High-spectral resolution AMBER imaging of the outer atmosphere of red supergiants

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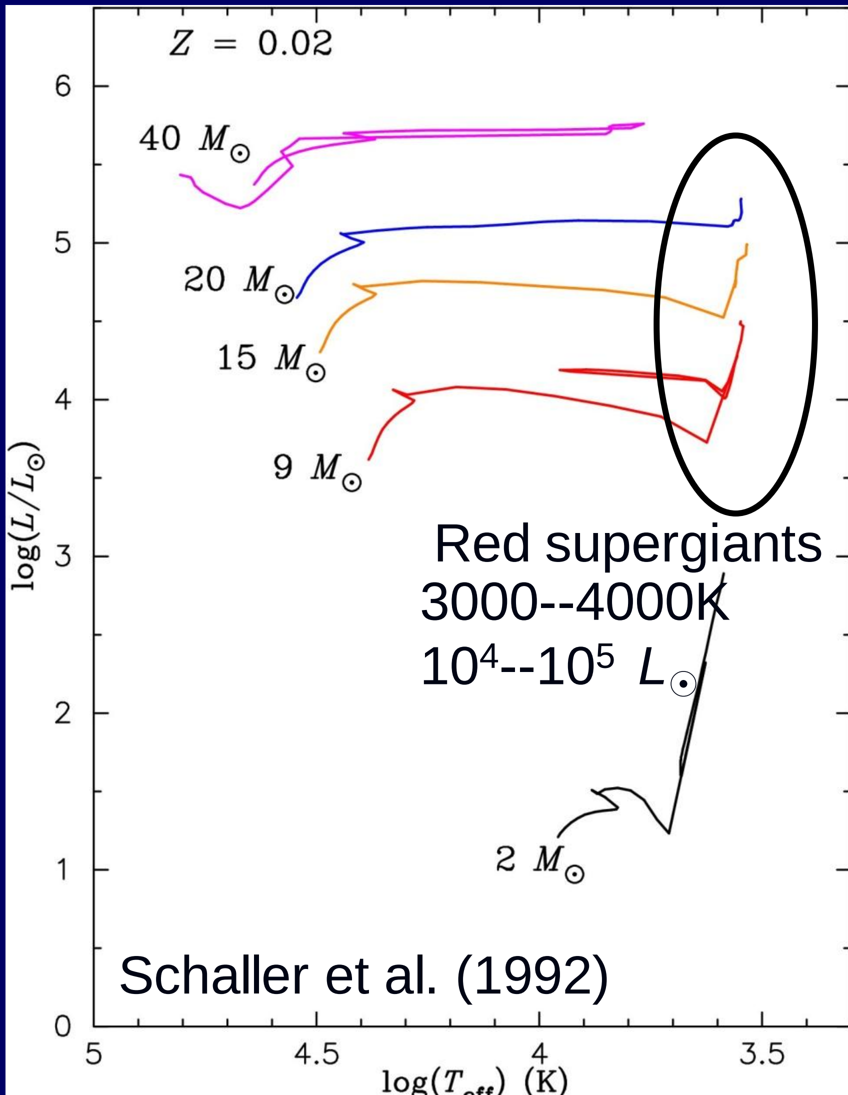
Introduction: Massive star evolution



Massive stars (> 8 $M_\odot$ stars)

✓ Rare in number, short-lived

However, great impact on their surrounding environment…

✓ UV ionizing radiation sources

✓ Strong winds, SN explosion
→ Mechanical energy input

✓ Chemical enrichment of ISM

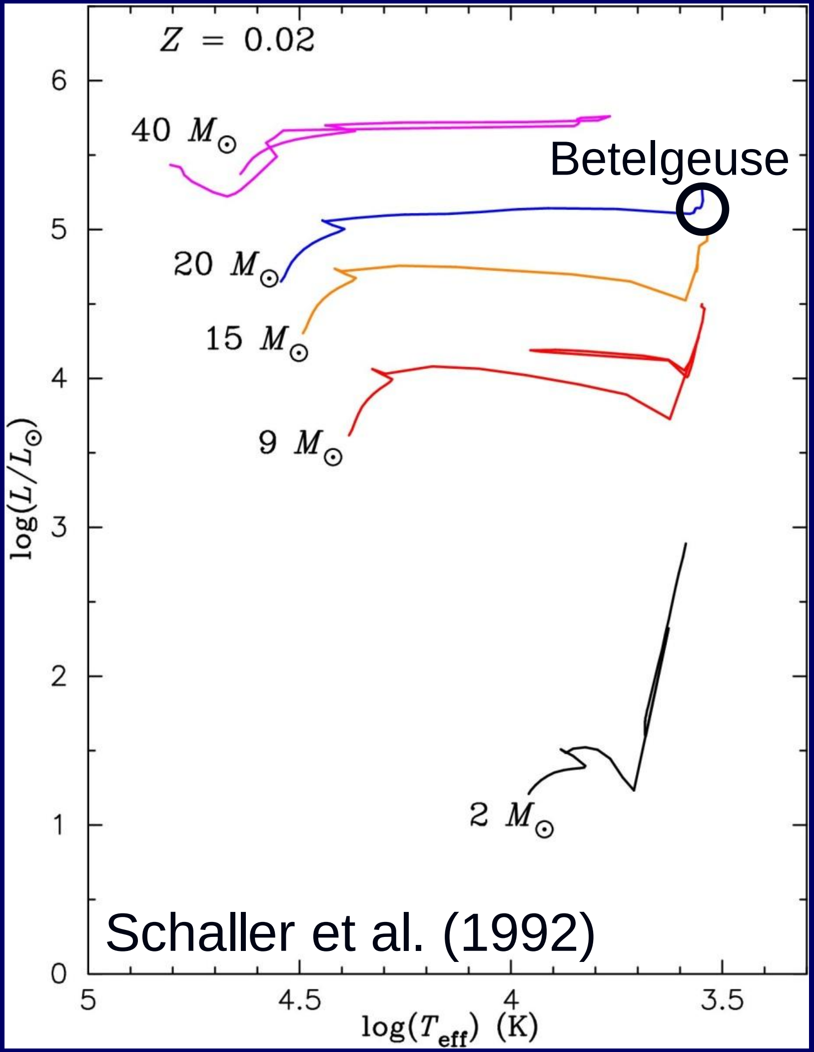
Evolution not yet well understood
= Mass loss determines the star's final fate

Mass loss in red supergiants

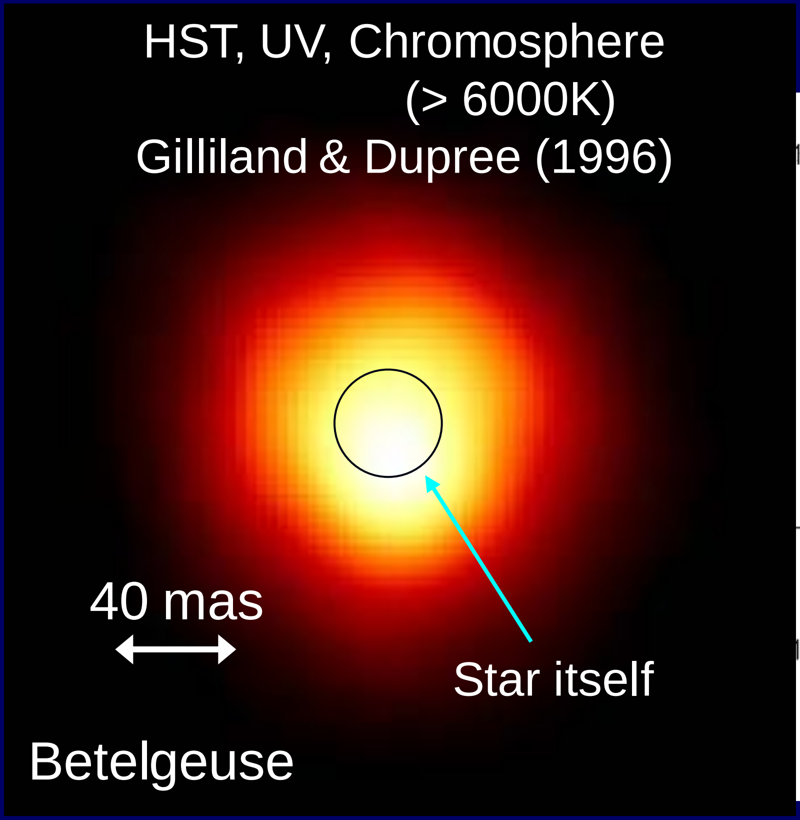
- ✓ Late evolutionary stage of massive stars (> 8 $M_\odot$)

- ✓ Significant mass loss ~10^{-7}--10^{-4} $M_\odot$/yr

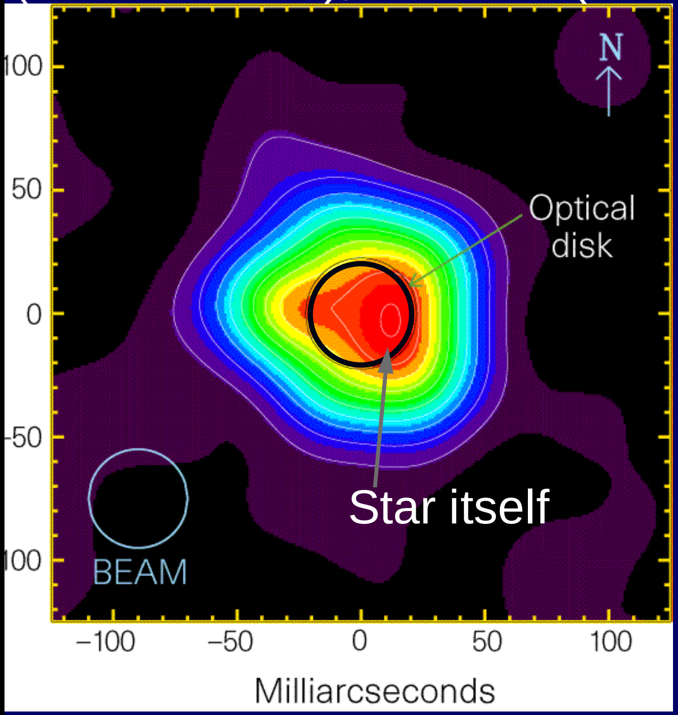
  → No theoretical model to explain the mass loss in red supergiants



Introduction: Betelgeuse's inhomogeneous atmosphere



VLA, 7mm, Cool neutral gas (3000—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)

Strong IR molecular lines form in the outer atmosphere
→ High spectral & spatial resolution observations
→ Long-Baseline Spectro-Interferometry

AMBER: near-IR interferometric instrument

Operating at 1.3 – 2.4μm

Angular resolution = 1 mas (2 μm)

Spectral resolution = 35, 1500, 12000

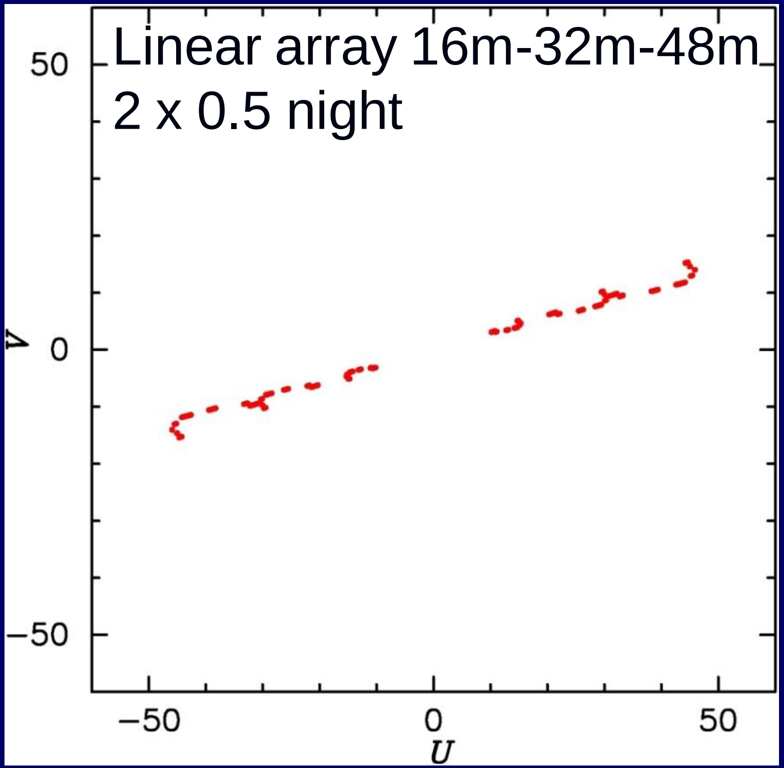
✓ Visibility & phase measurement in atomic/molecular lines
→ Information on the object's size and shape in spectral features

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

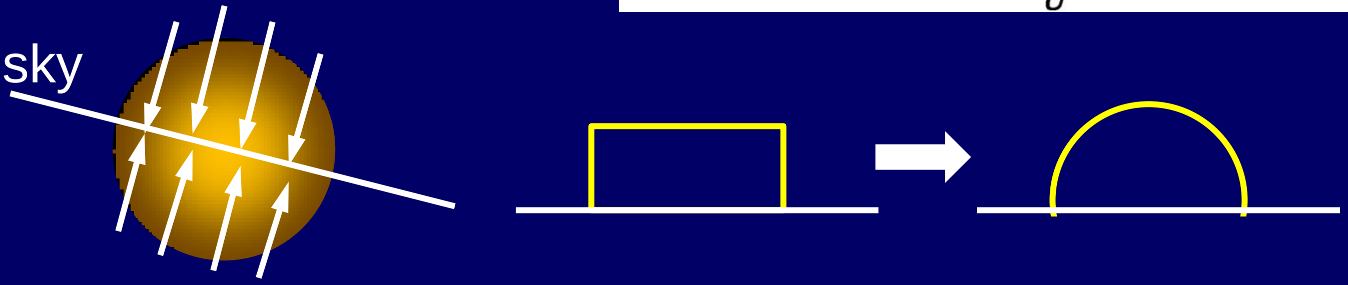
AMBER observations of Betelgeuse (2009)
1-D aperture synthesis imaging in the CO lines

Observations

- ✓ CO first overtone lines
  2.28 – 2.31 μm
- ✓ Dense, linear *uv* coverage
  1st to 5th visibility lobes
  Spatial resolution = 9.8 mas (λ/B)
  = 1/4 x stellar size
- ✓ 1-D projection image
  “squashed” onto the baseline vector



Baseline on the sky

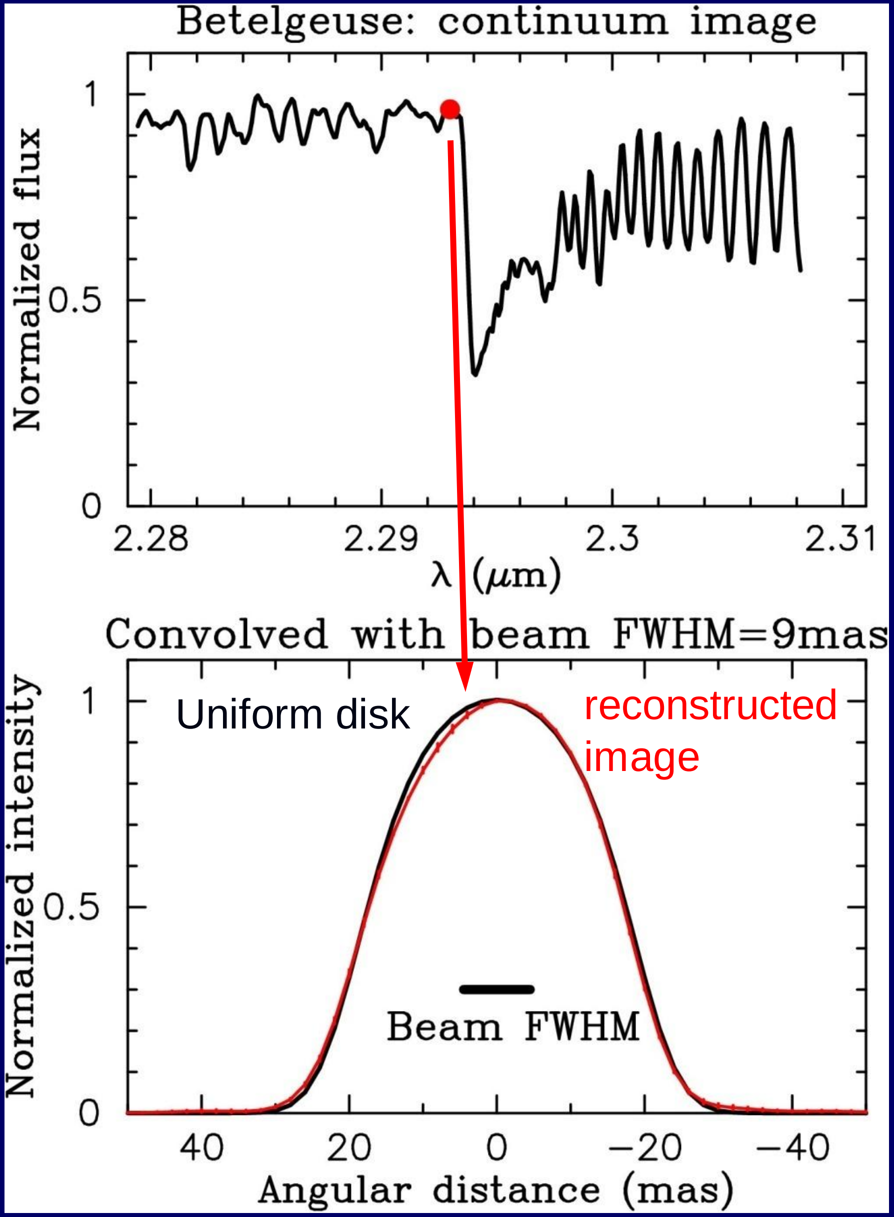


AMBER 1-D imaging of Betelgeuse: continuum

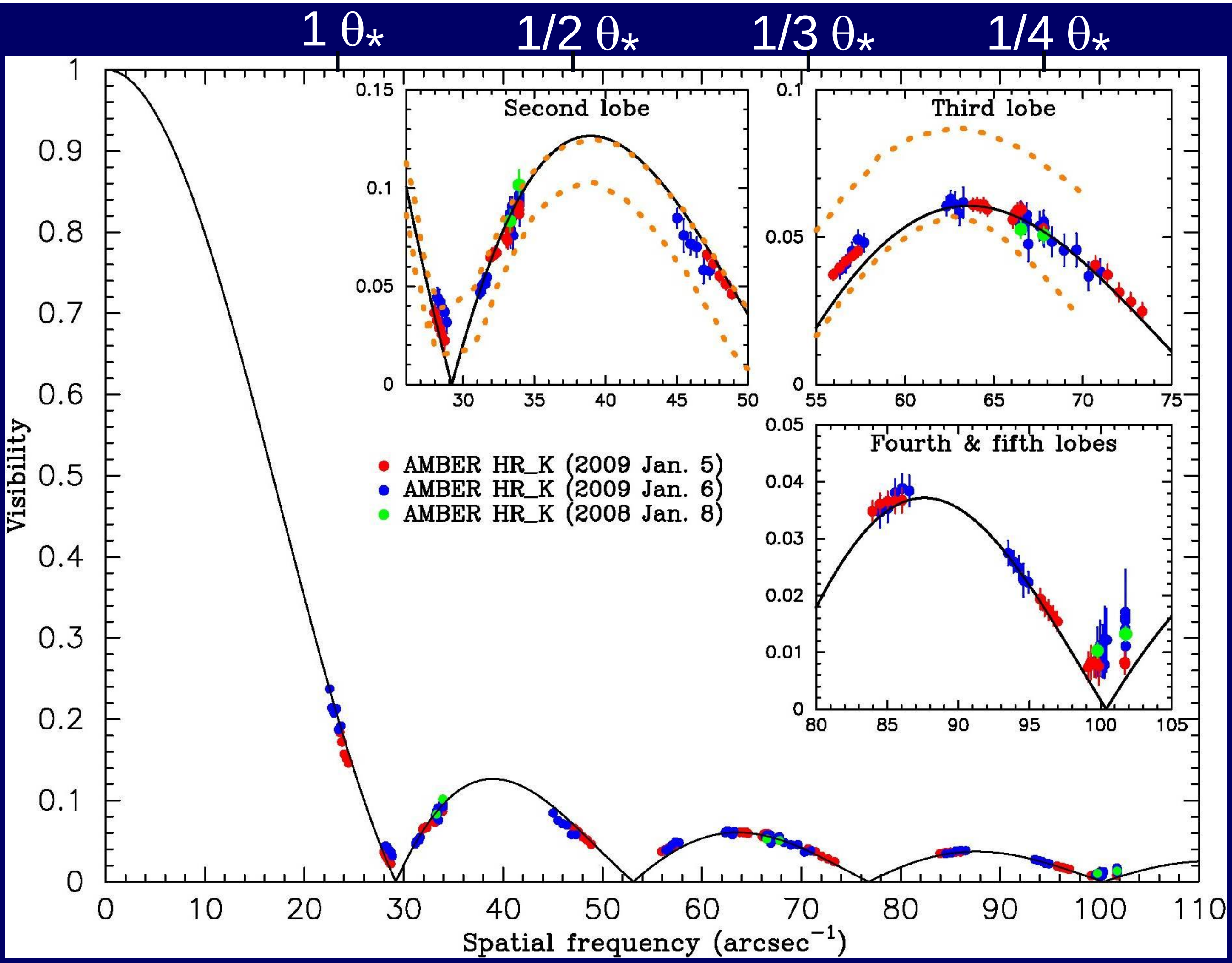
- ✓ MiRA package (Thiebaut 2008)
- ✓ Tests with simulated data of spotted uniform disks
  → Determine the appropriate initial models, prior, & regularization

Results: Continuum

- ✓ Slight deviation (5%) from a uniform or limb-darkened disk in the continuum



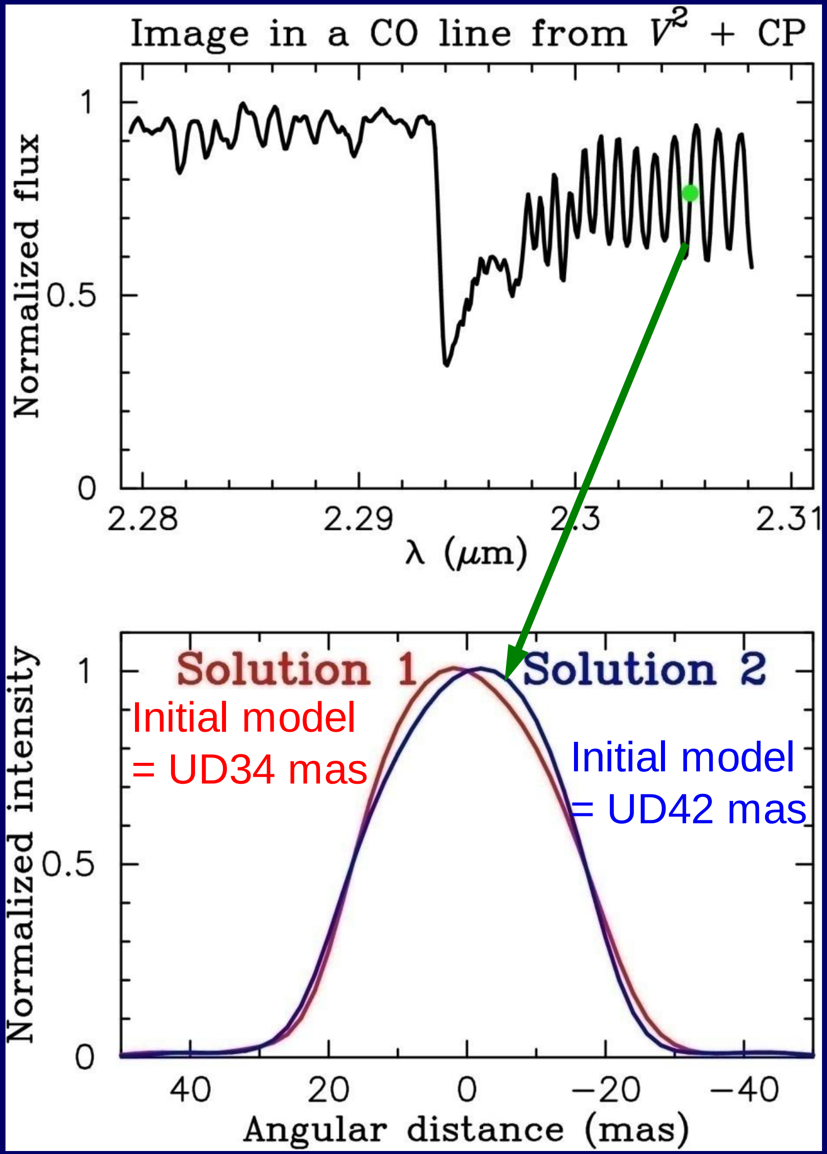
Betelgeuse in the 2.3 μm continuum: No or only marginal time variation between 2008 and 2009



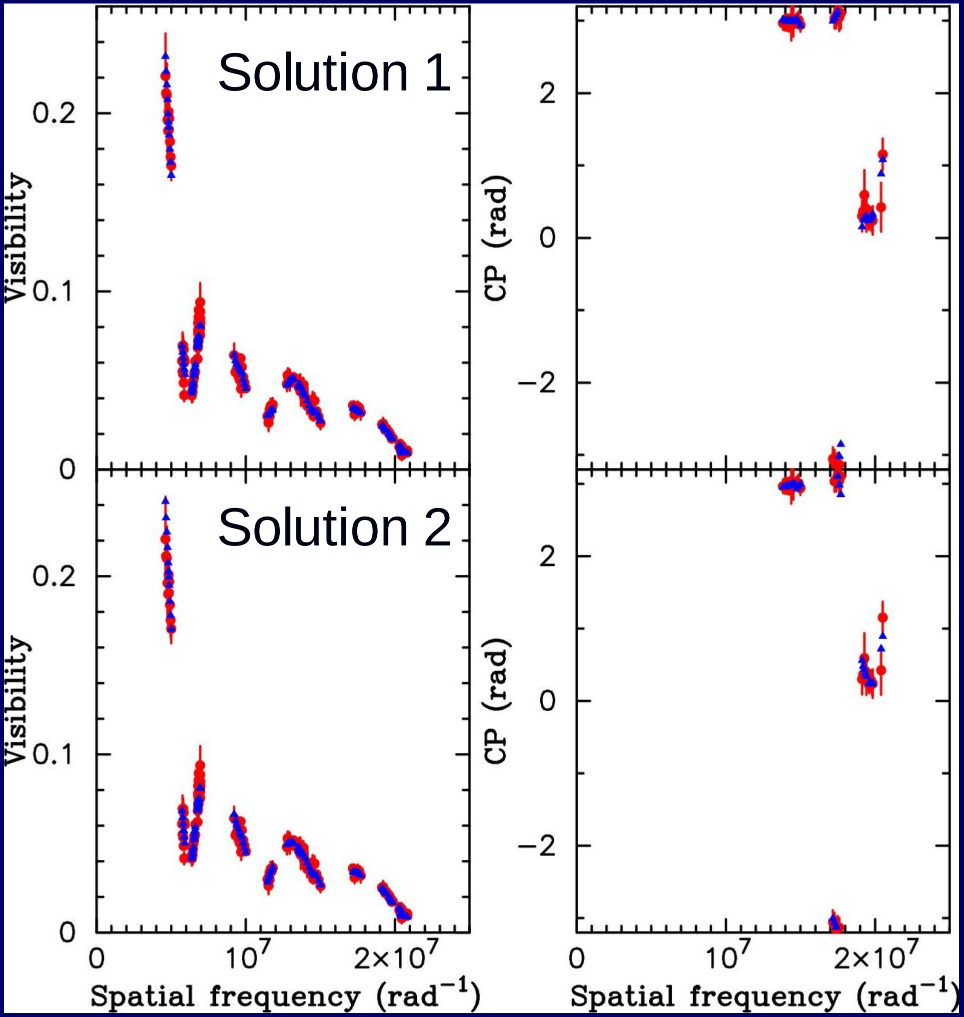
Time variation is much smaller than the maximum variation predicted by 3-D convection simulation (Chiavassa et al. 2009).
→ 3-D model predicts too pronounced inhomogeneities(?)

AMBER imaging of Betelgeuse: CO lines

✓ Image reconstruction with V^2 + Closure phase is not unique! (Fit to the data is equally good.)



AMBER observations of Betelgeuse: 1-D aperture synthesis imaging in the CO lines



Which one is correct? Both are wrong?

AMBER imaging of Betelgeuse: CO lines

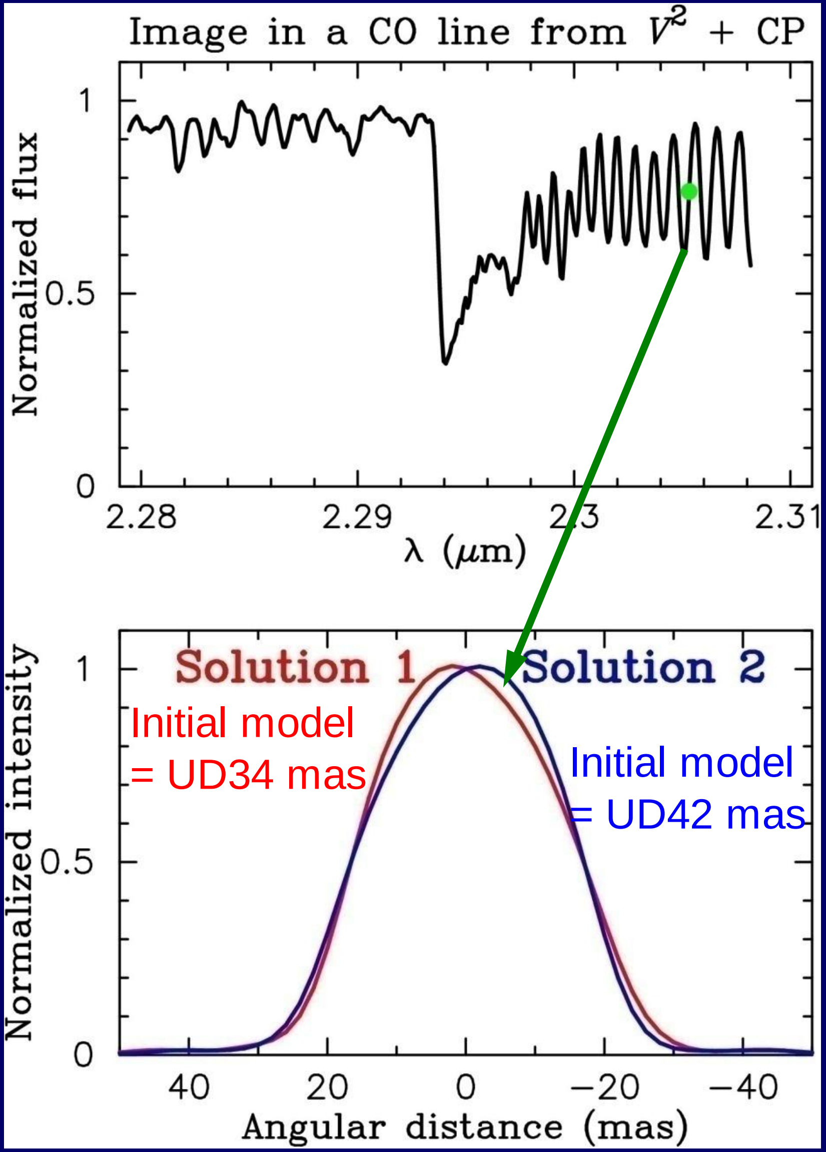
Self-calibration with differential phase

NPOI: Schmitt et al. (2009)
AMBER: Millour et al. (2011)

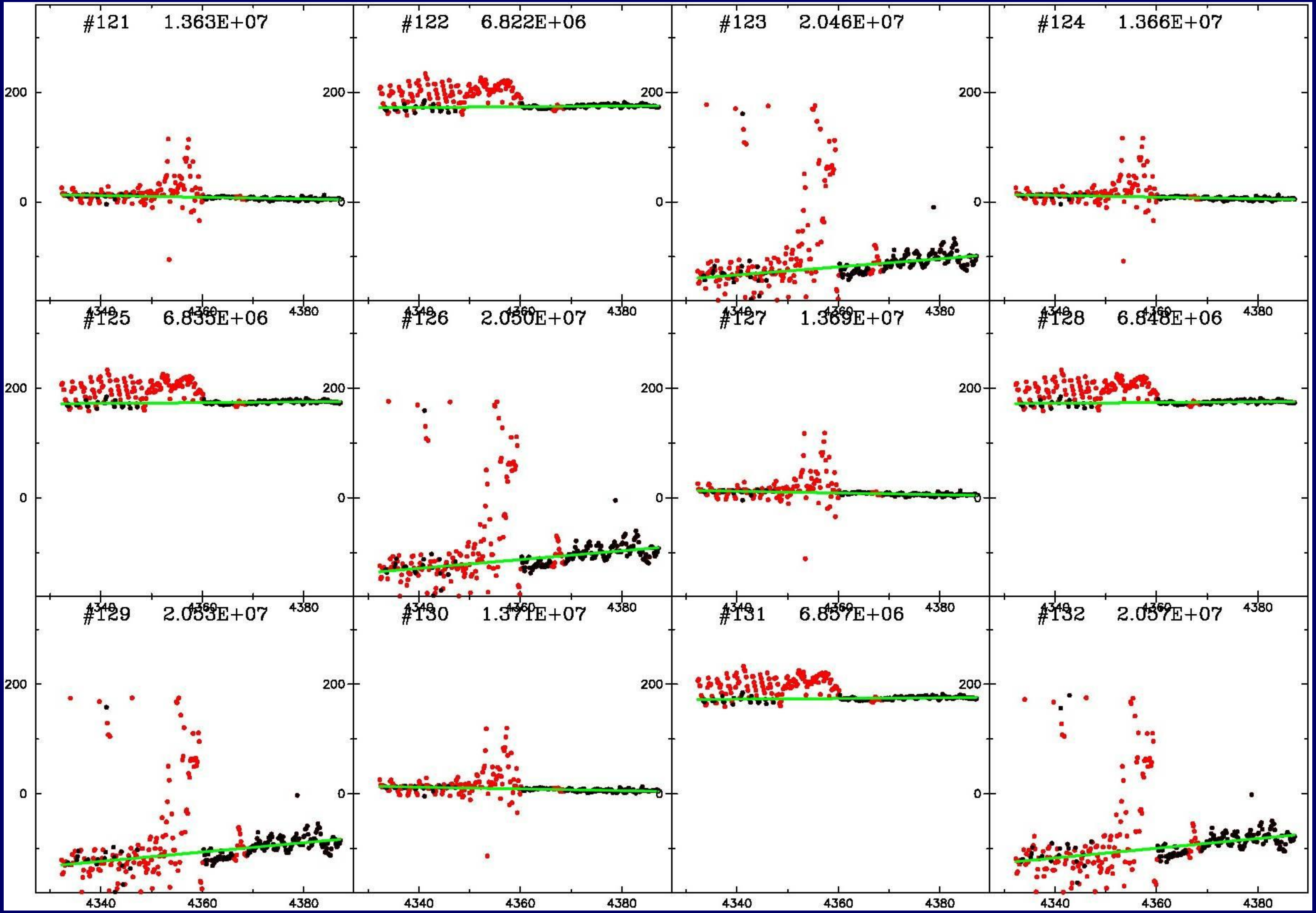
1) Reconstruct images at all continuum spectral channels from V^2 and CP

2) Compute the phase in the continuum images.
Interpolate for line spectral channels

3) Phase(lines) =
Interpolated phase(continuum)
+ Observed differential phase
→ Complex visibility



Fitting the continuum phase



AMBER imaging of Betelgeuse: CO lines

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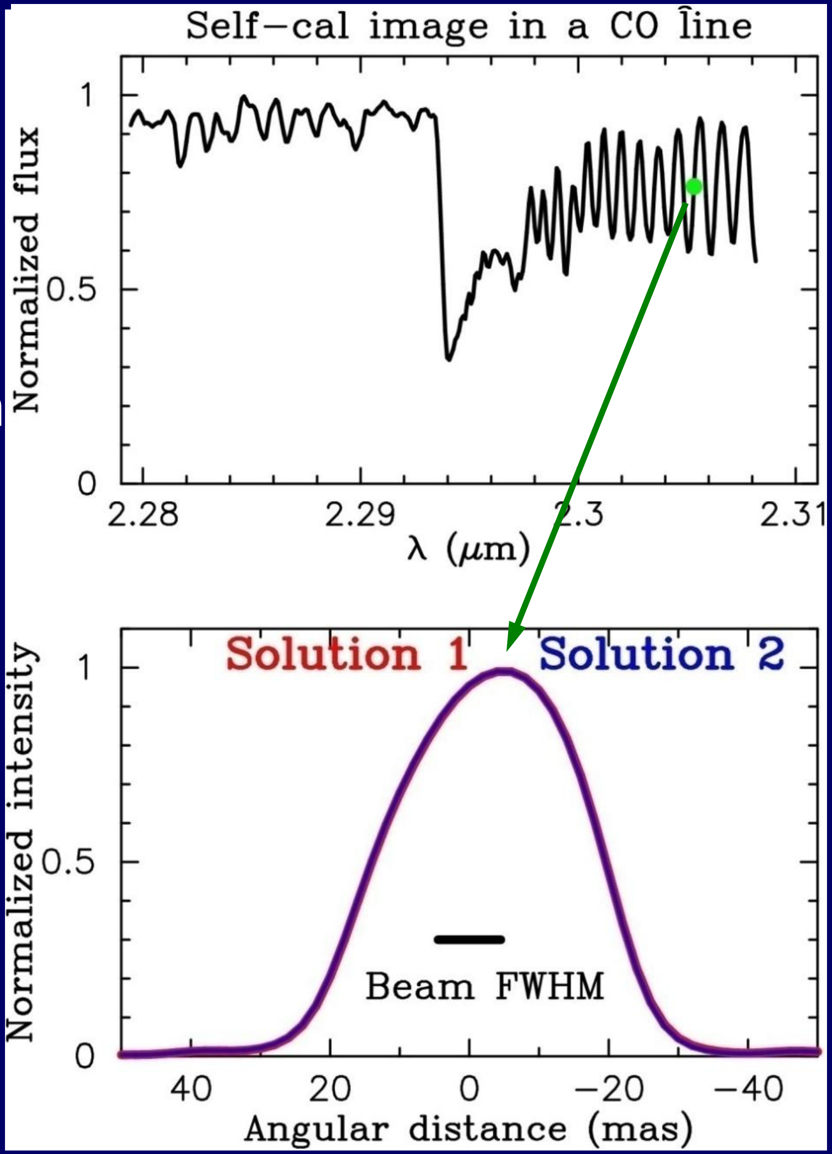
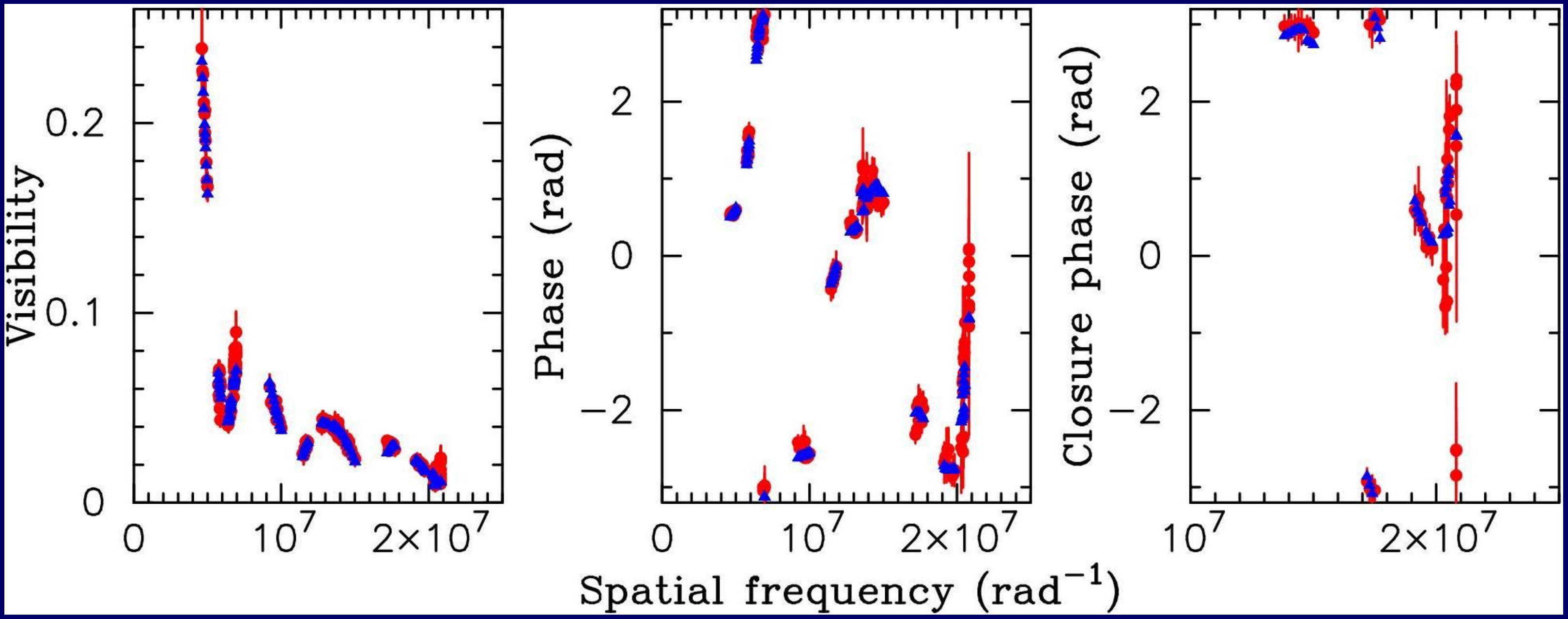
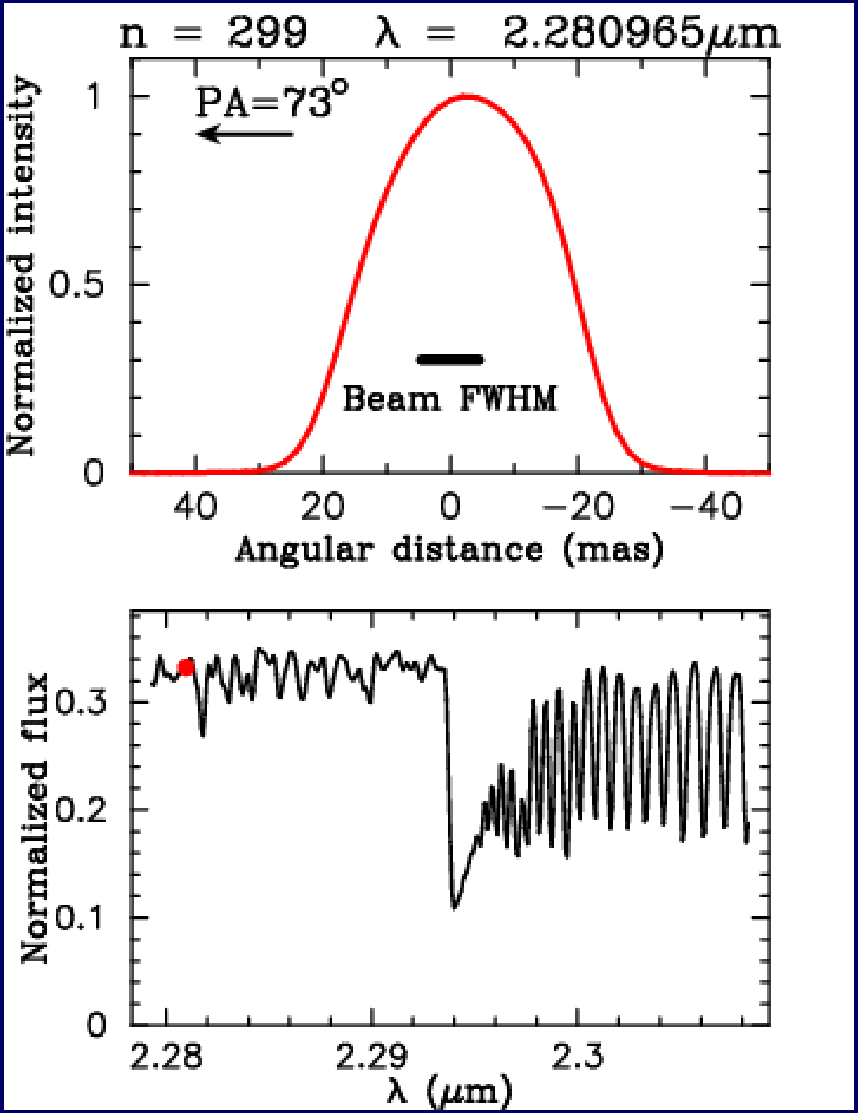




Visibility
0.2
0.1
0
0
10^7
2×10^7
Phase (rad)
2
0
−2
0
10^7
2×10^7
Closure phase (rad)
2
0
−2
10^7
2×10^7
Spatial frequency (rad^−1)

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



Spectral resolution = 6000

Ohnaka et al. (2011)

1-D imaging of Betelgeuse:
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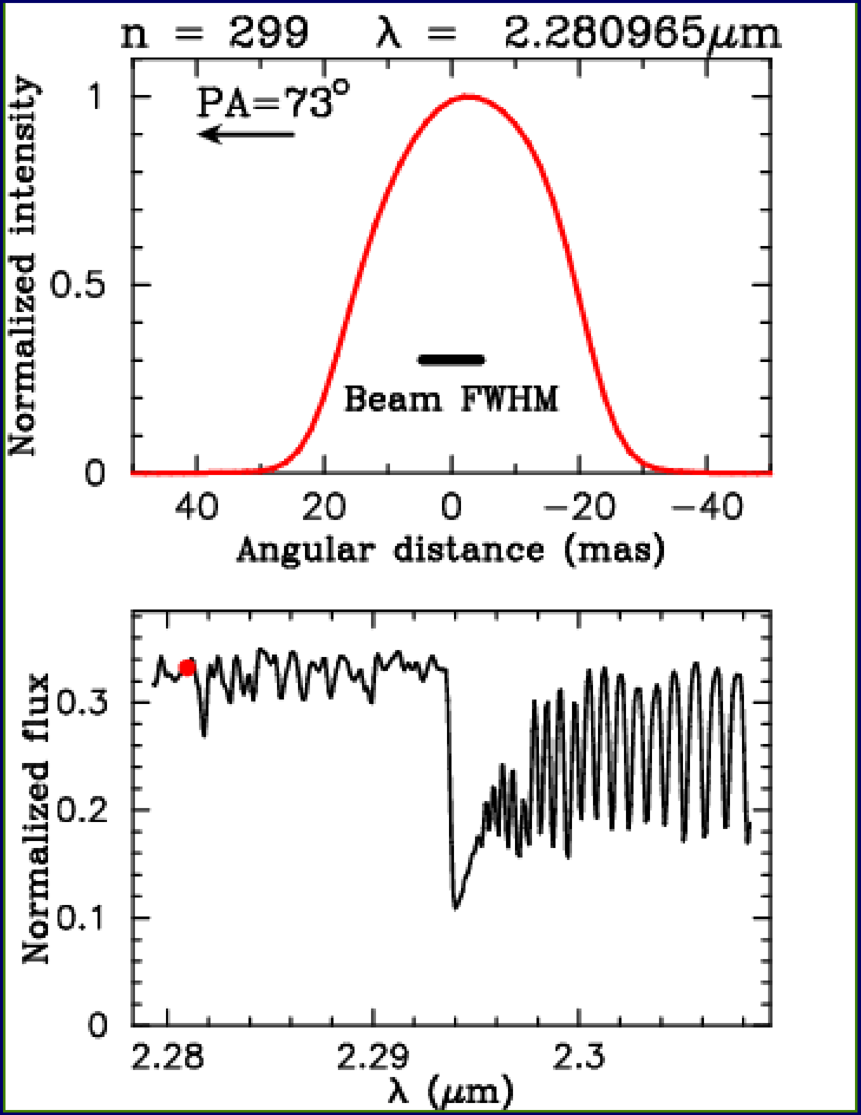
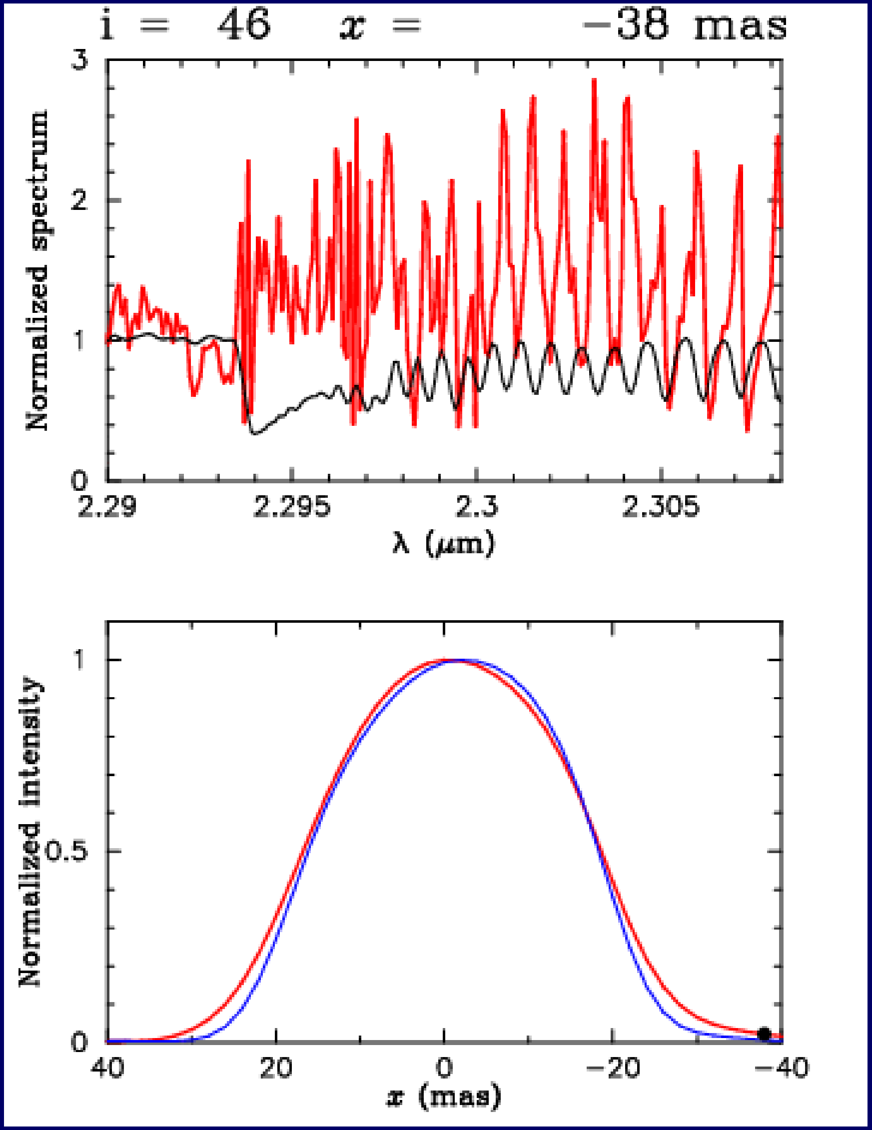


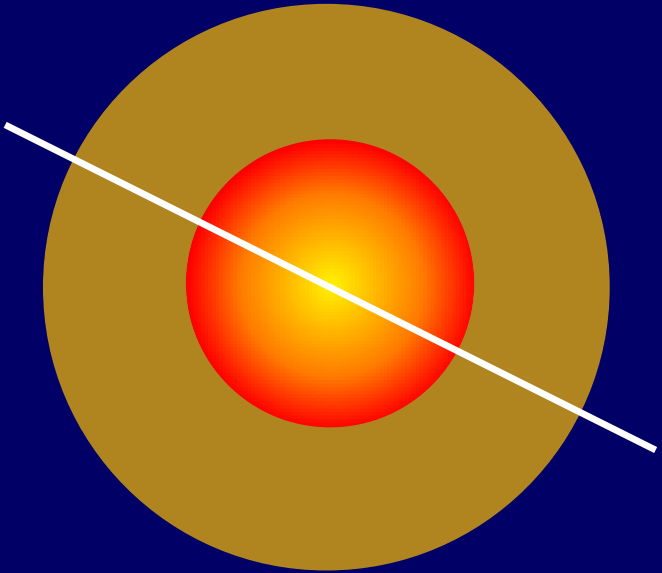
Spectral resolution = 6000

Ohnaka et al. (2011)

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

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





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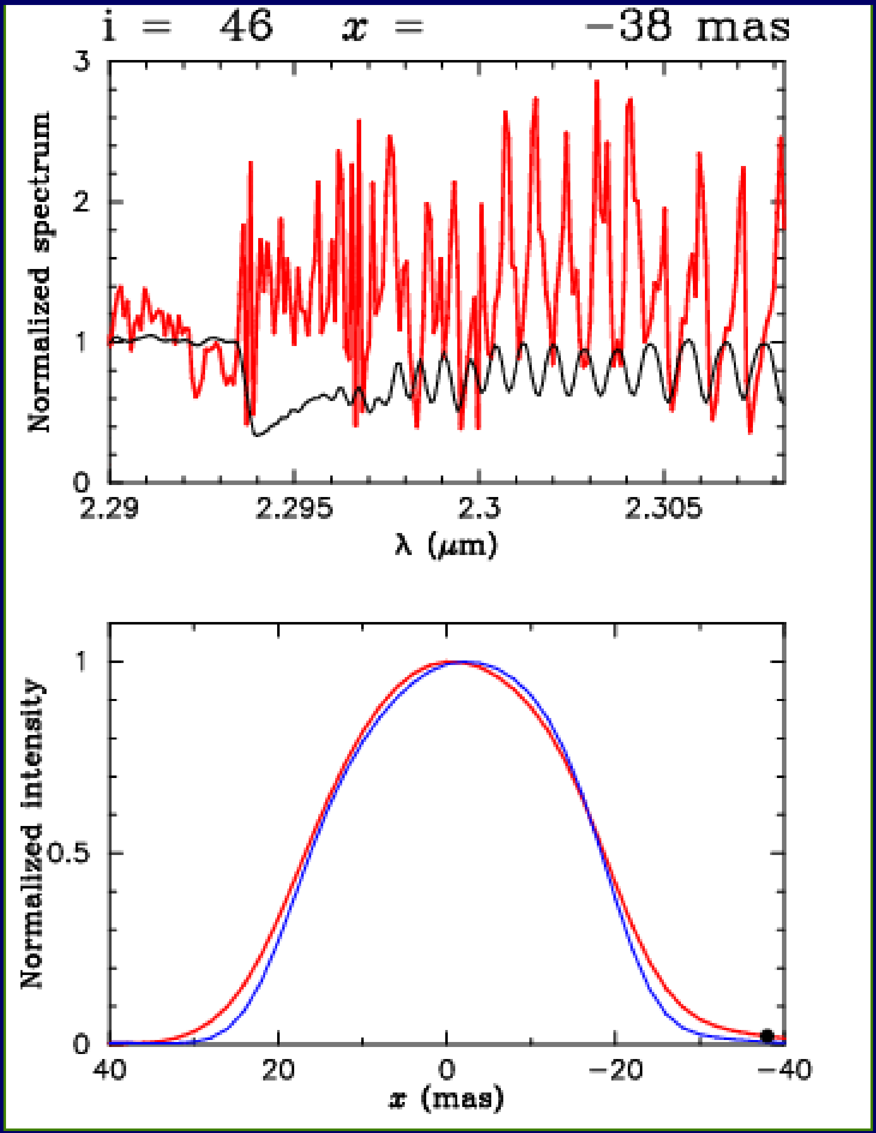
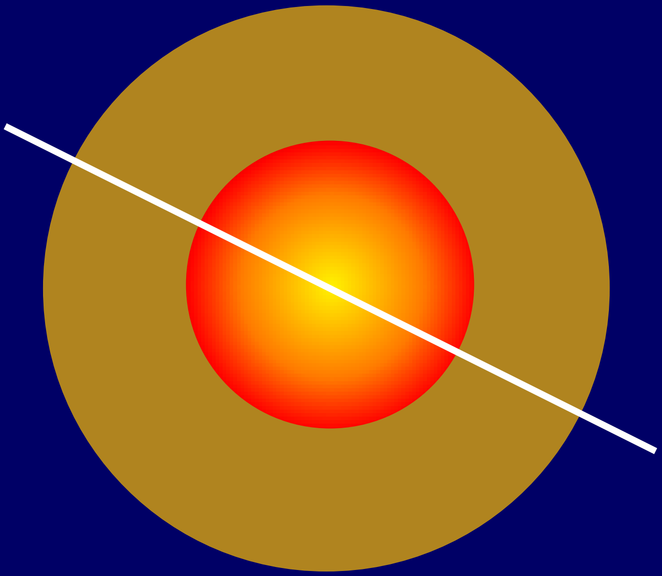
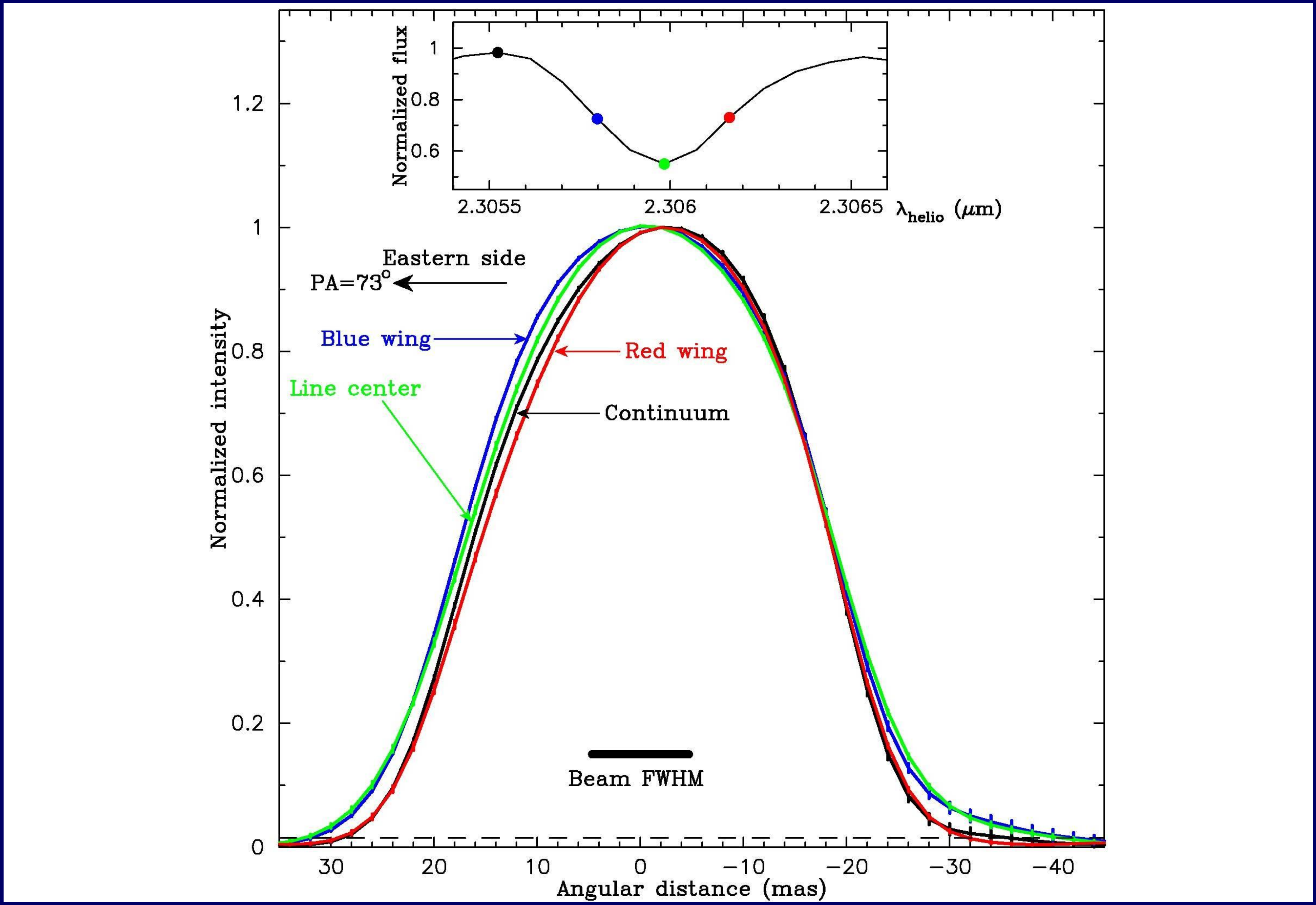


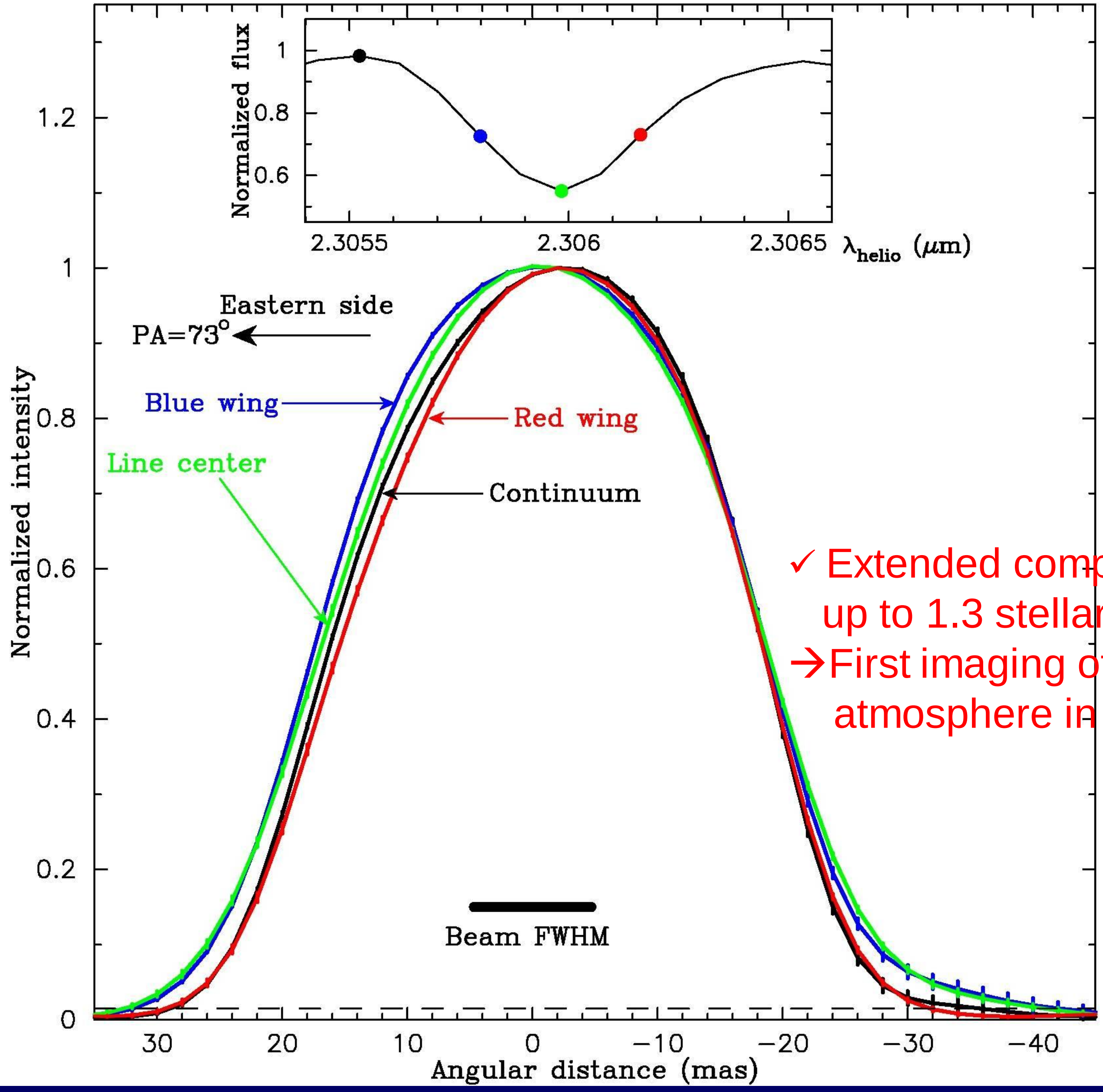


Movie http://www3.mpifr-bonn.mpg.de/staff/kohnaka/alfori2.html

AMBER 1-D imaging of Betelgeuse in the CO lines



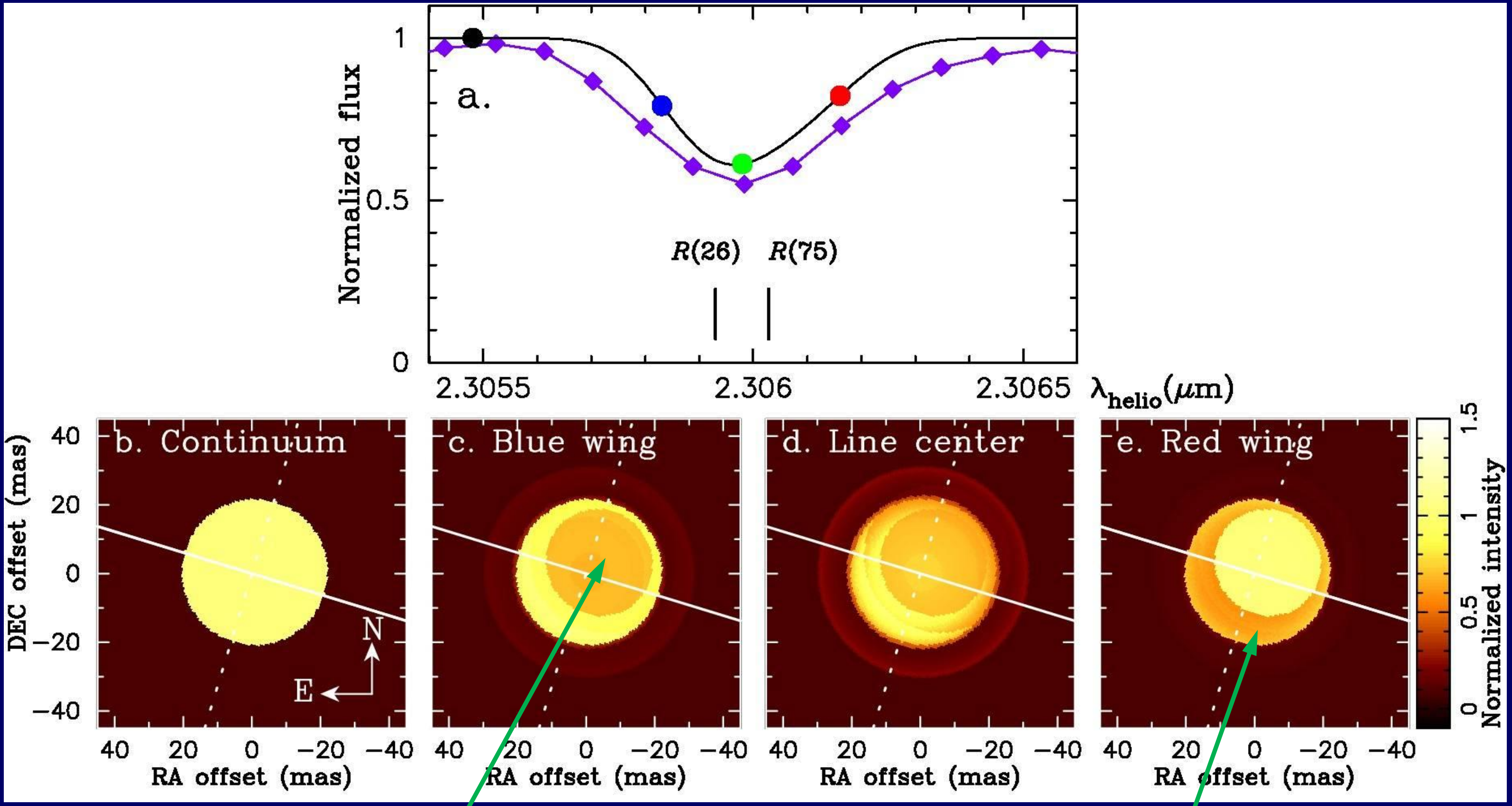
AMBER 1-D imaging of Betelgeuse in the CO lines



✓ Extended component up to 1.3 stellar radii

→ First imaging of the outer atmosphere in the CO lines

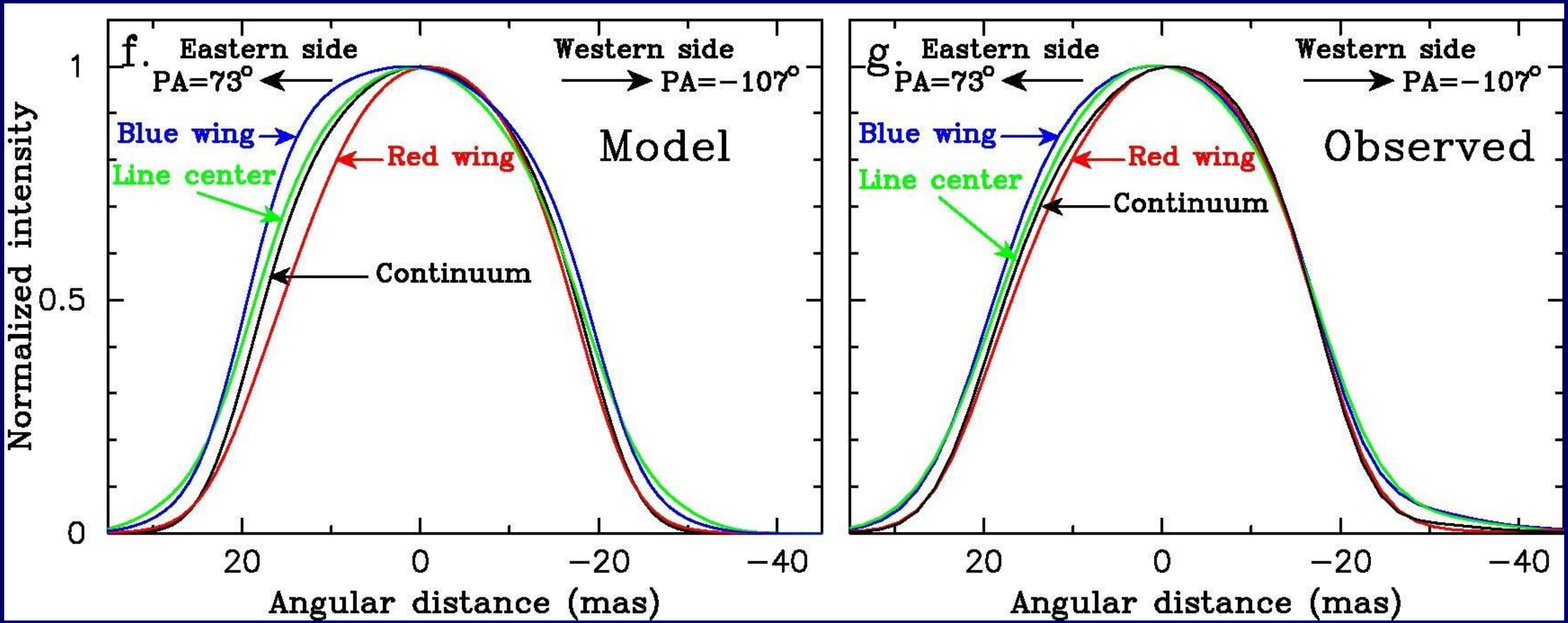
Modeling the inhomogeneous velocity field



Weak upwelling at 0—5 km/s

Strong downdraft with 20—30 km/s

Modeling the inhomogeneous velocity field



Origin of the inhomogeneous velocity field

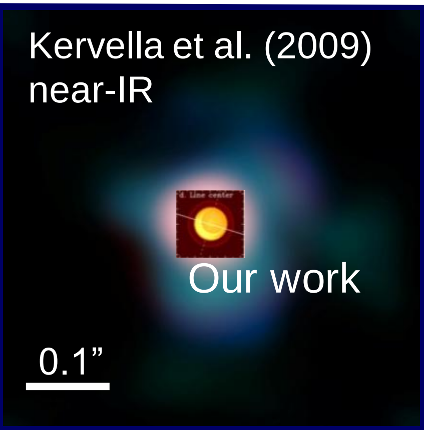
✓ Convection?

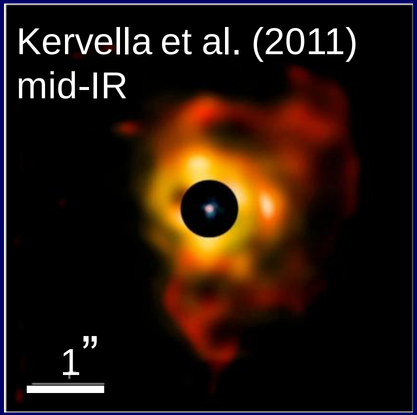
✓ Driven by MHD processes?
Magnetic field detected ~1 G
(Aurière et al. 2010)

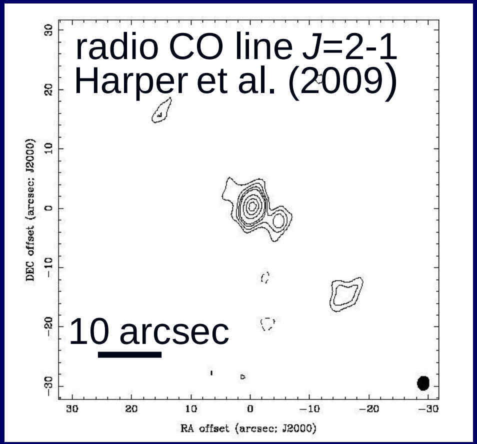
✓ Pulsation?
→ But variability amplitude is small
ΔV = 1 – 1.5 mag

✓ Clumpy mass loss

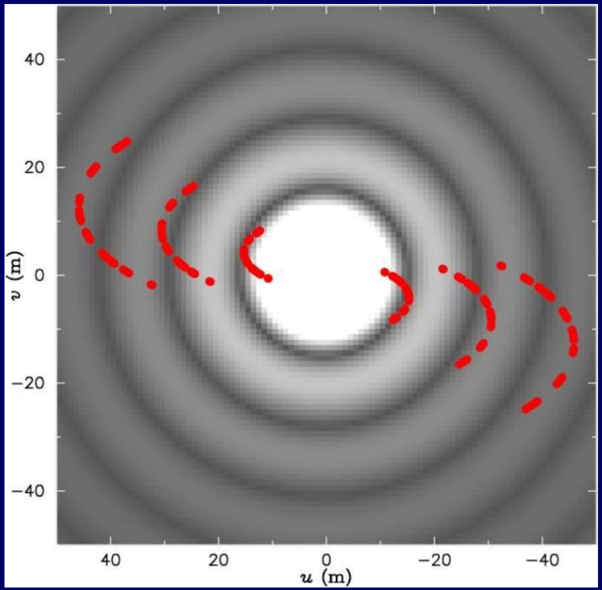
Temporally variable,
inhomogeneous velocity field
→ Clumpy mass loss(?)

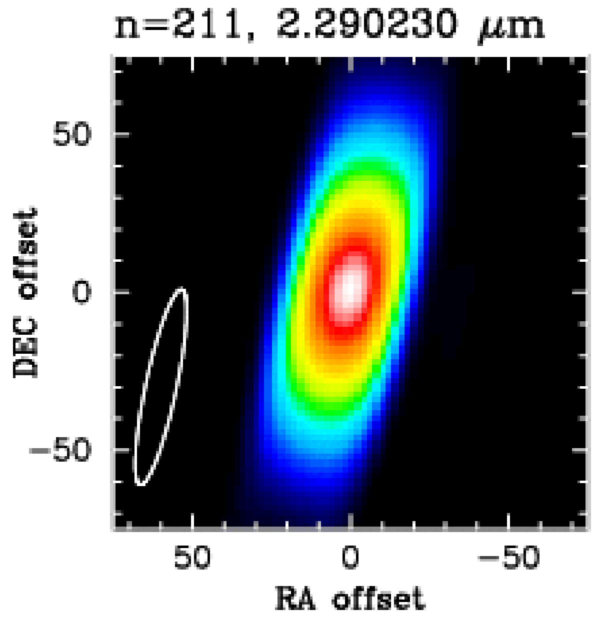


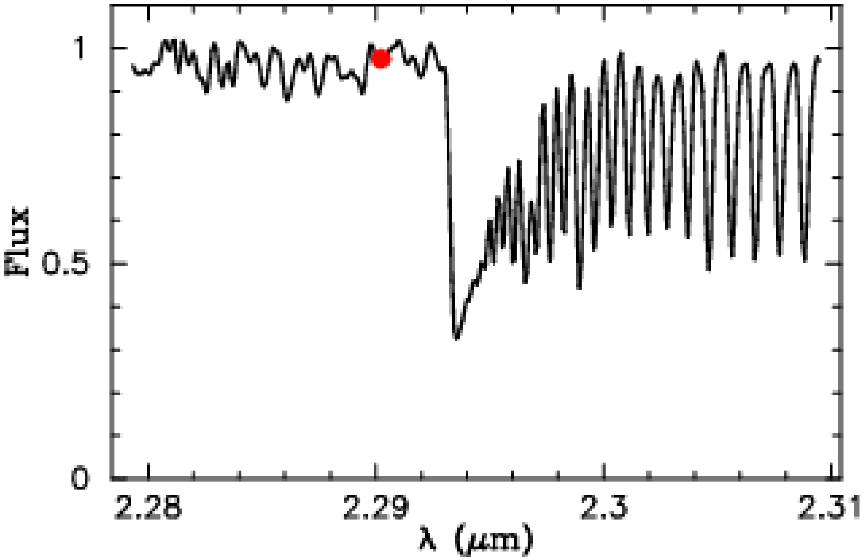




VLTI / AMBER imaging of the red supergiant Antares



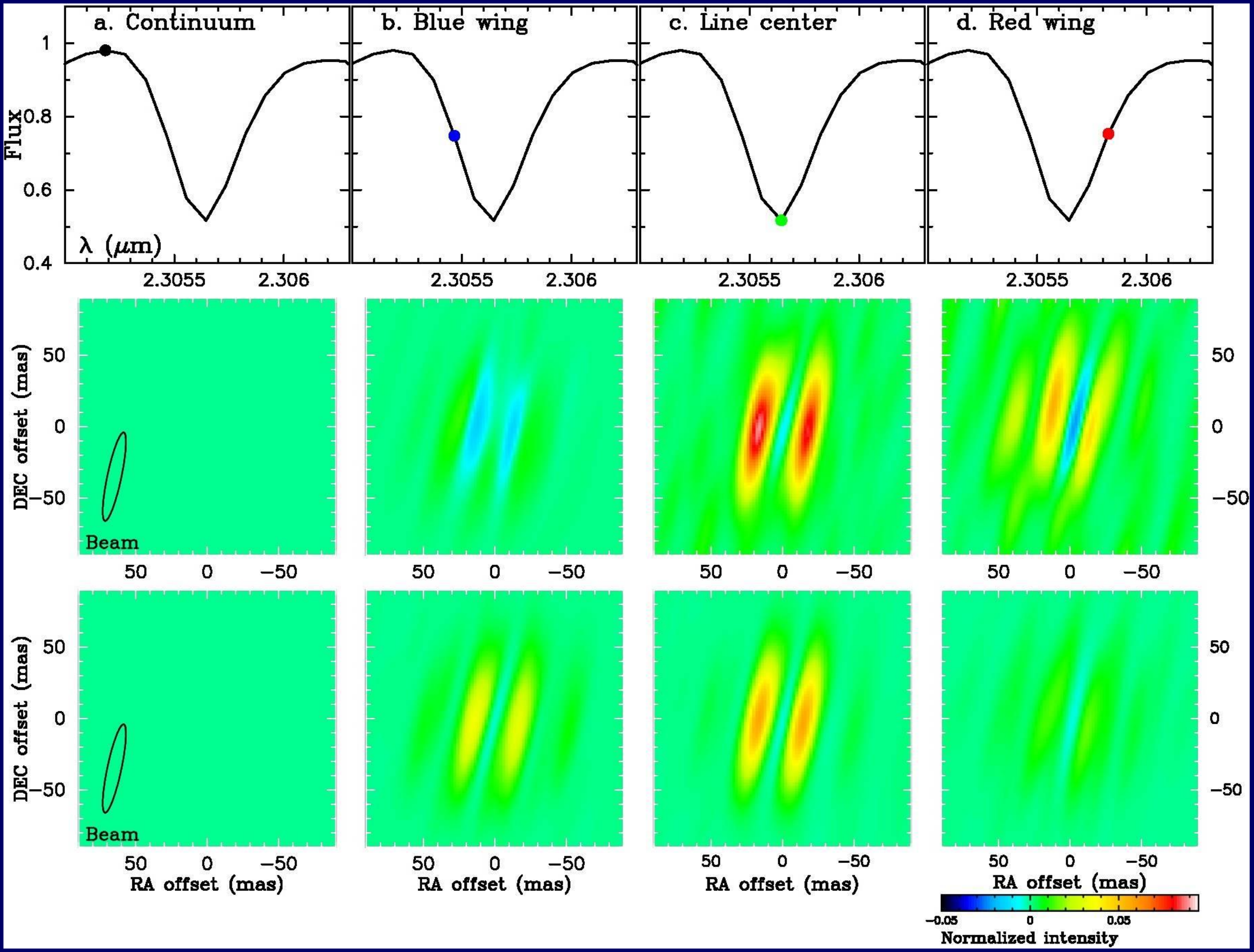




VLTI / AMBER imaging of the red supergiant Antares

2009

2010



Conclusion & Outlook

- ✓ 1-D imaging at high-spatial and high spectral resolution
- ✓ Betelgeuse appears different in the blue and red wings
- ✓ Stellar surface gas motions spatially resolved
- ✓ Long-term monitoring to follow the dynamics of the outer atmosphere
  E.g., Episodic, strong outward motion?
- ✓ 2-D imaging
  Antares is better for 2-D imaging with VLTI (southern target)

Thank you for your attention!

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