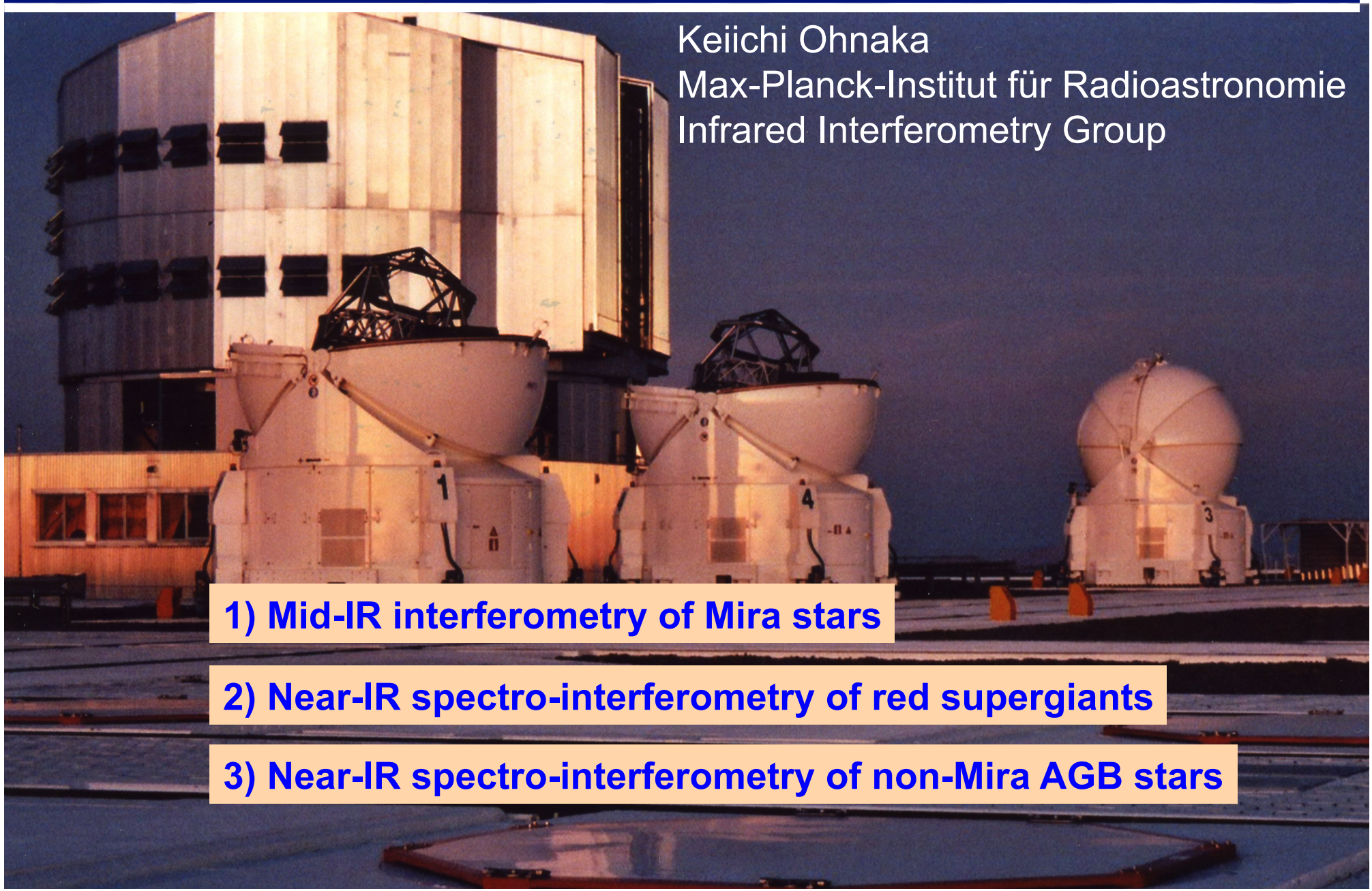
IR spectro-interferometry of cool evolved stars



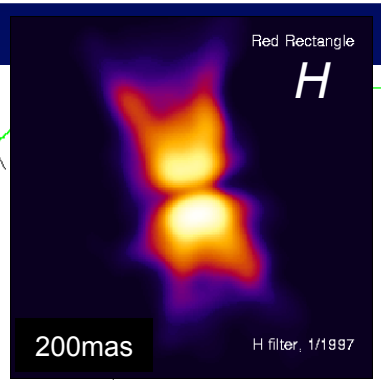
Keiichi Ohnaka
Max-Planck-Institut für Radioastronomie
Infrared Interferometry Group

1) Mid-IR interferometry of Mira stars

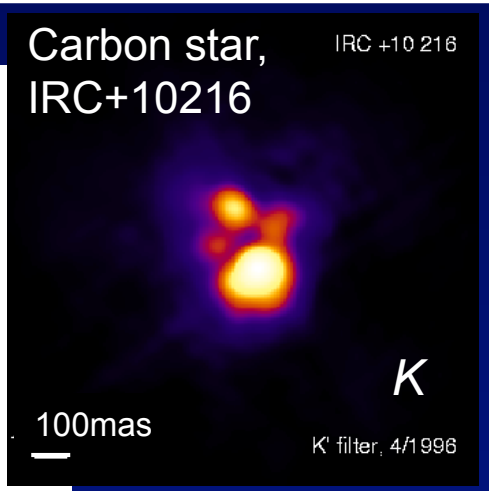
2) Near-IR spectro-interferometry of red supergiants

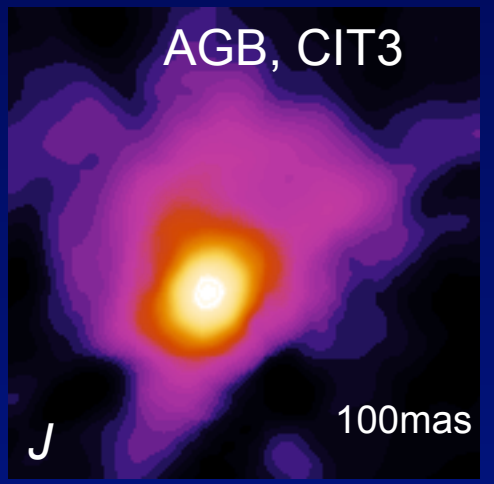
3) Near-IR spectro-interferometry of non-Mira AGB stars

Mass loss in AGB stars



Post-AGB
Red Rectangle





PN, Cat's Eye Nebula

✓ Driving mechanism not well understood

Mass-loss rates
= 10^{-8}—10^{-5} $M_\odot$/yr

Dust & Molecule forming region close to the star

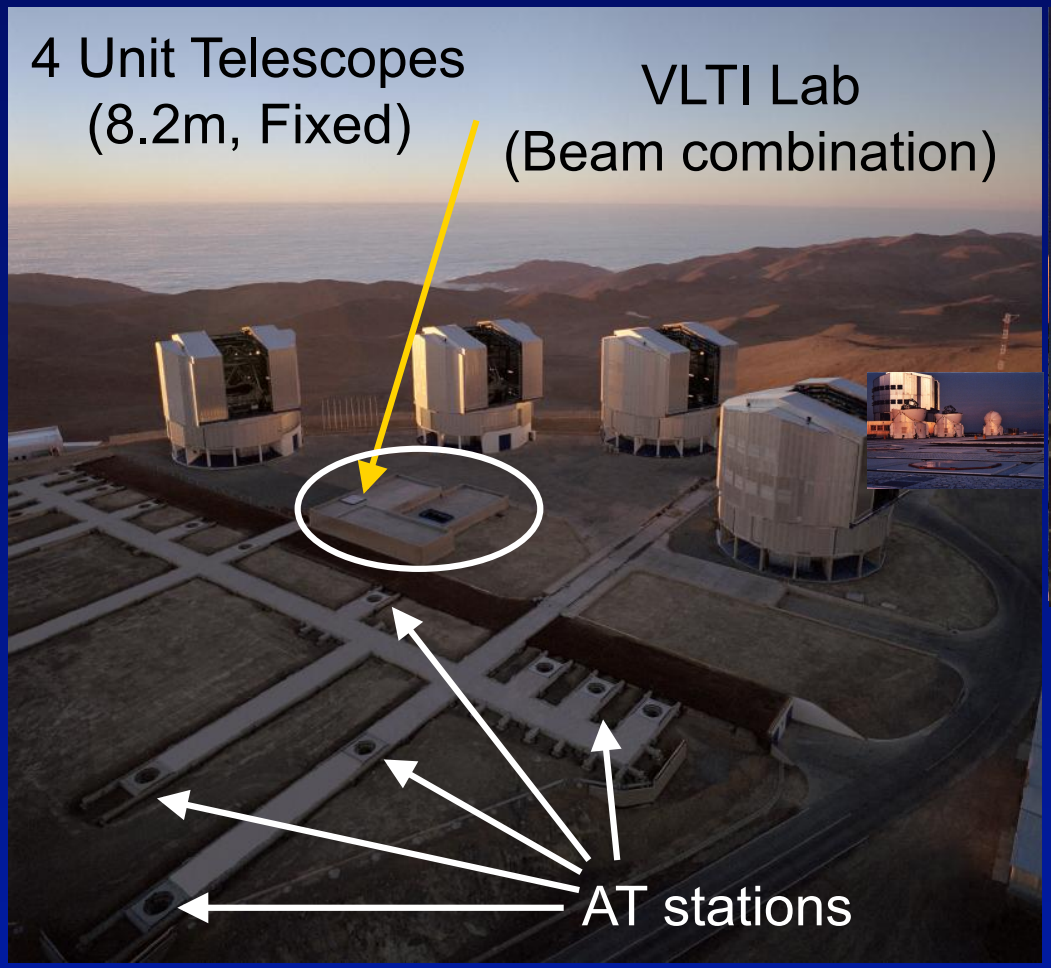
✓ Morphology change from AGB to planetary nebulae

How and at what stage?

→ High angular resolution
→ IR interferometry

Very Large Telescope Interferometer (VLTI)

4 Auxiliary Telescopes
(1.8m, Movable)

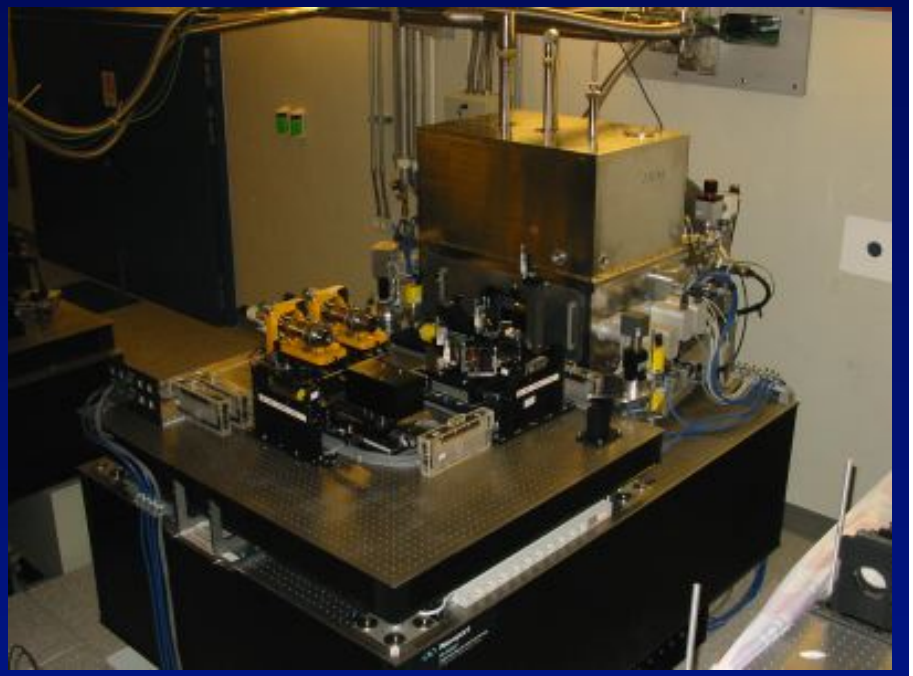


Change the array configuration depending on object's size/shape & Science cases

MIDI *N* band (8 – 13 μm)

Spectral dispersion (30 or 230)

→ Visibility measurements across molecular bands and dust features



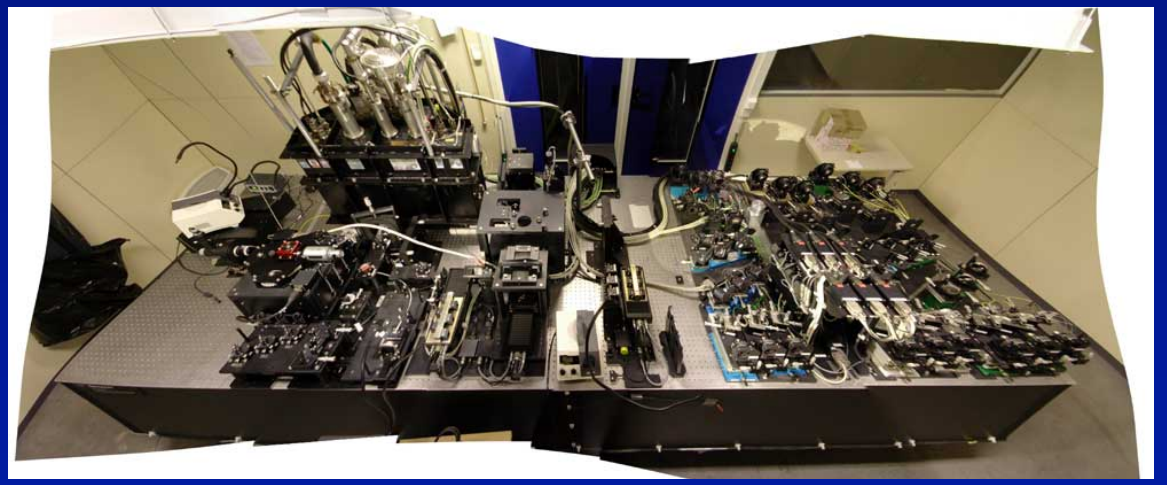
AMBER *J*, *H*, & *K* band (1 – 2.4μm)

Spectral resolution (35, 1500, 12 000)

Visibility measurements in atomic/molecular lines

3-way beam combiner

→ Closure phase (object's asymmetry, aperture synthesis imaging)



IR interferometry of Mira stars

Mira variables:
Large variability amplitude
~ 9 mag (in V)

Expanding dust shell

Extended outer atmosphere
1000—2000K, 2—5 Rstar

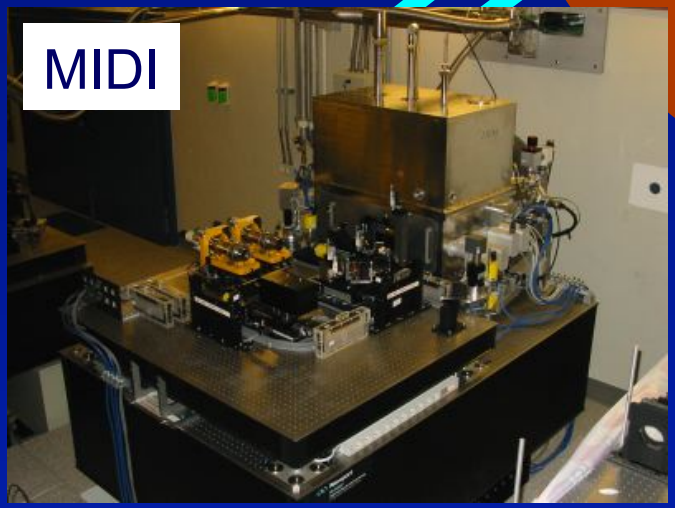
Dust formation

Photosphere

Spectro-interferometry
Spatial + Spectral resolution

Mid-IR (*N* band)

Near-IR (*JHK*)



"Big" MIDI/AT campaign on O-rich Mira stars

K. Ohnaka, M. Schöller, T. Driebe, S. Morel, G. Weigelt, M. Wittkowski

Scientific goals

Observe a few selected Miras at multiple epochs
with 3 different baselines
at different position angles

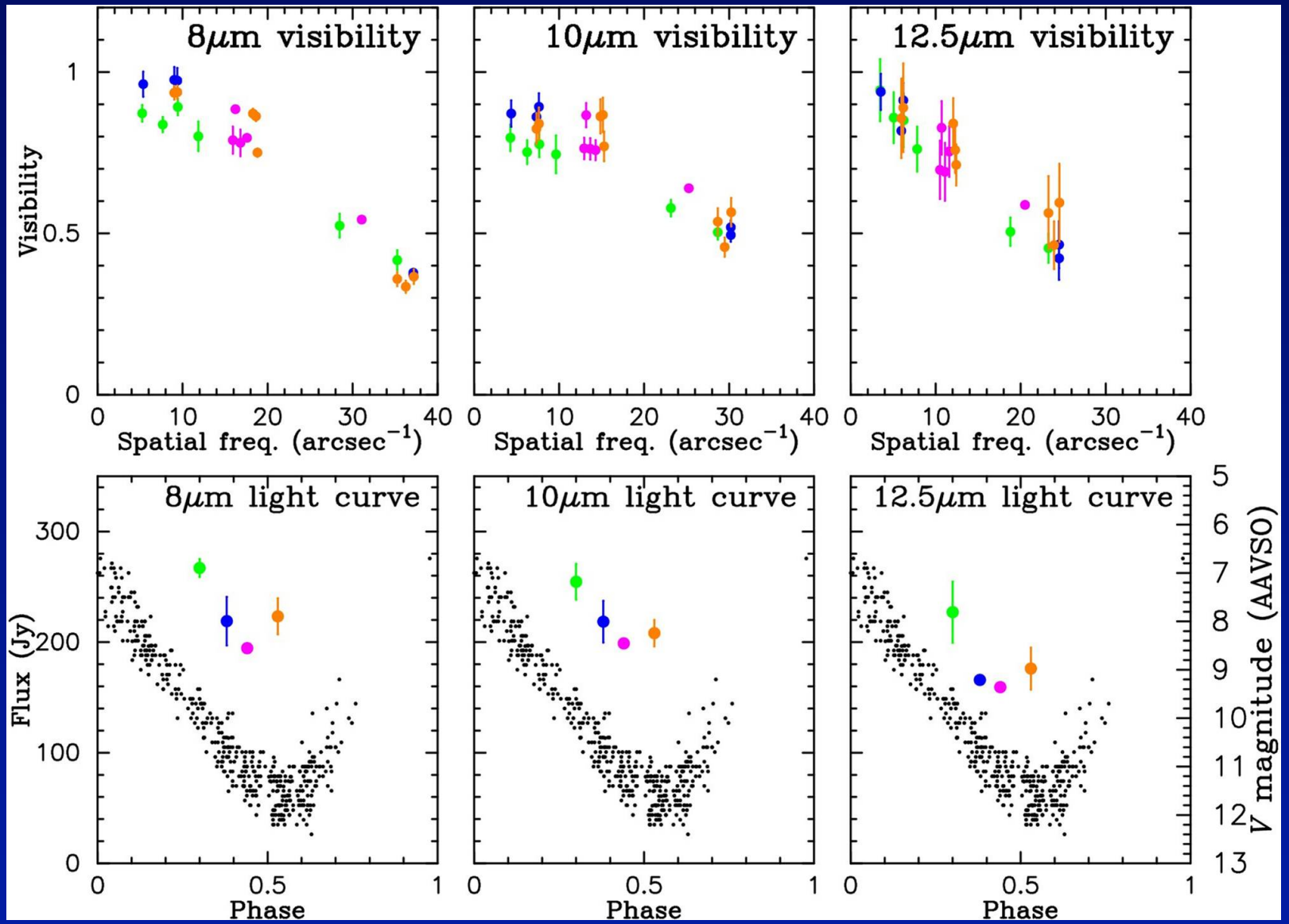
→ Measure phase dependence
radial structure of the outer atmosphere & dust shell
possible deviation from spherical symmetry

	R Car	R Cnc	Z Pup
Period	308 days	361 days	508 days
Variability in *V*	5—6 mag	5—6 mag	6—7 mag
# obs.	38	30	35
# epochs	9	6	4

Total observing time = 103 hours

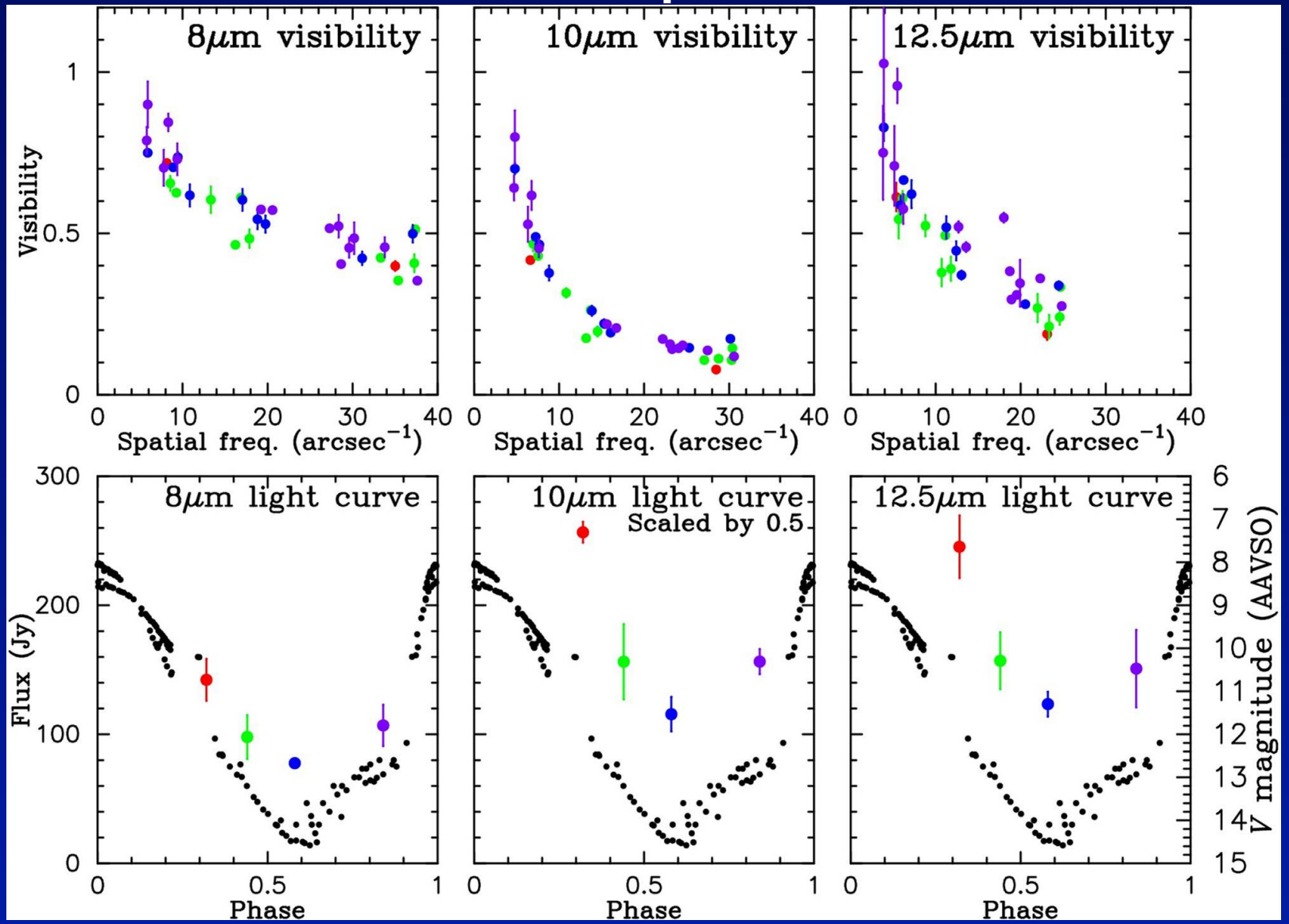
“Big” MIDI/AT campaign on O-rich Mira stars

R Cnc



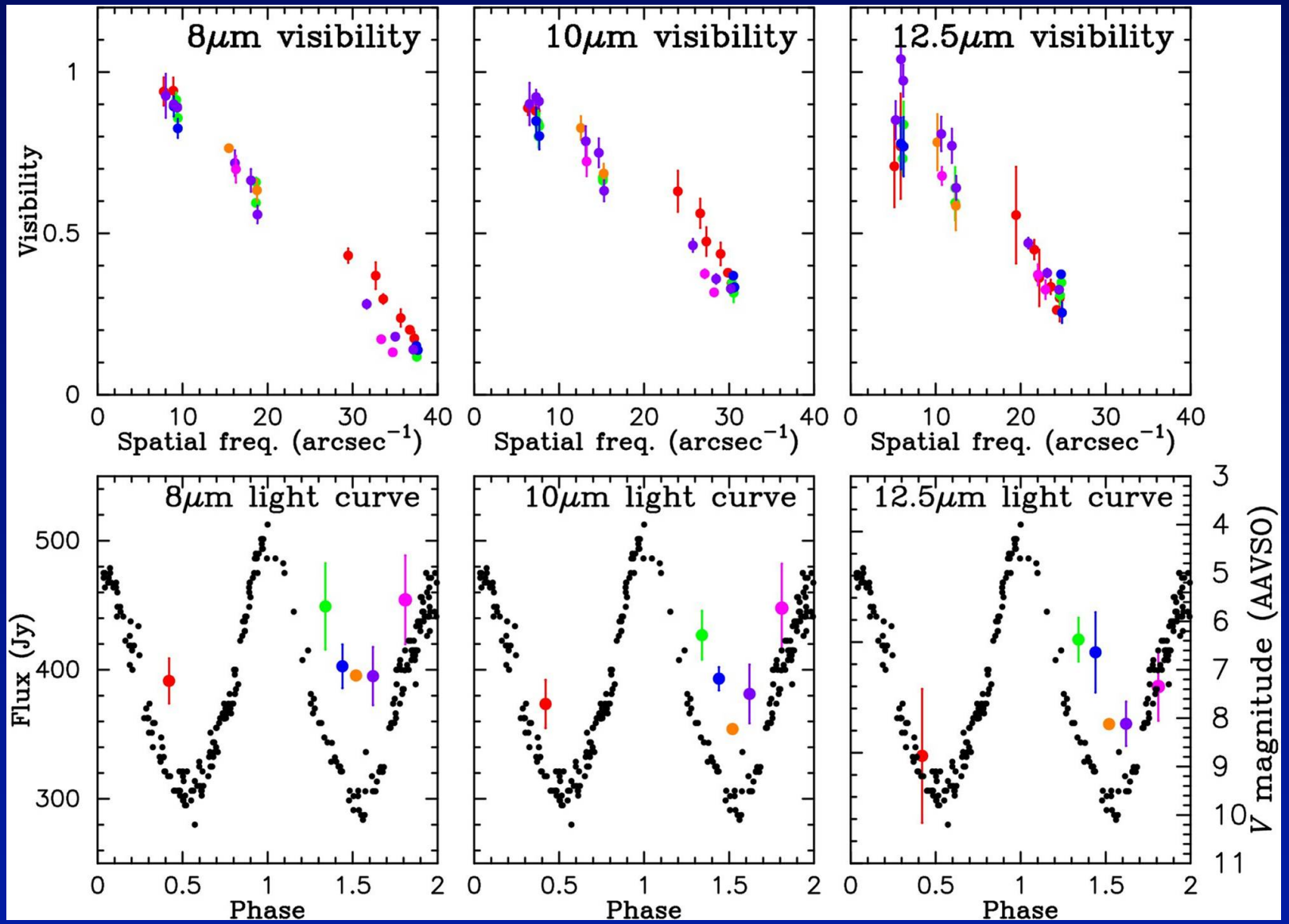
“Big” MIDI/AT campaign on O-rich Mira stars

Z Pup



“Big” MIDI/AT campaign on O-rich Mira stars

R Car



Results

- ✓ Only marginal temporal variations detected in 3 O-rich Miras

  In contrast to the C-rich Mira V Oph (Ohnaka et al. 2007)
  → O-rich Miras show lesser temporal variations?
  or observed just in “quiescent” cycles?

- ✓ No significant deviation from centrosymmetry in R Car & Z Pup
  PA coverage too small for R Cnc

- ✓ No cycle-to-cycle variation detected (R Car)
  But compared only at 1 phase

- ✓ Modeling is underway

Probing inhomogeneous structures in red (super)giants

Spatially resolving the dynamics in the atmosphere of Betelgeuse

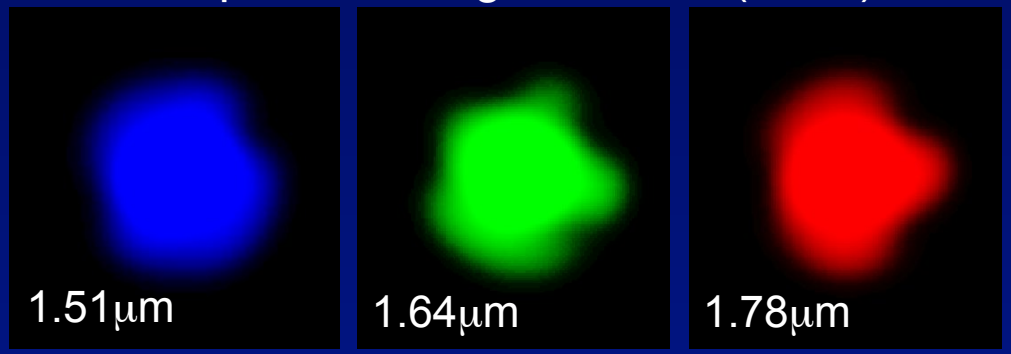
✓ Inhomogeneous structures detected

Miras: R Aqr (Ragland et al. 2008)
U Ori (Pluzhnik et al. 2009)
χ Cyg (Lacour et al. 2009)

Red supergiants: Betelgeuse

→ Key to understanding of mass loss mechanism in red (super)giants

R Aqr, IOTA, Ragland et al. (2008)



✓ CO first overtone lines @ 2.3 μm

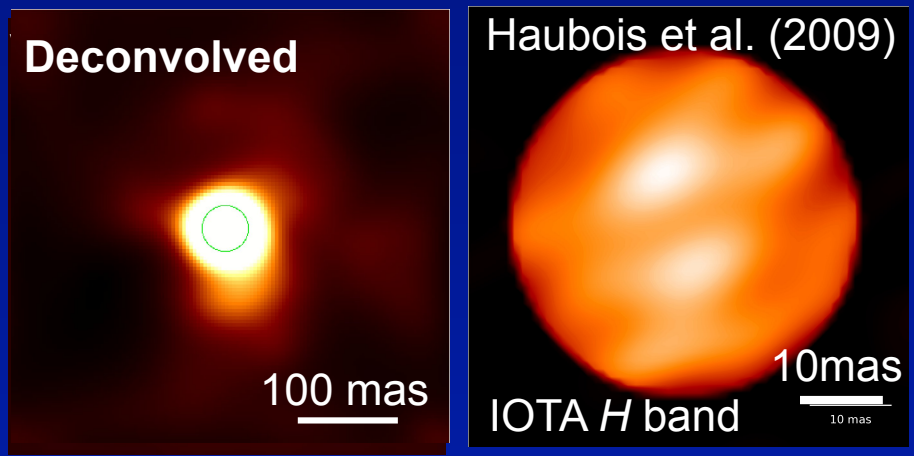
→ Probing the outer atmosphere
= wind acceleration zone

✓ AMBER high resolution spectro-interferometry

Betelgeuse = best-studied RSG
Baseline = 16-32-48m
Spectral resolution = 12000

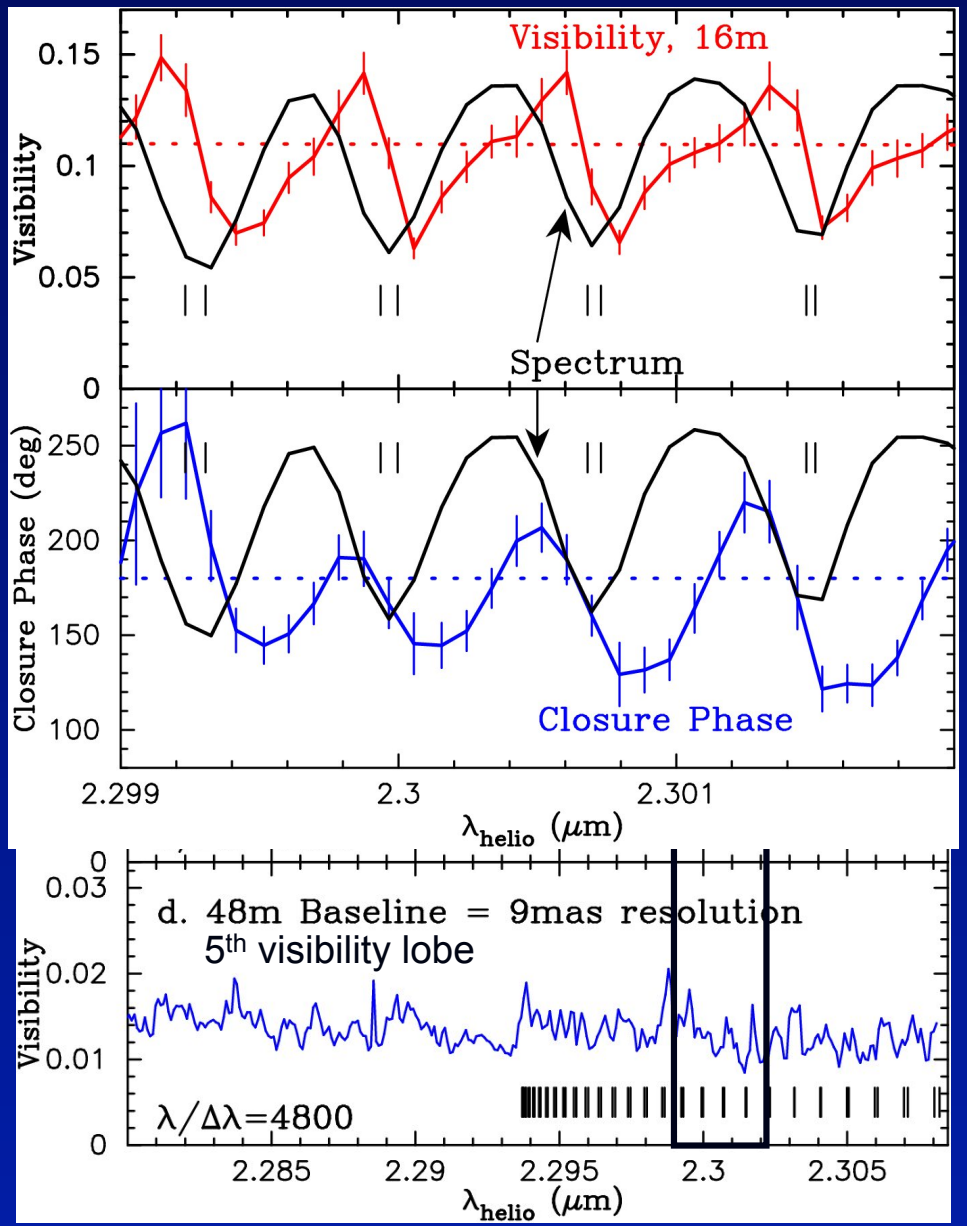
→ Individual CO lines resolved

Red supergiant Betelgeuse



AMBER observations of the red supergiant Betelgeuse

Spatially resolving the star in the CO lines



Observational results

- ✓ Spatially resolved in the individual CO lines for the first time
- ✓ 48m baselines = 9 mas resolution (Beam size = 1/5 ×star's size)

→ Highest resolution ever achieved for Betelgeuse at any wavelength

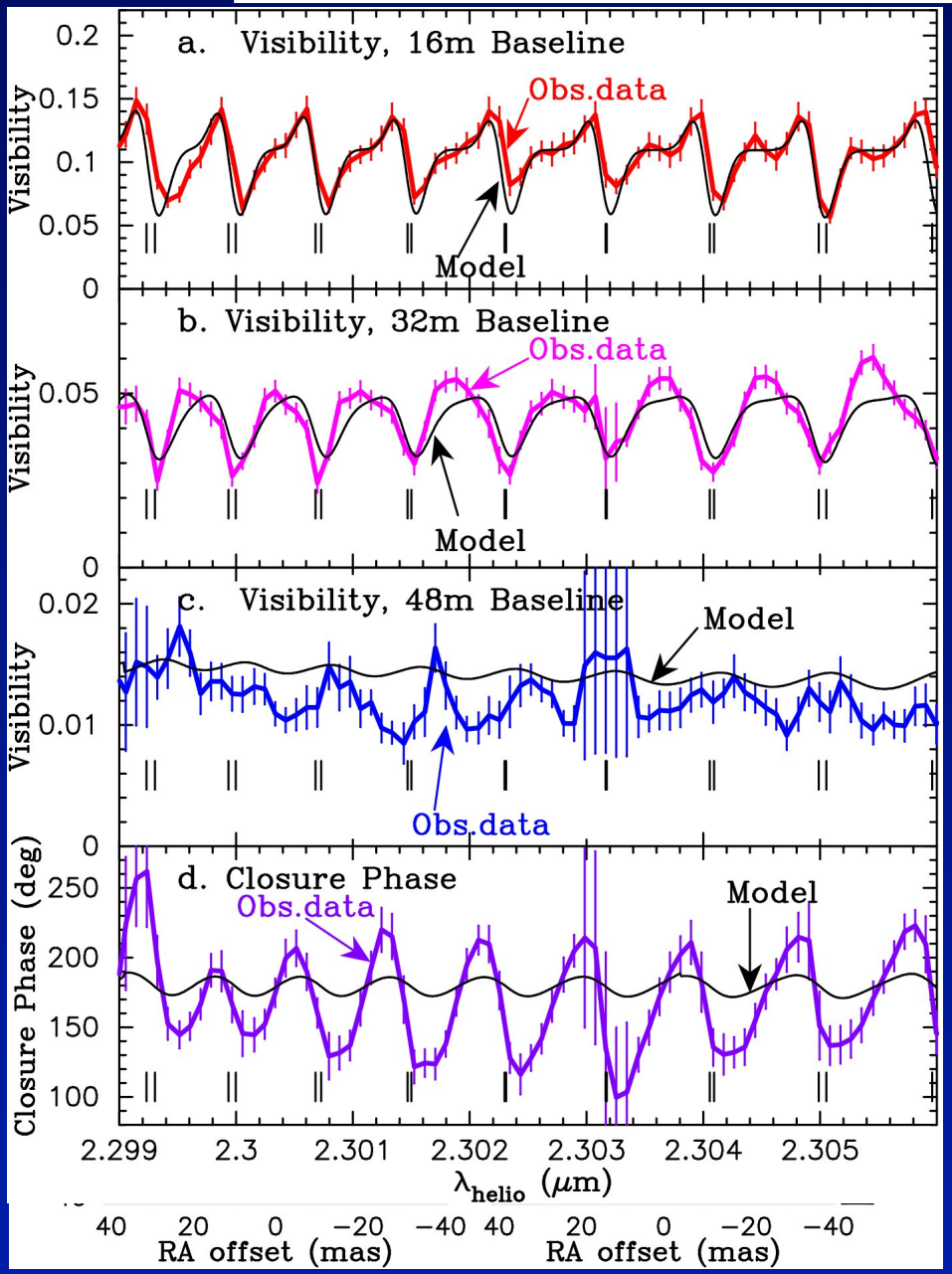
- ✓ Visibility & Closure phase asymmetric with respect to the line center

→ The star looks different in the red & blue wings

→ Inhomogeneous velocity field

AMBER observations of the red supergiant Betelgeuse

Model with an inhomogeneous velocity field



Results

✓ Gas motion in a stellar photosphere spatially resolved for the first time other than the Sun

Velocity amplitude = 10—15 km/s

✓ Extended CO layer detected

CO column density = ~10^{20} cm^{-2}

T~ 1800K

Radius ~ 1.4 R_*

✓ Vigorous gas motion in the outer atmosphere

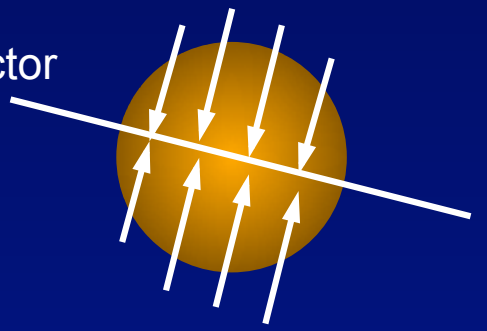
AMBER observations of the red supergiant Betelgeuse

1-D aperture synthesis imaging in the CO lines

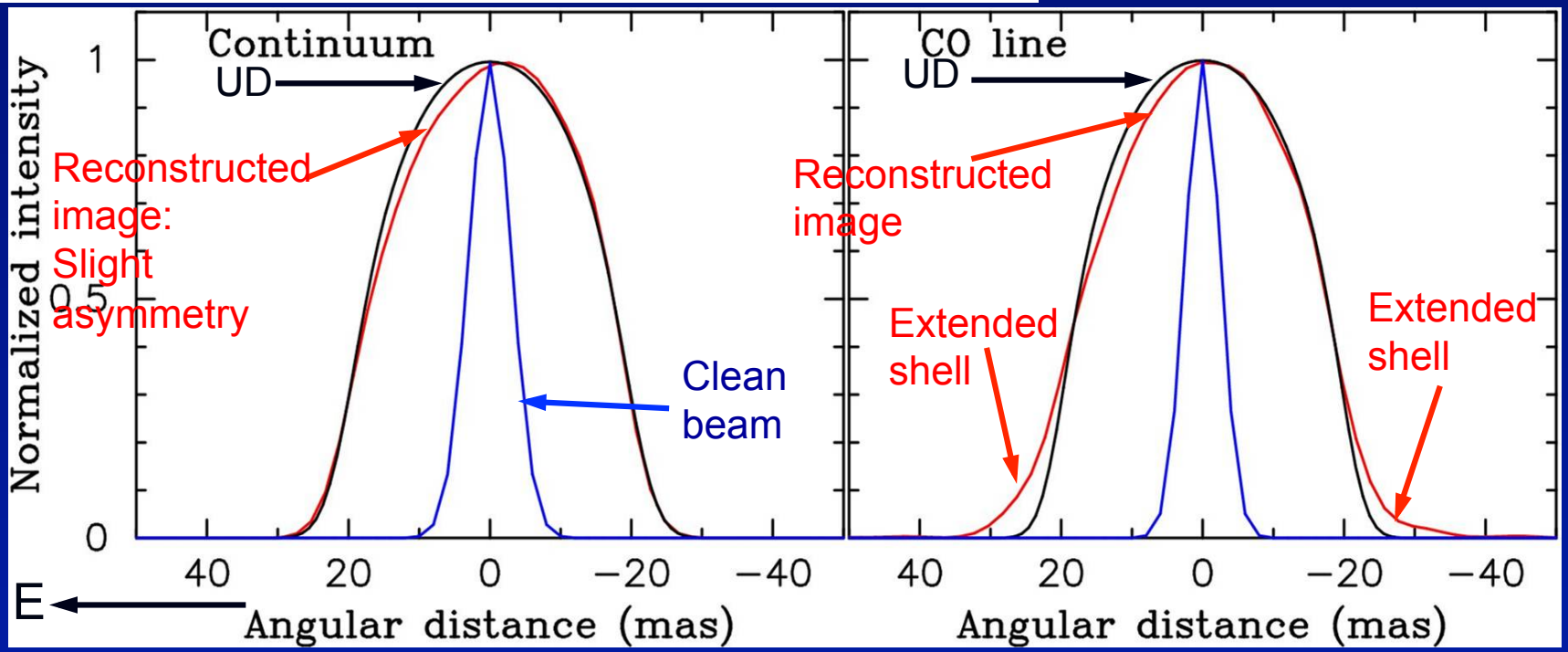
New data taken in Jan. 2009
54 (u,v) points along position angle = 70°
from the 1st to the 5th visibility lobe

Image reconstruction with MiRA (Thiébaut et al. 2008)

Intensity distribution projected onto the baseline vector



First high-spectral resolution aperture synthesis imaging in the individual CO lines



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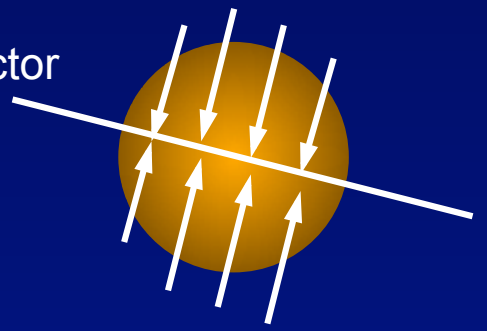

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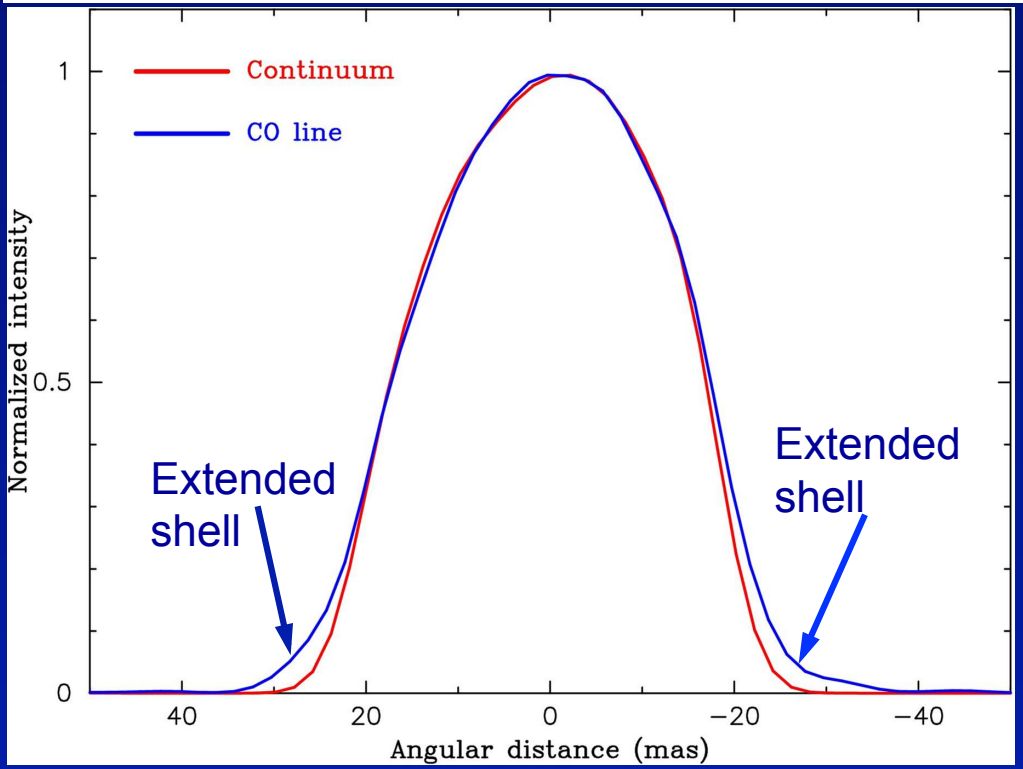


- ✓ First "line" image of the extended molecular layers in red supergiants
- ✓ CO shell size =
  1.4 × Continuum size
  → Agrees with the modeling

What about AGB stars -- less luminous counterparts?

✓ Mass loss mechanism of non-Mira AGB stars not well understood
Outer atmosphere of non-Mira AGB stars

semiregular & irregular variables
→ small variability amplitudes: ΔV = 1—2
→ No clear periodic variations
→ Still, mass-loss rates can be comparable to Miras (~10^{-7} $M_\odot$)

✓ Non-Mira AGB stars the majority of AGB stars

General Catalog of Variable Stars

Mira-type	6287 stars
semi-regular / irregular	9777 stars

✓ High spatial & spectral resolution
AMBER observations of the CO first overtone lines in a semi-regular variable BK Vir

BK Vir (yet another late M giant)
Angular diameter = 10.5 mas
Teff = 2900K
d = 180 pc (parallax known)
L = 2700 $L_\odot$
M = 1 – 2 $M_\odot$
log g = 0.0
Mass-loss rate = a few x 10^{-7} $M_\odot$

AMBER observations of the semi-regular AGB star BK Vir

Observations

Baseline = 16-32-48m
Spectral resolution = 12000
2.26—2.31μm
DIT = 6s with FINITO
→ Absolute calibration uncertain
→ Visibilities scaled to UDD=10.5mas in the continuum

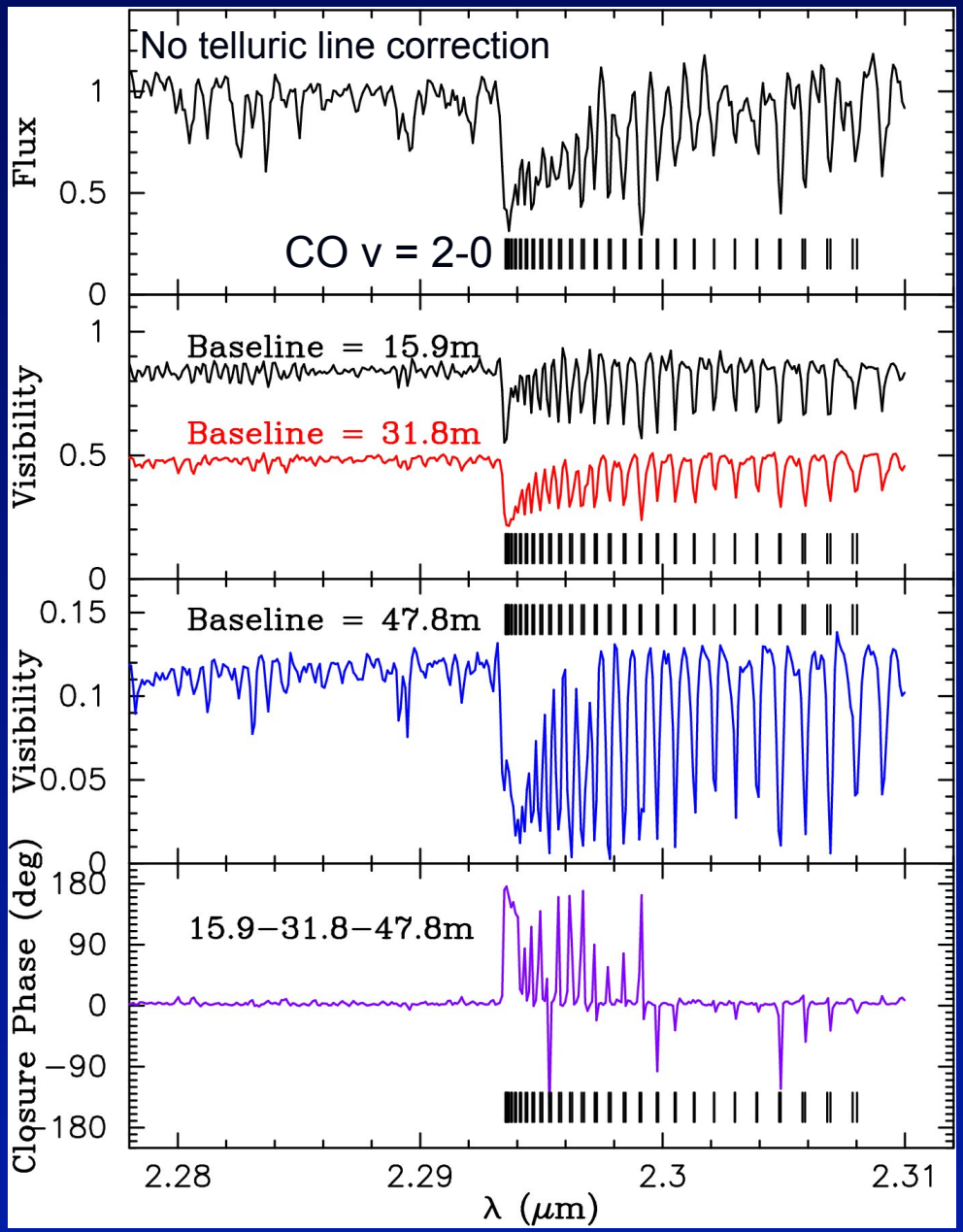
Observational results

✓ Size(CO lines) / Size (cont.) = 1.14 —1.33

✓ Inhomogeneities in CO lines

✓ No asymmetry with respect to line center

→ Velocity amplitude much smaller than in Betelgeuse, < 5 km/s



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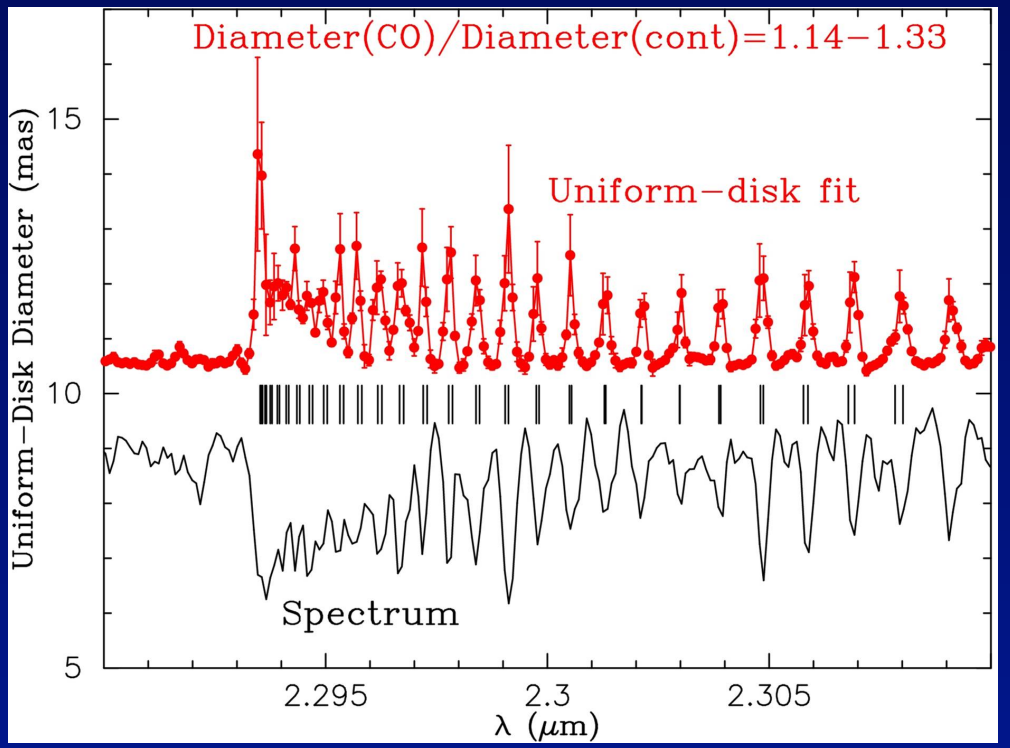

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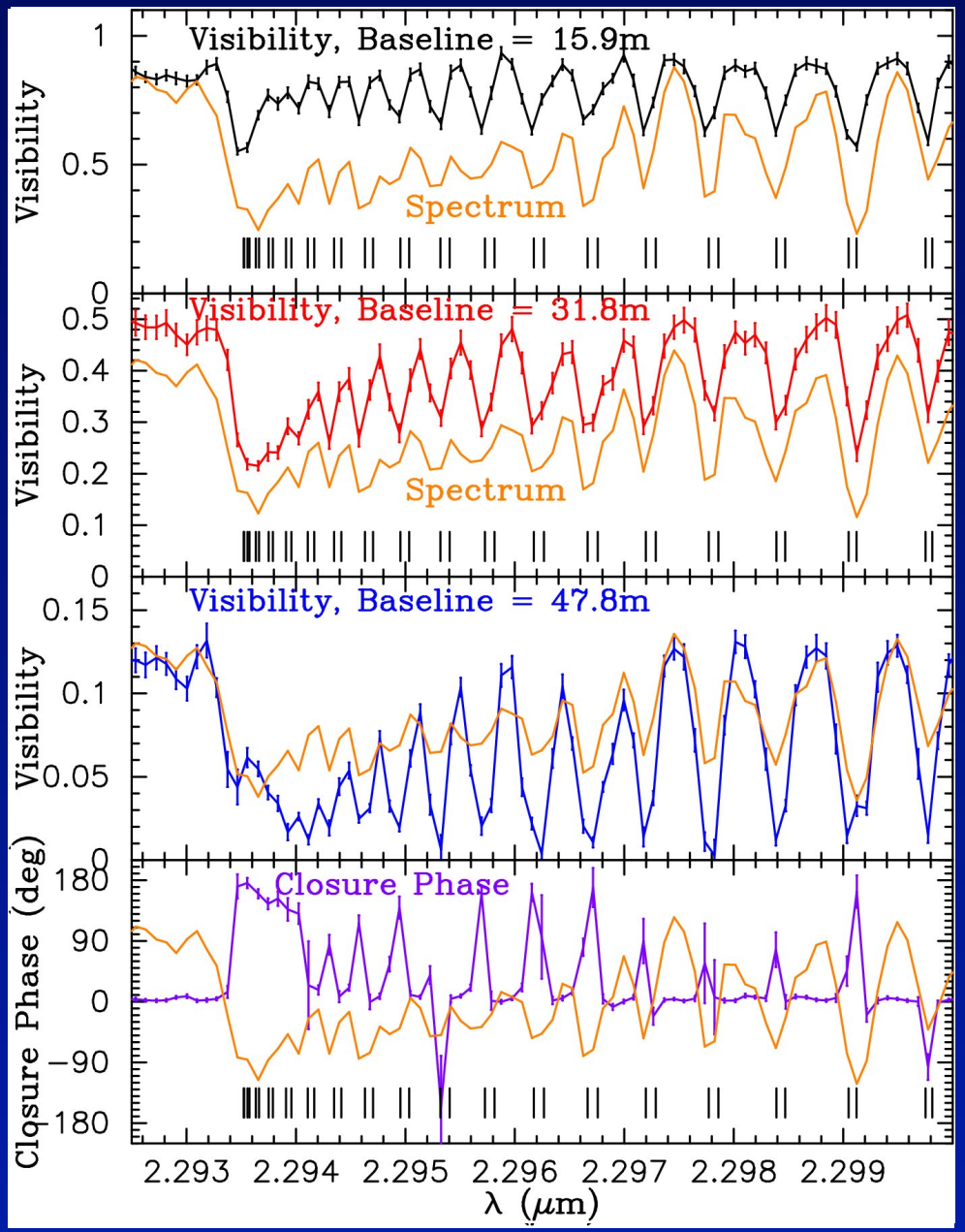
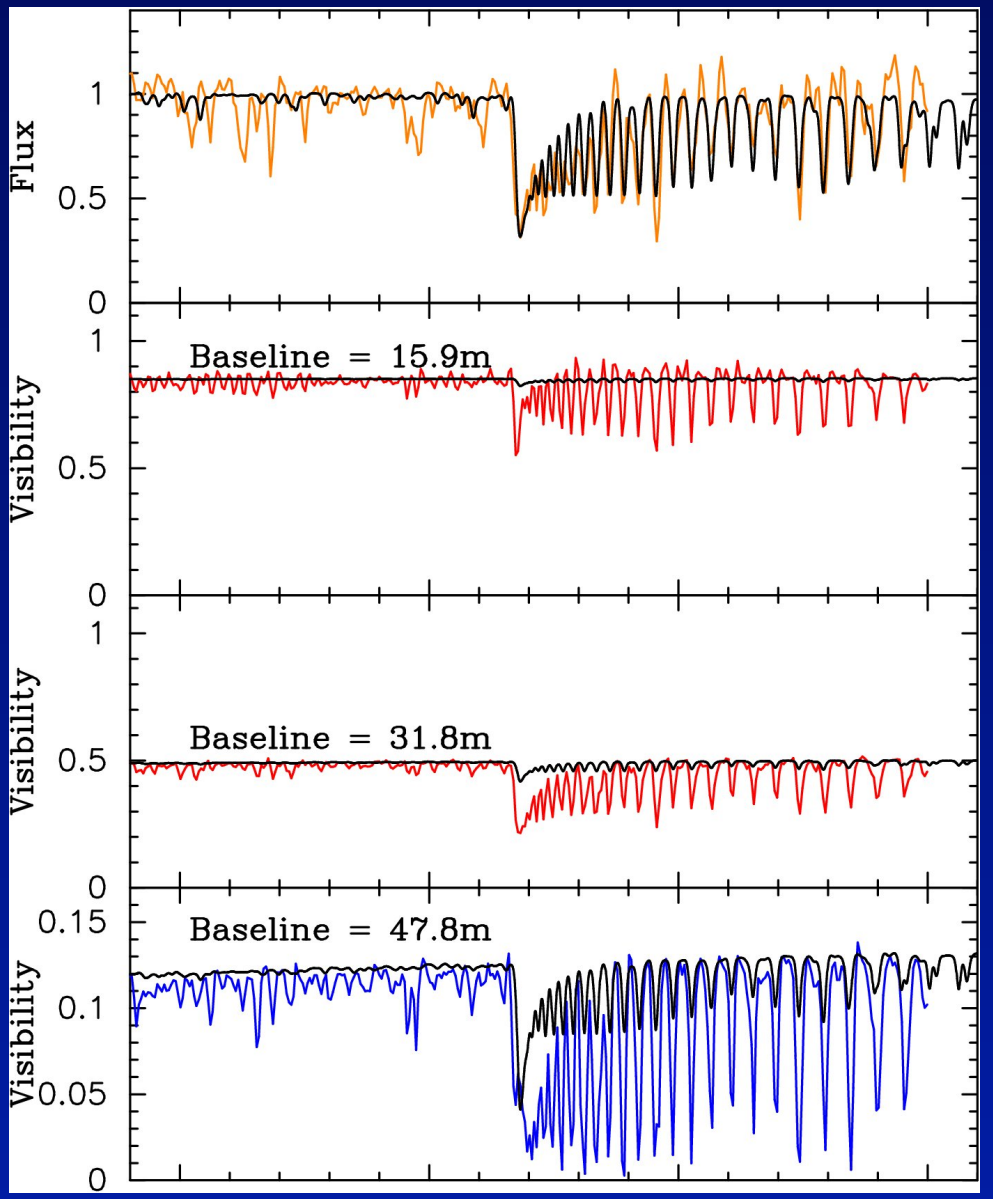


AMBER observations of the semi-regular AGB star BK Vir

✓ Comparison with MARCS model
1-D, spherical model
(Gustafsson et al. 2008)
*T*eff = 3000K
$Z = Z_{\odot}$, moderately CN-processed
$M = 1\ M_{\odot}$
log *g* = 0.0
→ Pressure & temperature distributions
→ Computation of monochromatic intensity profile (& visibility)
+ spectrum (Ohnaka et al. 2006)

✓ MARCS model spectrum agrees well with the observation.
But the star is much more extended in the CO lines



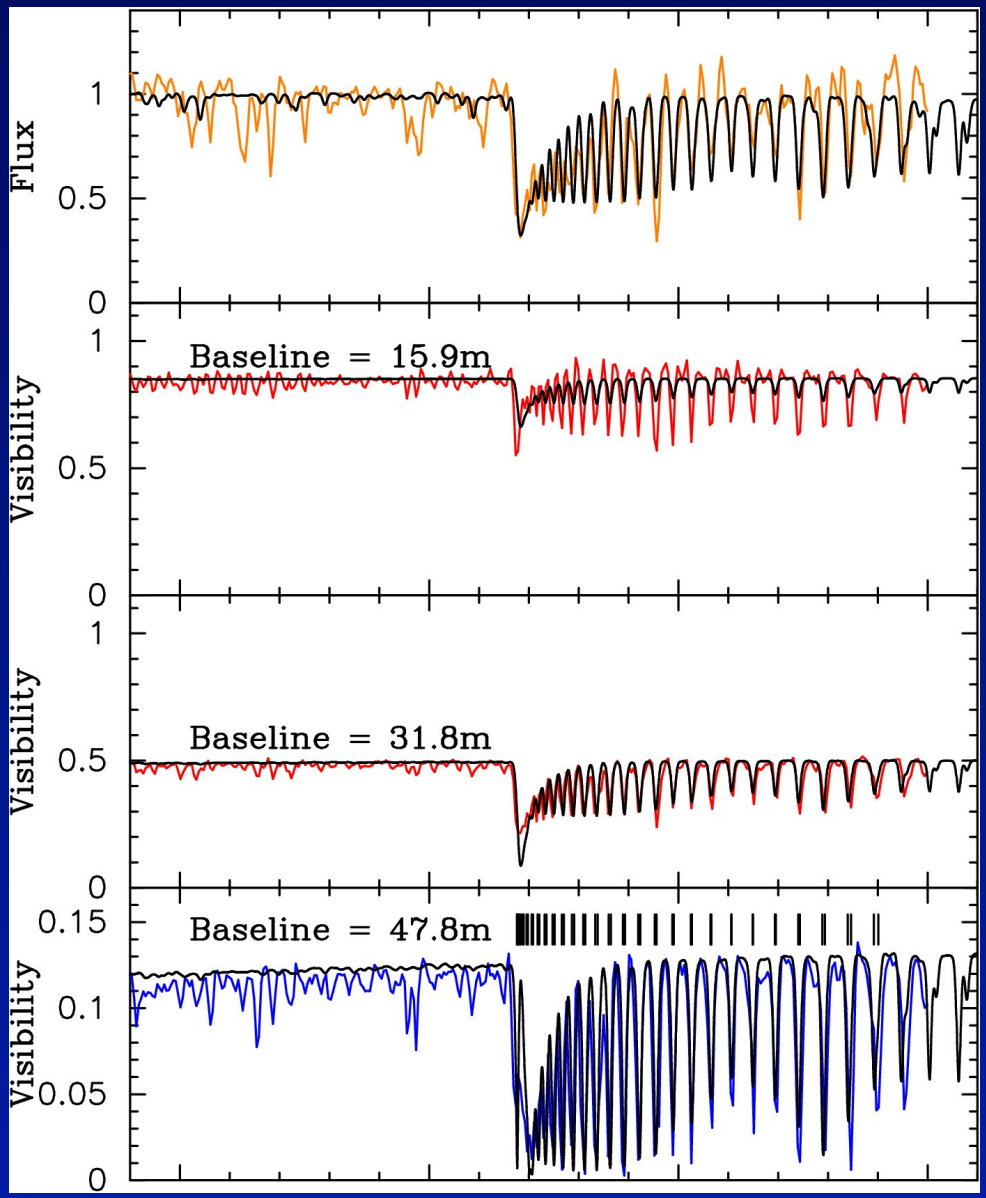
AMBER observations of the semi-regular AGB star BK Vir

- ✓ MARCS model (photosphere) + extended CO layer

  CO column density = ~10^{22} cm^{-2}
  temperature = 1800 K
  radius = 1.5 Rstar

- ✓ Temperature & radius similar to Betelgeuse, but much more dense in BK Vir

- ✓ Origin of the extended CO layer unknown.
  Low wind speed & low mass-loss rate model of Winters et al. (2000) for C-rich stars?



Concluding remarks

1) Monitoring temporal variations in 3 Miras with MIDI/AT

Only marginal temporal variations are detected
No significant deviation from centrosymmetry is detected

2) Spatially resolving the inhomogeneities in the CO first overtone lines in red (super)giants

Betelgeuse

Inhomogeneous velocity field spatially resolved

1-D high spectral resolution aperture synthesis imaging in the CO lines

BK Vir

CO line forming region much more extended than photospheric models

Inhomogeneities in the extended CO layer

Velocity amplitude is much smaller than in Betelgeuse

Mid-IR interferometry of time variations in Mira stars

O-rich Miras

- ✓ ISI, a few wavelengths near 11μm
  - *o* Cet: Weiner et al. (2003)
  - 6 Miras: Tatebe et al. (2006)
- ✓ VLTI/MIDI, 8—13mm
  - S Ori: Wittkowski et al. (2007)

C-rich Miras

- ✓ VLTI/MIDI
  - V Oph, Ohnaka et al. (2007)
- ☹ Only a few visibility points at each epoch in MIDI studies so far

N-band UD diameter of the C-rich Mira V Oph