The importance of atmospheric molecular layers for the mass-loss process of cool evolved stars

Markus Wittkowski (ESO),

and several collaborators on different projects

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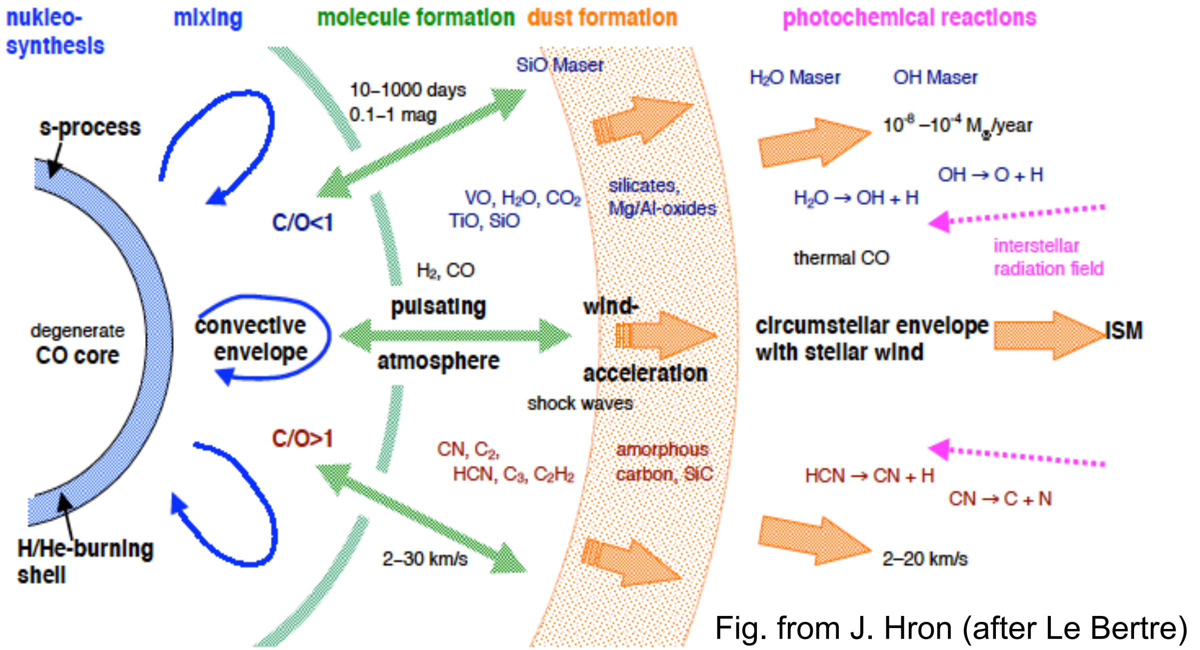

Fig. from J. Hron (after Le Bertre)

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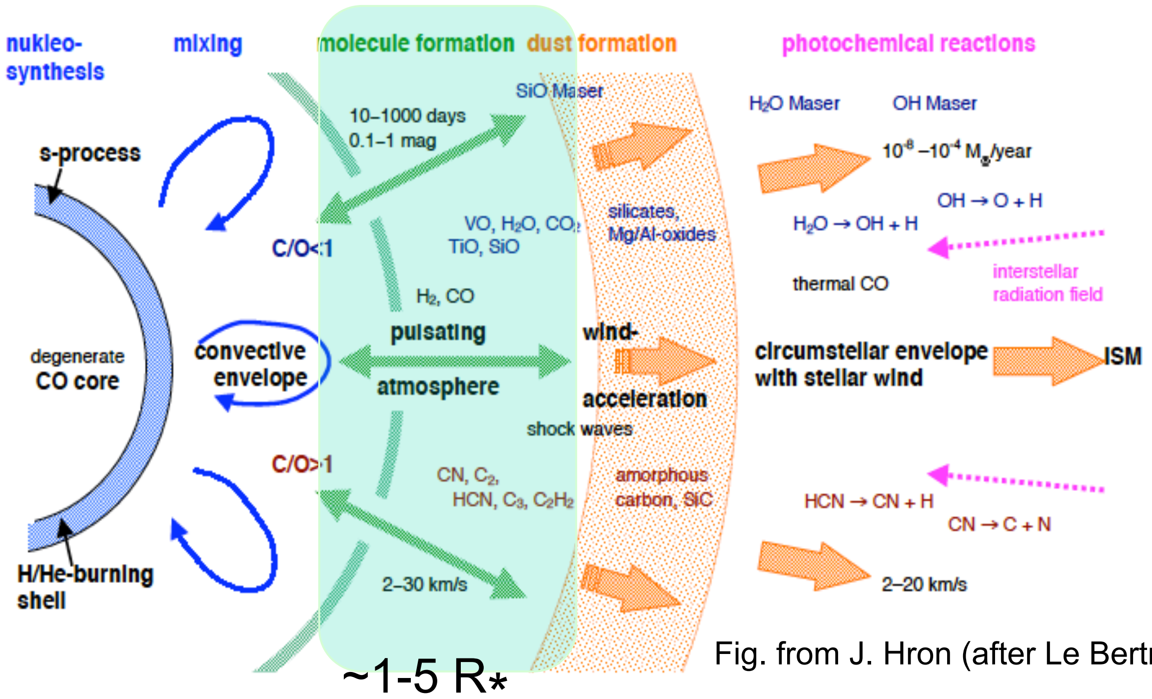
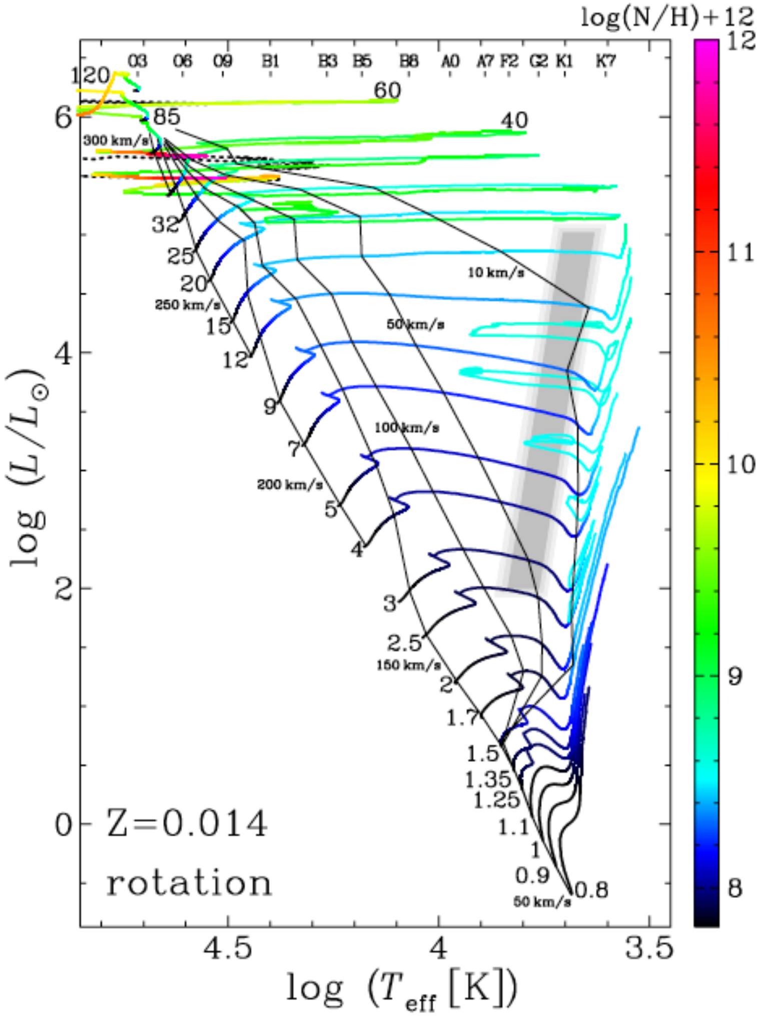


Fig. from J. Hron (after Le Bertre)

Cool evolved stars



Evolutionary tracks with rotation from Ekström et al. (2012)

- Red giants, AGB stars, red supergiants
- Along the Hayashi track in the HR diagram
- Low effective temperatures between about 2500K and 4000K and low surface gravities

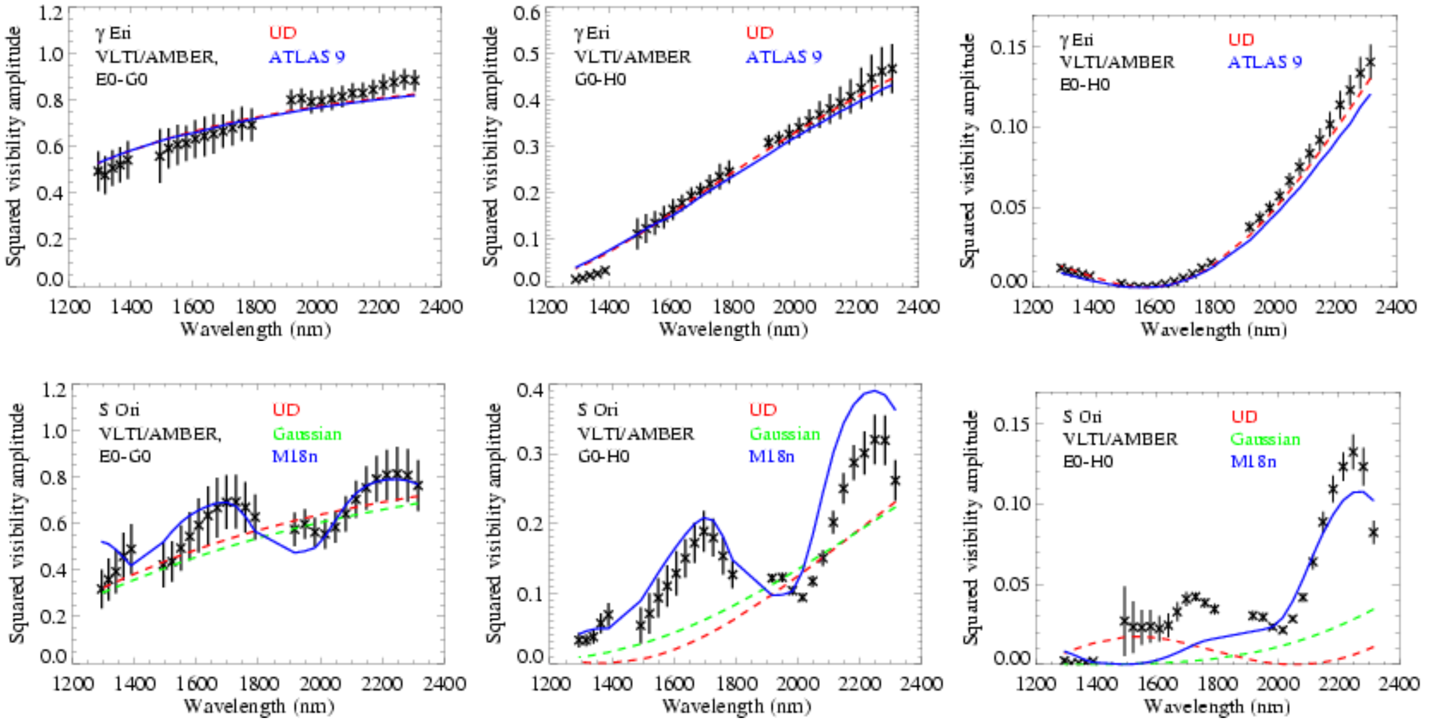
Cool evolved stars: Mass loss

- Thought to be triggered by pulsation-driven extended atmospheres, dust formation, and radiative acceleration on dust grains dragging along the gas. Well constrained for carbon-rich Miras. Further details are surprisingly little understood, in particular for oxygen rich Mira stars, and even less for semi-regular AGB stars, RSGs, and red giants.
- Dust grains and inner radii may be in principle similar between oxygen-rich AGB stars and RSG stars, but with differences in the details. Details on seed particles and the dust condensation sequence is not clear for oxygen-rich stars.
- Shaping processes toward PNe thought to be dominated by the effects of companions.
- Effects of companions, and of other shaping mechanism (convection, magnetic fields) on the inner atmospheric molecular layers, where the mass loss is initiated?

Molecular layer scenario - Traditions

- Tsuji (2001) and earlier: Based on ISO data: “We confirm that a rather warm molecule forming region should exist as a new M giant component of the atmosphere of red giant stars and that this should be a general phenomenon in late-type stars” – “MOLsphere”
- Bessel, Scholz, Wood (1996); Hofmann, Scholz, Wood; Hofmann, Scholz (1998) and earlier: non-Mira and Mira M giant models: Dynamic model atmospheres of M giants naturally produce extended molecular layers in agreement with observed spectra
- Similar for dynamic atmospheres of carbon stars
- *Narrow-band* interferometry with IOTA of a Mira star and a RSG by Perrin et al. (2004, 2005) confirmed the molecular layer scenario by spatially resolved observations.

AMBER spectro-interferometry: Mira stars



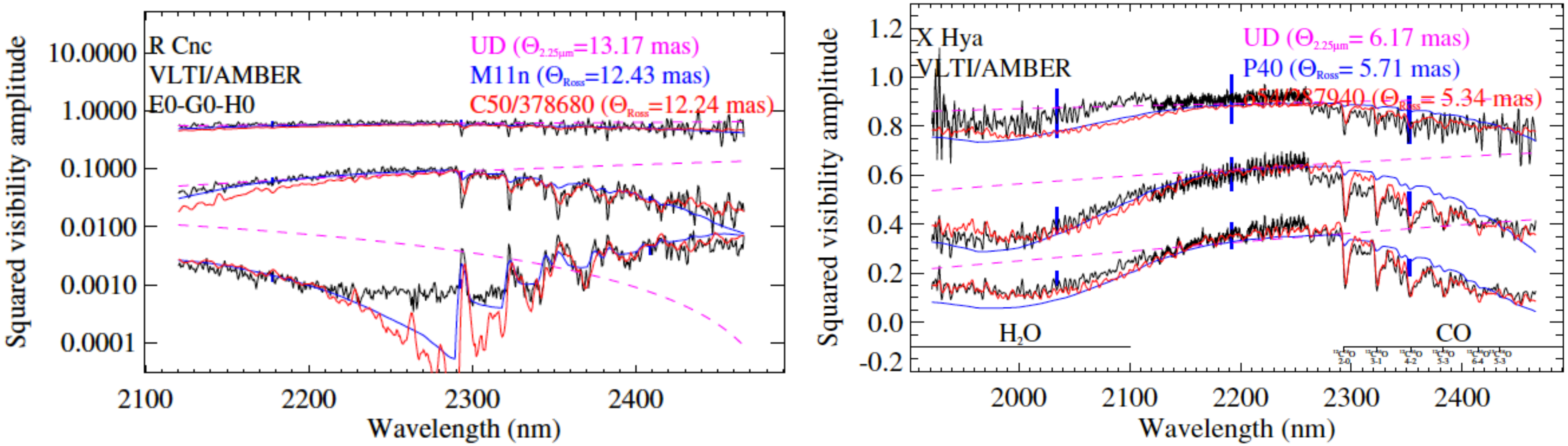
M giant

Mira

The bumpy visibility curve is a signature of molecular layers lying above the photosphere.
At some wavelengths, the molecular opacity is low, we see the photosphere, the target appears smaller.
At other wavelengths, the molecular opacity is larger, we see the water shell, the target appears larger.
AMBER allows us to probe different layers of the extended atmosphere.
Visibility and UD diameter variations with wavelength resemble reasonably well the predictions by dynamic model atmospheres including molecular layers, in particular water vapor and CO.

Wittkowski, et al. 2008

Mira stars and pulsation models



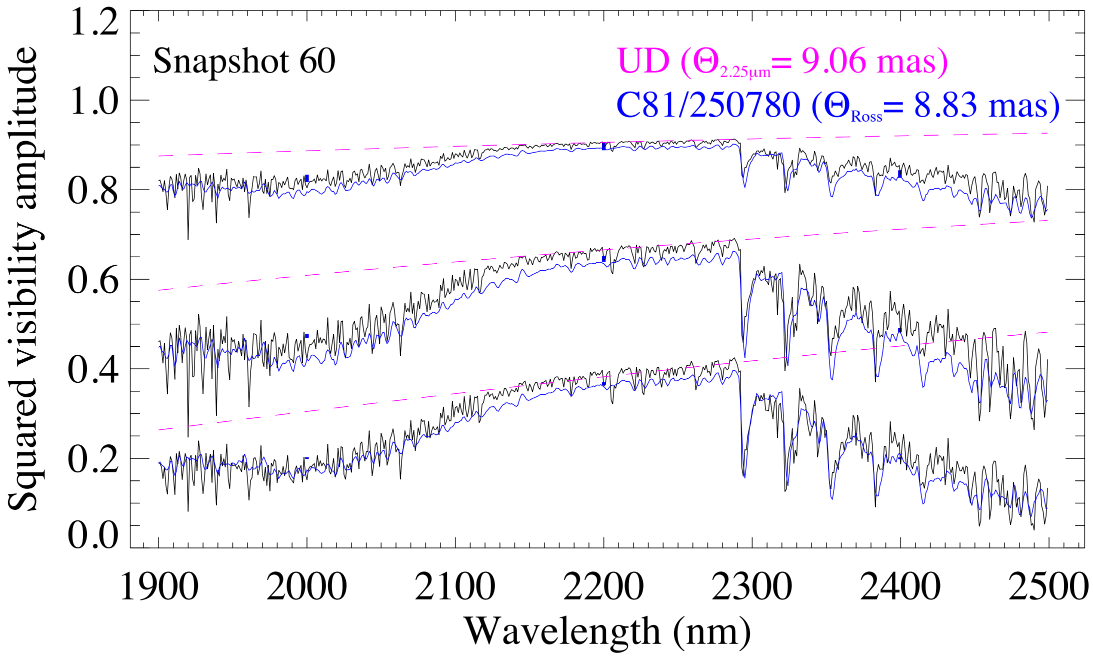
Visibilities are well consistent with predictions by the latest dynamic model atmosphere series based on self-excited pulsation models and including atmospheric molecular layers (CODEX models by Ireland, Scholz, & Wood 2008, 2011). However, these models do not yet explain an outflow/mass loss.

Best-fit parameters (phase, T_{eff}, distances) consistent with independent estimates. Teff also determined from best-fit angular diameter and simultaneous SAAO photometry.

Wittkowski et al. 2011

Pulsation models versus convection models

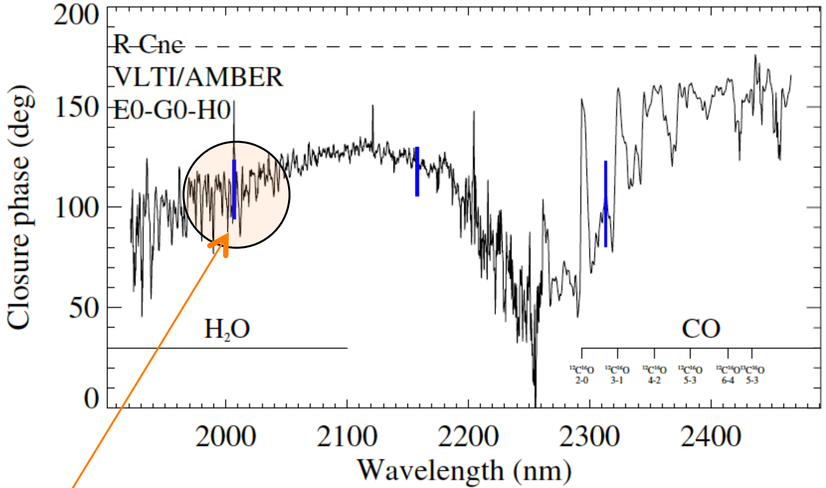
Freytag & Höfner (2008): “The strong atmospheric shock waves associated with the giant convection cells lead to a levitation of the upper atmospheric layers in the 3D models. This is comparable to the effect of stellar pulsations – simulated by a variable membrane below the photosphere (piston) – in the 1D models.”

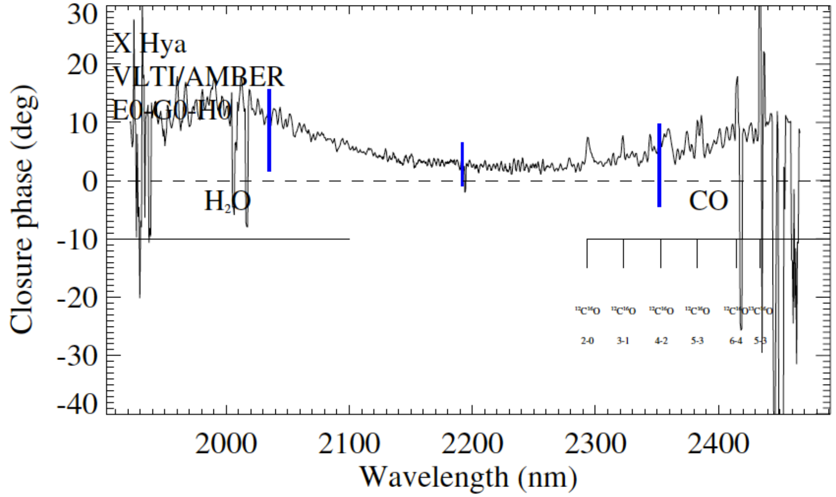


Indeed, synthetic visibility data from these 3D simulations are well consistent with those from CODEX 1D self-excited pulsation models.

Chiavassa/Wittkowski, in progress

Wavelength-dependent closure phases





For example, one unresolved spot at separation 4 mas contributing 3% of the total flux

Wavelength-dependent closure phases indicate deviations from point symmetry at all wavelengths and thus a complex non-spherical stratification of the atmosphere. In particular, the strong closure phase signal in the water vapor and CO bandpasses is interpreted as a signature of large-scale inhomogeneities/clumps of molecular layers.

These might be caused by pulsation- and shock-induced chaotic motion in the extended atmosphere as theoretically predicted by Icke et al. (1992) and Ireland et al. (2008, 2011).

Wittkowski et al. 2011

VLTI/AMBER two-epoch imaging of the Mira X Hya

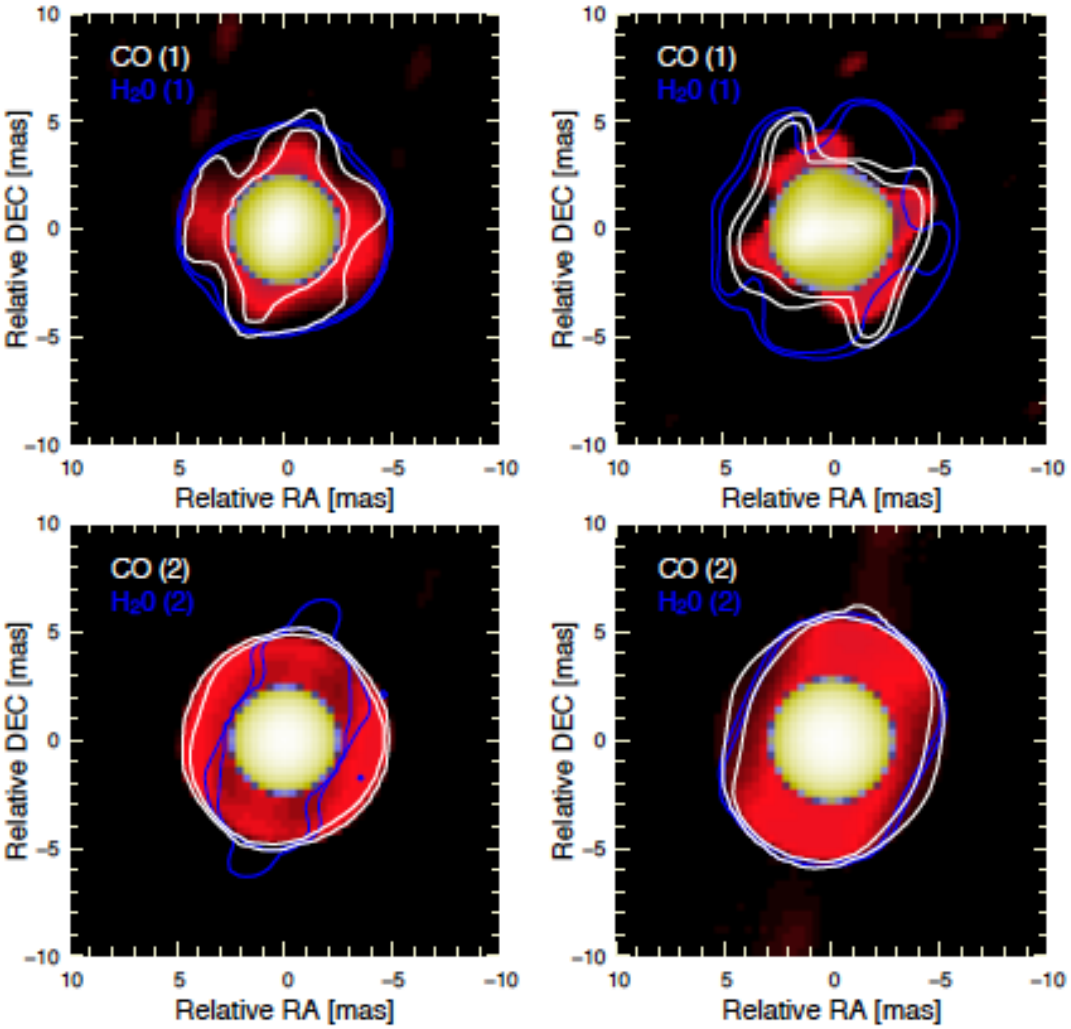
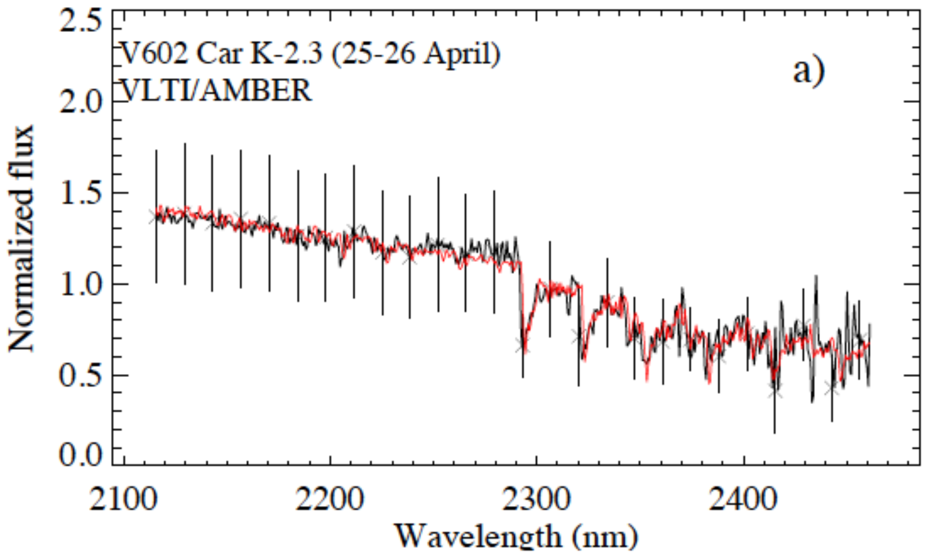


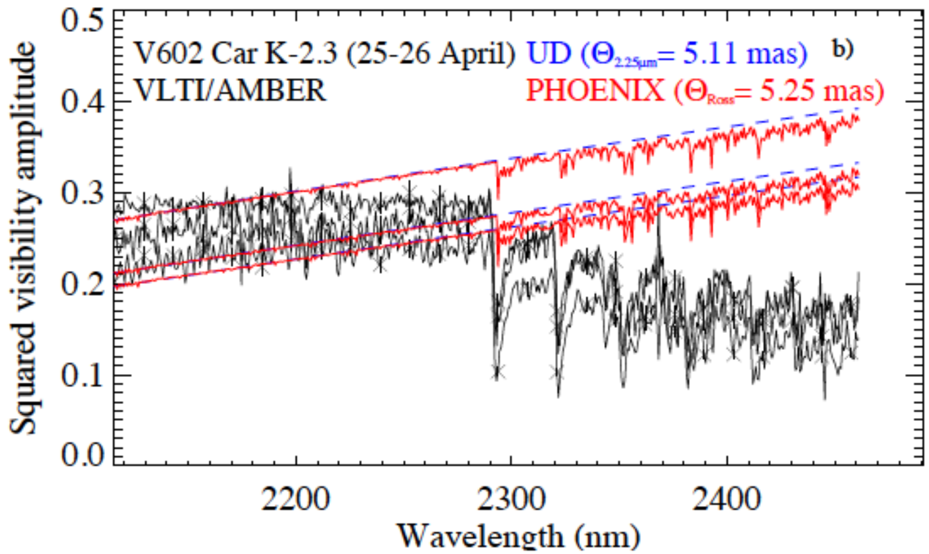
Fig. 16. Continuum images overplotted (Fig. 13) with H_2O (blue) and CO (white) intensity contours (from Figs. 14 and 15). Intensity contour levels represent 2% and 5% of the maximum intensity of each image and allow to compare the extension and shape of the environment between spectral bands for Epoch A (left panels) and B (right panels). Upper panels represent the Cont (1), H_2O(1) and CO(1) bands whereas the lower panels represent the Cont (2), H_2O(2) and CO(2) bands.

- Angular scale change between phase 0.0 and 0.2
- 1D CODEX profiles consistent with spectral variation of squared visibilities
- Reconstructed model-dependent images reproduce closure phase, showing phase-dependent material inhomogeneities located in the atmospheric molecular layers

Haubois et al. 2015, A&A, submitted

AMBER spectro-interferometry: RSGs



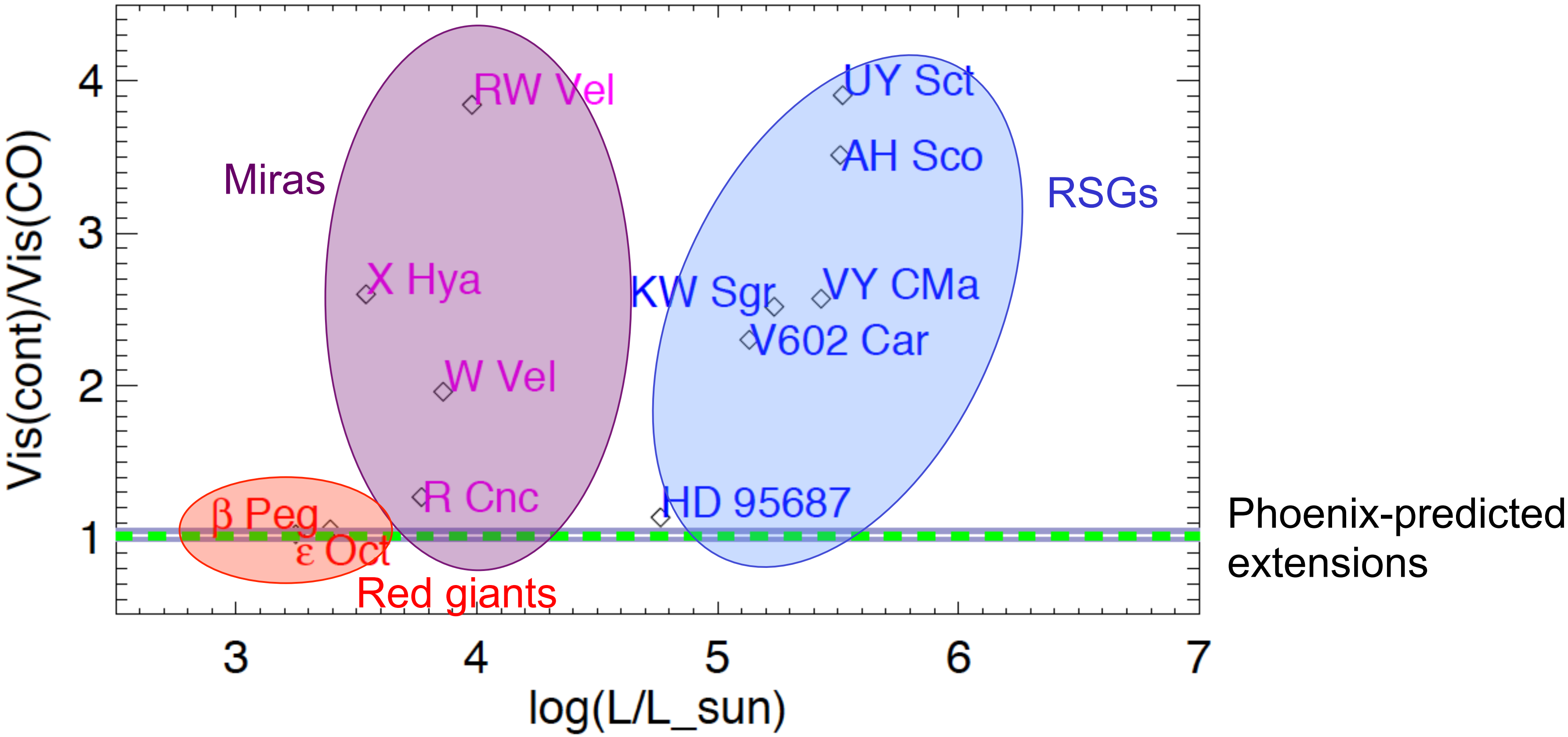


The PHOENIx model atmospheres reproduce the spectra fairly well, but do not predict the drops of the visibility in the water vapor and CO bands.

This means that the molecular opacities are included, but that the models are too compact compared to our observation.

Arroyo-Torres et al. 2013; 2015

RSGs: Atmospheric extension versus luminosity

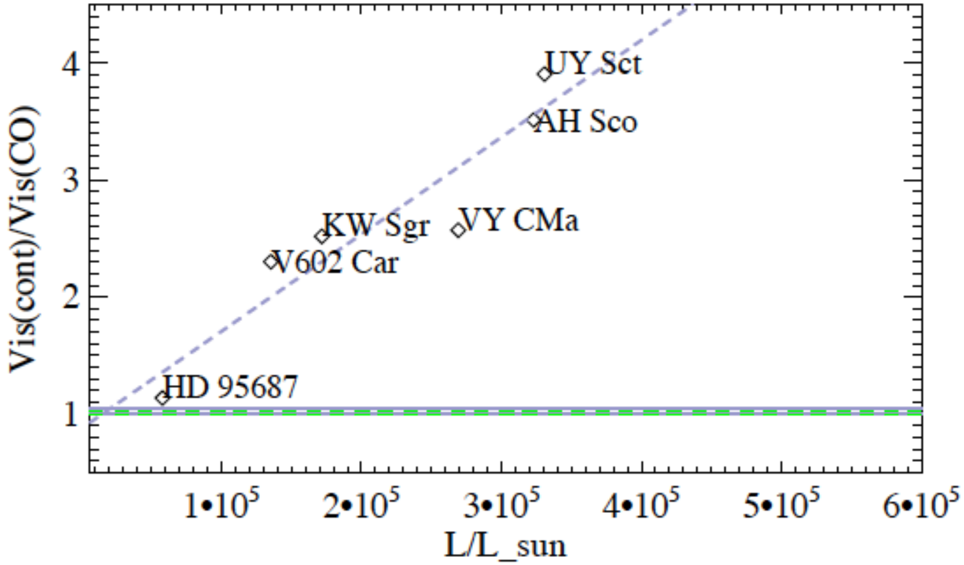


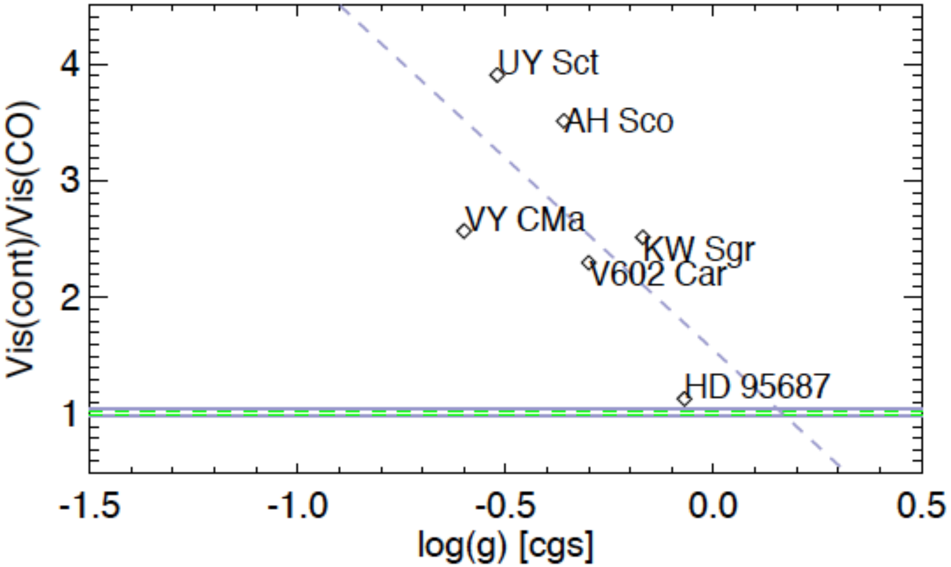
RSG stars and Mira stars have similar atmospheric extensions.

Mira model extensions are of the order of 2-3 photospheric radii.

Arroyo-Torres et al., 2015

RSGs: Atmospheric extension versus luminosity

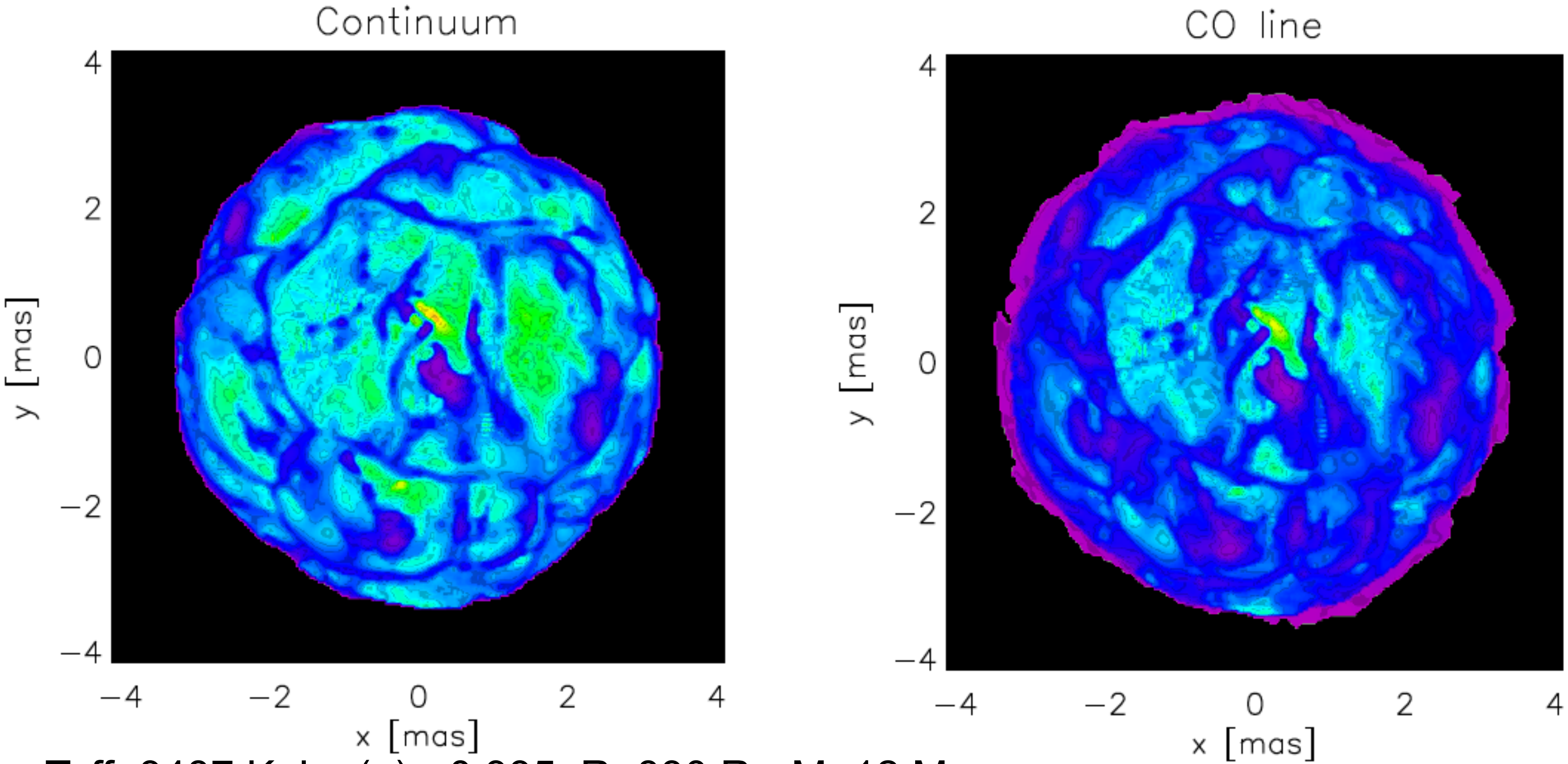




- The atmospheric extension of RSGs (based on the 1st CO bandhead) increases with increasing luminosity and decreasing surface gravity
- This correlation is not observed for Miras, pointing to a different physical mechanism
- Considerable extensions are only observed for luminosities above about 10^5 L_{sun} and below log g ~ 0.0

Arroyo-Torres et al., 2015

Comparison to convection models

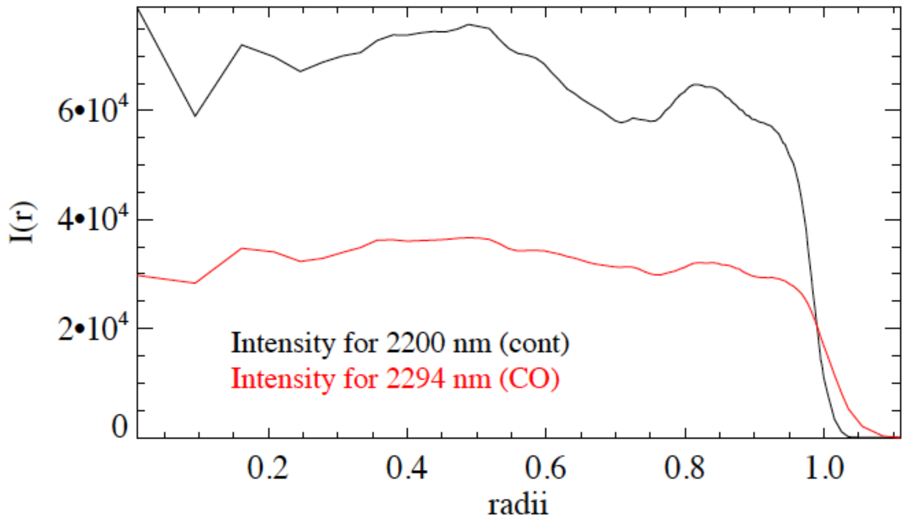


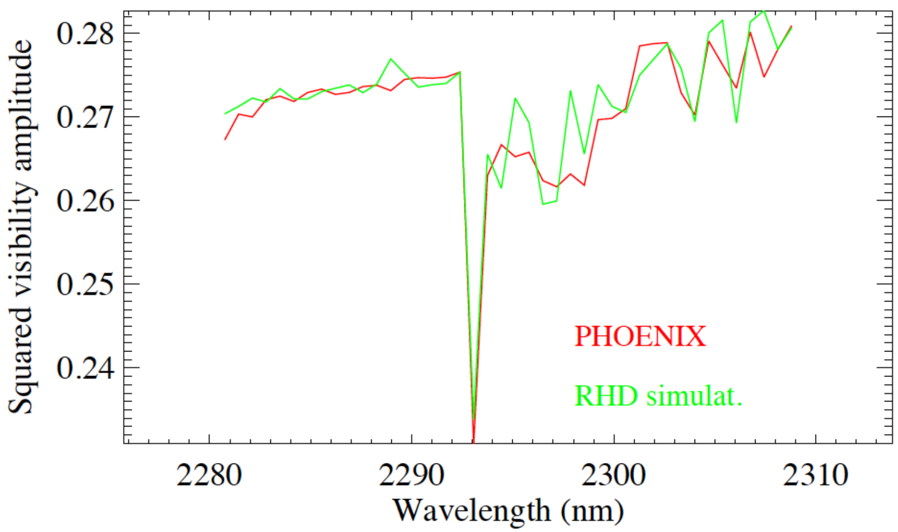
Teff=3487 K, log(g)=-0.335, R=830 $R_\odot$, M=12 $M_\odot$

The detailed surface structure in the CO line intensity map appears less corrugated and the details (eg.,intergranular lanes) almost disappear. The CO line surface looks slightly more extended (purple color close to the stellar limb).

Arroyo-Torres et al., 2015

Comparison to convection models

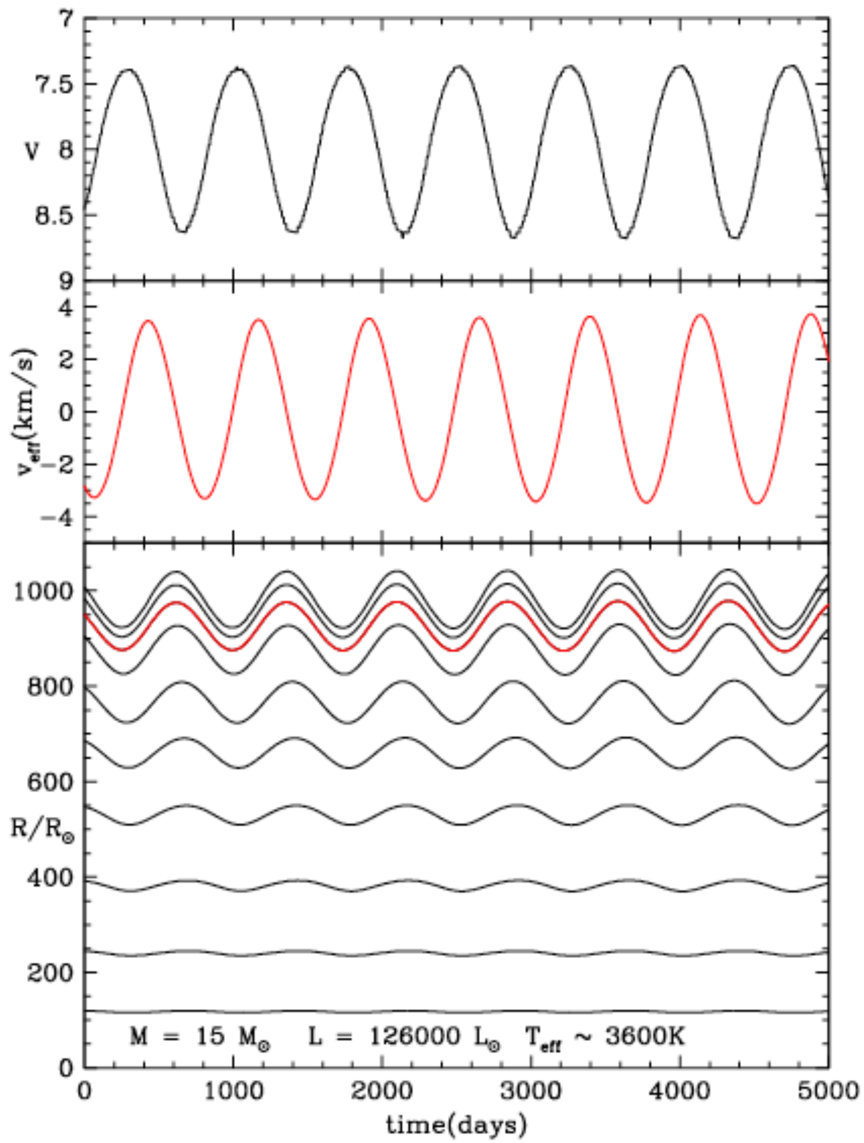




- The intensity in the CO line is lower by a factor of about 2 compared to the intensity in the continuum, which is consistent with observed flux spectra
- The CO line surface is slightly more extended than the continuum surface, but only by a few percent (~7% at the limb)
- The model-predicted visibility curves of the 3D RHD simulation are very similar to the hydrostatic PHOENIX model at the AMBER resolution and can thus not explain the large observed atmospheric extensions of RSG stars

Arroyo-Torres et al., 2015

Comparison to pulsation models (V602 Car)



- Amplitude of the photospheric radius variation is about 10% with radial velocities of up to about 5 km/ sec.
- The model reproduces the amplitude of the visual lightcurve of V602 Car of ~ 1 mag
- The velocities are consistent with observed long-term measurements (e.g Gray et al 2008)
- Whilst shock fronts enter the stellar atmosphere in a typical CODEX model of a Mira variable at or below optical depth 1, leading to a geometric extension of the stellar atmosphere of the order a few Rosseland radii it turns out that no shock fronts reach at any phase the atmospheric layers in case of the RSG model.
- The RSG pulsation model leads to an atmosphere as compact as the hydrostatric PHOENIX model, and can not explain the observed atmospheric extensions

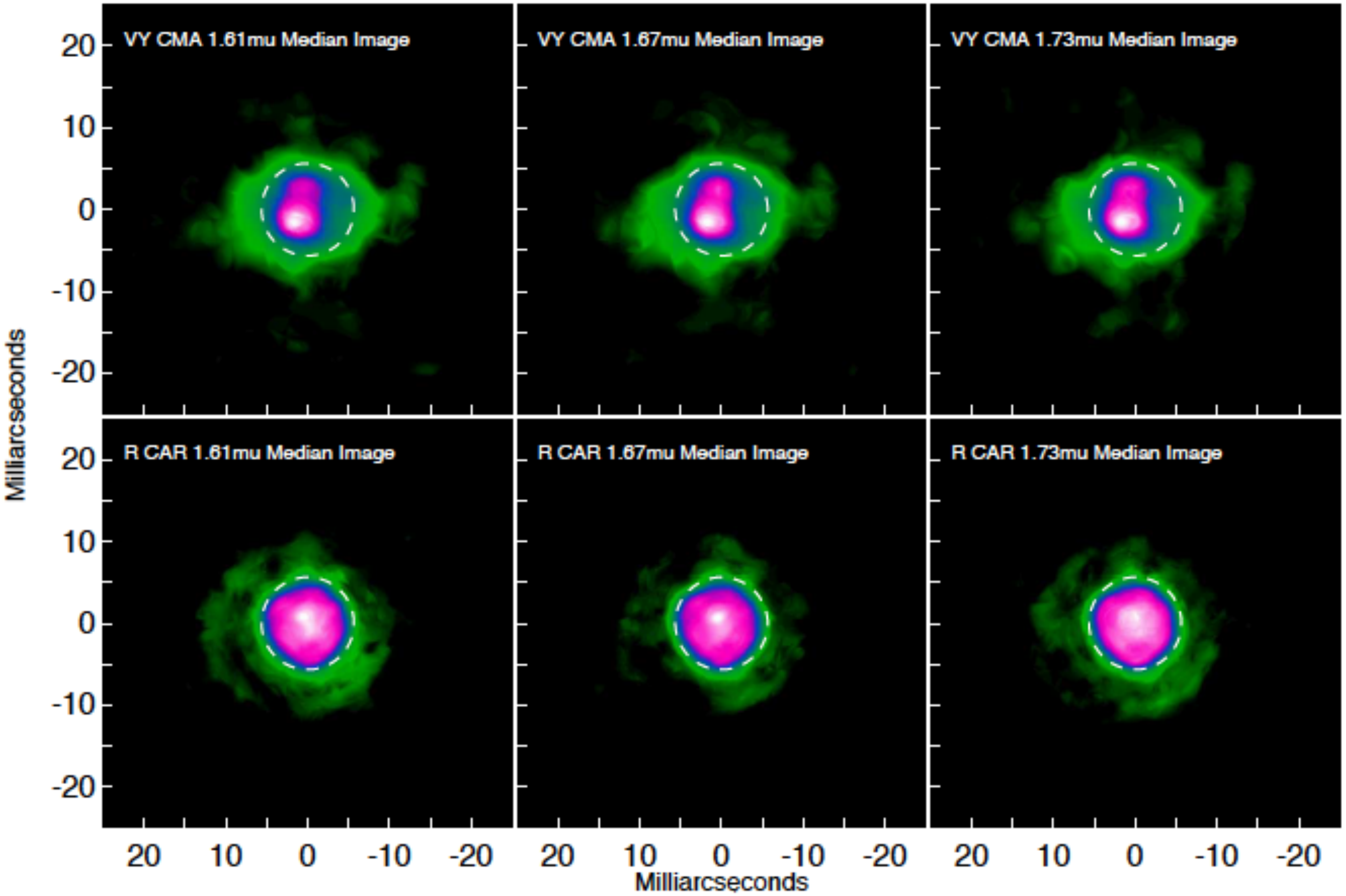
Arroyo-Torres et al., in prep

Alternative mechanisms for RSGs

- Velocities higher than those predicted by pulsation models have been observed on time scales much shorter than the variability period (e.g. Josselin & Plez 2007, Gray et al. 2008) . Possibly caused by convective motion.
- There is an observed correlation of atmospheric extension with increasing luminosity, pointing to a radiatively driven acceleration
- Hypothesis: Higher velocities and shocks give rise to a significant Doppler shift, so that radiation pressure on Doppler-shifted lines could accelerate the material -- in a way reminiscent of what happens in the winds of hot stars
- Dust might form at small radii (a few stellar radii) as for Miras and acceleration on dust grains might drive the wind

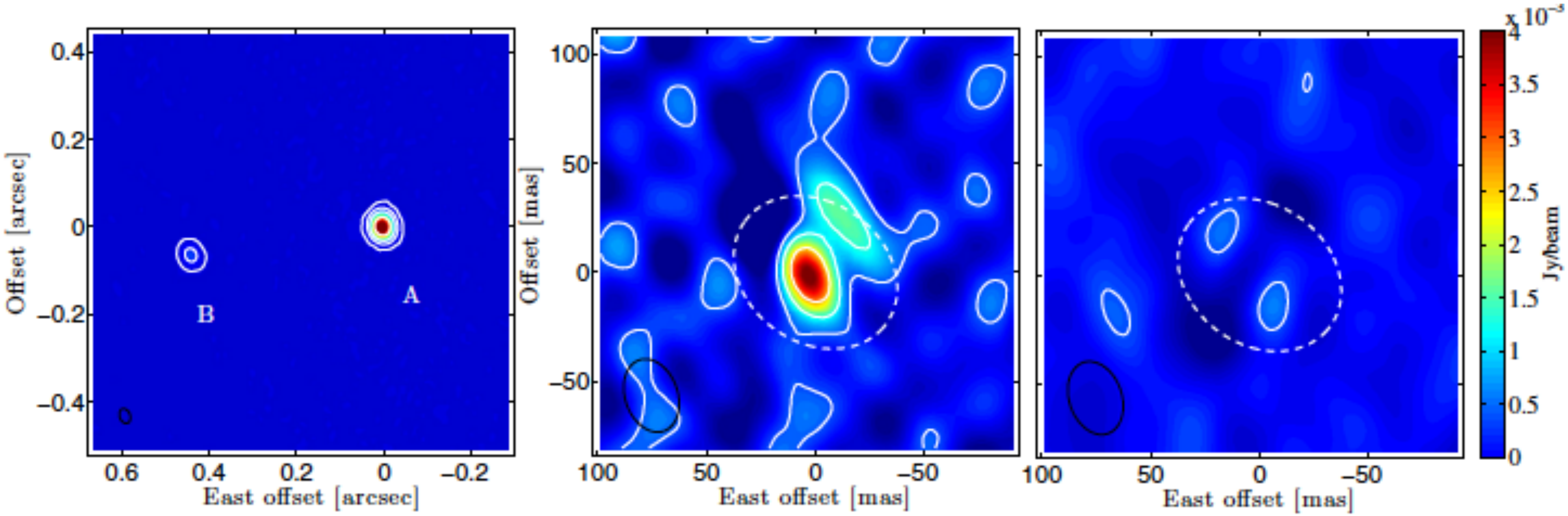
Arroyo-Torres et al., 2015

VLTI/PIONIER images of the RSG VY CMa and the Mira star R Car



Monnier et al. 2014, SPIE, 9146, 91461Q

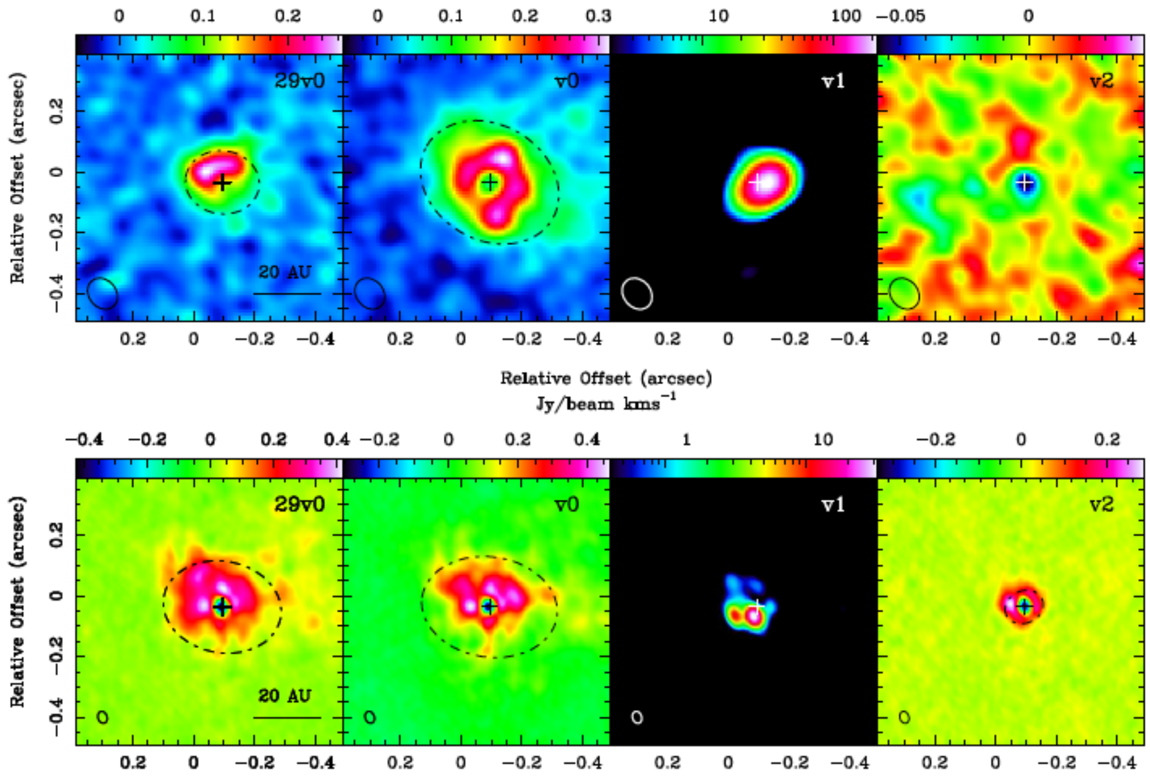
ALMA continuum emission toward Mira AB



- Extended atmosphere resolved for the first time at these frequencies
- For Mira A the diameter is ~3.8 x 3.2 AU in Band 3 and ~4.0 x 3.6 AU in Band 6.
- Additionally, a bright hotspot ~0.4 AU, with **Tb** ~ 10 000 K, is found on the stellar disk of Mira A, likely due to magnetic activity

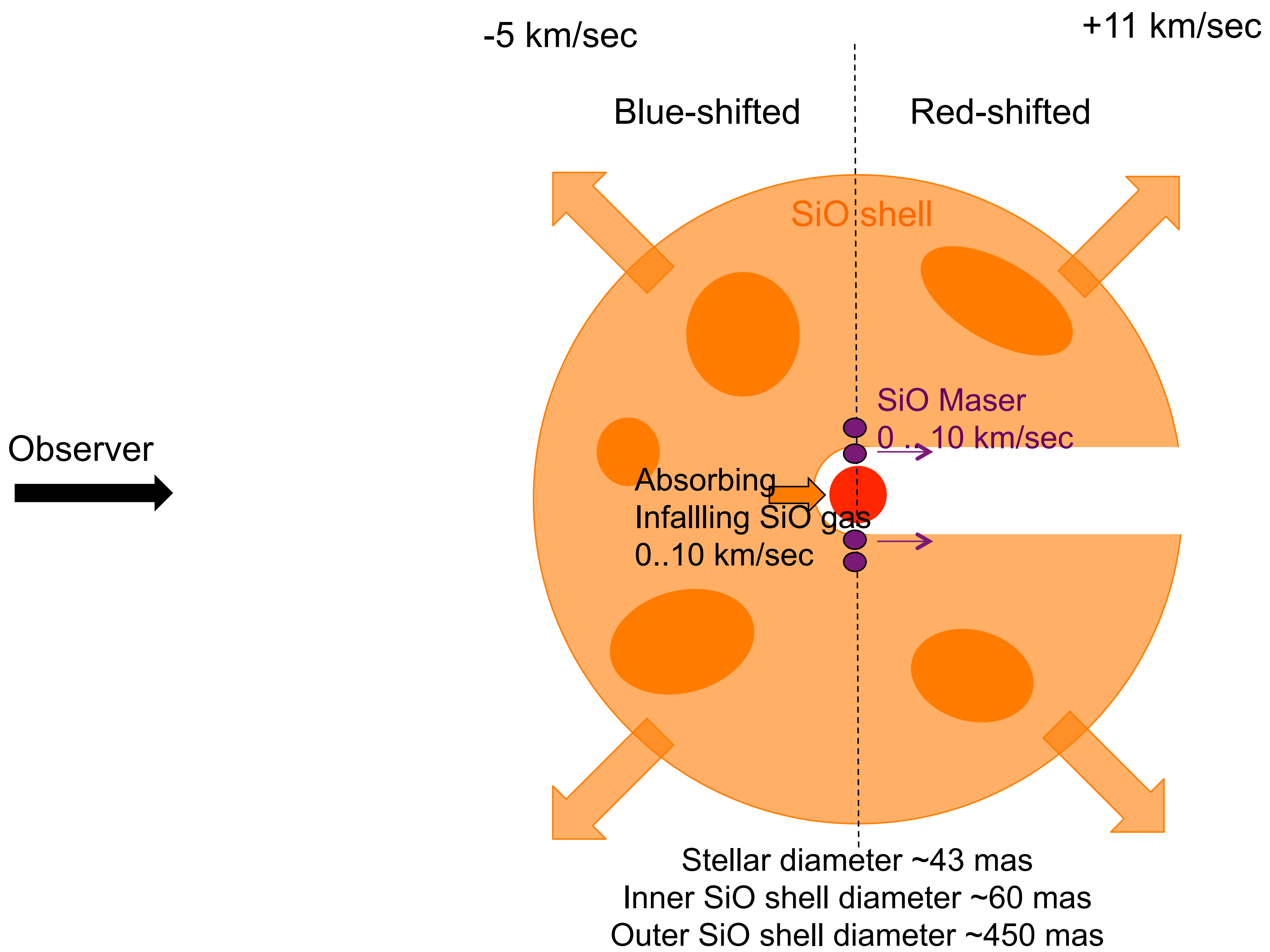
Vlemmings et al. 2015

SiO emission toward o Ceti with ALMA
Band 3:J=2-1 ; Band 6: J=5-4

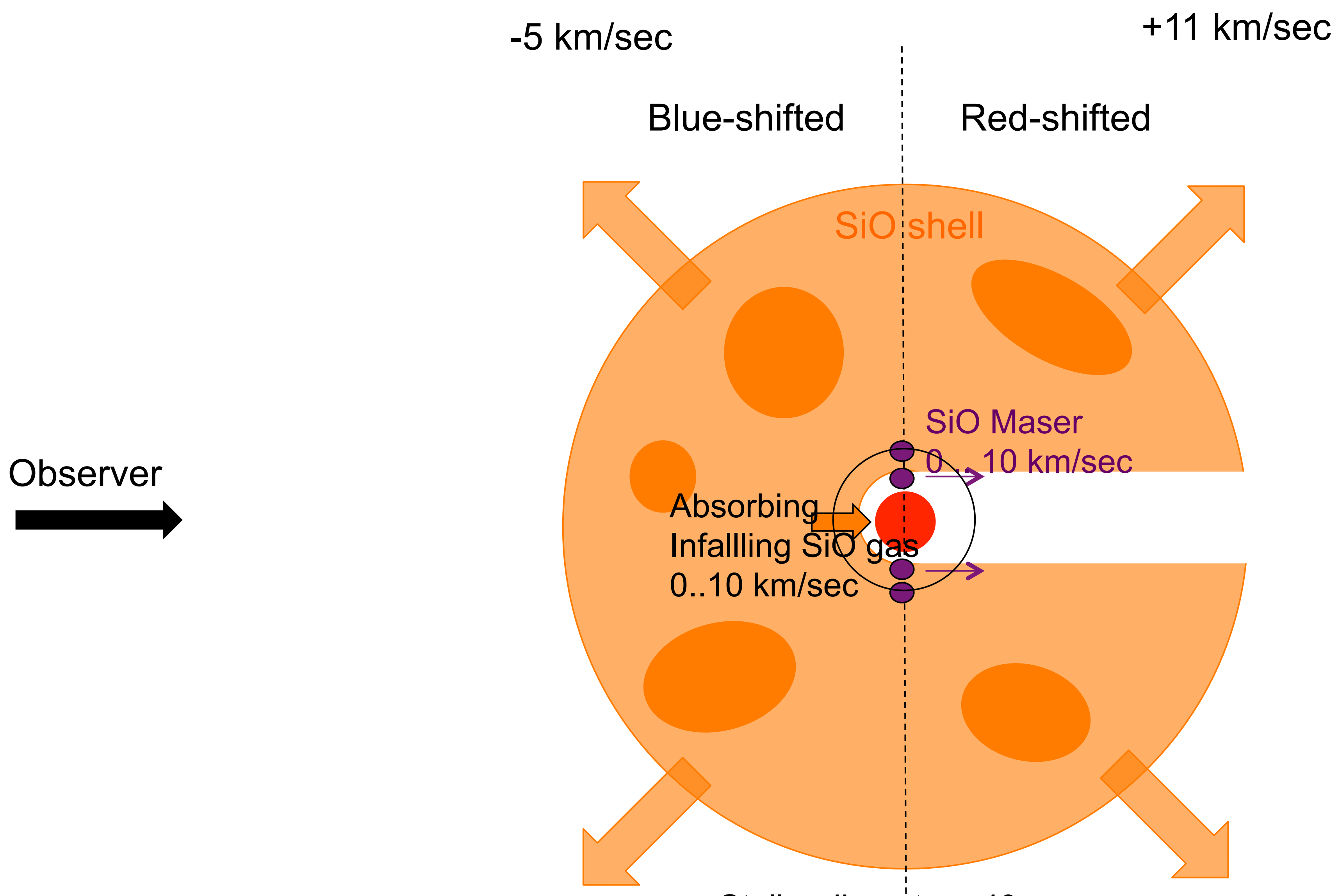


- Ground state transitions: Clumpy expanding shell like morphology with FWHM size ~20 x 40 AU
- Brightest clump(s) of te ^{28}SiO, v=0, J=2-1 transition shows evidence for maser emission
- The v=1 transitions show clear evidence for maser emission at 3-7 AU with velocity offsets of ~8 km/sec
- Several transitions show central intensity levels significantly below the subtracted continuum red-shifted velocities, indicative of absorbing infalling SiO gas in front of the star (related to shock fronts).

Wittkowski, Humphreys et al. , submitted



-5 km/sec
+11 km/sec
Blue-shifted
Red-shifted
SiO shell
SiO Maser
0 .. 10 km/sec
Observer
Absorbing
Infallling SiO gas
0..10 km/sec
Stellar diameter ~43 mas
Inner SiO shell diameter ~60 mas
Outer SiO shell diameter ~450 mas



Stellar diameter ~43 mas
Inner SiO shell diameter ~60 mas
Outer SiO shell diameter ~450 mas

Inner dust shell diameter (Danchi et al, Lopez et al.): ~100 mas

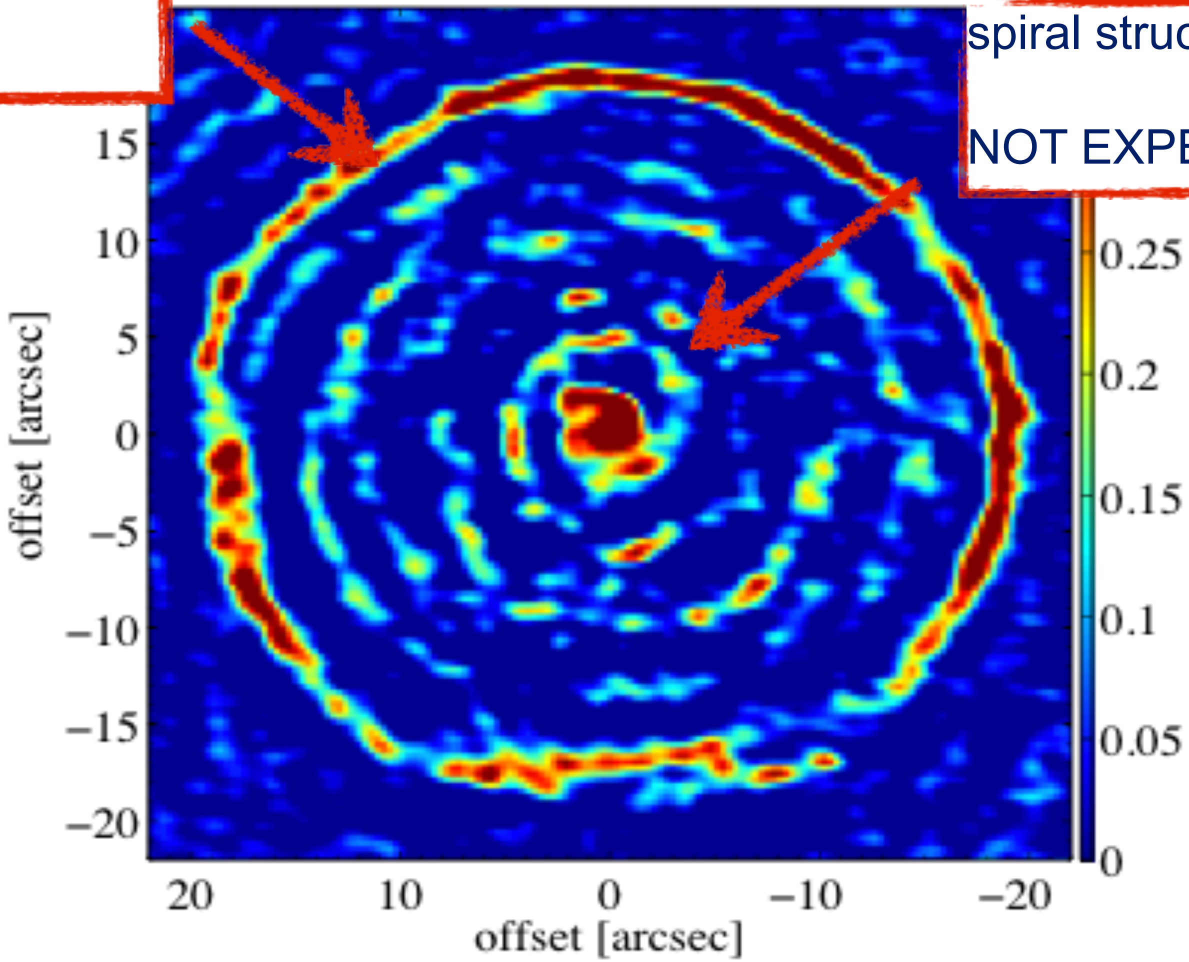
R Scl: ALMA Cycle 0 band 7 CO(3-2)

detached shell

EXPECTED

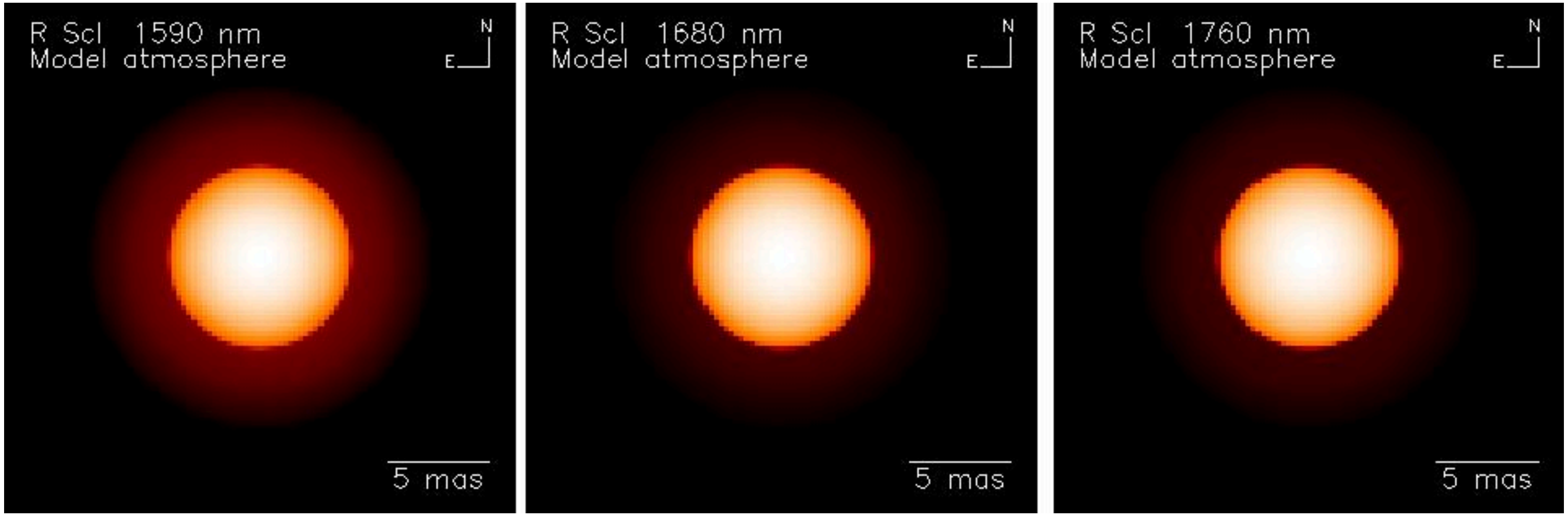
spiral structure

NOT EXPECTED



Maercker et al. 2012

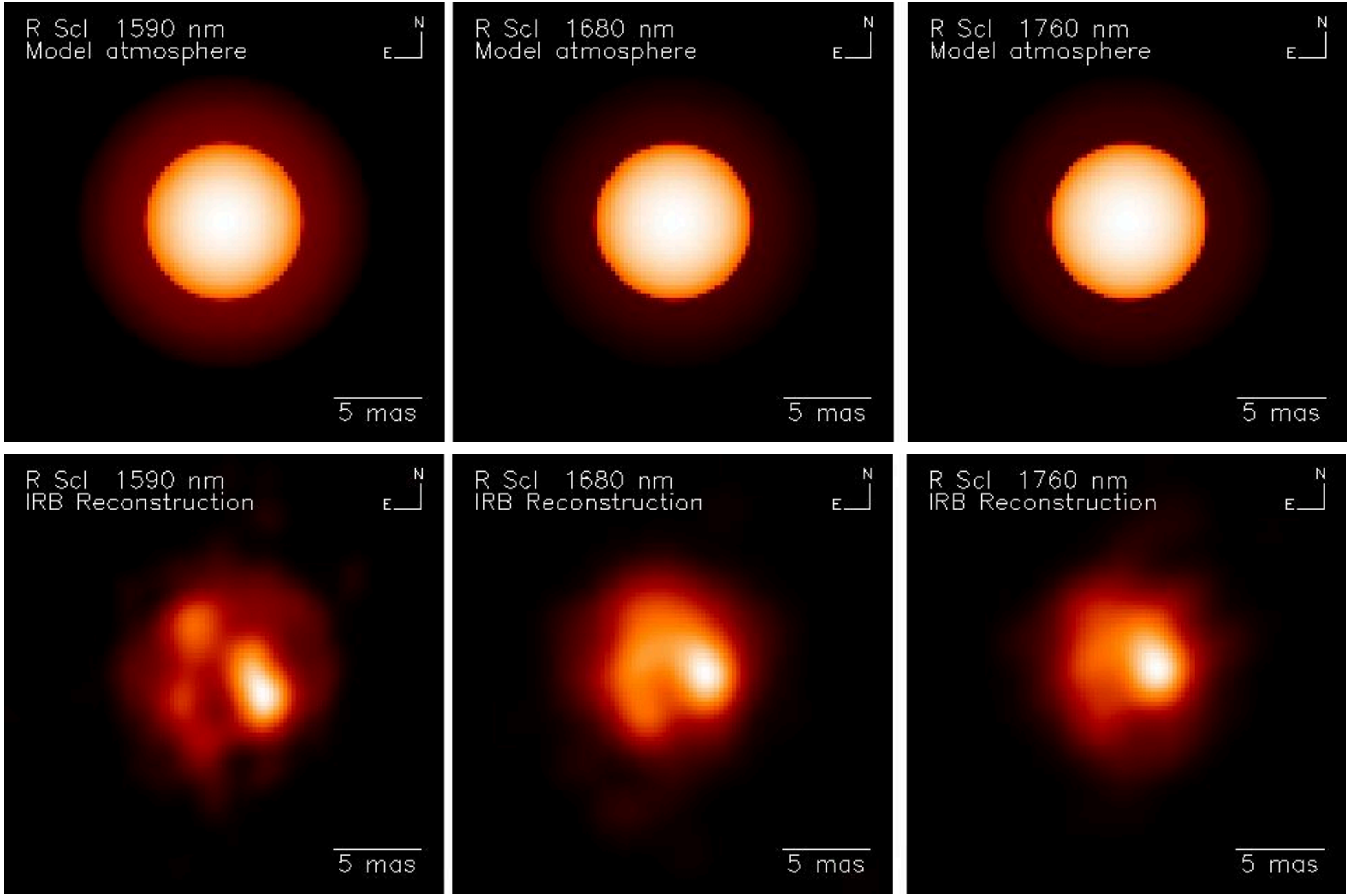
VLTI/PIONIER image of R Scl



Best-fit model atmosphere predictions based on the carbon star grid by Mattsson et al. 2010; Eriksson et al. 2014).
Note that the best-fit model does not have a mass loss.

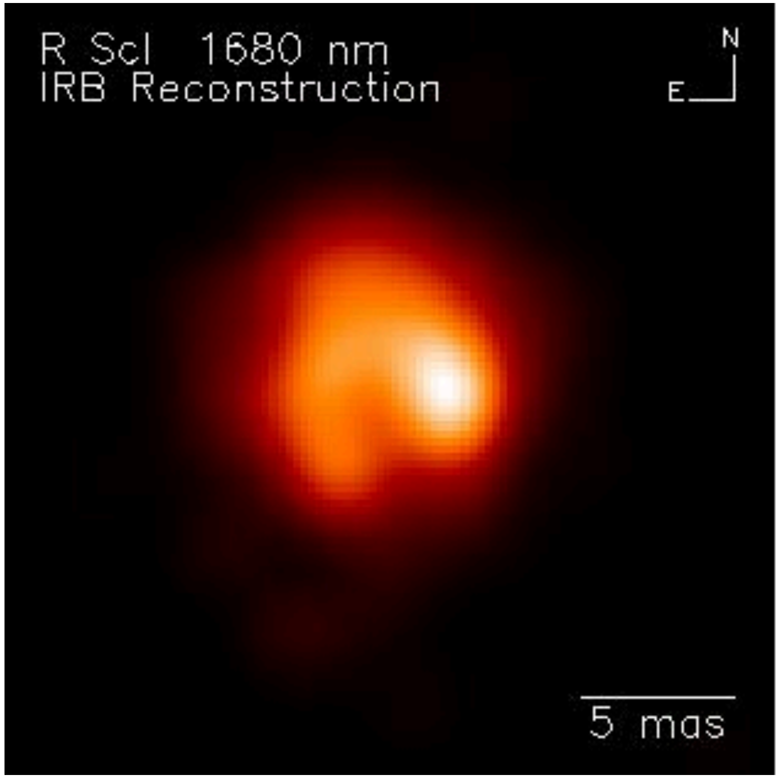
Wittkowski et al., in prep

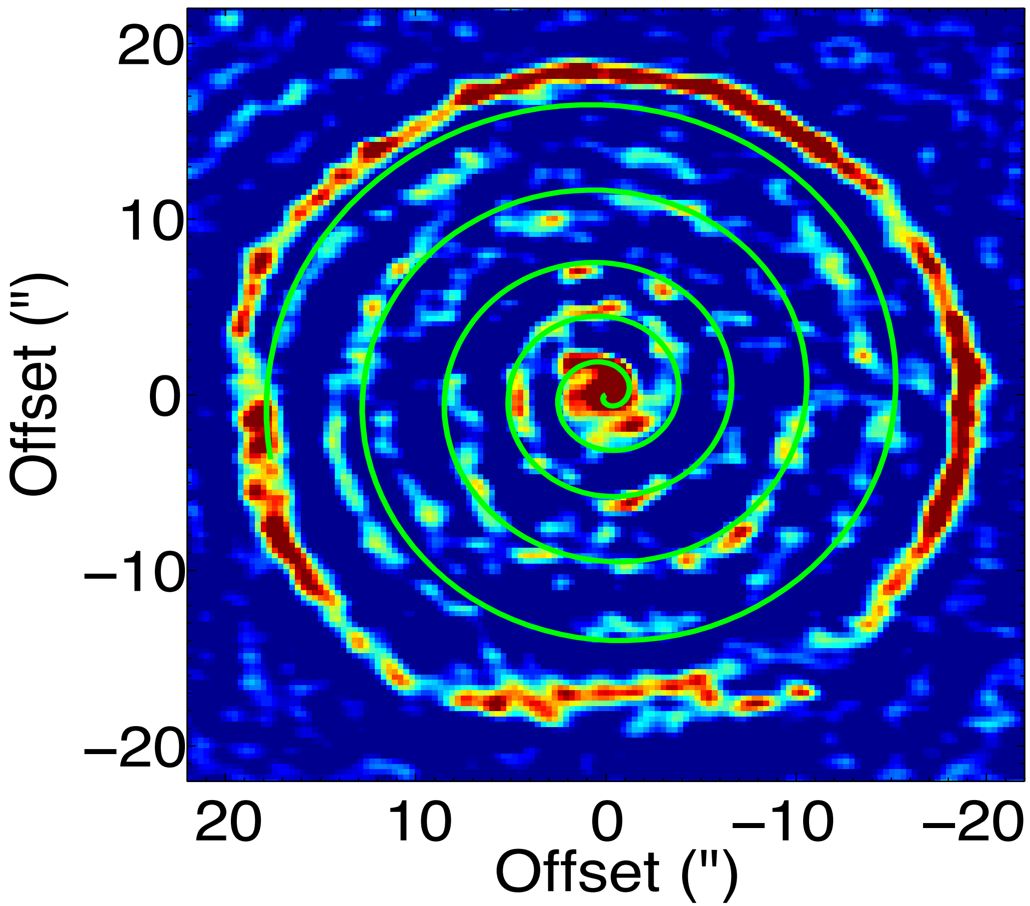
VLTI/PIONIER image of R Scl



Wittkowski et al., in prep

VLTI/PIONIER image of R Scl





- Dominant (mass-loosing?) spot on the surface of R Scl.
- Spiral structure consistent with large spiral, or simply a random convective morphology?

Summary

- Process of how molecular layers are extended to regions where dust forms is in general not well understood, unless maybe for Miras
- 1D dynamic model atmospheres, as well as 3D convection simulations can both explain observed atmospheric extensions of Miras
- Neither of these can explain observed extensions of red supergiants
- Molecular layers and mass-loss of semiregular AGB stars and red giants are poorly investigated
- Observed correlation of atmospheric extension with luminosity for RSGs supports a scenario of radiative acceleration on molecular lines
- Near-IR images obtained with interferometry show dominant (mass-loosing) spots
- Millimeter ALMA imaging with long baselines already provides complimentary information on resolved stellar disks

Cool evolved stars: Pulsations

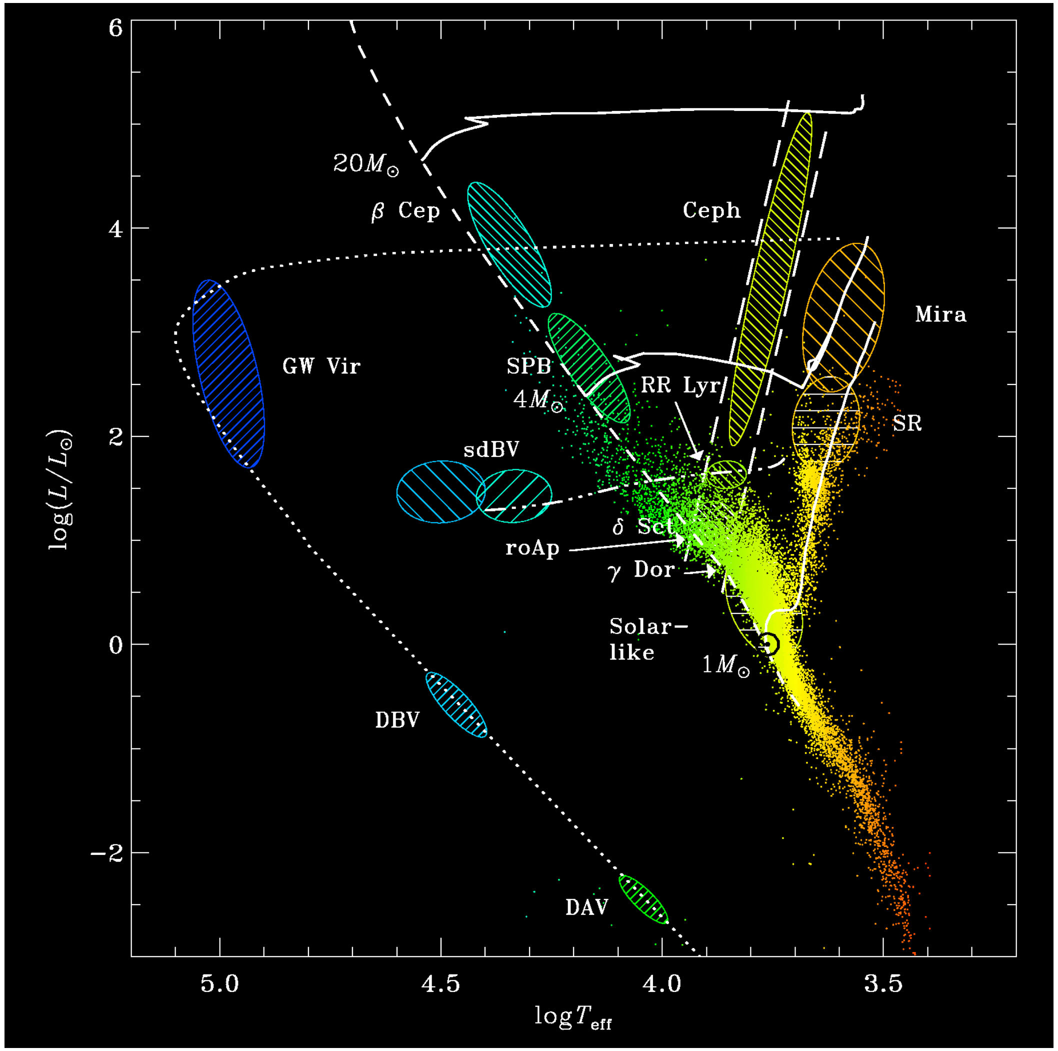
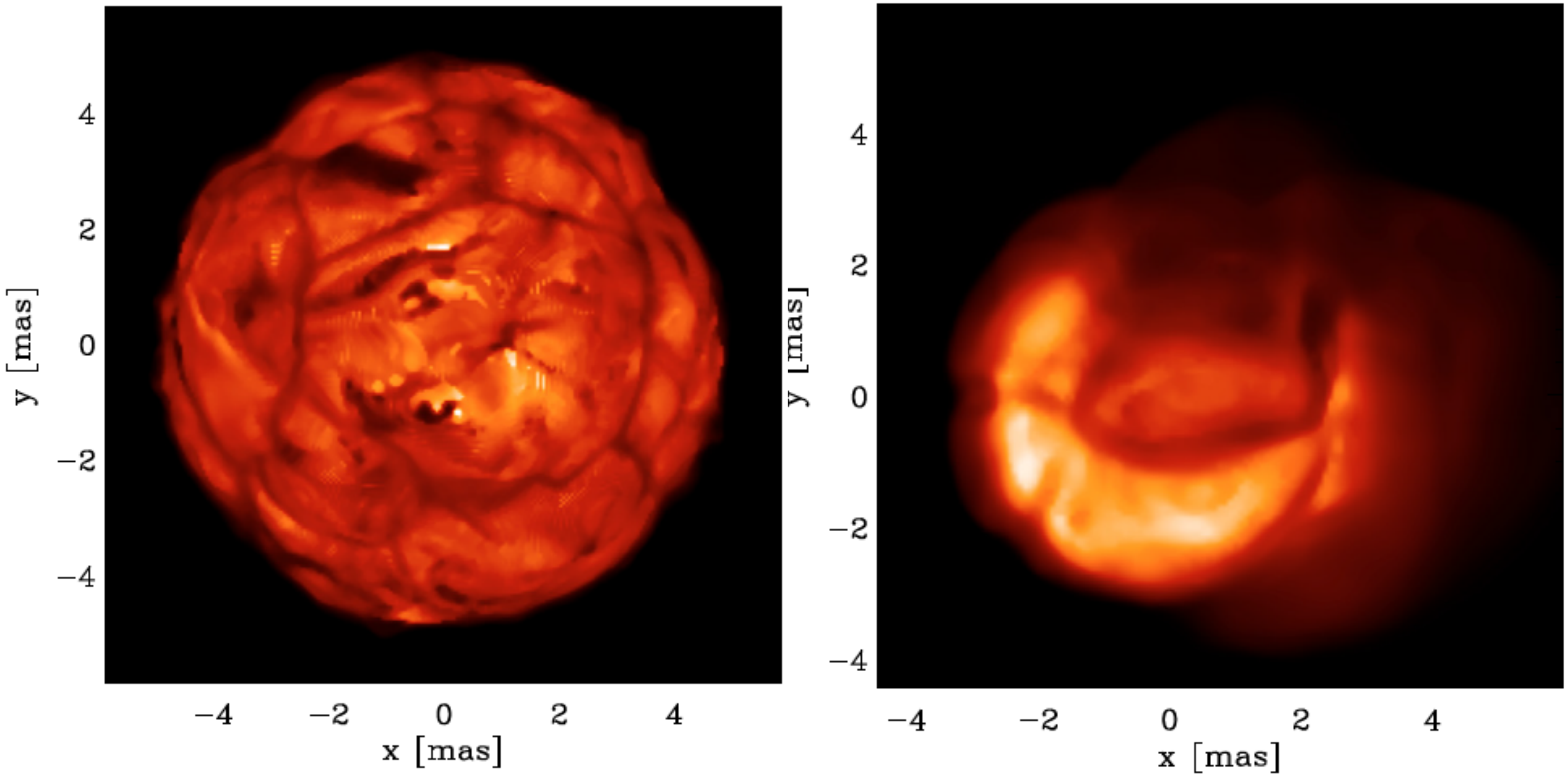


Fig. from Jørgen Christensen-Dalsgaard

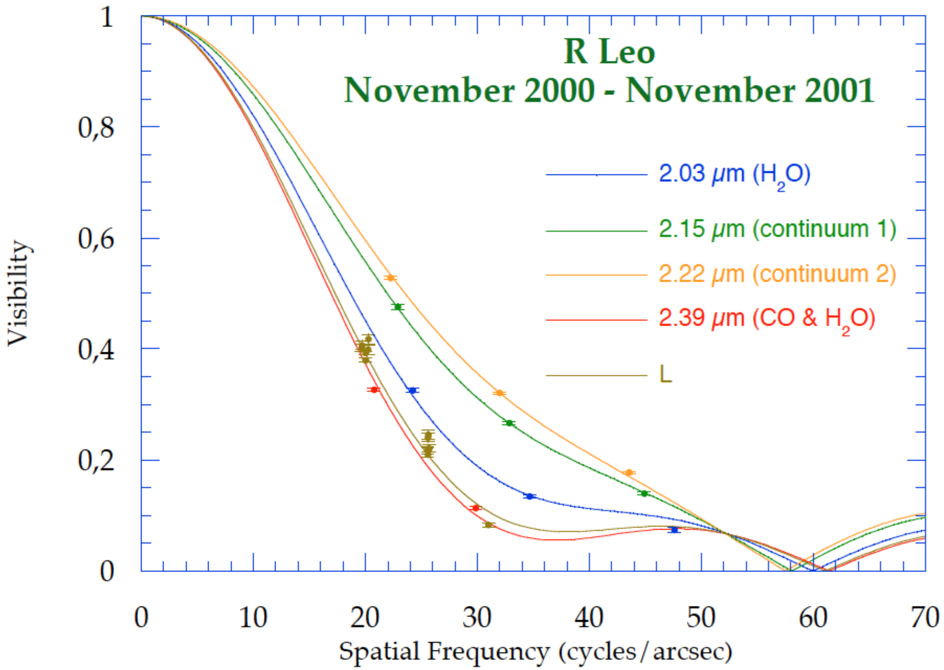
- AGB stars are affected by pulsations with typical periods of the order of 1 yr and amplitudes of 0.5-1 mag (near-IR, bol.)
- For Mira stars, it is established that fundamental mode pulsations lead to shock fronts that travel through the atmospheres and levitate them.
- Less clear for overtone-mode pulsating semi-regular AGB stars
- Variable red supergiants have typical amplitudes of 0.25 mag, i.e. ~3 times less than AGB stars (e.g. Wood et al. 1983).

Cool evolved stars: Convection

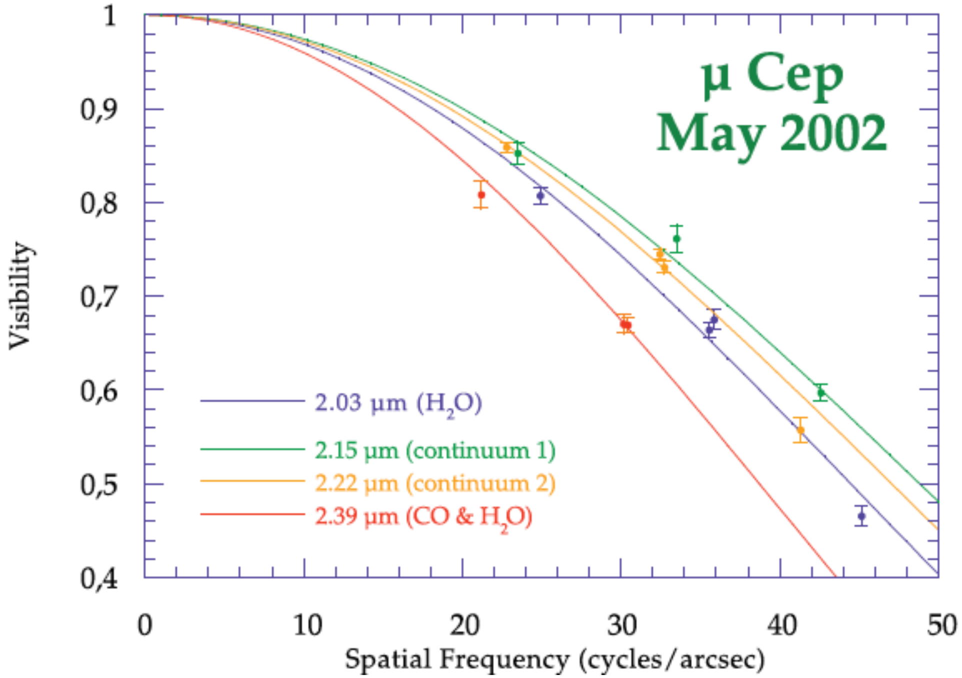


3D simulations at 1.6 μm of a RSG (left) and AGB (right) star from Chiavassa et al. (2010)

Cool evolved stars: Molecular shell scenario



Perrin et al. (2004)



Perrin et al. (2005)

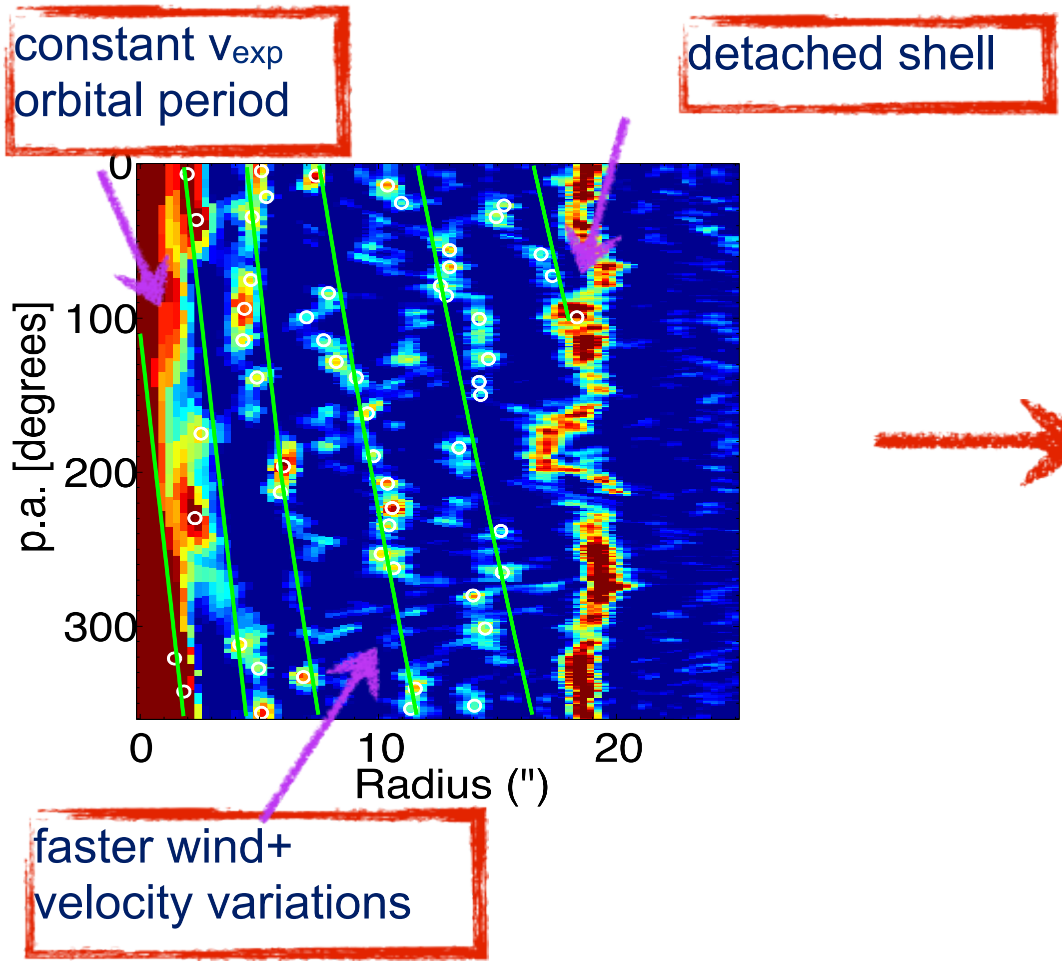
Narrow-band interferometry with IOTA of a Mira star (left) and a RSG (right) by Perrin et al. (2004, 2005).

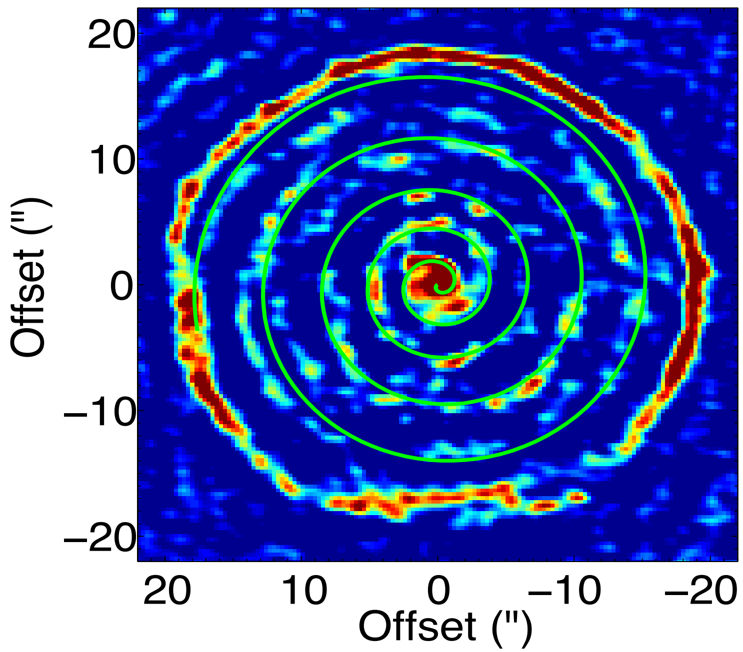
It is established that both Mira stars and RSG stars are surrounded by molecular layers.

What do we believe has happened?

1) Detached shell due to thermal pulse

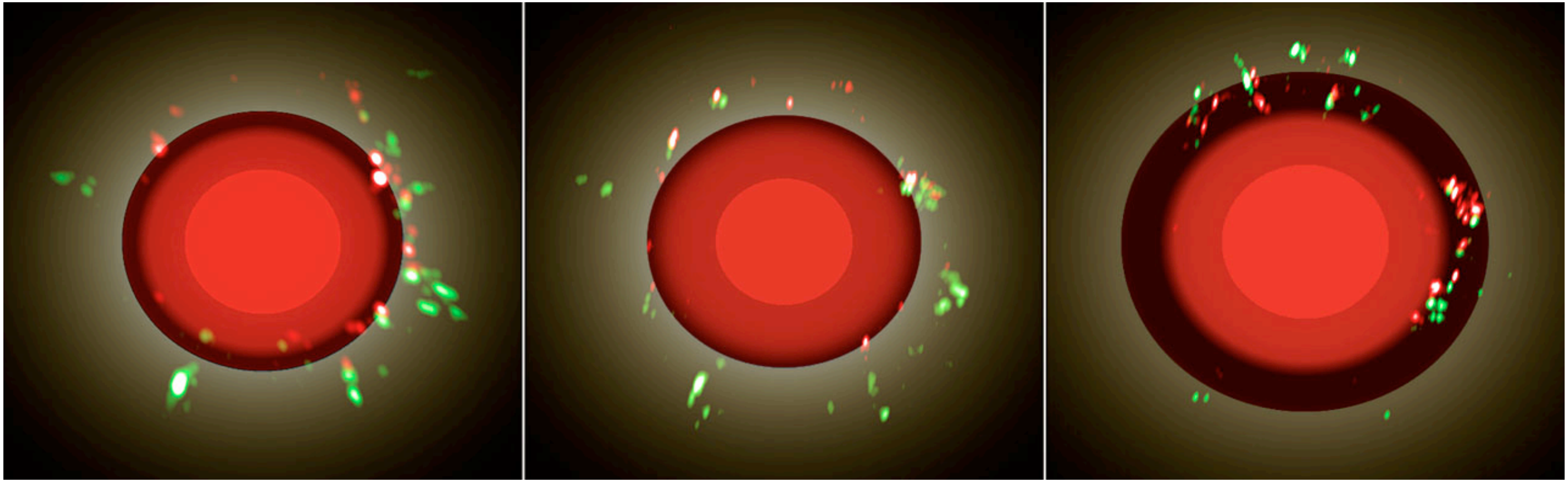
2) Spiral structure due to binary interaction





Maercker et al. 2012

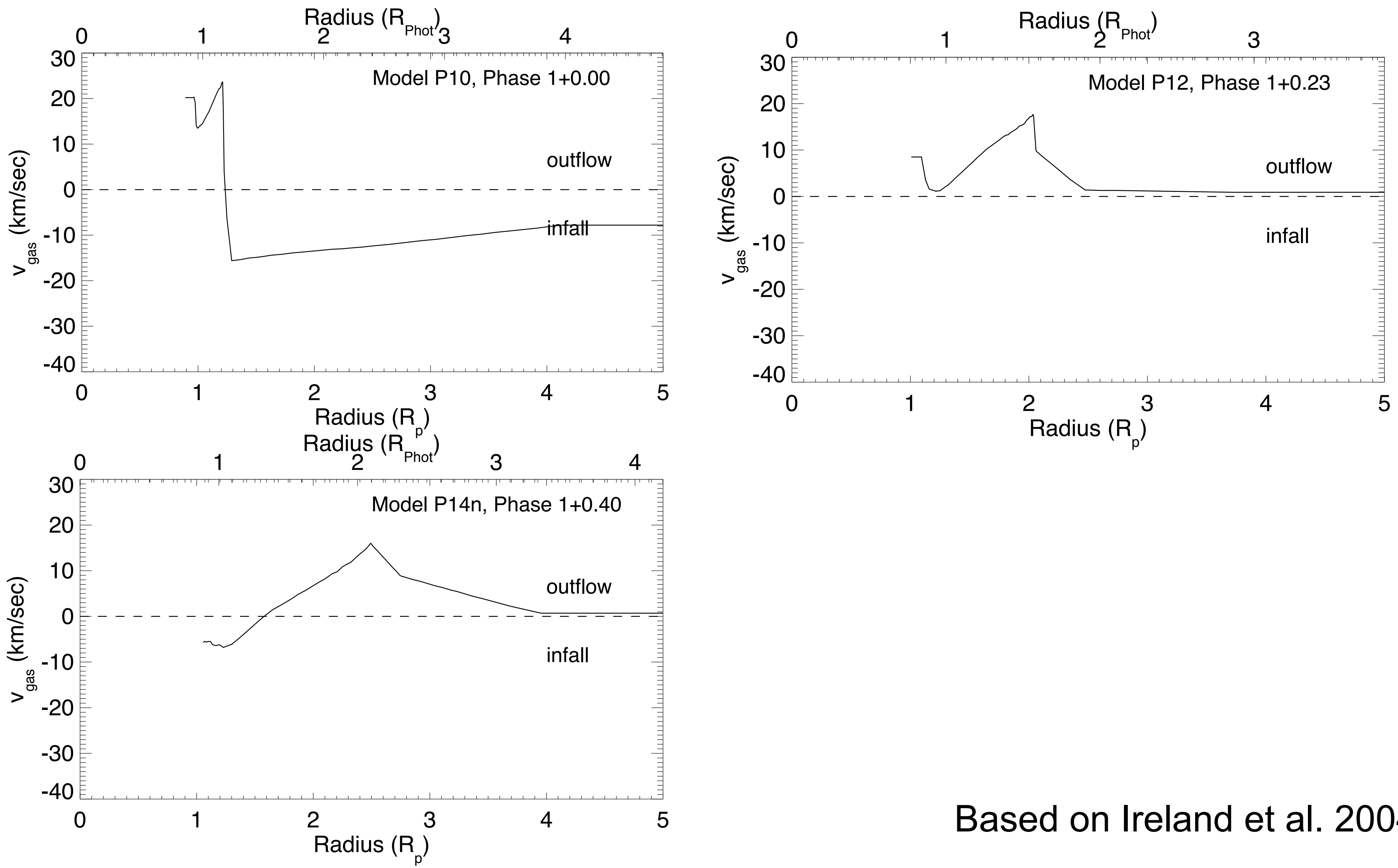
MIDI and VLBA/SiO maser observations of S Ori



- (red) v=2, J=1-0, 42.8 GHz (green) v=1, J=1-0, 43.1 GHz maser images on MIDI model with photosphere, molecular layer, Al_2O_3 dust.
- Al_2O_3 dust has an inner radius of ~2 stellar radii, and may be co-located with the SiO maser region.
- The location of the SiO maser emission is consistent with earlier such observations and with theoretical models by Gray et al. 2009.
- The maser velocity structure indicates a radial gas expansion with velocity ~10 km/sec.

Wittkowski, et al. 2007

Velocity profiles based on dynamic models



Based on Ireland et al. 2004a/b