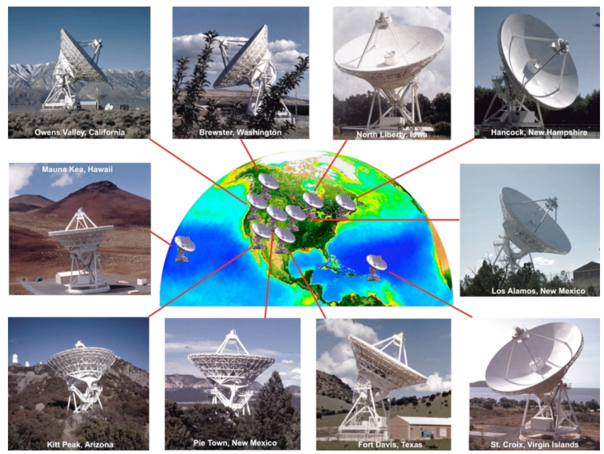
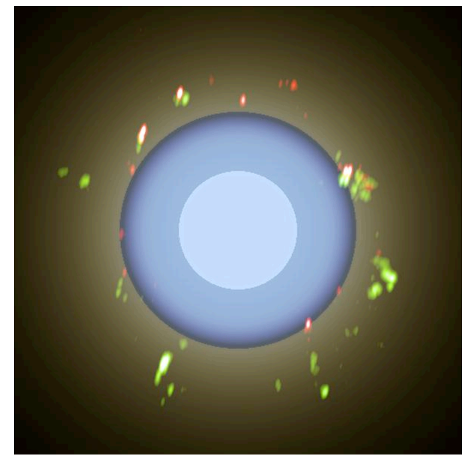
VLT Interferometry of non-Mira and Mira giants

(1) VLTI/VINCI observations of the M giants psi Phe, gam Sge, alf Cet.

(2) Program of coordinated interferometry of oxygen-rich evolved stars at near-infrared, mid-infrared, and radio wavelengths using the VLTI in conjunction with the VLBA. Concentrated on the Mira variables S Ori, GX Mon, RR Aql, and the supergiant AH Sco.





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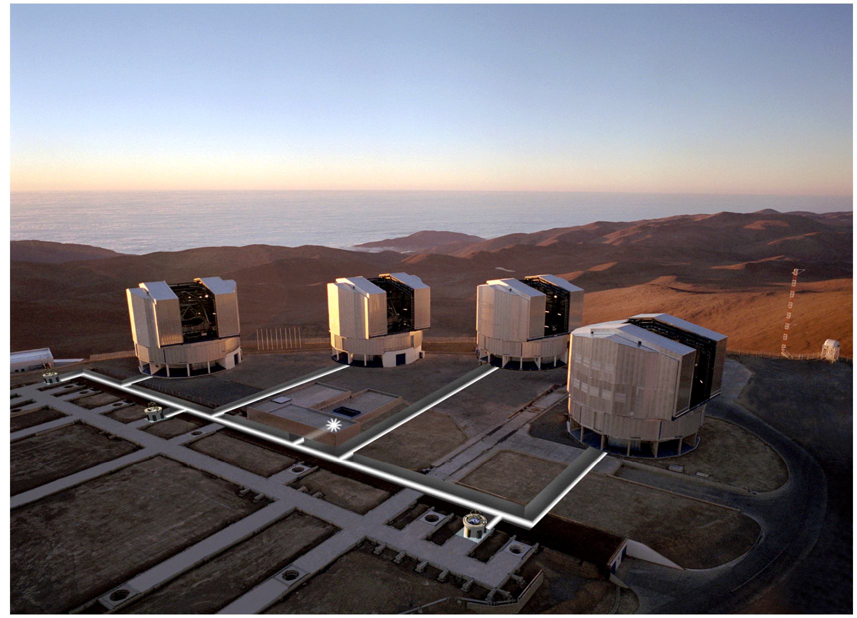
The ESO VLT Interferometer

- Four fixed 8-m Unit Telescopes (UTs). Max. Baseline 130m.
- Four 1.8-m Auxiliary Telescopes (ATs), relocateable on 30 different stations. Baselines 8 – 200m.
- Near-infrared (J, H, K) closure-phase instrument AMBER. Spectral resolutions 35, 1500, 10000.
- Mid-infrared 8-13 μm 2-beam instrument MIDI. Spectral resolutions 30, 230.
- Fringe tracker (FINITO).
- Dual feed phase referencing (PRIMA).



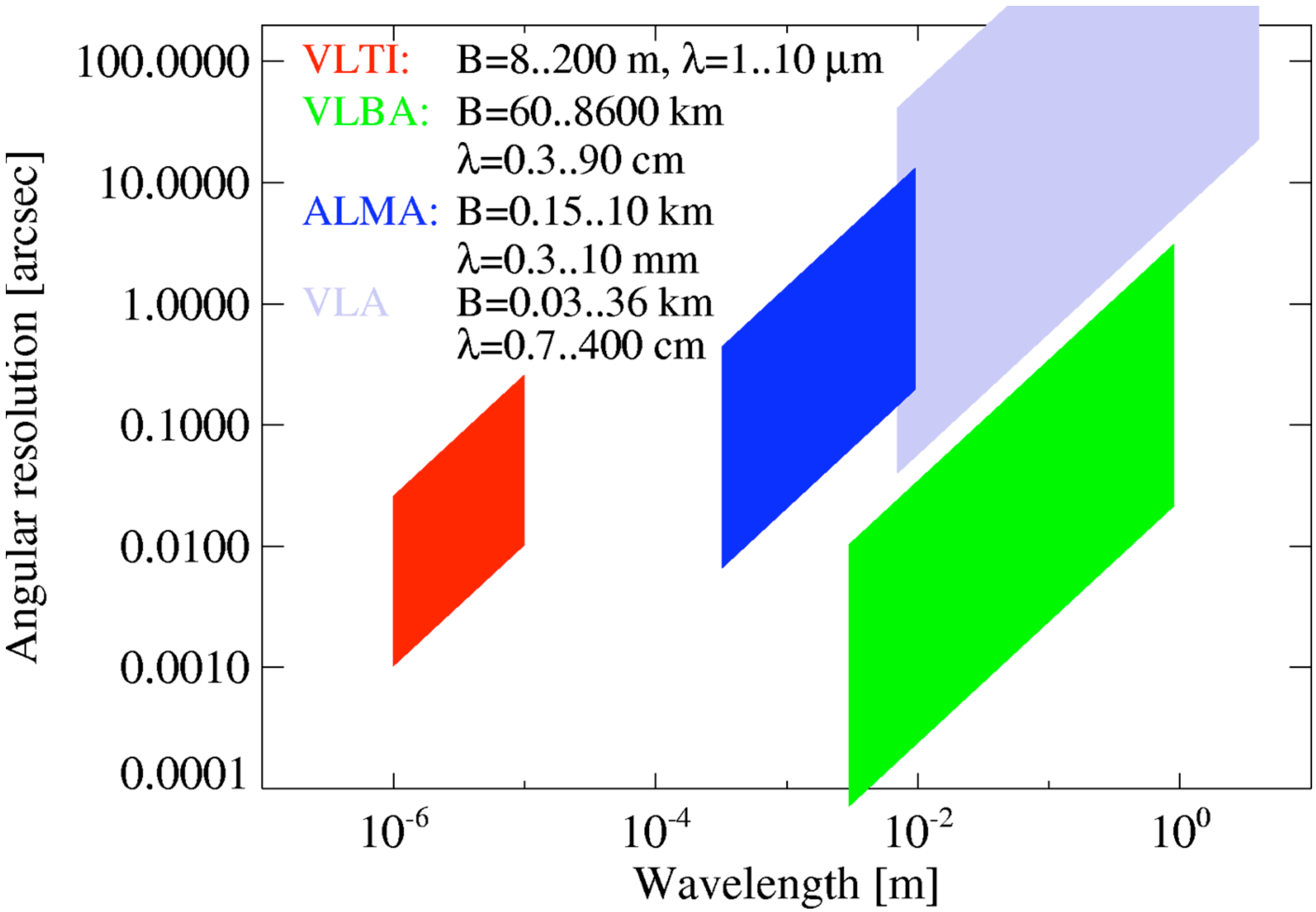
AT1 and AT2 with Open Domes

ESO PR Photo 07b/05 (14 March 2005)

Observing periods with the VLTI

	# of progr.	# in service	# in visitor	Hours service	Nights visitor
P73 MIDI	21	17	4	77 h	3.5 n
P74 MIDI	19	13	6	86 h	2.7 n
P75 MIDI	27	21	6	152 h	7.2 n
P76 MIDI	25	21	5	77 h (UT) + 231 h (AT)	6.5 n (UT)
P77 MIDI	29	19	10	85 h (UT) + 324 h (AT)	3.7 n (UT)
P76 AMBER	21	19	2	71 h	4.0 n
P77 AMBER	15	12	3	51 h	4.4 n

Comparison of VLTI, VLBA, and ALMA



- VLTI, VLBA, and ALMA can observe the same targets in terms of angular resolution and sensitivity.
- They provide complementary information on different components and regions.

Telescopes:

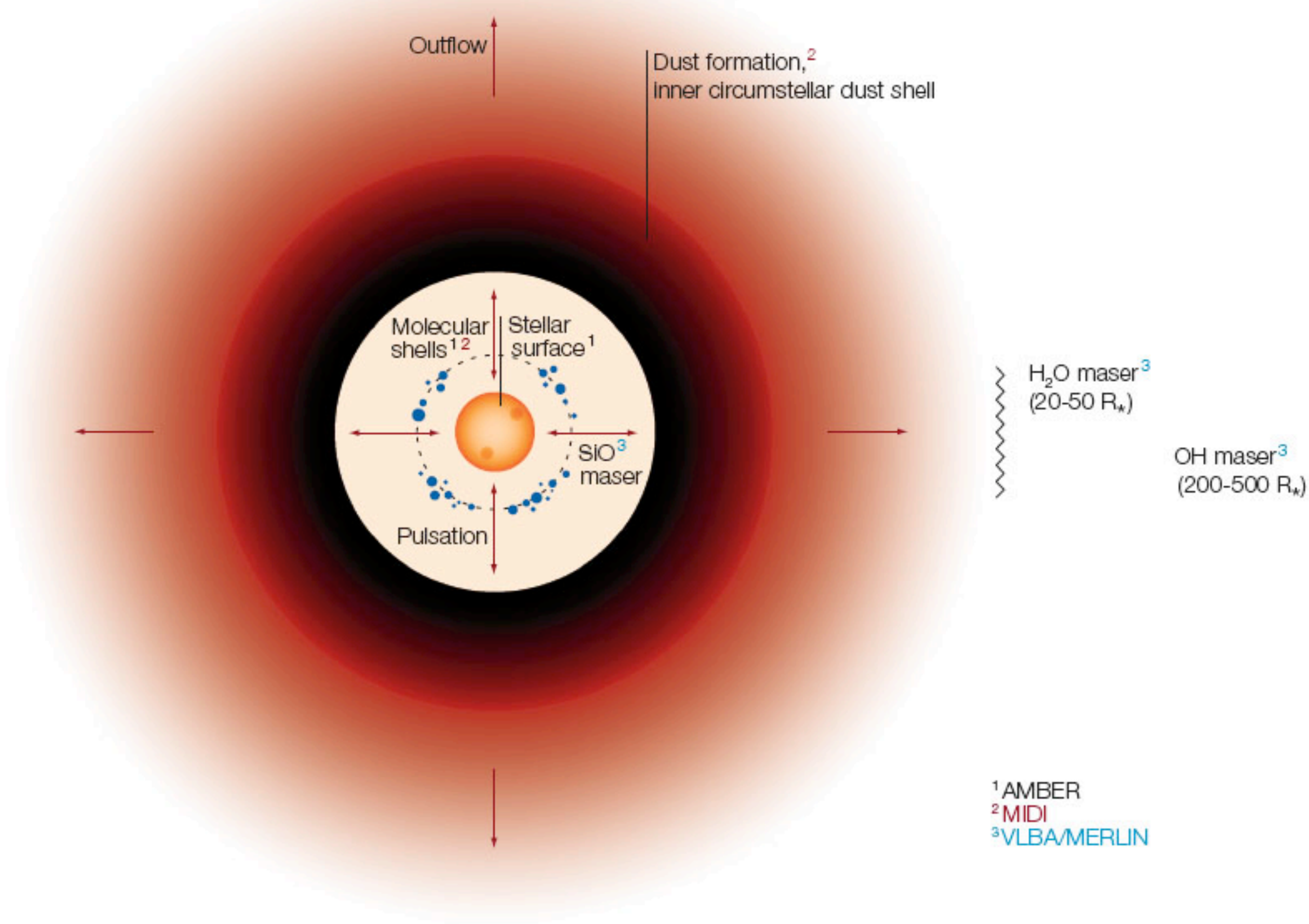
VLTI : 4 x 8m + 4 x 1.8 n

VLBA : 10 x 25 m

ALMA : 64 x 12 m

VLA : 27 x 25 m

Sketch of an oxygen-rich Mira star



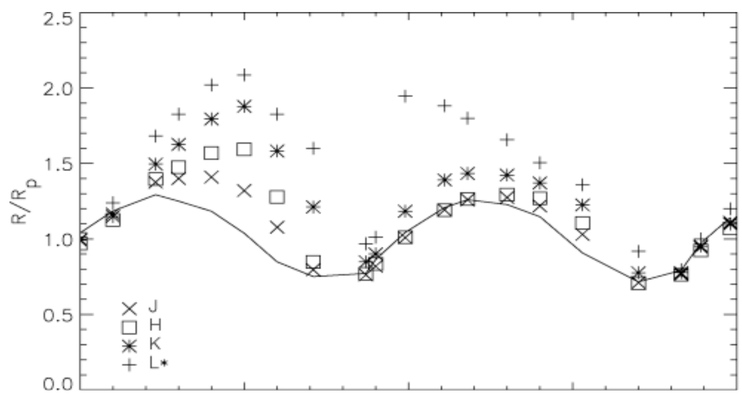
Maser observations with the VLBA

- The VLBA is a system of 10 25m radio telescopes; 0.3-90 GHz, angular resolution down to sub-milli-arcsecond.
- SiO, OH, H_2O, maser emission toward evolved stars can well be spatially resolved.
- Maser radiation appears in maser spots of sizes 10^13-10^16 cm, each with its own well-defined velocity; related to molecular clouds of common velocity with certain temperature and density conditions.
- Each spot emits beamed radiation to the observer.
- SiO masers are tangentially amplified with respect to the stellar radiation, leading to ring-like structures.

Variation with phase of stellar diameters and SiO maser shell radii of Mira stars

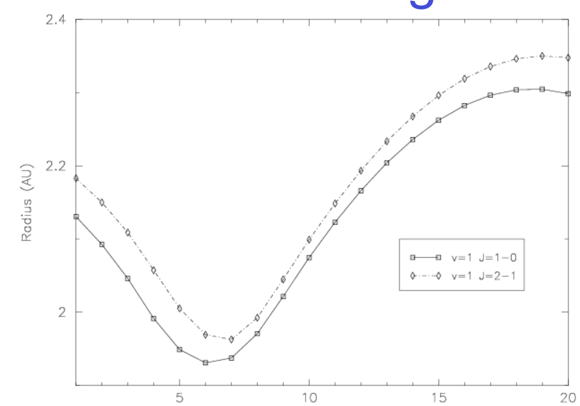
Theory:

Stellar diameter:



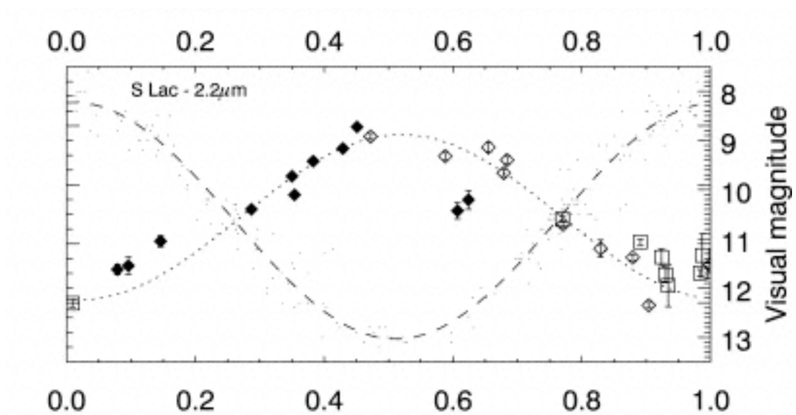
Ireland, Scholz, & Wood 2004

SiO maser ring radii :

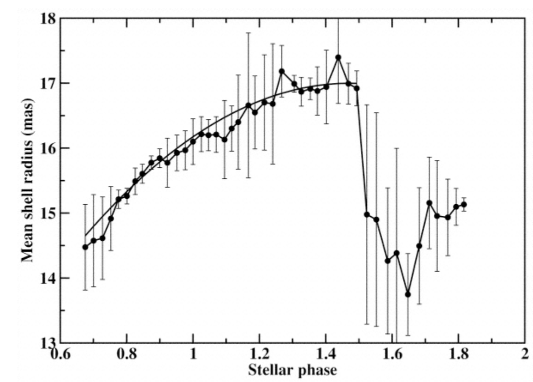


Humphreys et al. 2002

Observations:

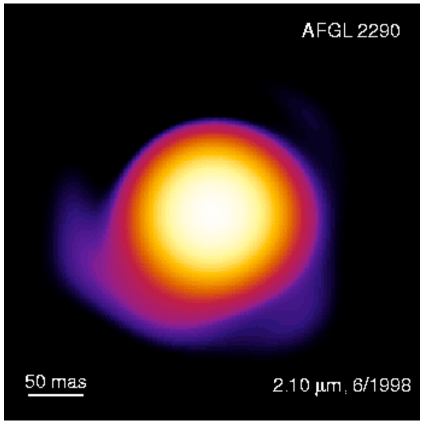


Thompson et al. 2002

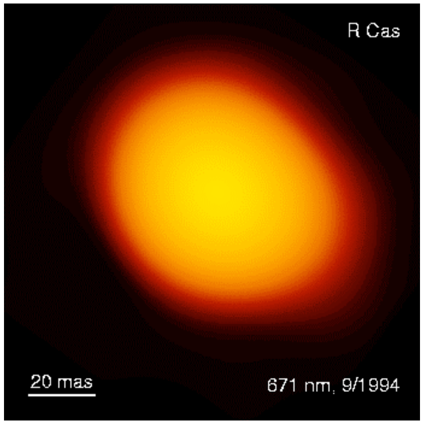


Diamond & Kemball 2003

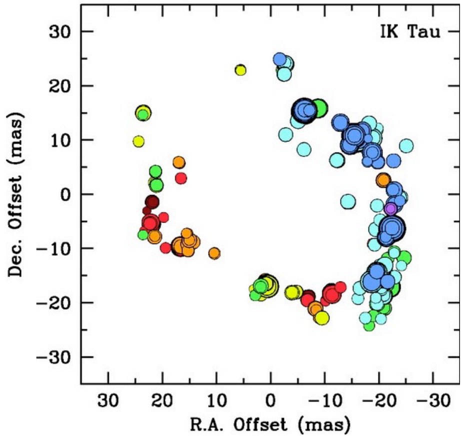
From spherically symmetric AGB stars to axisymmetric/bipolar Planetary Nebulae ?



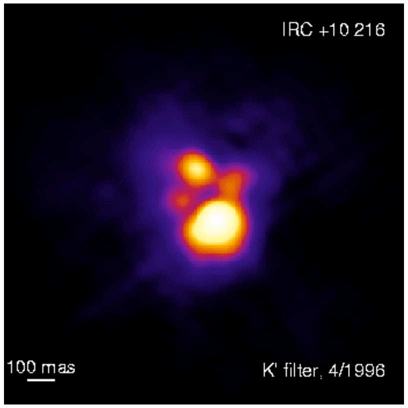
Oxygen-rich AGB star AFGL 2290
Gauger et al. 1999



Mira star R Cas in TiO absorption.
Weigelt et al. 1996

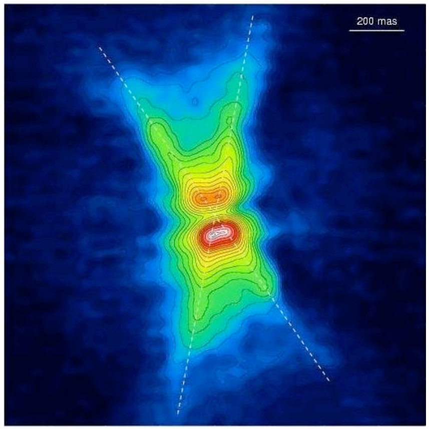


SiO maser shell around the Mira star IK Tau
Boboltz & Diamond 2005



Carbon-star IRC+10216
Weigelt et al. 1998

Cat's Eye Nebula (PN)
HST Image Archive



Red Rectangle
Tuthill et al. 2002

Basic uncertainties in VLTI/VLBA studies of the atmosphere and the CSE of evolved stars

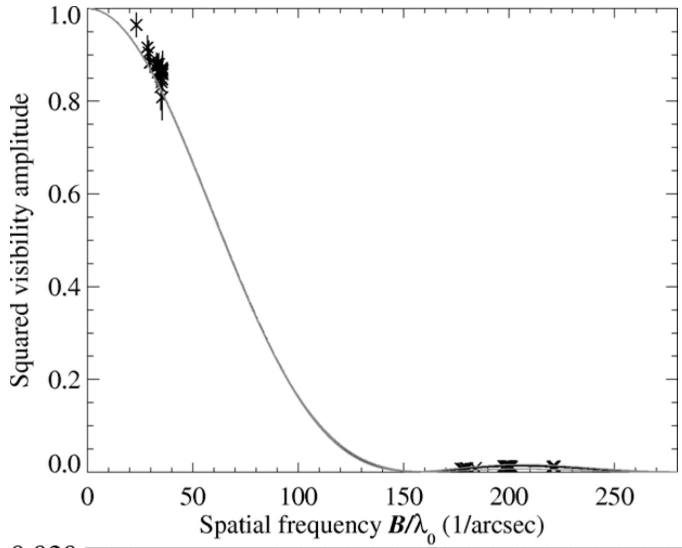
- In practice, observational bandpasses include a blend of photons arriving from the photosphere and from overlying molecular shells.
  -> Use of atmosphere models to relate the observed data to a well defined Rosseland-mean or continuum diameter.
  -> Observe in narrow continuum bands

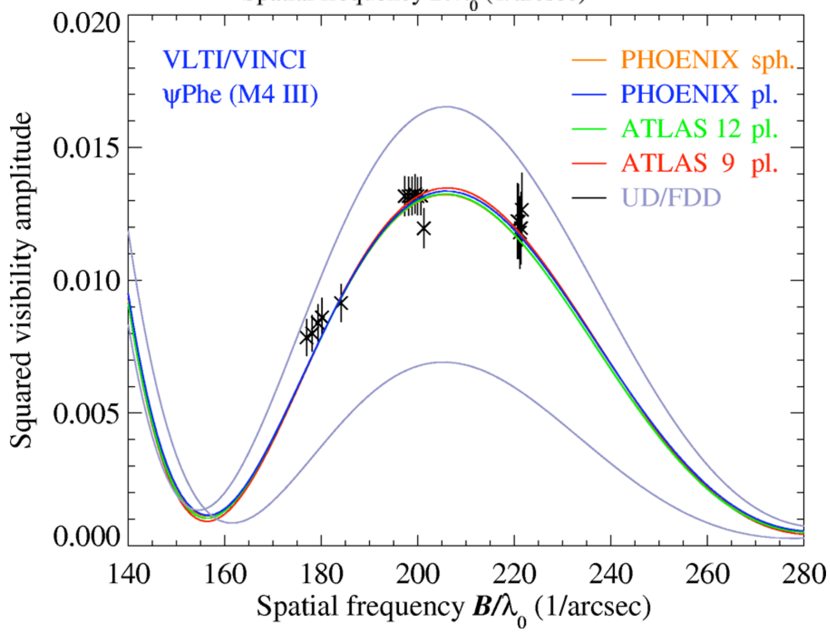
- For pulsating stars, the relative positions between different layers are expected to change with stellar phase and cycle.
  -> Time series of concurrent observations.

- Astrometric information between observations at different facilities and wavelengths is often lost (e.g. between VLBA and VLTI observations).
  -> Astrometry with respect to the same reference source (not yet possible with VLTI, but will be with the PRIMA facility).

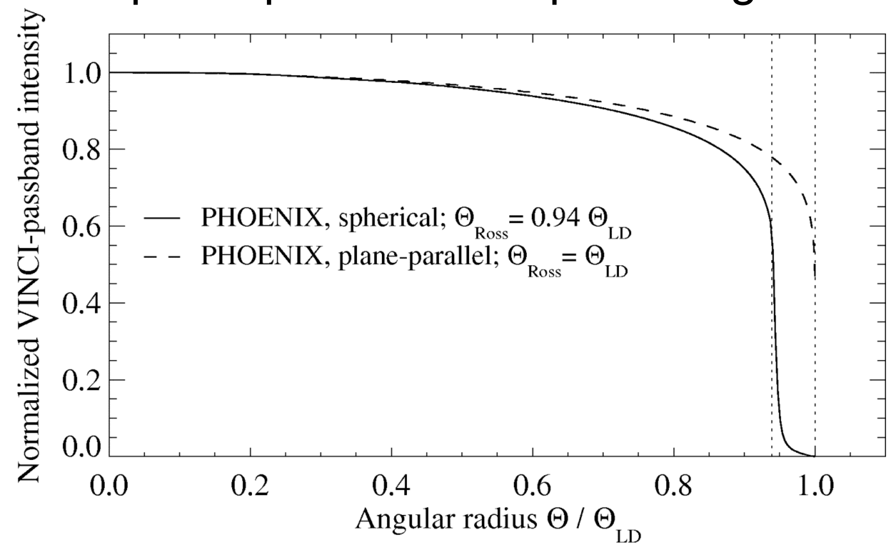
- Asymmetric structures might be expected already on the AGB, but models are spherical, and asymmetric structures are difficult to probe with a 2-beam instrument like MIDI.

VLTI/VINCI observation of the M4 giant Ψ Phe





Intensity profiles of the PHOENIX models
With plane-parallel and spherical geometry:



High-precision stellar parameters:

Θ_{Ross} = 8.13 +/- 0.20 mas

R_{Ross} = 86 +/- 3 R_{sun}

T_{eff} = 3550 +/- 50 K

M = 1.3 +/- 0.2 M_{sun}; log g = 0.68 +/- 0.11

Wittkowski, Aufdenberg & Kervella 200

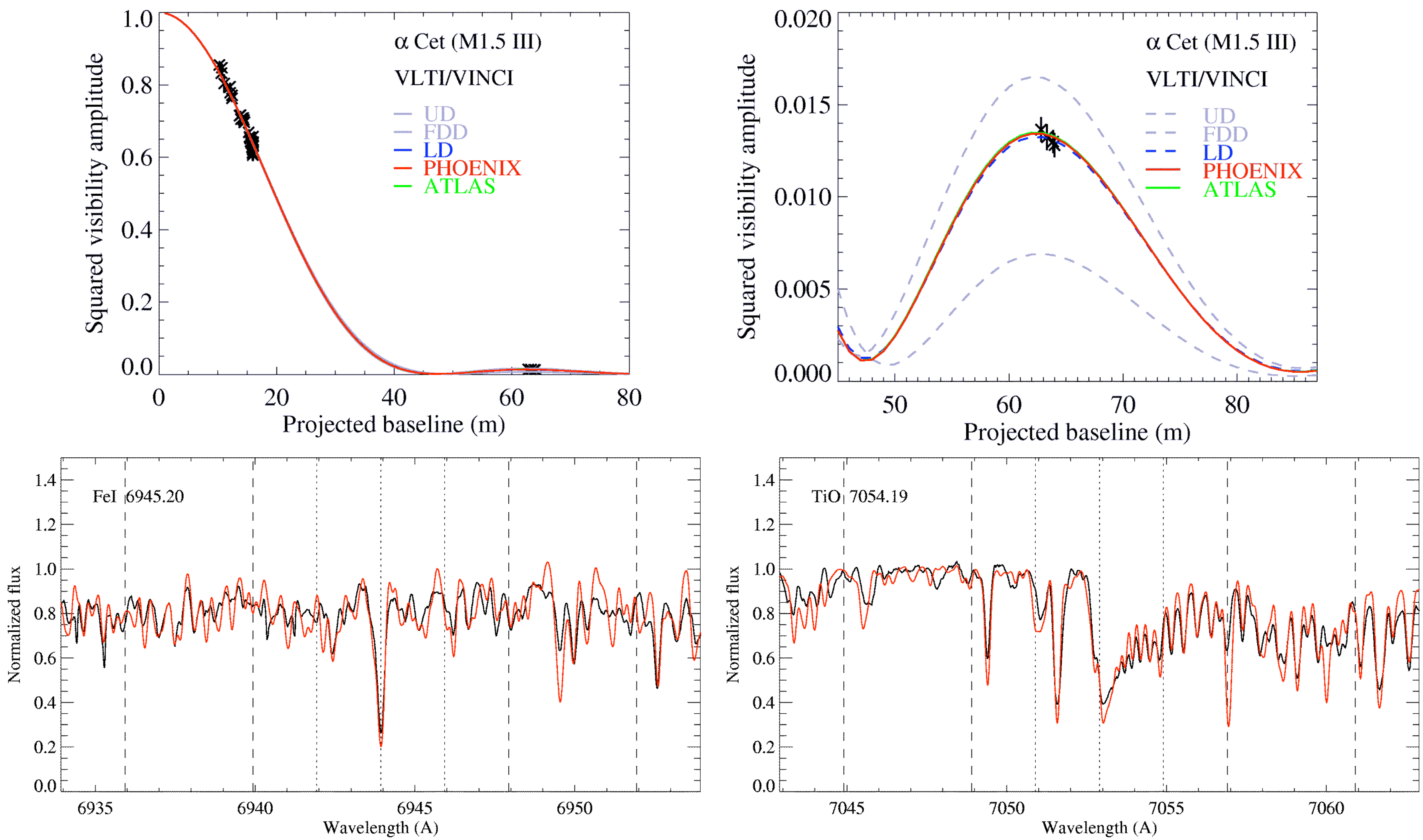
VLTI/VINCI +NPOI observations of gam Sge

Model atmosphere	NPOI (526 nm to 852 nm)	VLTI/VINCI (2190 nm)
ATLAS 9, plane-parallel, $T_{\rm eff}$ = 3750 K, $\log g = 1.0$	$\Theta_{\rm LD} = 6.18 \pm 0.06$ mas	$\Theta_{\rm LD} = 6.08 \pm 0.02$ mas
	$\chi^2_\nu = 2.2$	$\chi^2_\nu = 0.6$
PHOENIX, plane-parallel, $T_{\rm eff} = 3750$ K, $\log g = 1.0$	$\Theta_{\rm LD} = 6.11 \pm 0.06$ mas	$\Theta_{\rm LD} = 6.09 \pm 0.02$ mas
	$\chi^2_\nu = 2.3$	$\chi^2_\nu = 0.6$
PHOENIX, spherical, $T_{\rm eff} = 3750$ K, $\log g = 1.0$, $M = 1.3\,M_\odot$	$\Theta_{\rm LD} = 6.30 \pm 0.06$ mas	$\Theta_{\rm LD} = 6.34 \pm 0.02$ mas
	$\chi^2_\nu = 2.4$	$\chi^2_\nu = 0.6$
	$\Theta_{\rm Ross} = 6.02 \pm 0.06$ mas	$\Theta_{\rm Ross} = 6.06 \pm 0.02$ mas
	$\overline{\Theta_{\rm Ross}} = 6.06 \pm 0.02$ mas	

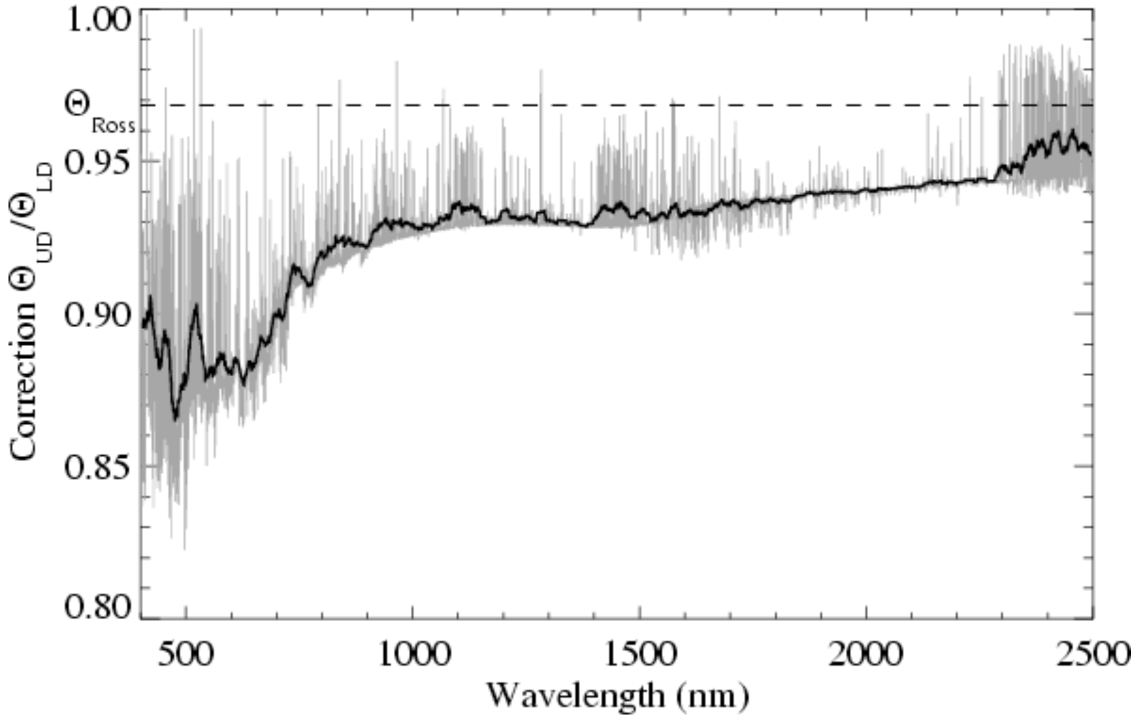
Plane-parallel ATLAS 9, plane-parallel PHOENIX, and spherical PHOENIX models are all well consistent with the visual NPOI as well as with the near-infrared VINCI visibility values, but lead to somewhat different Rosseland diameters.

Wittkowski et al. 2006a

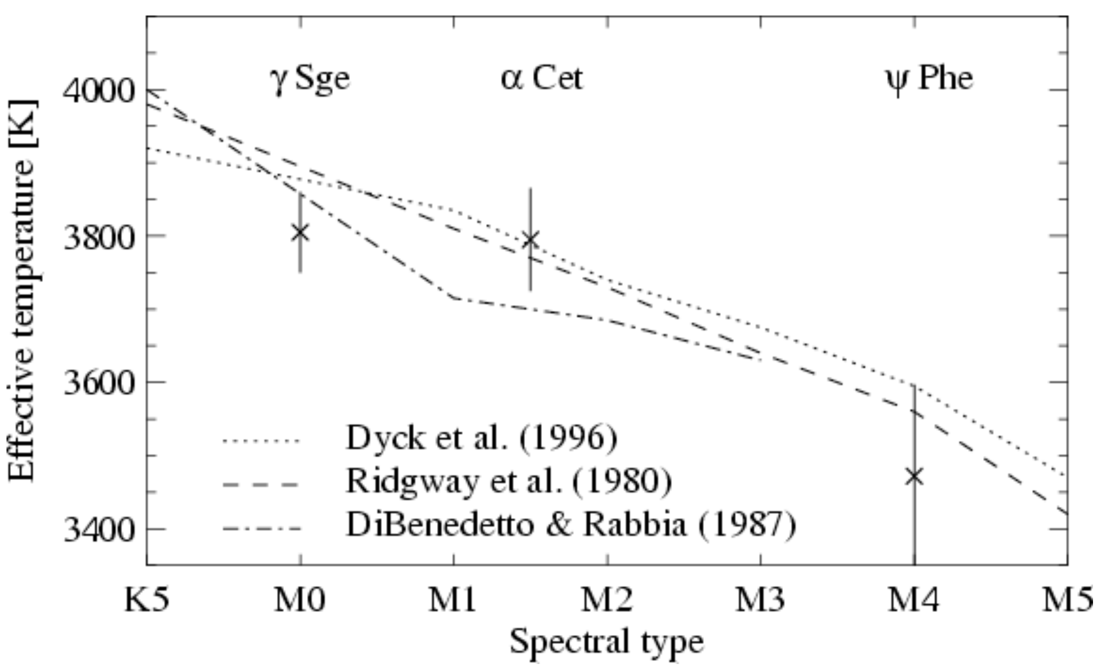
VLTI/VINCI and UVES observations of Menkar



Wittkowski et al. 2006b

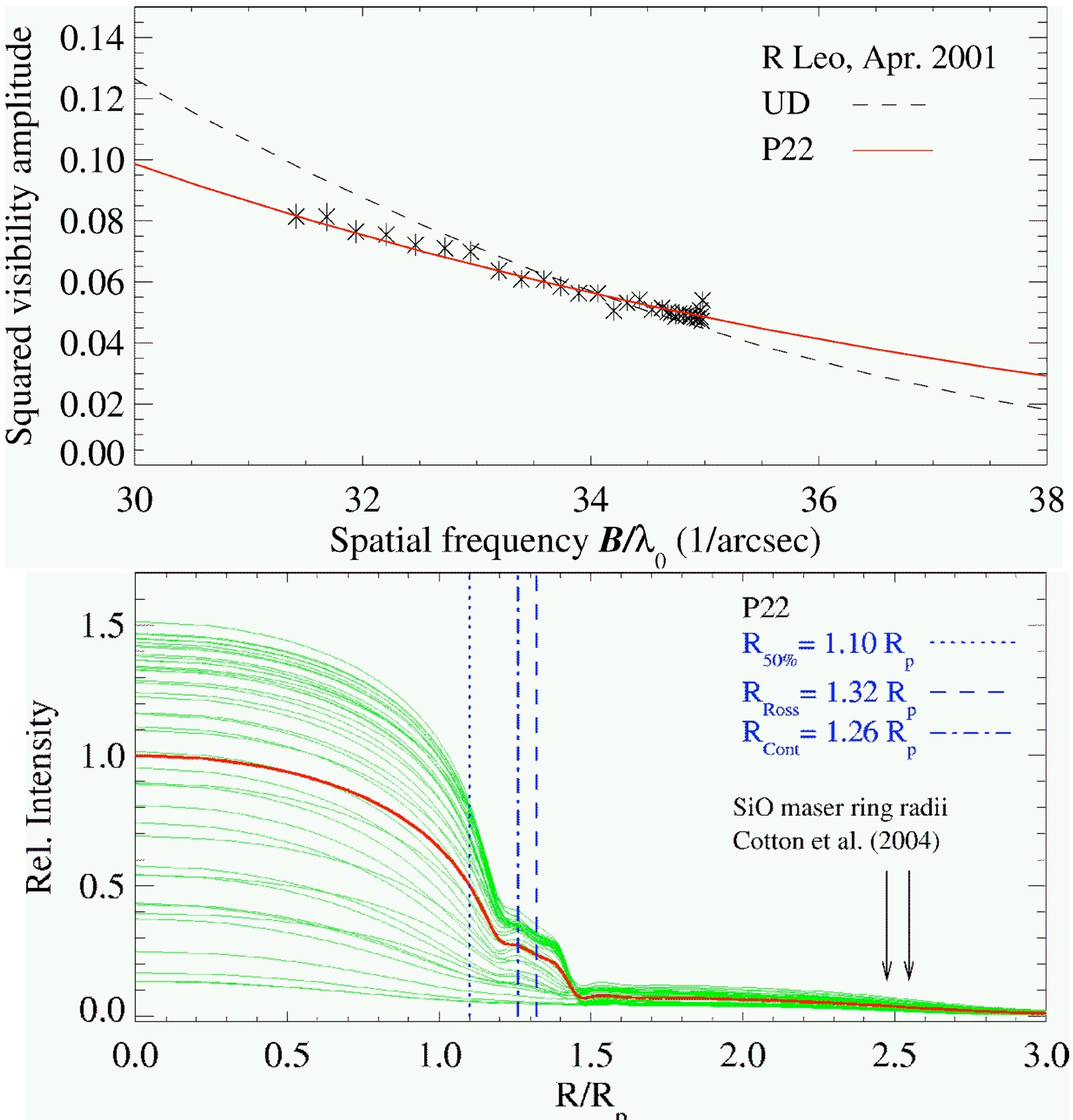


Factor between the UD diameter and the limb-darkened (0%) diameter for the example of the spherical PHOENIX model for Menkar.
Resolution: 0.5 nm/ 20 nm



The M0 giant gam Sge,
the M1.5 giant alf Cet, and
the M4 giant psi Phe
compared to calibrations of the effective temperature.

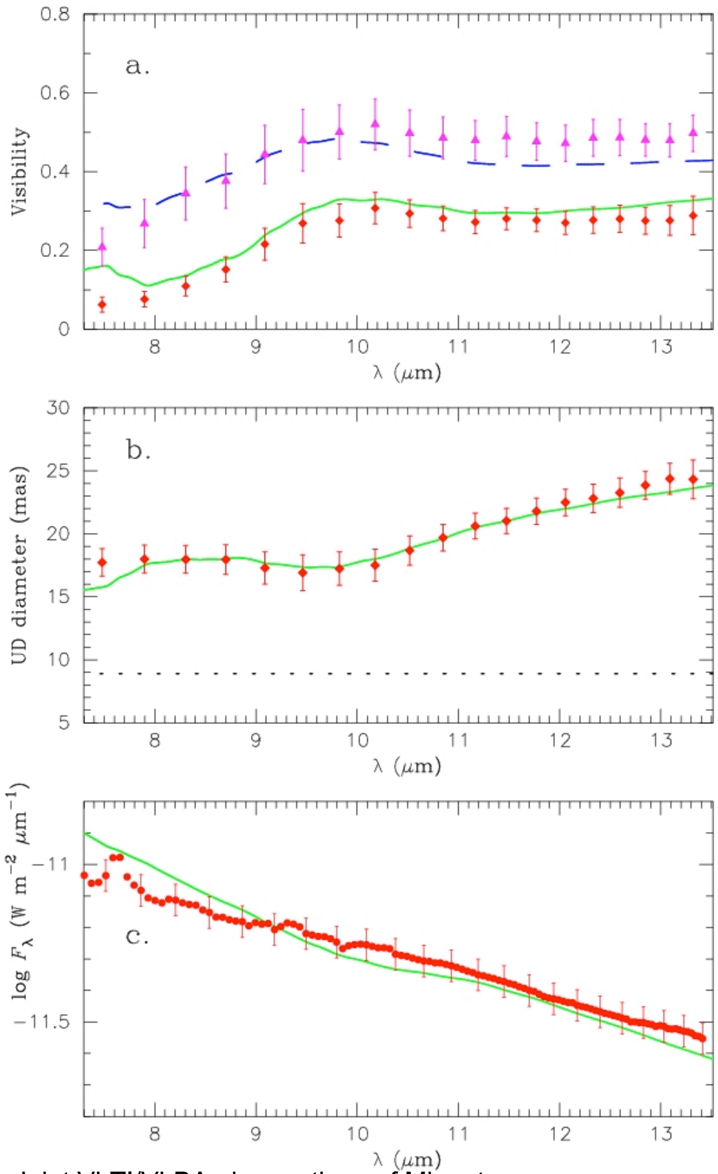
The intensity profile of R Leo (NIR K-band)



- Observations in April 2001 and January 2002 at stellar phases 0.08 and 1.02.
- Intensity profile is clearly different from a UD model already in the first lobe of the visibility function.
- Visibility is consistent with dynamic model atmospheres that include effects from molecular layers.
- Diameter and T_{eff} derived.
- Cotton et al. (2004) derived SiO maser observations in April 2001, i.e. very close to one of our VINCI epochs.
- Dust shell radius by Danchi et al. (1994) at ~5 R_*.

Fedele et al. 2005

MIDI observations of the Mira star RR Sco



- Visibility from 8-13 microns with a spectral resolution of 30.
- Equivalent uniform disk diameter constant at ~17 mas for 8-10 μm and increases to ~24 mas at 13 μm.
- UD diameter in the K-band at about the same time is 10.2 mas (VINCI).

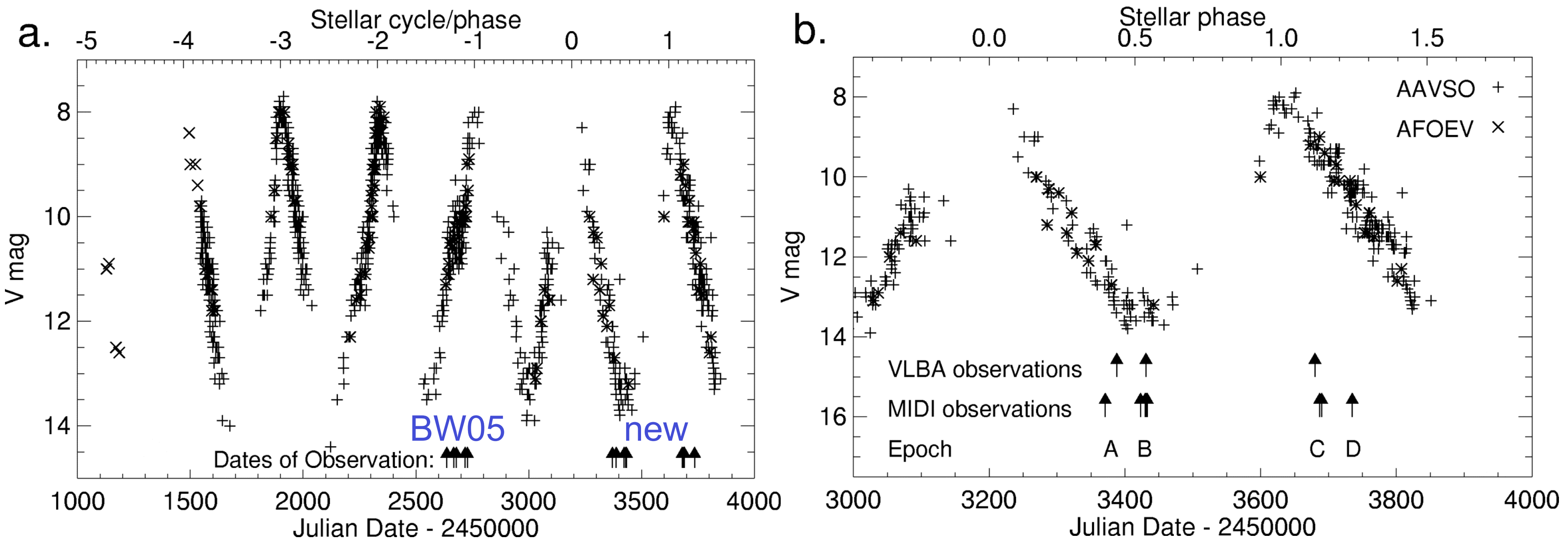
Well-fitting model :

- Stellar continuum diameter 9 mas.
- Molecular layer of SiO and H_2O extending to 2.3 stellar radii with a temperature of 1400 K (opt. thick).
- Dust shell of silicate and corundum. Inner radius 7-8 stellar radii (opt. thin).

Ohnaka et al. 2005, A&A, 429, 1057

Concurrent VLTI and VLBA observations of S Ori

S Ori : M6.5e-M9.5e; V=7.2-14.0; P~430d; d~480 pc; SiO and OH maser



First coordinated VLTI/VLBA observations:
VINCI: 25 Jan – 31 Mar 2003, phases 0.80 - 0.95.
VLBA : 29 Dec 2002, phase 0.73

Boboltz & Wittkowski 2005

New VLTI/MIDI and VLBA observations:
3 contemporaneous (differences < 0.04 *P*) epochs
between Dec 2004 and Nov. 2005 at phases 0.44, 0.56, 1.15, (1.27).

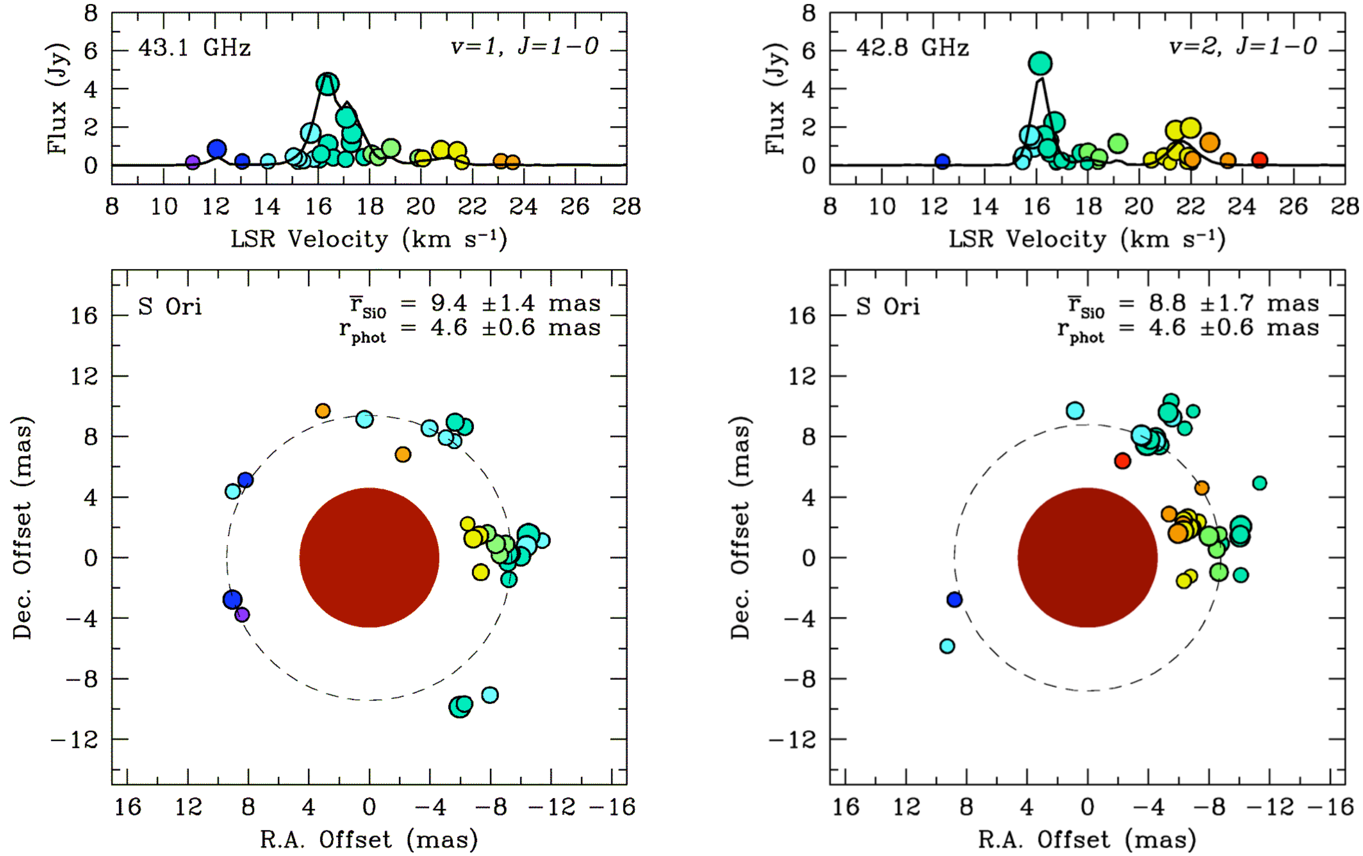
Wittkowski, Boboltz, et al., submitted

Modeling of the infrared interferometric data

- We model the stellar atmosphere using Scholz & Wood models: P and M series (Ireland et al. 2004a/b). These are complete self-excited dynamic model atmospheres of Mira stars that include the effects from molecular layers lying above the continuum-forming layers.
- We model the dust shell using the radiative transfer code mcsim_mpi (Ohnaka et al. 2006). Dust chemistry follows the work by Lorenz-Martins & Pompeia (2000): IRAS LRS spectra of AGB stars can be described by shells of Al_2O_3 grains, silicate grains, or a mix thereof.

  S Ori: Al_2O_3 grains alone, confirmed by our study.
- Model parameters: Model phase; R_{in}, τ_V, density gradient p; Θ_{phot} fitted.

VINCI and VLBA observations of S Ori (BW05)



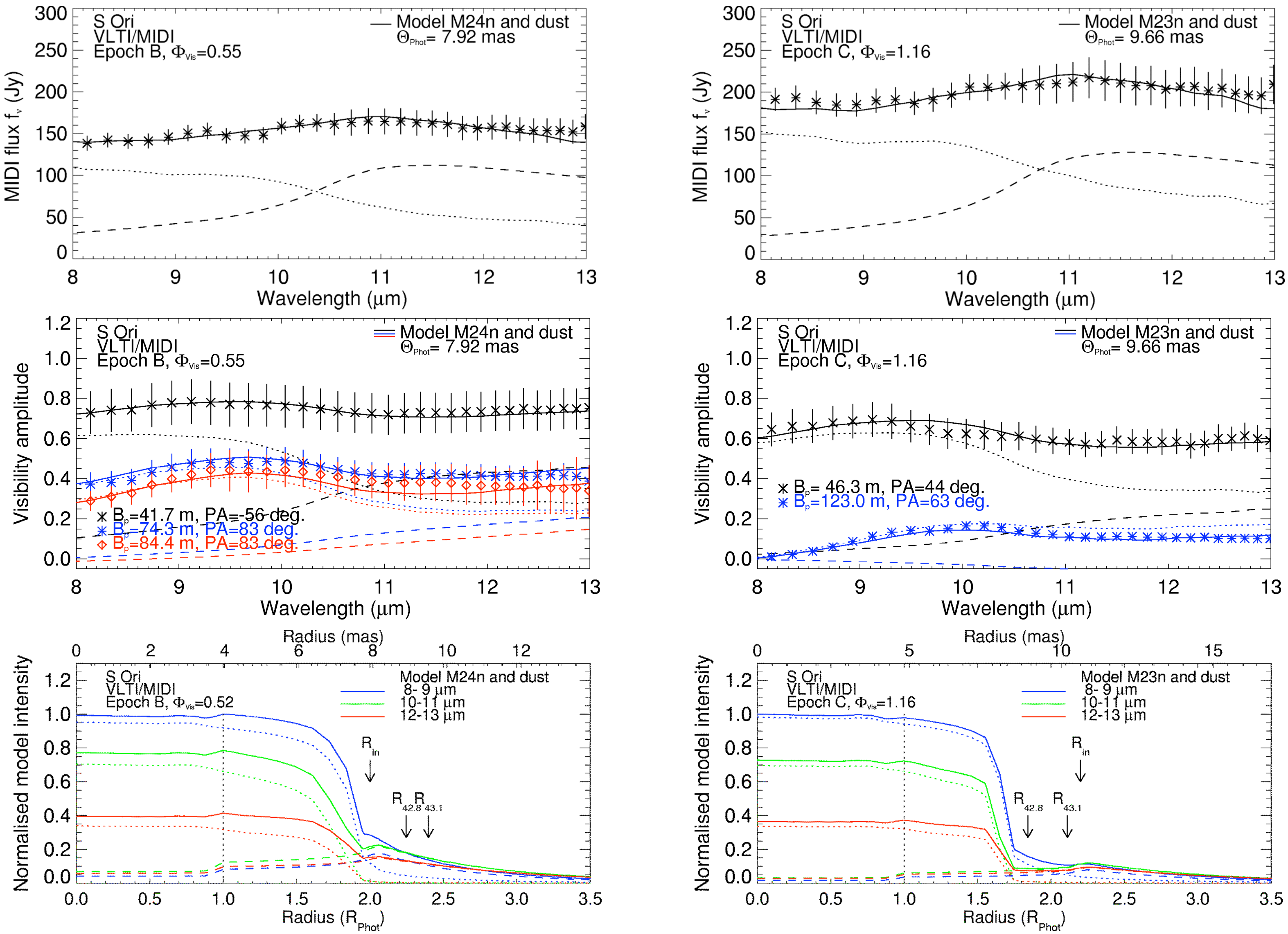
VLTI/VINCI data: K-band UD diameter 10.5 mas (phase 0.80) - 10.2 mas (0.95).

Extrapolation to phase 0.73 and correction $\Theta_{UD/cont}$=> Θ_{cont}=9.2 mas

SiO maser ring radius: 2.0 R_* (43.1 GHz) and 1.9 R_* (42.8 GHz) at stellar phase 0.73, free of the usual uncertainty inherent in comparing observations widely spaced in phase.

Boboltz & Wittkowski 2005

MIDI observations of S Ori (Dec. 2004 - Dec. 2005)



MIDI total flux

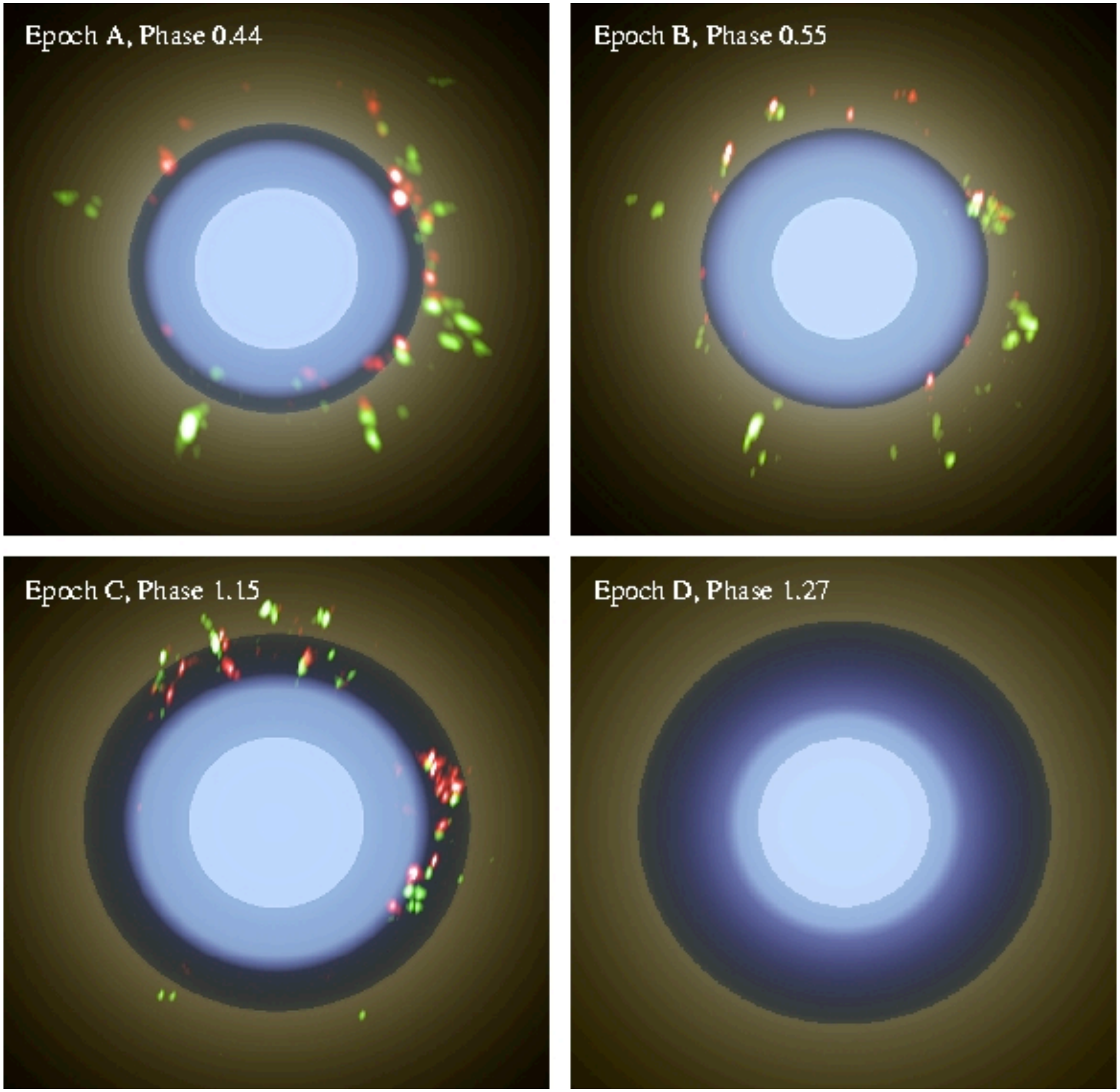
MIDI visibility

Model intensity

M22
Al_2O_3 grains
τ_V=2.5
R_{in}=1.8 R_*
p=3.5

Θ_*=9.0 mas

$R_{43.1}$=2.2 R_*
$R_{42.8}$=2.1 R_*



M24n
Al_2O_3 grains
τ_V=2.5
R_{in}=2.0 R_*
p=3.5

Θ_*=7.9 mas

$R_{43.1}$=2.4 R_*
$R_{42.8}$=2.3 R_*

M23n
Al_2O_3 grains
τ_V=1.5
R_{in}=2.2 R_*
p=3.0

Θ_*=9.7 mas

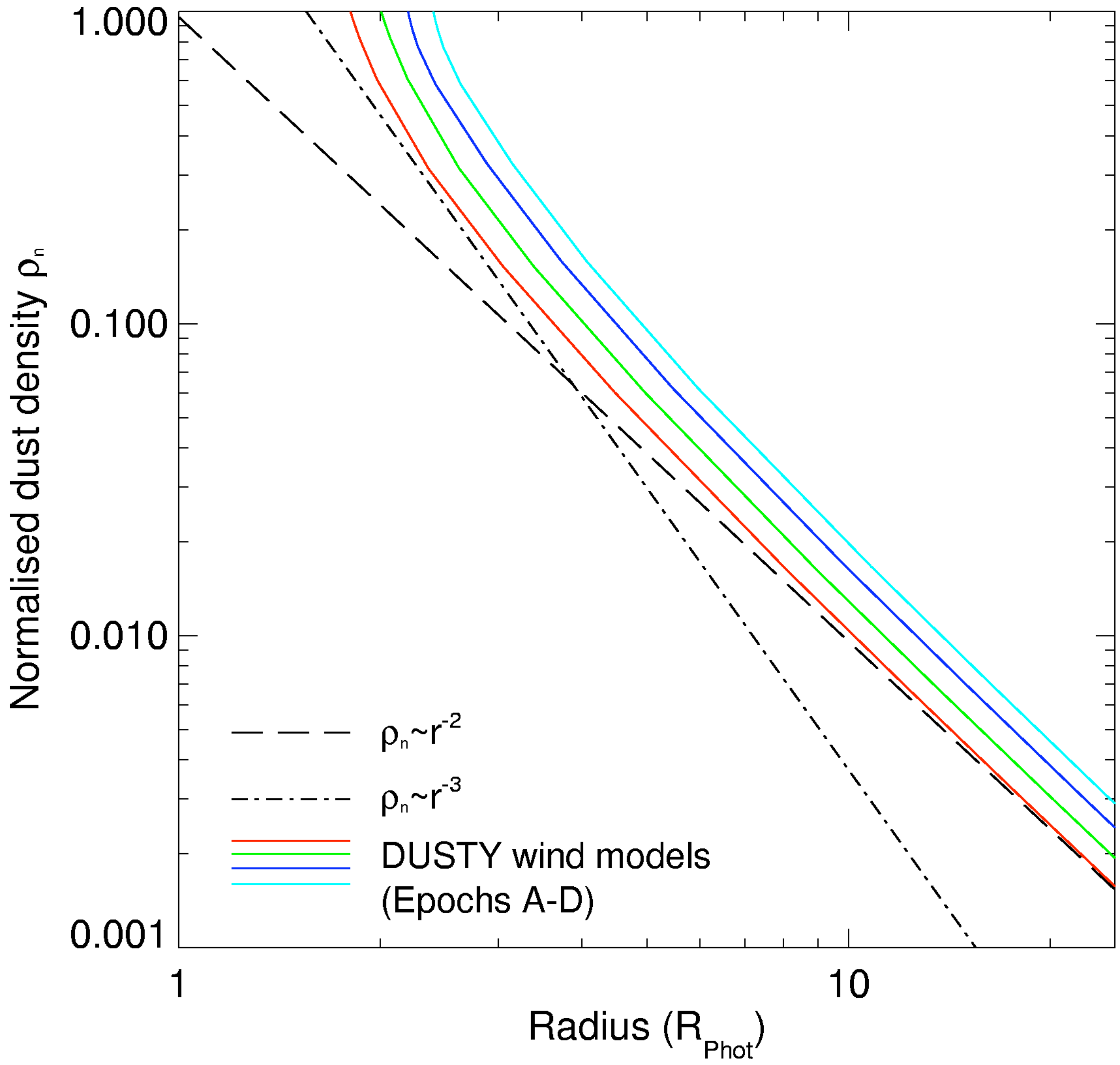
$R_{43.1}$=2.1 R_*
$R_{42.8}$=1.9 R_*

M21n
Al_2O_3 grains
τ_V=1.5
R_{in}=2.4 R_*
p=2.5

Θ_*=9.5 mas

(red) v=2, J=1-0, 42.8 GHz and (green) v=1, J=1-0, 43.1 GHz maser images on MIDI model

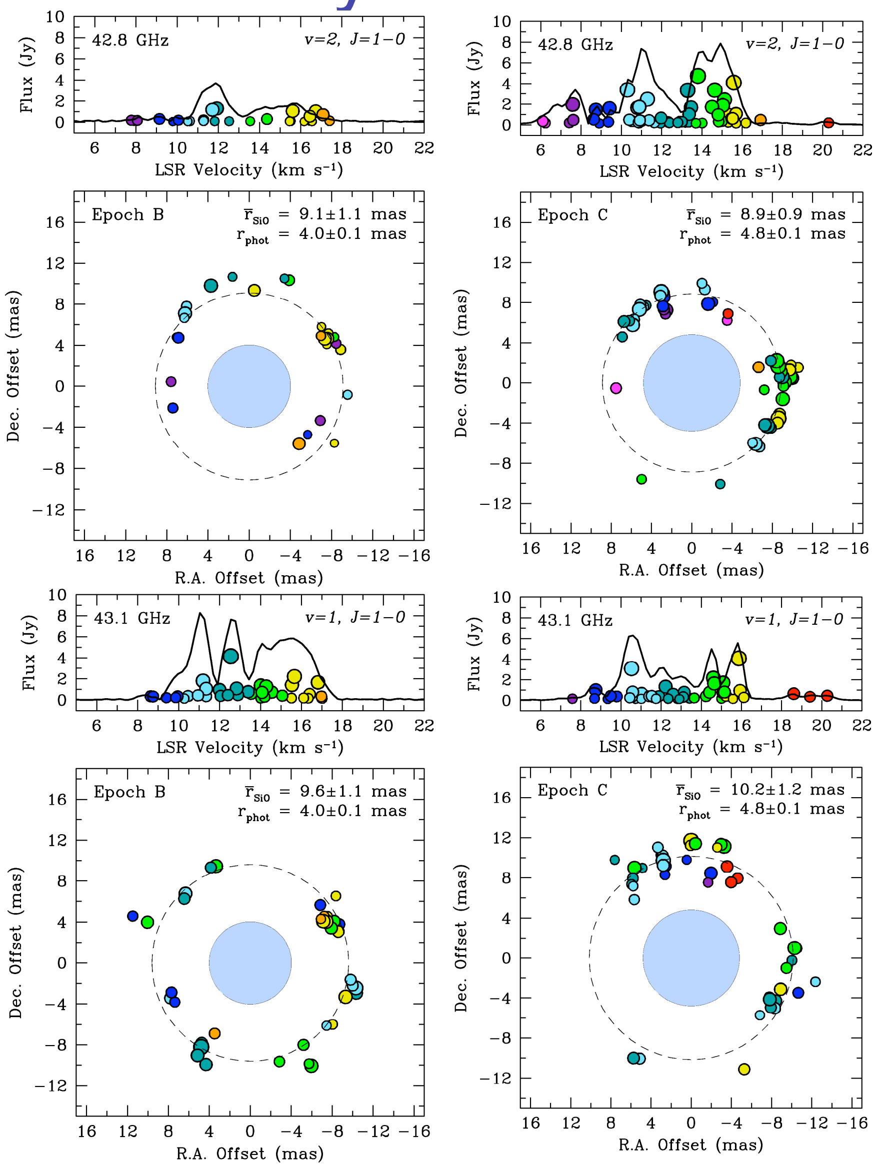
Density profile derived from a wind model

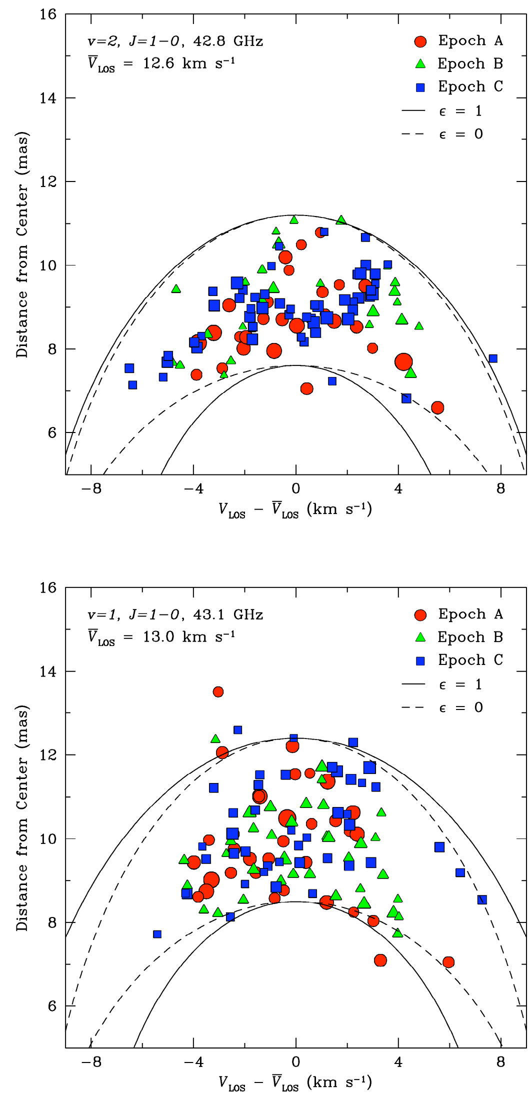


Wind model calculated with DUSTY (Ivezic & Elitzur 1997), using our best-fit parameters for the dust shell.

The density profile is proportional to r^{-2} for distances larger than about 10 stellar radii, but shows steeper gradients closer to the star.

Velocity structure of the maser spots

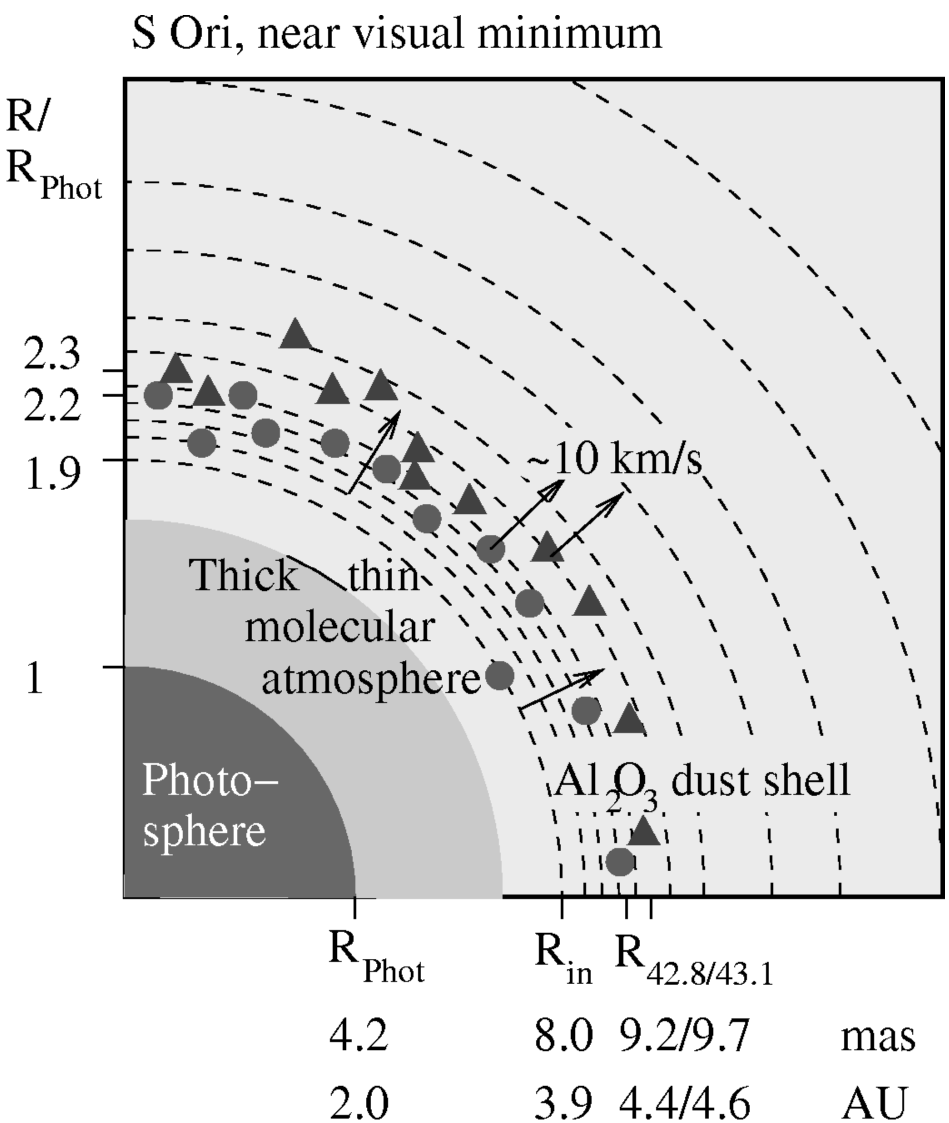


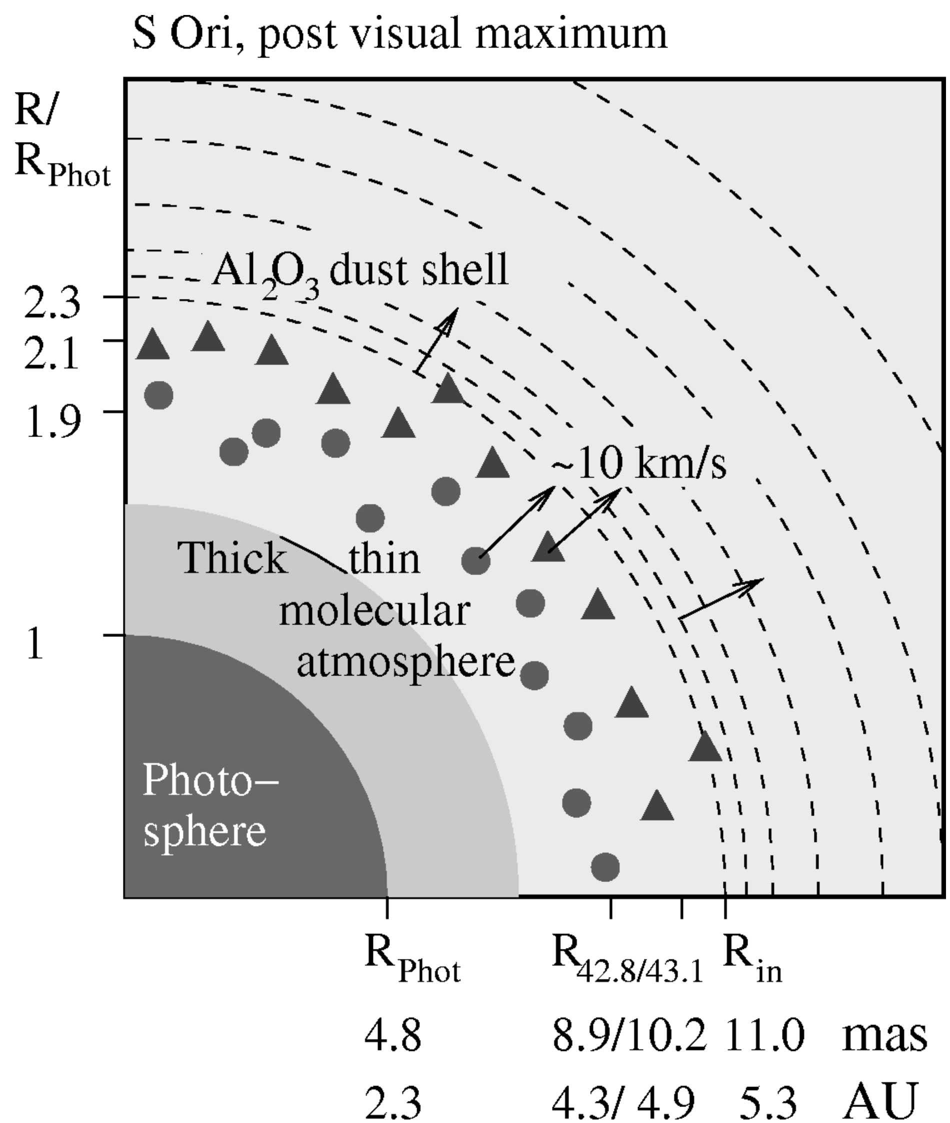


Best scenario:
Expanding spherical shell with a velocity between 7 km/sec and 10.5 km/sec.

Angle between maser plane and LOS:
90 deg. +/- 25 deg.

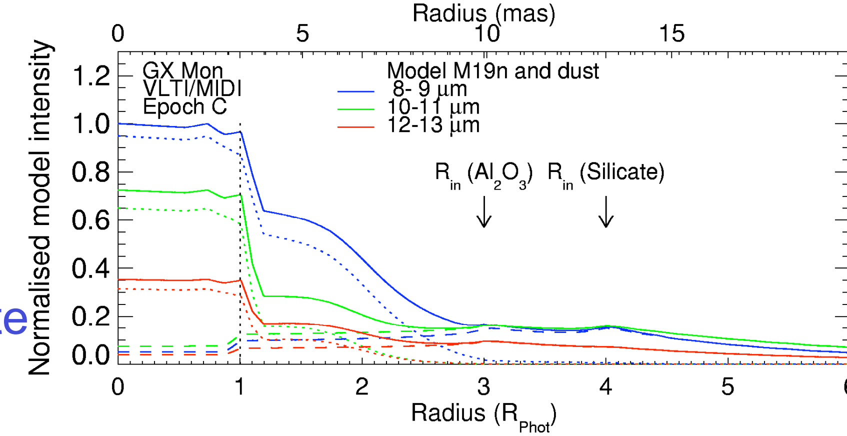
Sketch of the radial structure of S Ori's CSE

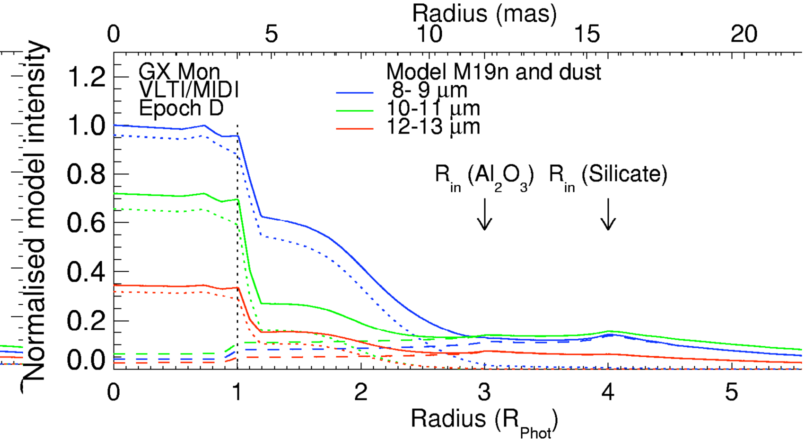


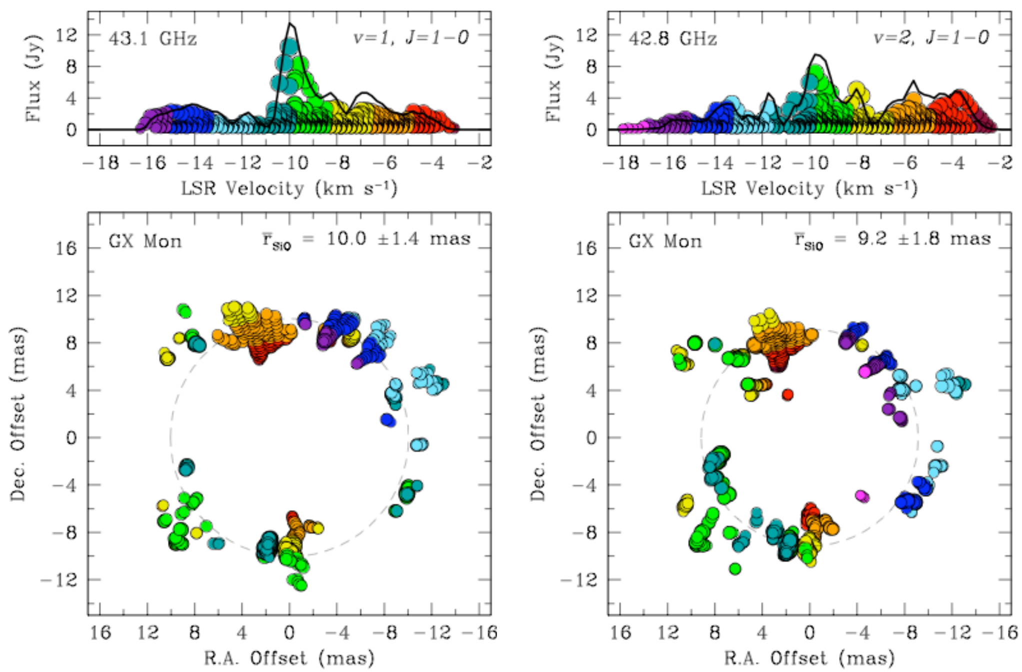


The Mira variable GX Mon (work in progress)

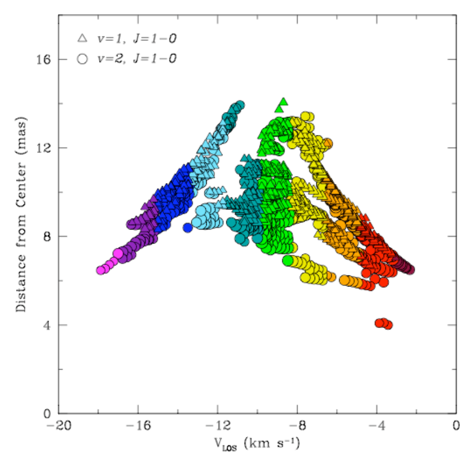
2 MIDI epochs:
15 Nov. 2005 &
27 Dec. 2005
Dust shell of
Al_2O_3 *and* Silicate



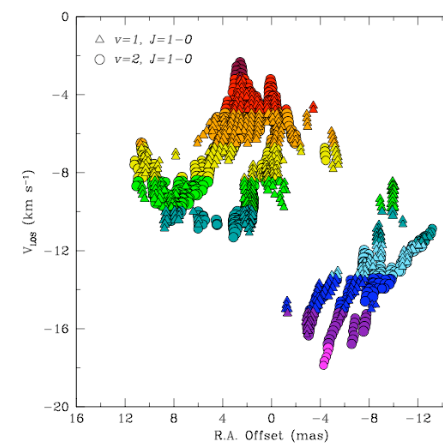




Single VLBA epoch: 8 April 2006



-> expansion



-> rotation ?

Summary

- S Ori shows significant phase dependences of photospheric radii and dust shell parameters.
- SiO masers and Al_2O_3 dust grains form at relatively small radii of ~1.8-2.4 photospheric radii, and are colocated near visual minimum.
- Our results of S Ori suggest increased mass-loss and dust formation close to the surface near visual minimum and an expanded dust shell after visual maximum.
- In the case of S Ori, silicon is not bound in silicates.
- In the case of GX Mon, Al_2O_3 grains at relatively small radii -again colocated with the SiO masers- *and* silicate grains at larger radii can be seen. Clearly higher optical depth than in the case of S Ori.
- Velocity structure of the maser spots indicate radial gas expansion.

- To come: Finer monitoring using MIDI/ATs; addition of NIR monitoring using AMBER/ATs; monitoring over more than one period; extension to H_20 and OH maser (wind region); comparison to new modern models of pulsation and dust formation.