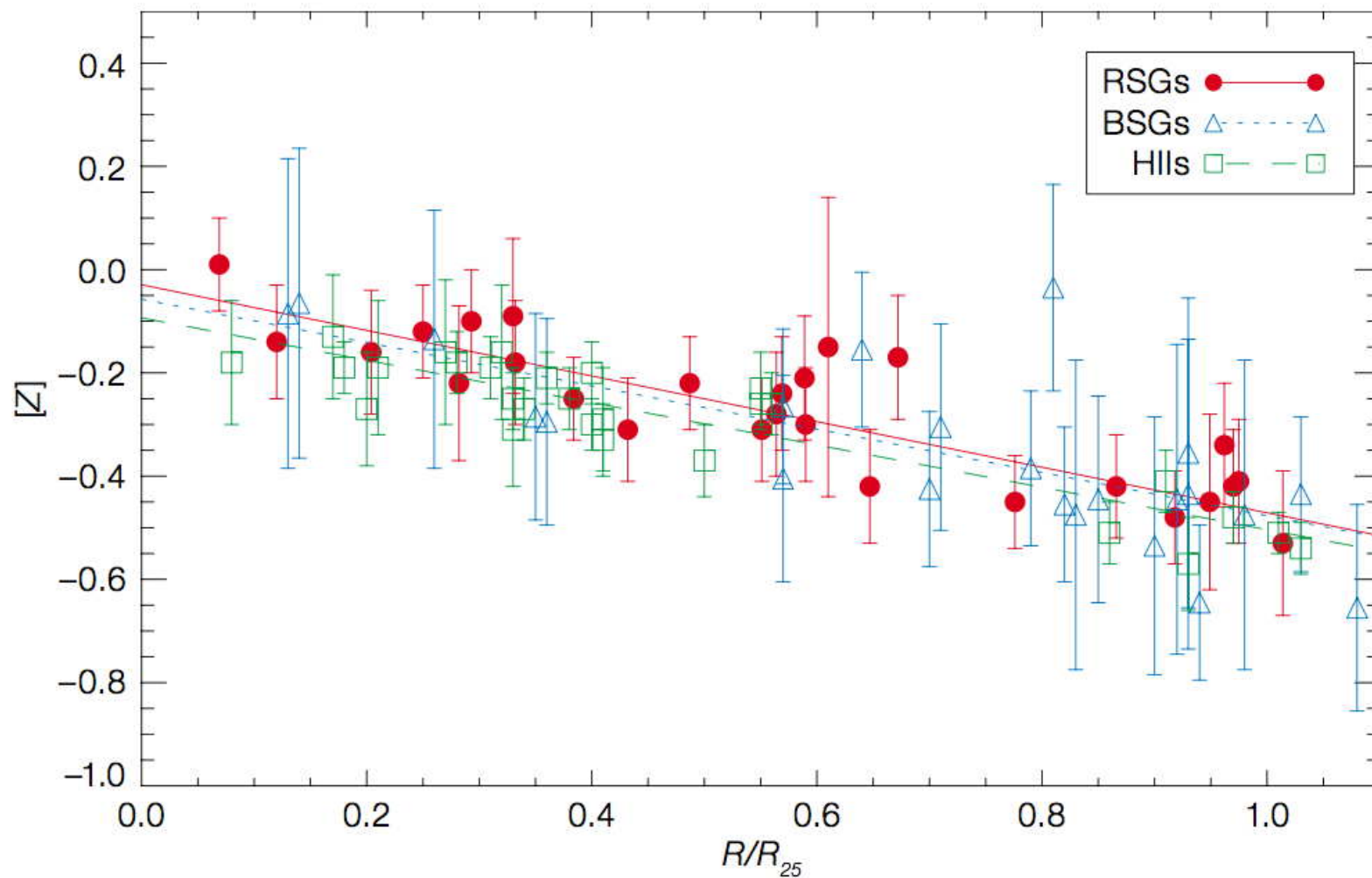
Betelgeuse SN video: <https://www.youtube.com/watch?v=dtWeH4-Ugy4>

Extra-galactic – Local Group



The Red Supergiant Content Of M31, P. Massey & A. Evans,
ApJ 826, 224 (2016)

Metallicity Gradient in NGC300



Red Supergiants As Cosmic Abundance Probes: The Sculptor Galaxy Ngc 300, J.A.Gazak et al., ApJ 805, 182 (2015)

(Some of the) Areas Not Mentioned

- RSG evolution
- Chemistry in envelopes
- Mass loss physics
- Nucleosynthesis
- Binary evolution
- Polarization
- Global oscillations
- Galactic evolution, structure and abundances
- RSGs, SNe and failed SNe
- RSG traces in SN shells

Hot topics – From the Inside Out

Asteroseismology

Binary physics and evolution

- * Long time-baseline precision photometry
- * Evolutionary models and resonant modes
- * Limb darkening and atmospheric depth
- * Surface structure and convection
- * Surface motions
- * Inner envelope structure and motions
- * Mass loss rate and dependencies
- * Dust grain chemistry and growth
- Mass loss physics
- * Mass loss history
- * Envelopes and PN
- Supernovae and failed supernovae
- Tracers in SN shells
- * Evolutionary tracks from Local Group galaxies
- * Abundance patterns in other galaxies