Spatially resolving the gas dynamics over the surface of red supergiants with the Very Large Telescope Interferometer

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Mass loss in red supergiants

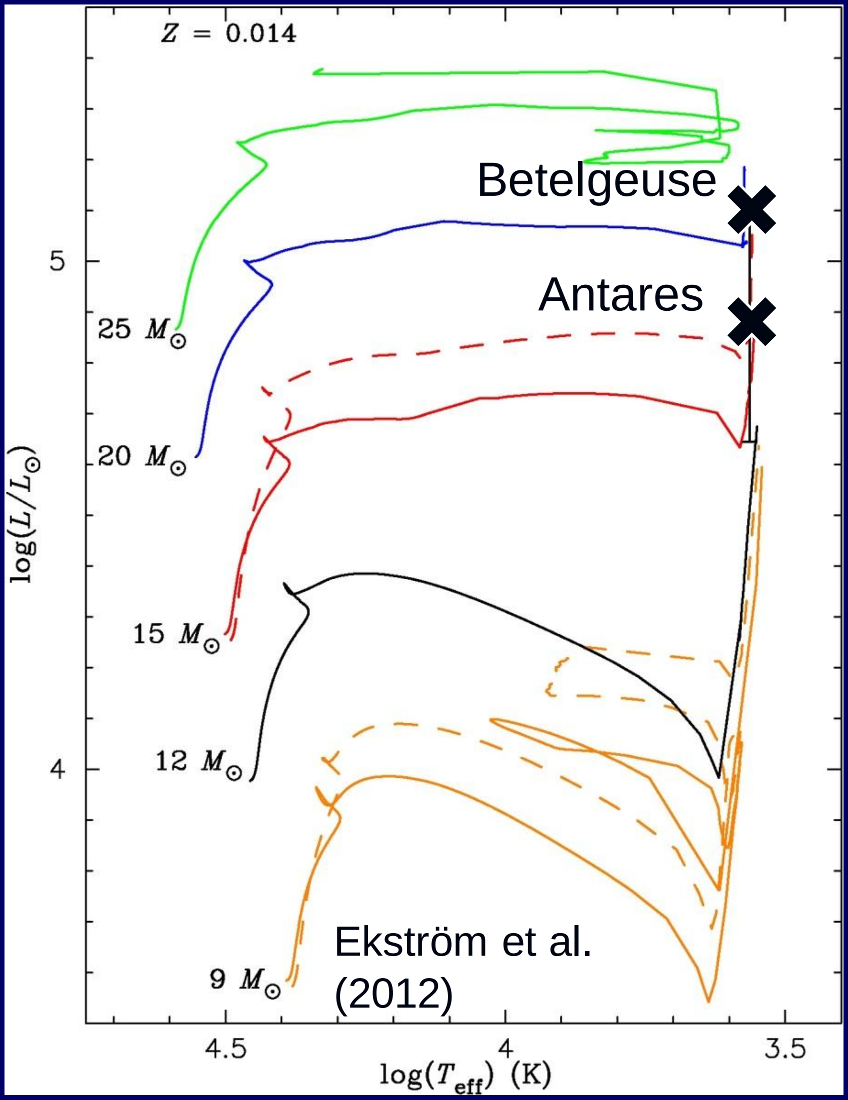
- ✓ Significant mass loss
  ~10^{-7}--10^{-4} $M_\odot$/yr
  (even with little or no dust)

  → No theoretical model to explain the mass loss in red supergiants

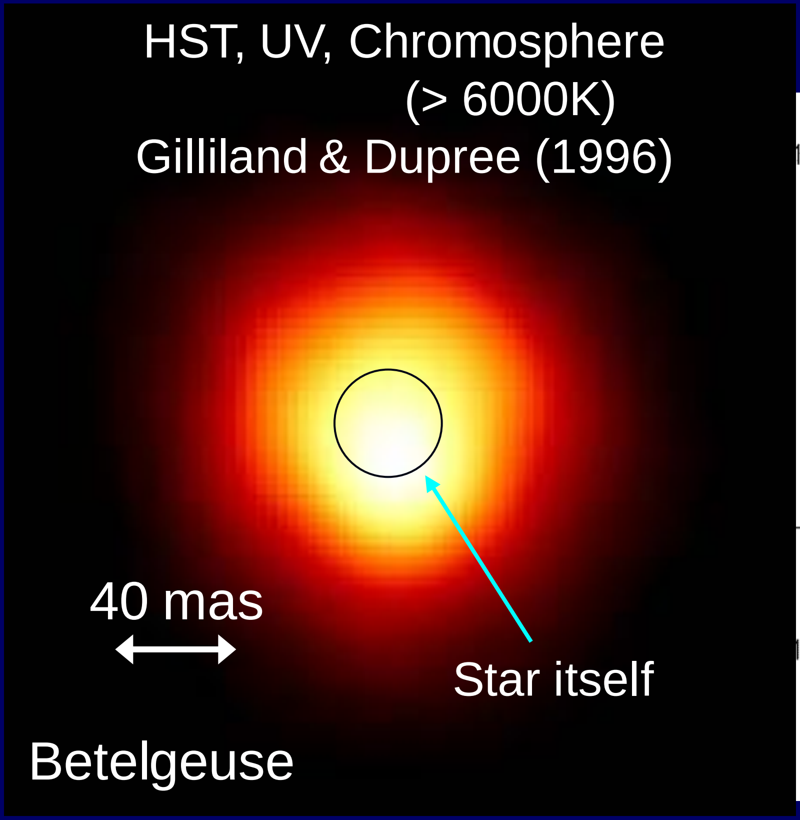
- ✓ Influences the maximum progenitor mass of SN IIp (most common SNe)

  Progenitor mass of SN IIp
  Smartt et al. (2009)
  Theory : ~25 $M_\odot$
  Observation: ~17 $M_\odot$

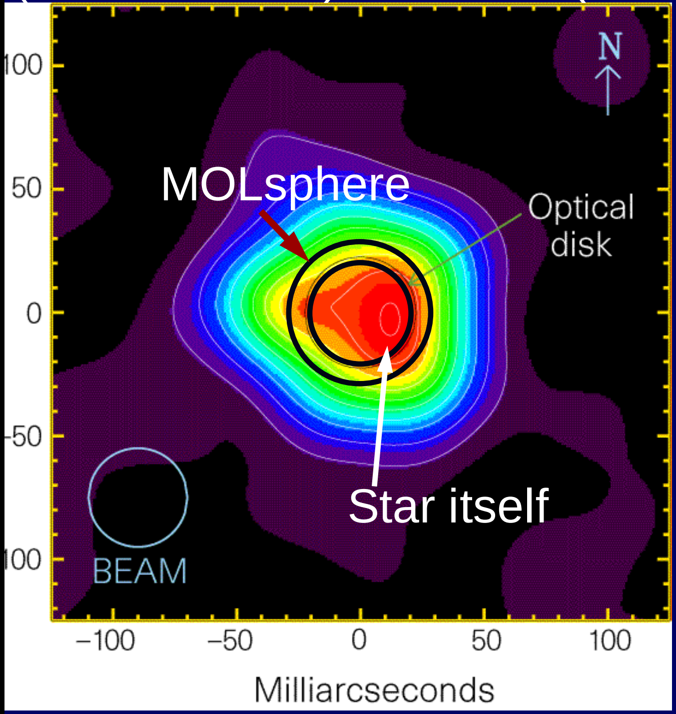
  Mass loss reduces stellar mass and/or obscures stars?
  → Yesterday's talks
  (S. Ekström, C. Georgy)



Introduction: RSGs' inhomogeneous atmosphere



VLA, 7mm, Cool neutral gas (1000—4000K), Lim et al. (1998)



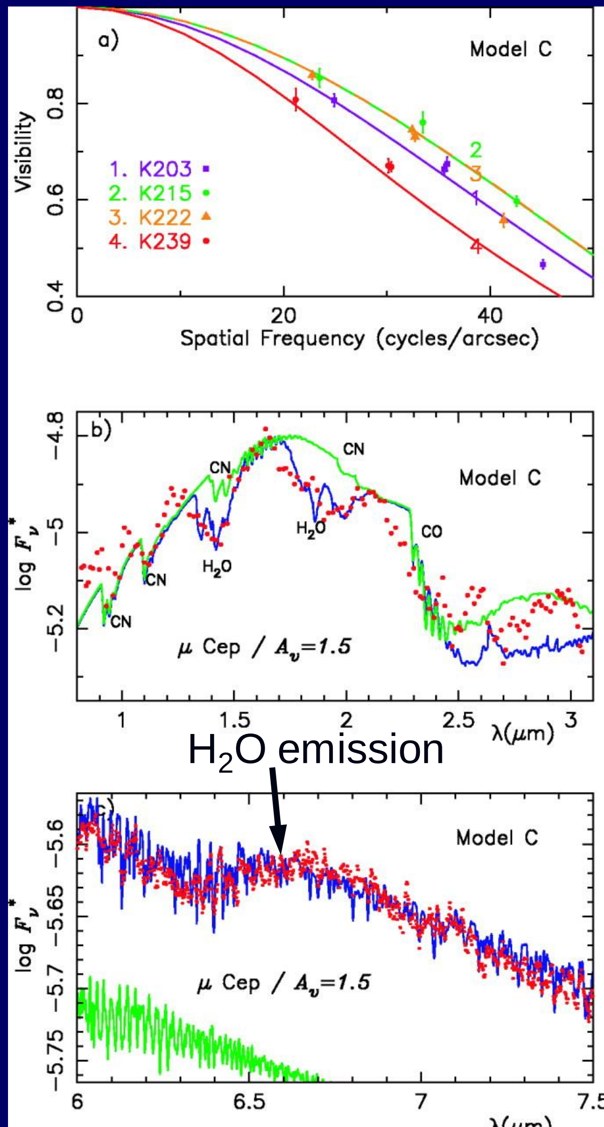
Co-existence of hot plasma and cool gas
→ Hot plasma with a small filling factor embedded in cool gas (Harper & Brown 2001, 2006)

Introduction: RSGs' inhomogeneous atmosphere

MOLsphere (Tsuji 1978, 1997, 2000, 2006) in K—M (super)giants

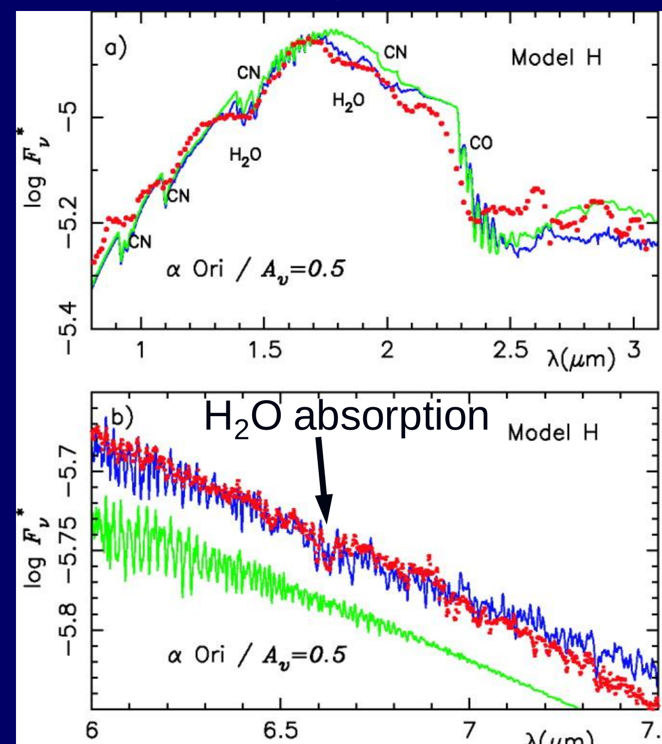
Water vapor (unexpected for K & early M stars) up to 1.3—2 R_{star}

μ Cep

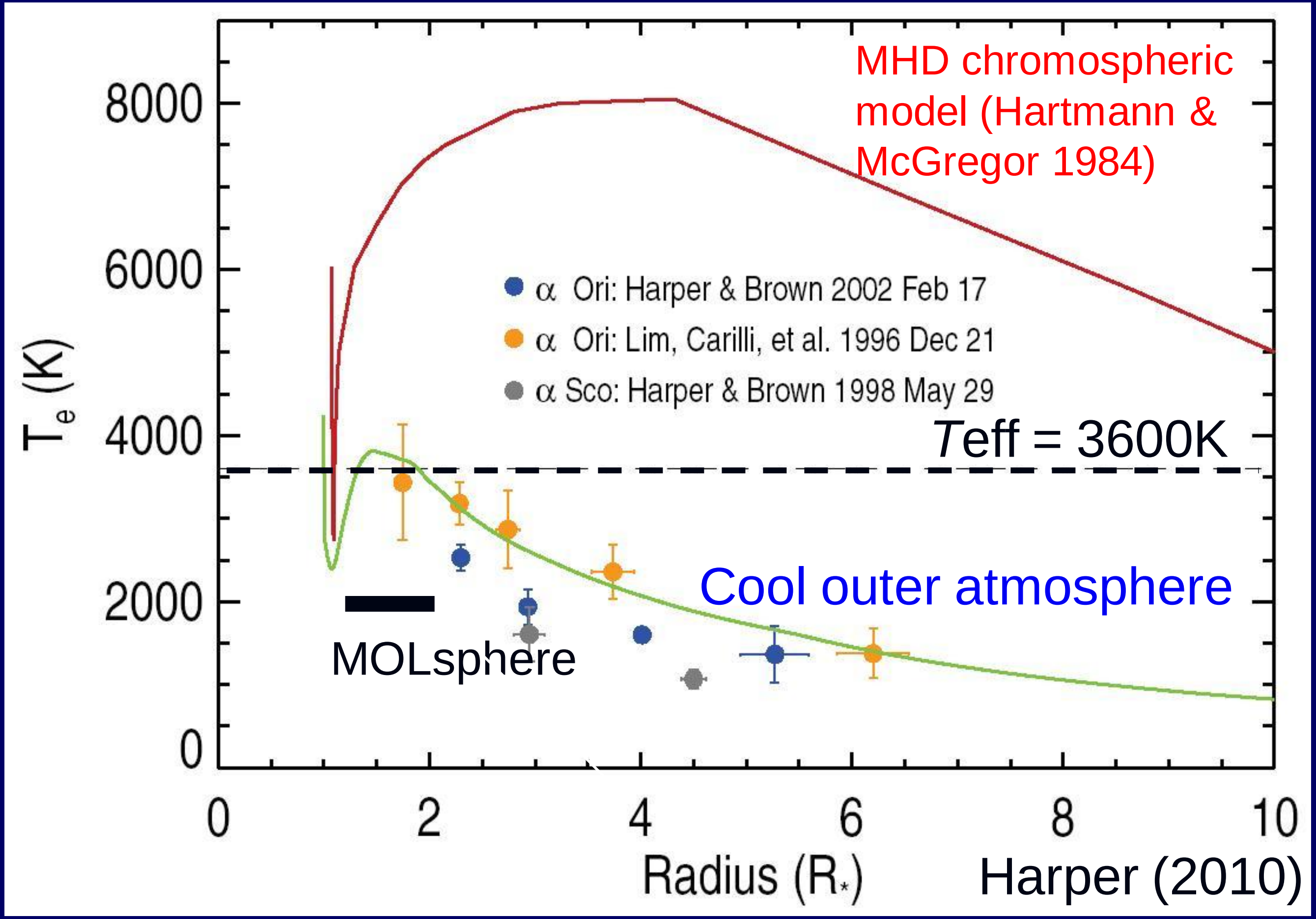


Tsuji (2006)

Betelgeuse



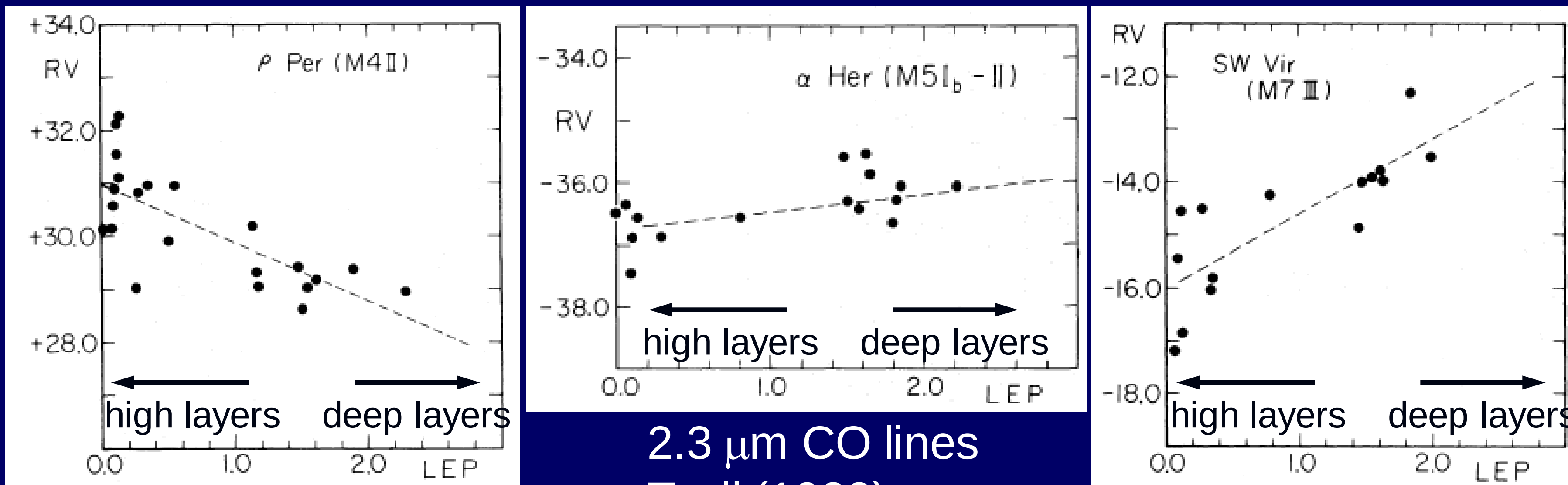
Introduction: RSGs' inhomogeneous atmosphere



Introduction: Probing the atmospheric dynamics

✓ Radial velocity measurements

High-spectral resolution spectra (R ~ 100,000)



2.3 μm CO lines

Tsuji (1988)

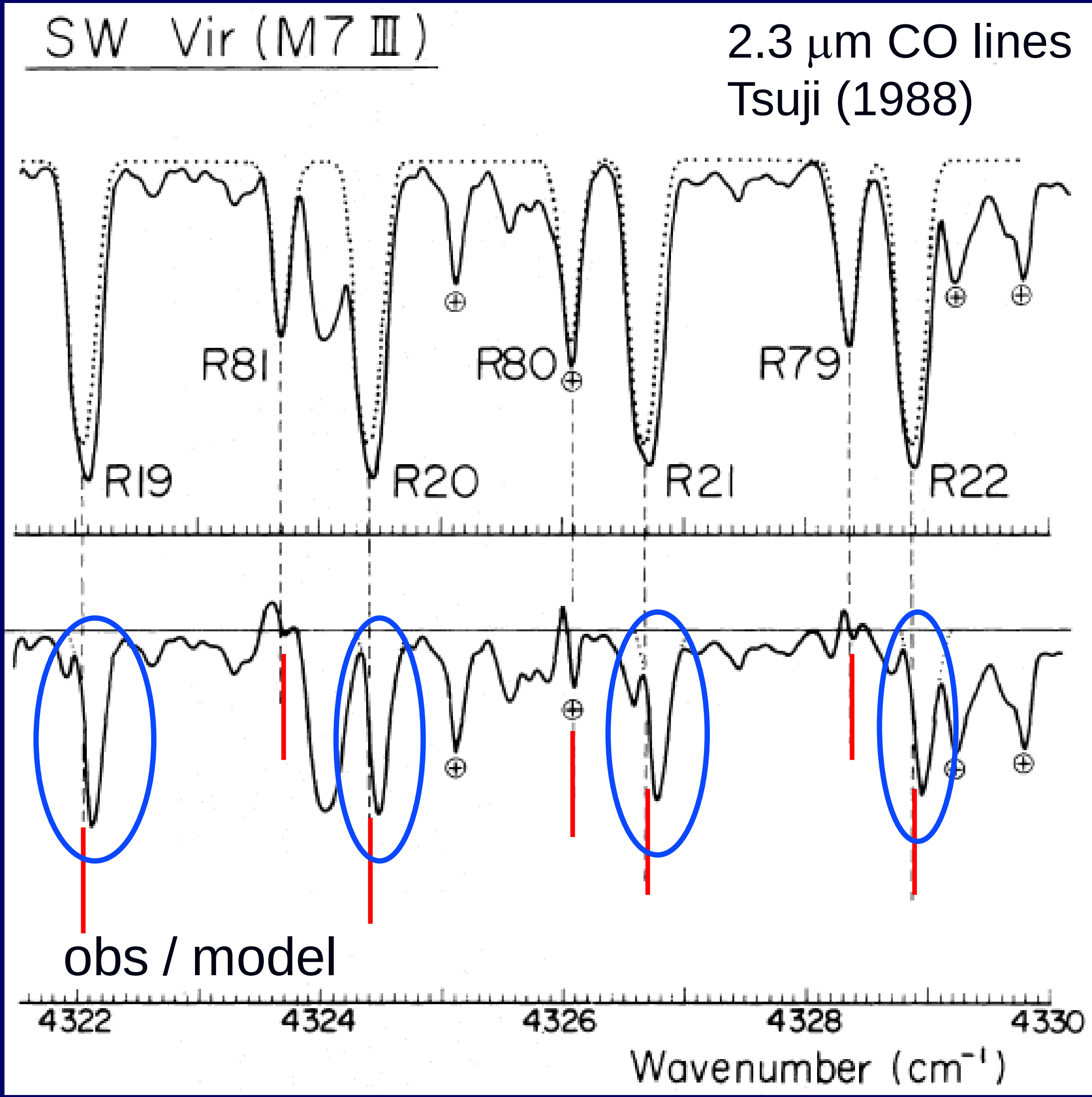
✓ Difference in radial velocity between strong and weak CO lines

= -3 … +5 km/s

✓ Variation among stars (probably time variation as well)

Introduction: Probing the atmospheric dynamics

✓ Separating the absorption due to the MOLsphere:
Obs. spectra divided by photospheric model spectra



Analysis of separated CO absorption from MOLsphere

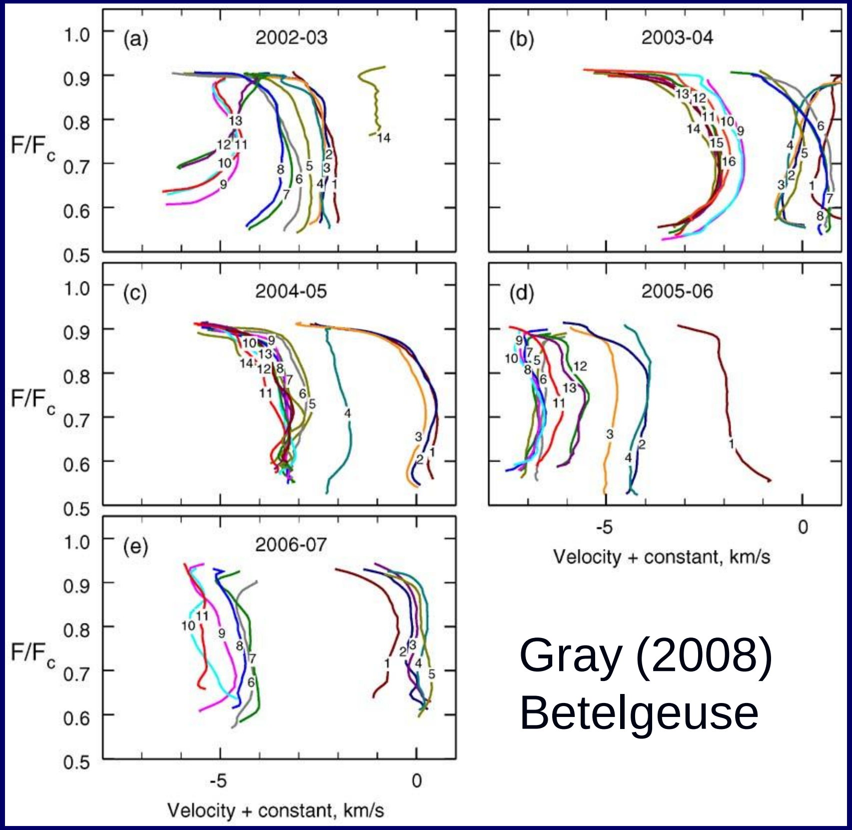
✓ T = 1000---2000 K
✓ CO column density ~ 10^{20} cm^{-2}
✓ turbulent velocity ~ 10 km/s

→ See also poster by Ryde et al.

Introduction: Probing the atmospheric dynamics

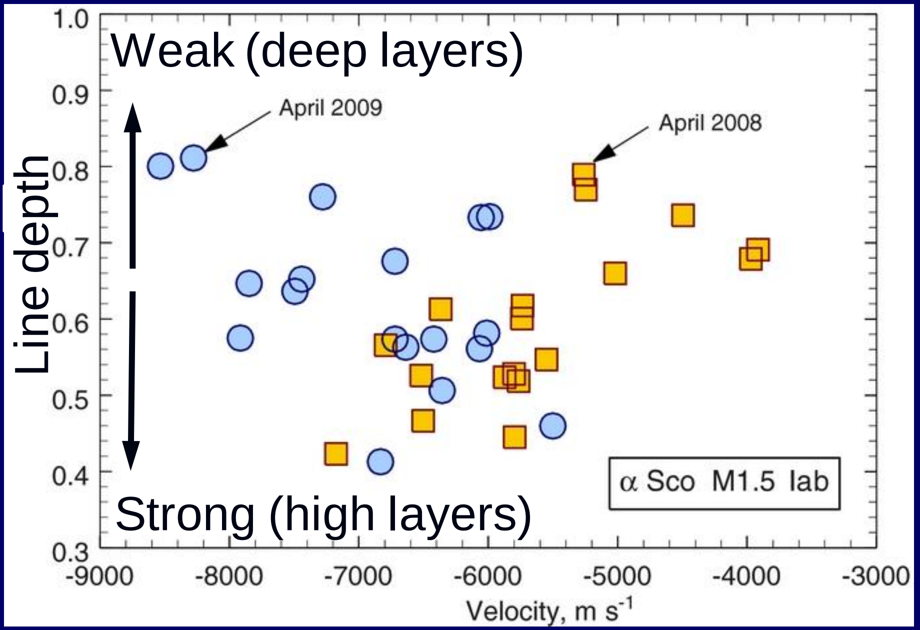
High-spectral resolution spectra (R ~ 100,000)

Line profile (bisector)



→ Indicative of convective motions

Line shifts vs line depth



Antares (Gray 2012)

→ Convection may penetrate only the lower photosphere

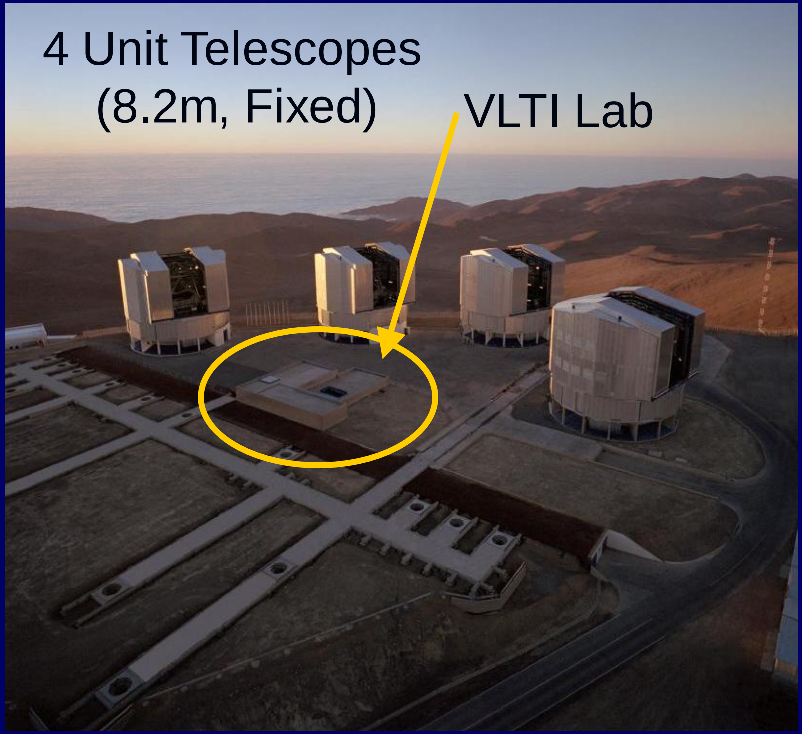
However, difficult to invert the line profile (integrated over the stellar surface) to mass motions

We need high-spatial and high-spectral resolution to spatially resolve the structure and dynamics of the photosphere and MOLsphere

Long-Baseline Spectro-Interferometry

Very Large Telescope Interferometer (VLTI)

Chile, Cerro Paranal



4 Auxiliary Telescopes
(1.8m, Movable)

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

AMBER: near-IR interferometric instrument

Operating at 1.3 – 2.4μm

Angular resolution = 1 mas (2 μm)

Spectral resolution = 35, 1500, 12000

✓ Visibility, phase = Fourier transform of the object's intensity *I*(x,y)
= pieces of information on the object's size and shape

✓ Visibility & phase measurement in atomic/molecular lines
→ Information on the object's size and shape in spectral features

✓ Aperture synthesis imaging is also possible
if enough *uv* points are sampled.

Spatially resolving MOLsphere in the CO lines

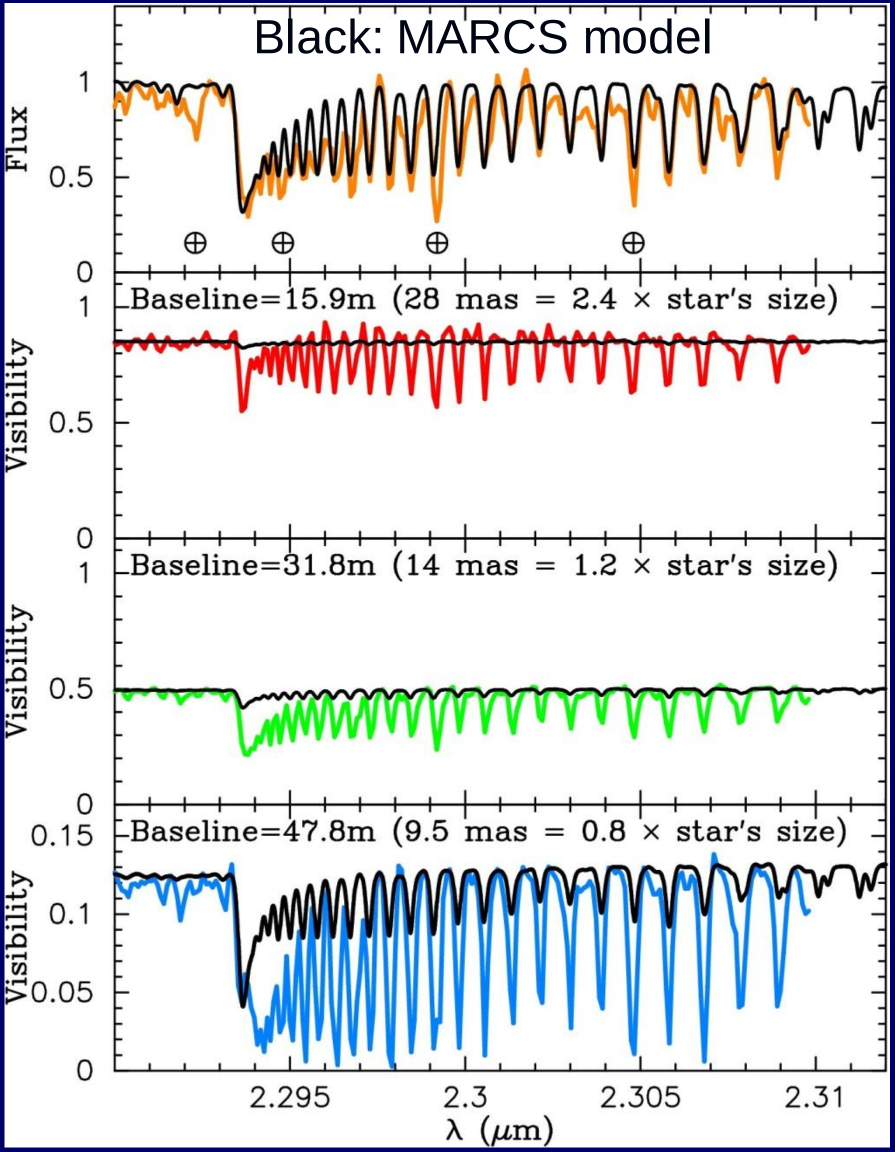
M7 giant BK Vir

✓ Observed spectrum reproduced by MARCS model (spherical, hydrostatic)

✓ Observed visibilities (angular size) cannot be explained by MARCS

Observed visibilities much lower than MARCS model
→ Star appears much larger than MARCS predicts

✓ MARCS + extended CO layers can explain the observations



Ohnaka et al. (2012)

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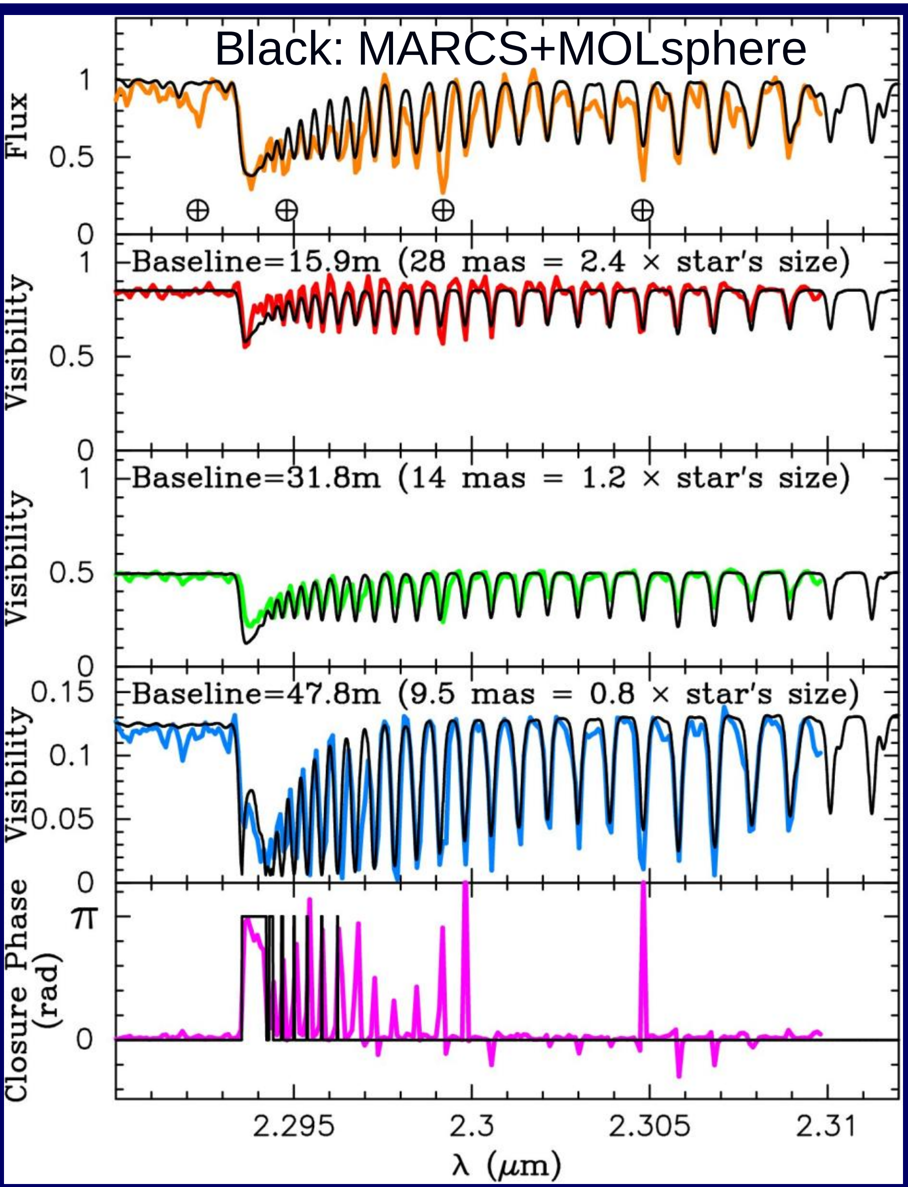


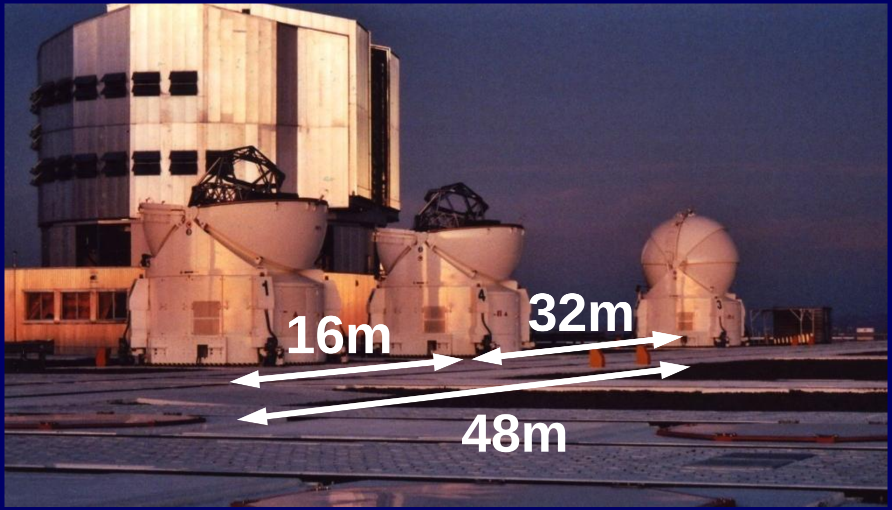
Ohnaka et al. (2012)

AMBER observations of Betelgeuse (I): 2008

Scientific goals

✓ CO first overtone lines @ 2.3 µm
→ Probe the outer atmosphere

✓ AMBER high-resolution spectro-interferometry
Spectral resolution = 12000
Betelgeuse = Closest, best-studied red supergiant
Baseline = 16-32-48m



AMBER observations of Betelgeuse in the 2.3 μm CO lines (2008)

Results

1) CO first overtone lines @ 2.3 μm

Spectral resolution = 12000

Spatial resolution = 9.8 mas

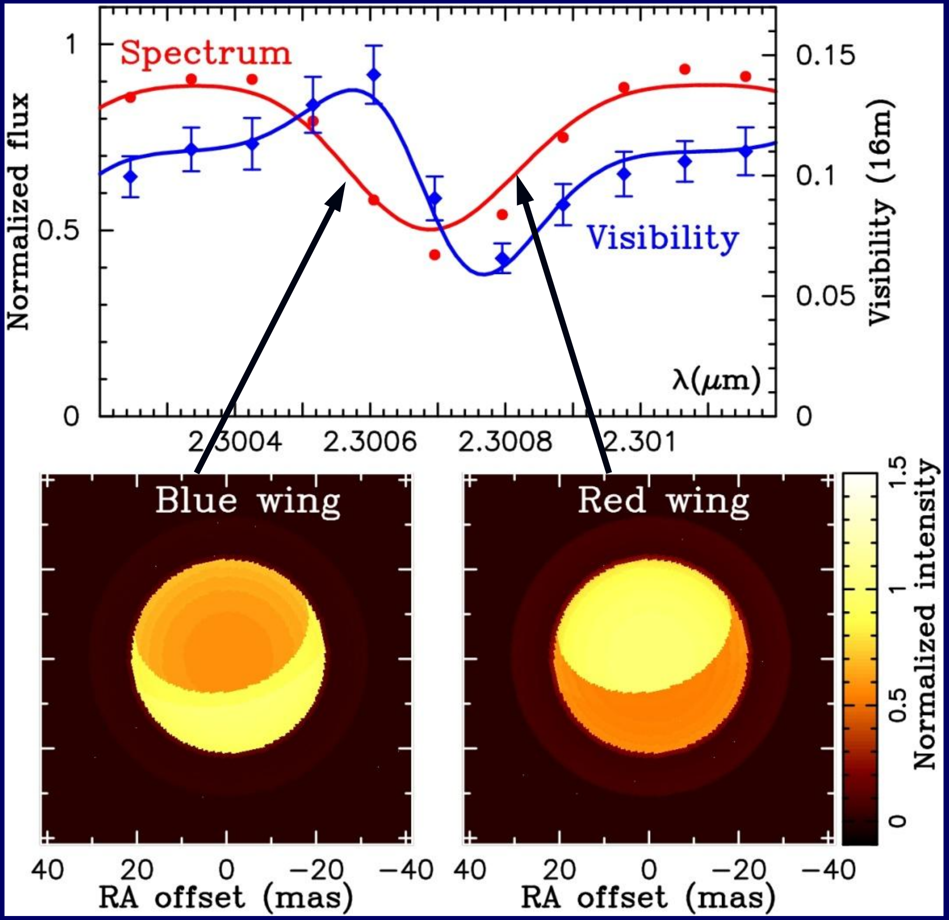
→ Highest resolution on Betelgeuse

2) Visibility asymmetric with respect to the line center

→ The star looks different in the red & blue wings of the CO lines

3) Gas motions in a stellar photosphere spatially resolved for the first time other than the Sun

Velocity amplitude = 10—15 km/s



Ohnaka et al. (2009)

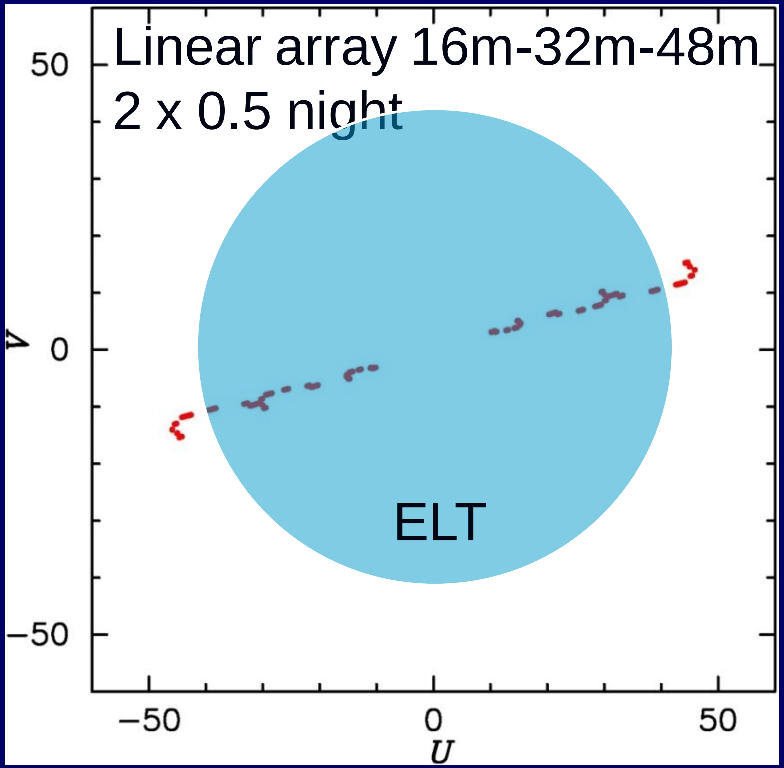
AMBER observations of Betelgeuse (2009)
1-D aperture synthesis imaging in the CO lines

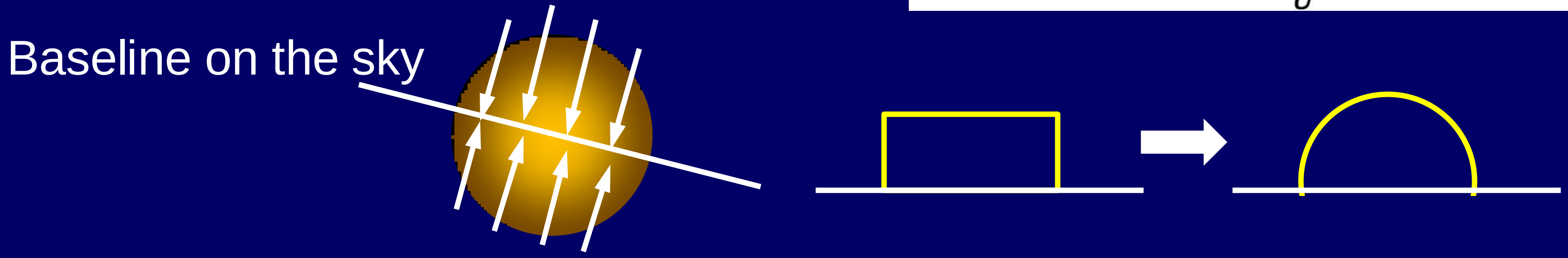
Observations

- ✓ CO first overtone lines
  2.28 – 2.31 μm

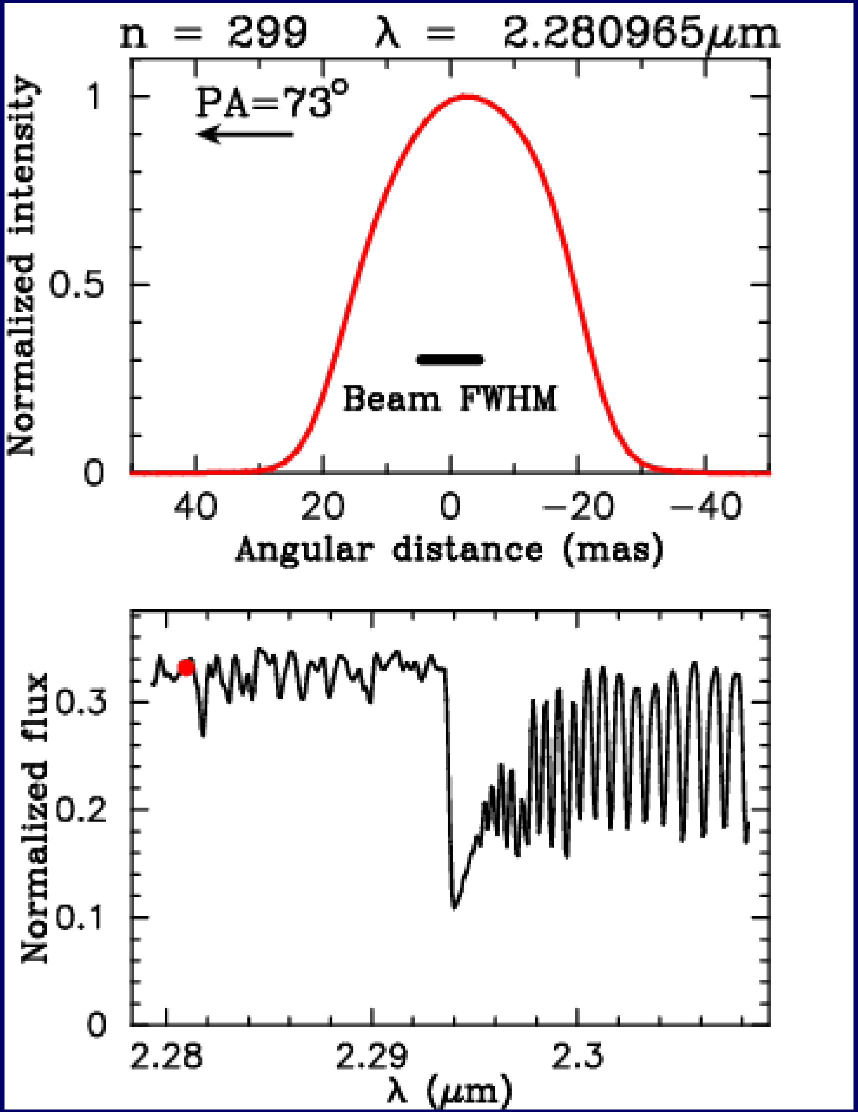
- ✓ Dense, linear *uv* coverage
  Spatial resolution = 9.8 mas
  = 1/4 x stellar size

- ✓ 1-D projection image
  "squashed" onto the baseline vector





1-D imaging of Betelgeuse: First aperture synthesis imaging in CO lines

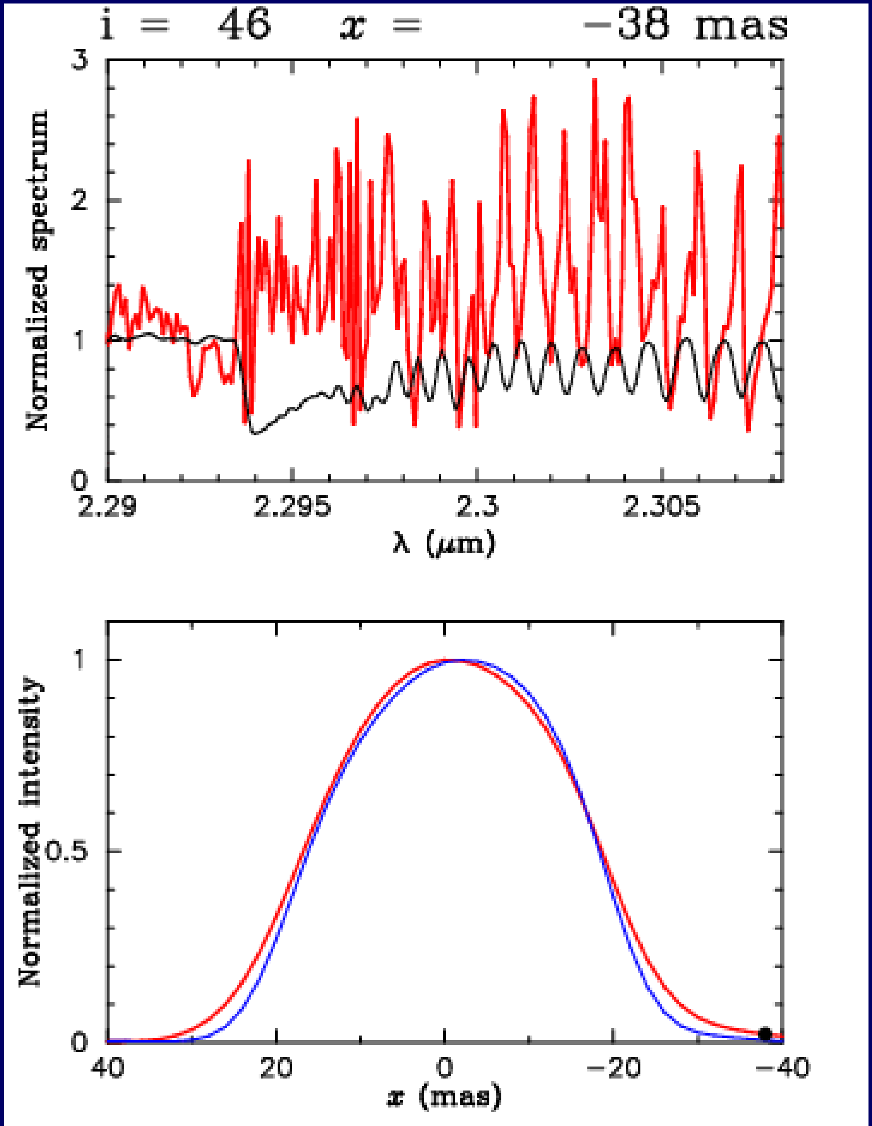


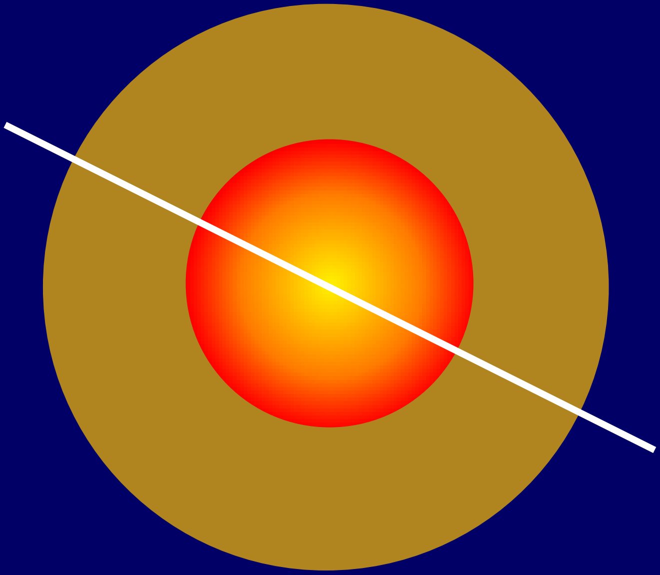
Spectral resolution = 6000

Ohnaka et al. (2011)

Movie available at http:www3.mpifr-bonn.mpg.de/staff/kohnaka/alfori1.html

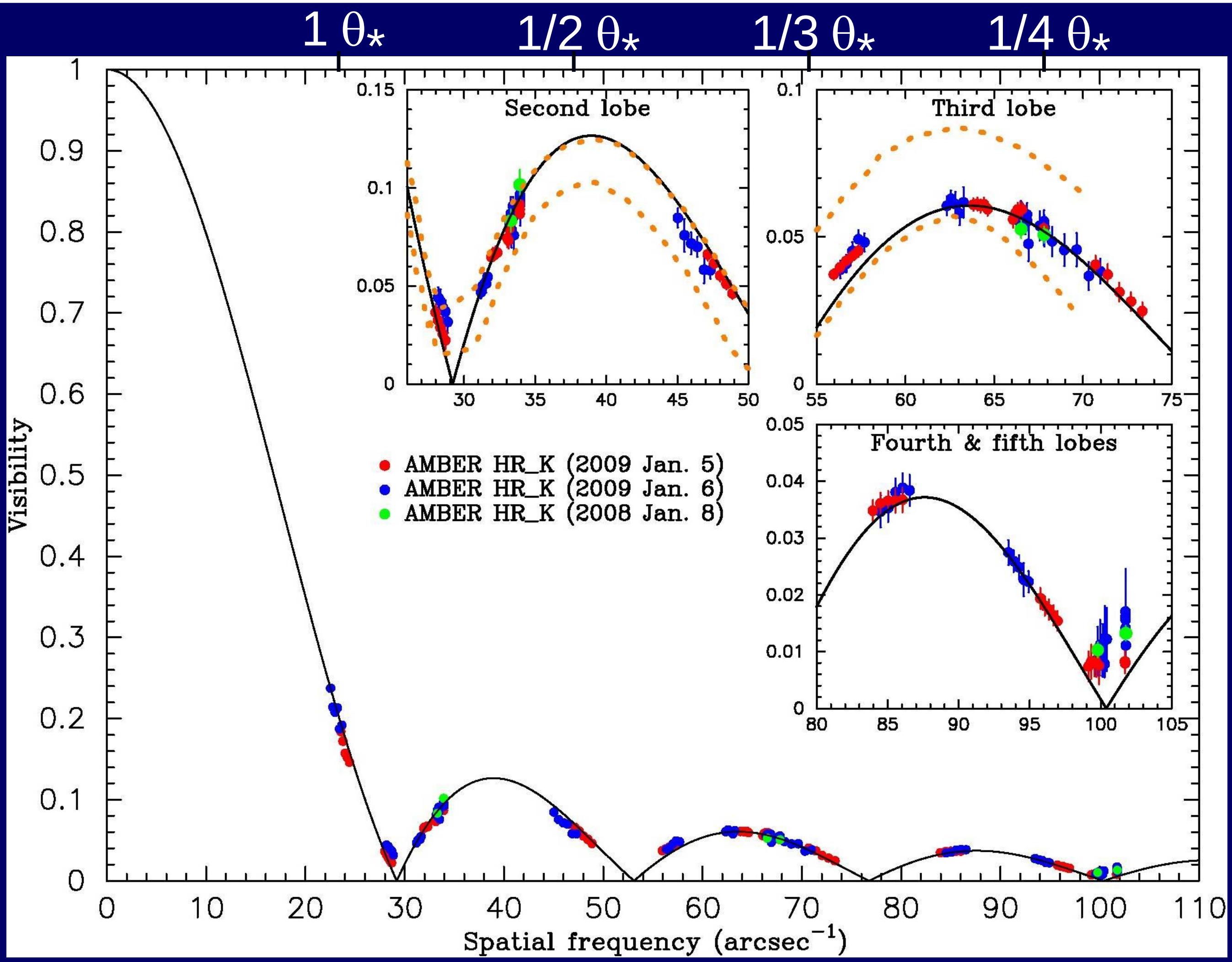
1-D imaging of Betelgeuse:
Spectrum of the CO lines at each spatial position





Movie available at http:www3.mpifr-bonn.mpg.de/staff/kohnaka/alfori2.html

Betelgeuse in the 2.3 μm continuum: No or only marginal time variation between 2008 and 2009



Time variation is much smaller than the maximum variation predicted by 3-D convection simulation (Chiavassa et al. 2009).

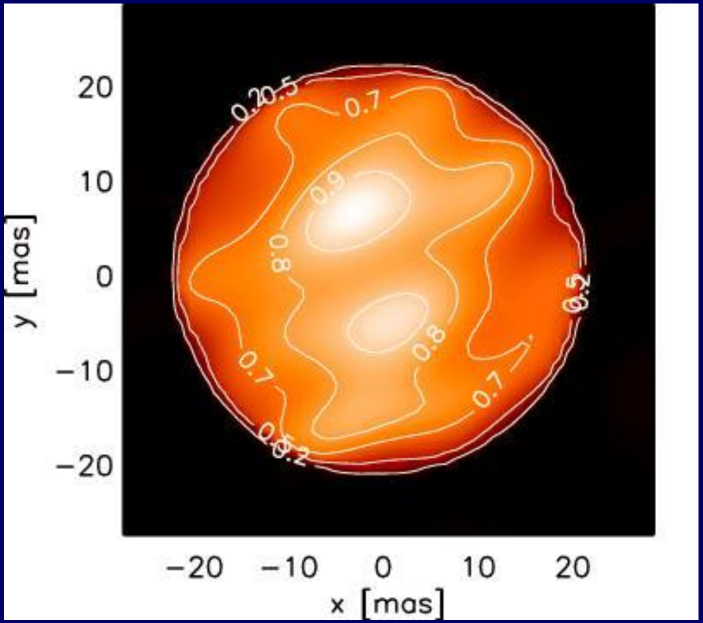
→ 3-D model predicts too pronounced inhomogeneities(?)

1.64 μm vs. 2.3 μm images of Betelgeuse

1.64 μm image with 2 spots

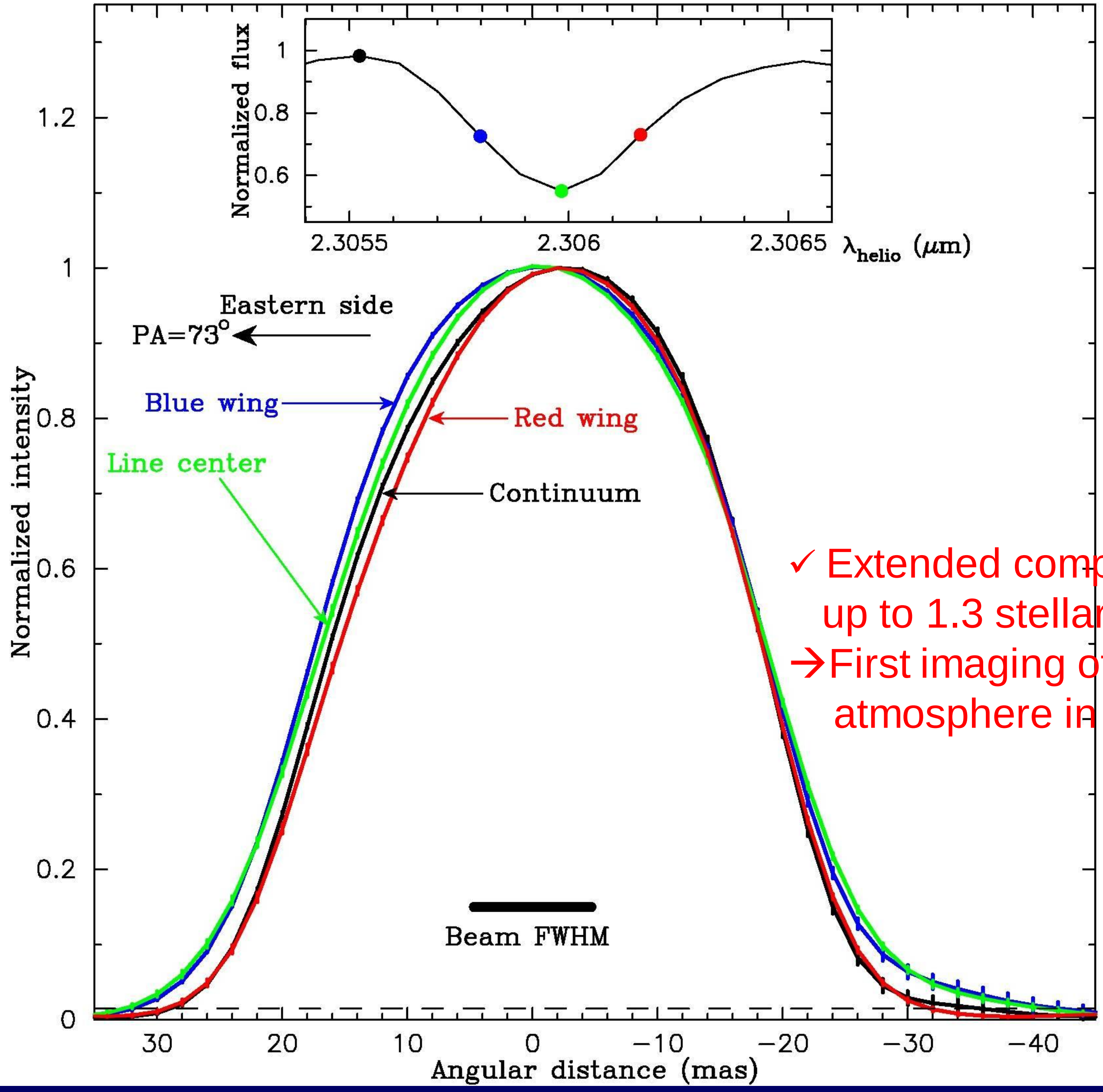
Possible reasons:

- ✓ Position angle coverage (1-D vs. 2-D)
- ✓ Continuum vs. molecular features (spectral resolution = 12000 vs 16)
- ✓ More inhomogeneous at 1.64 μm: seeing deeper, more convective layers



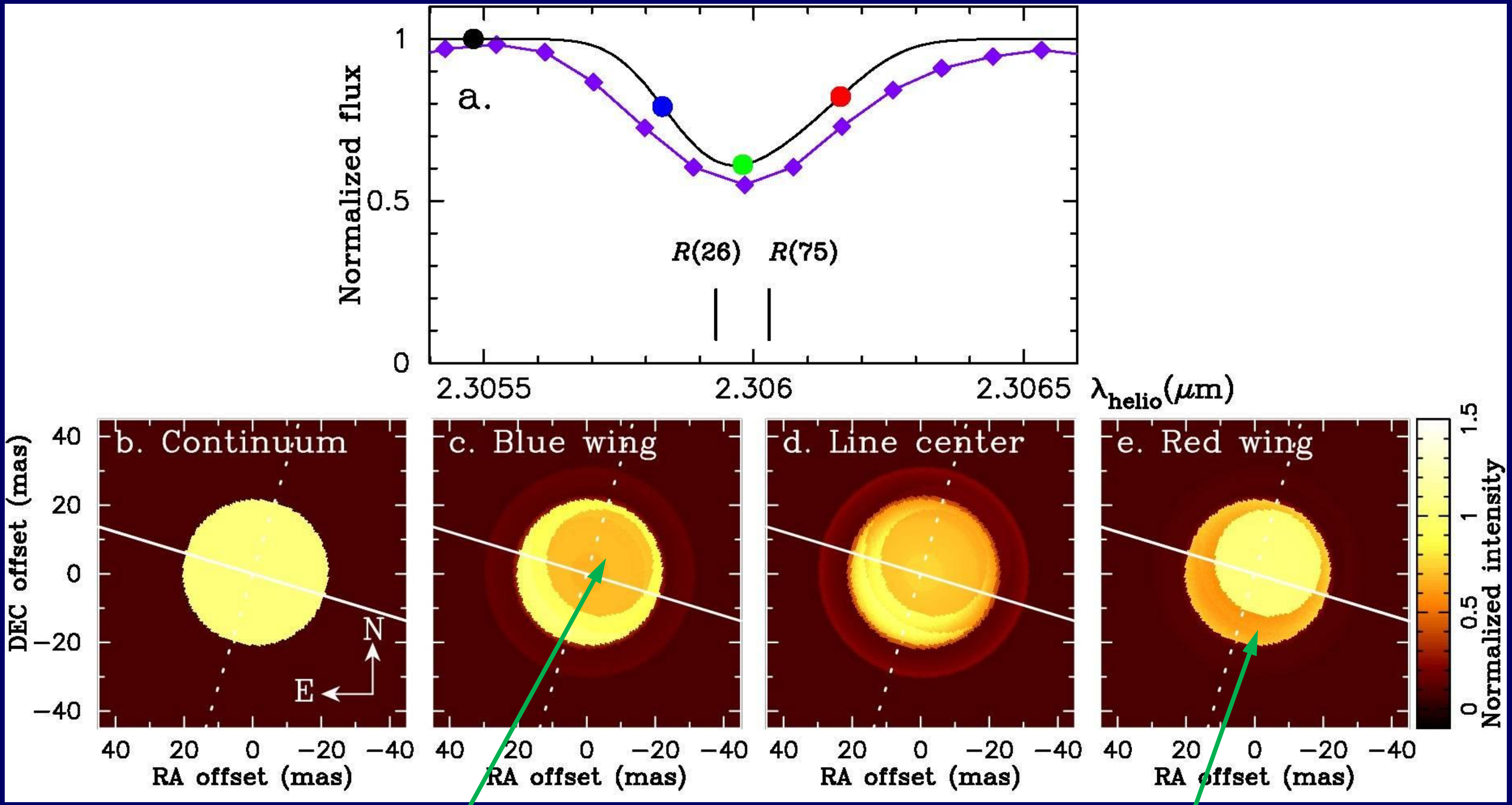
IOTA observations
Haubois et al. (2009)

AMBER 1-D imaging of Betelgeuse in the CO lines



- ✓ Extended component up to 1.3 stellar radii
- → First imaging of the outer atmosphere in the CO lines

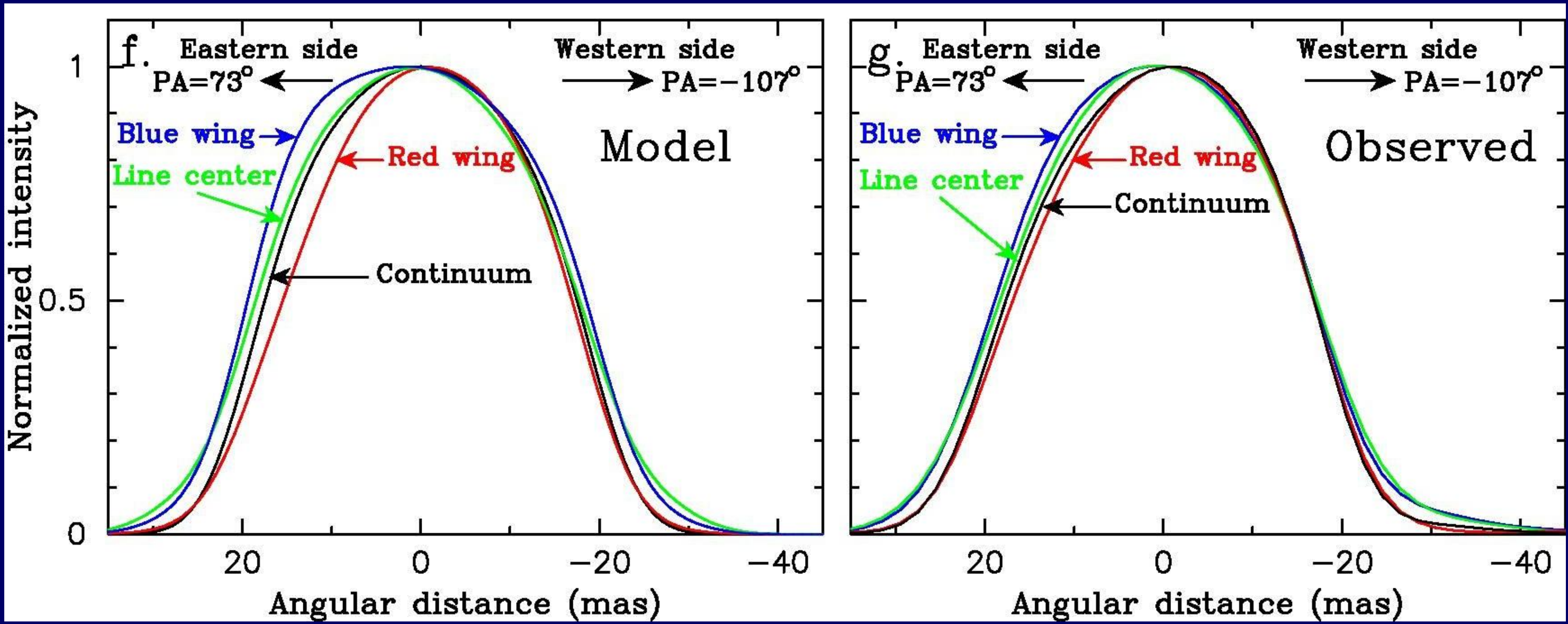
Modeling the inhomogeneous velocity field



Weak upwelling at 0—5 km/s

Strong downdraft with 20—30 km/s

Modeling the inhomogeneous velocity field



- ✓ Drastic change in the velocity field between 2008 and 2009

  2008: Both upwelling and downdrafting with 10—15 km/s

  2009: Weak upwelling at 0—5 km/s &
  Strong downdrafts with 20—30 km/s

- ✓ No systematic outflow within ~1.5 stellar radii

Origin of the inhomogeneous velocity field

✓ Convection?

But …
Observationally estimated density ~ 10^{-14} g/cm^3 at 1.3 R_{star}
3-D convection model < 10^{-22} g/cm^3 at 1.2 R_{star}

✓ Driven by MHD processes?

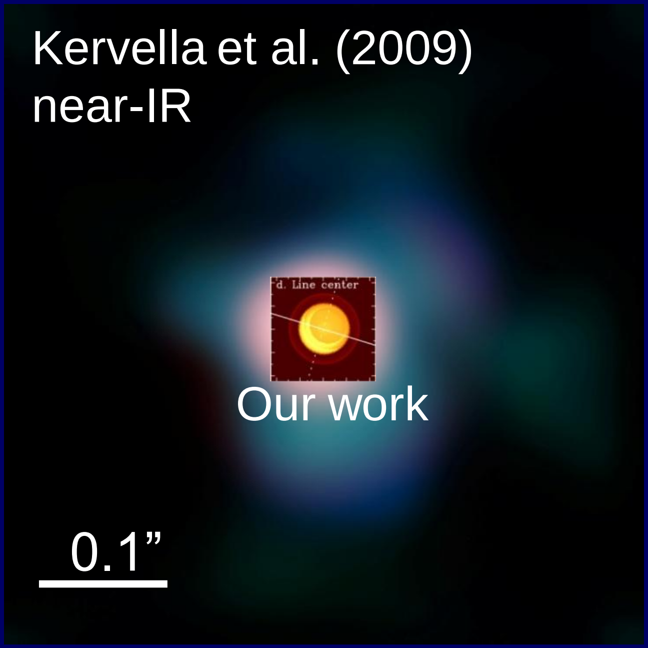
MHD simulations (Suzuki 2007, Airapetian et al. 2000)
→ But no self-consistent simulation yet for red supergiants
Magnetic field detected ~1 G (Aurière et al. 2010)

✓ Pulsation?

→ But variability amplitude is small
ΔV = 1 – 1.5 mag

✓ Clumpy mass loss

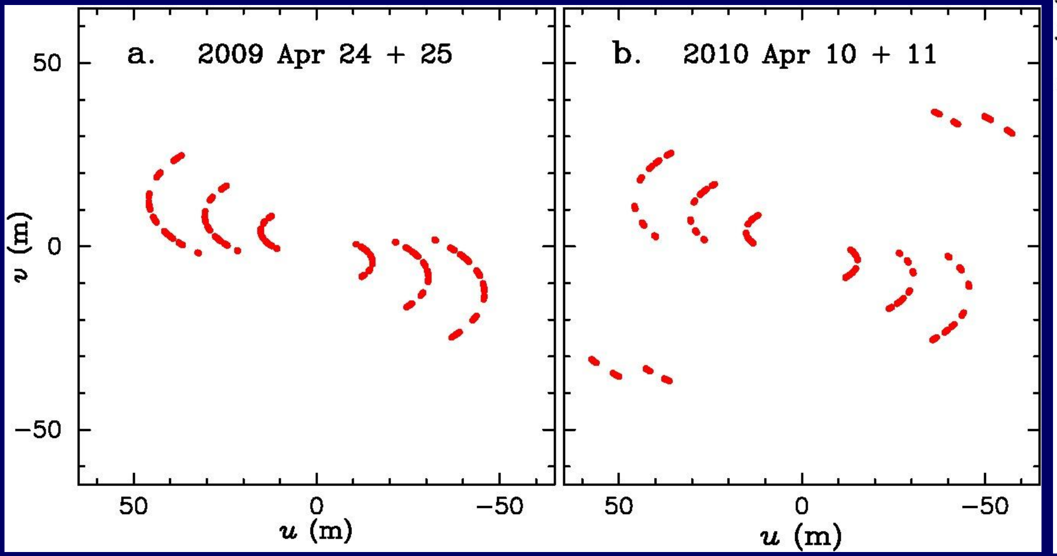
Temporally variable,
inhomogeneous velocity field
→ Clumpy mass loss
P. Kervella's talk tomorrow

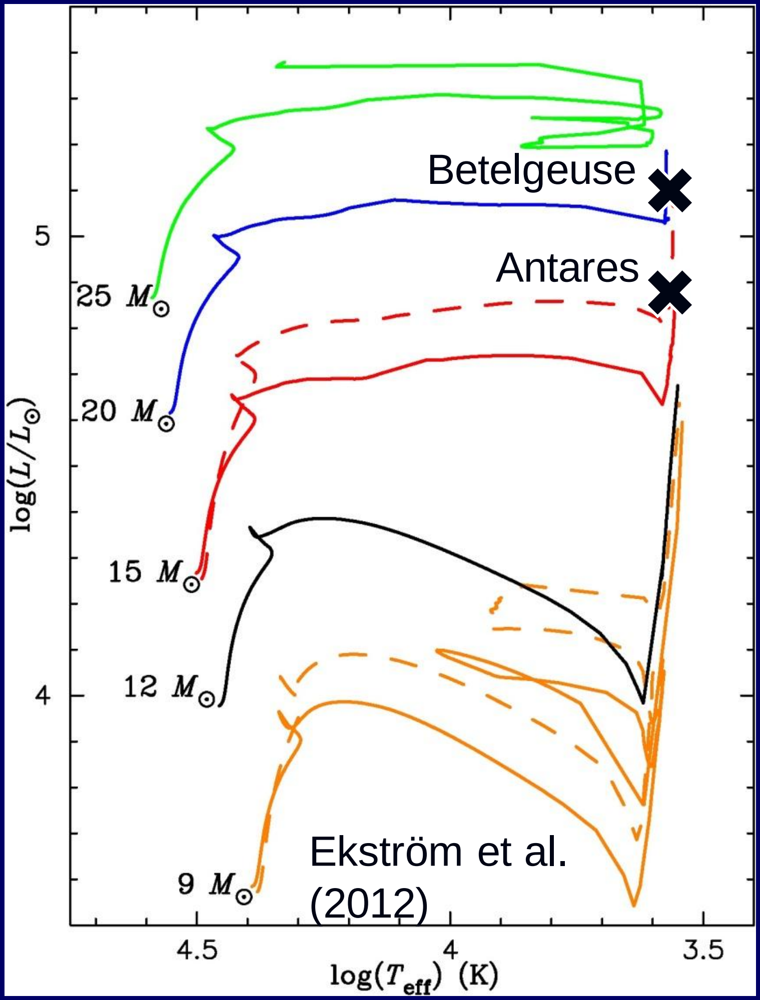


VLTI / AMBER imaging of the red supergiant Antares

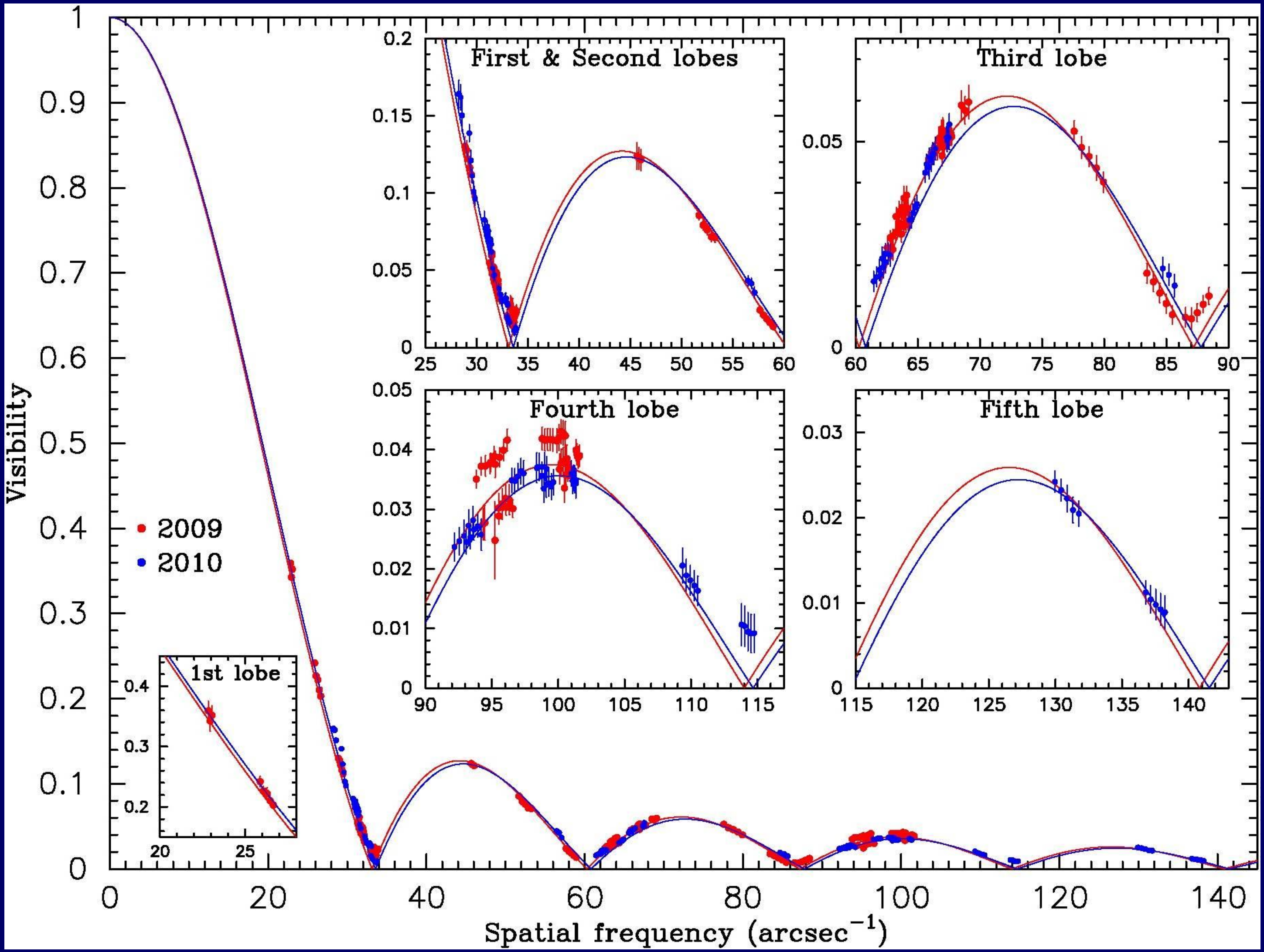
Antares: slightly lower luminosity
less massive (~15 $M_\odot$)
Dust emission weaker

VLTI/AMBER
2009 April & 2010 April





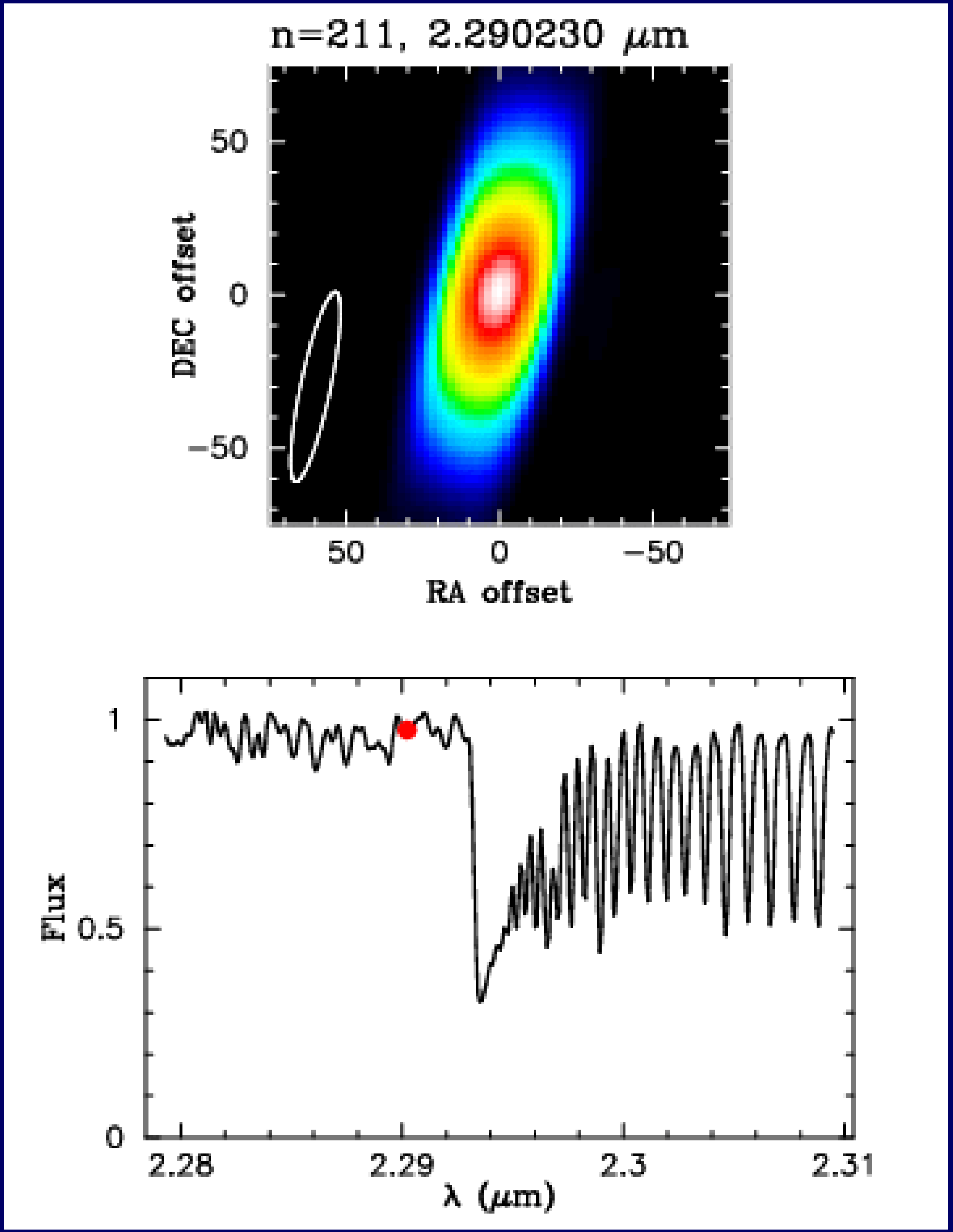
VLTI / AMBER imaging of the red supergiant Antares



Deviation from limb-darkened disks and time variation are small

→ Similar to Betelgeuse

VLTI / AMBER imaging of the red supergiant Antares

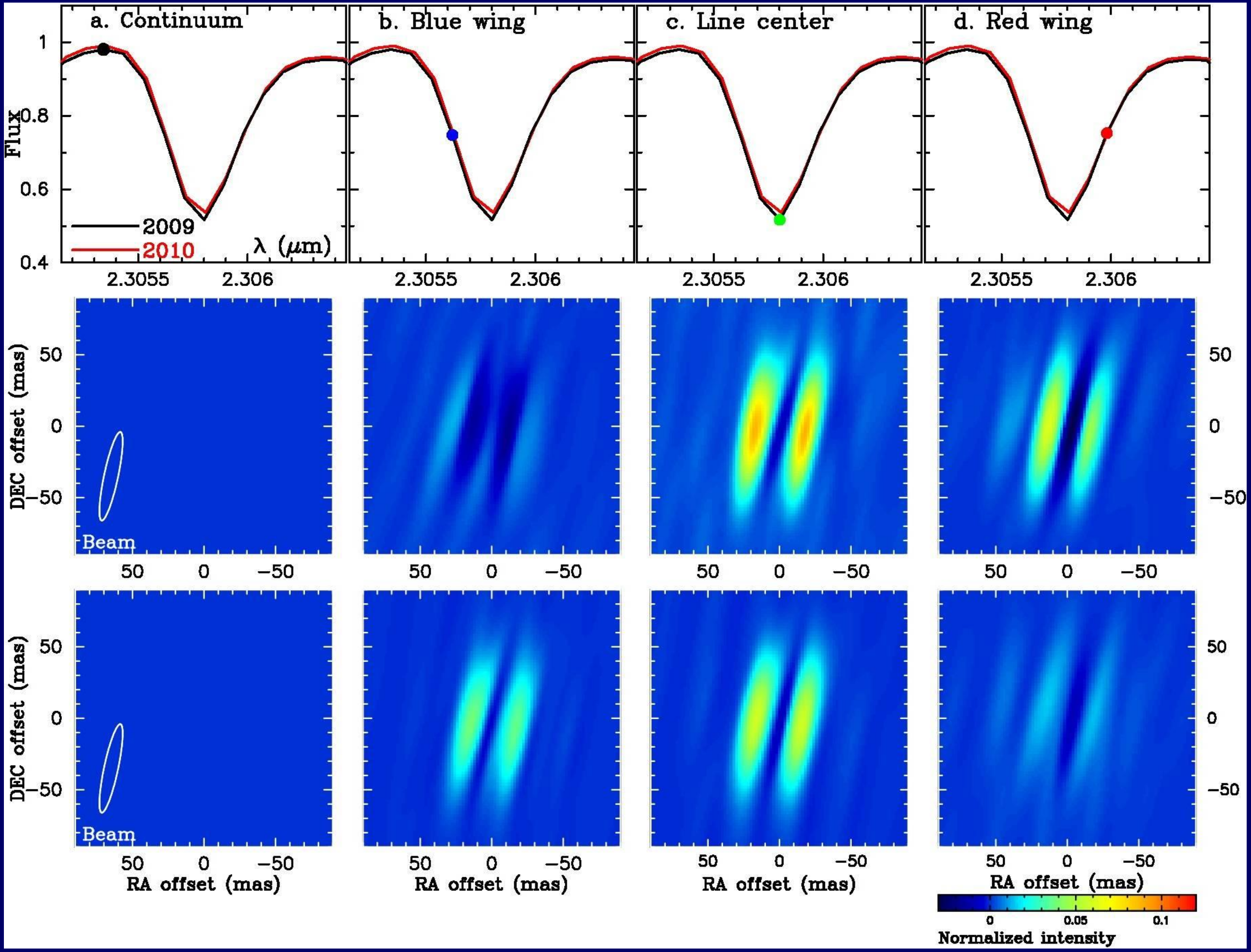


VLTI / AMBER imaging of the red supergiant Antares

Continuum-subtracted images
→ Change in dynamics within 1 year

2009

2010



Outlook

- ✓ Long-term monitoring to follow the dynamics of the outer atmosphere
  E.g., Episodic, strong outward motion?
- ✓ Probing the velocity field at different heights using different lines
- ✓ Better 2-D imaging
  Now feasible with more telescope configurations available
- ✓ MOLsphere affects TiO bands in the visible and H_2O lines at 12 μm
- ✓ What is the spatial scale of inhomogeneities in the continuum?

Thank you for your attention!

Artist’s impression of mass loss
from Betelgeuse (L. Calçada)
ESO Press Release, July 29, 2009