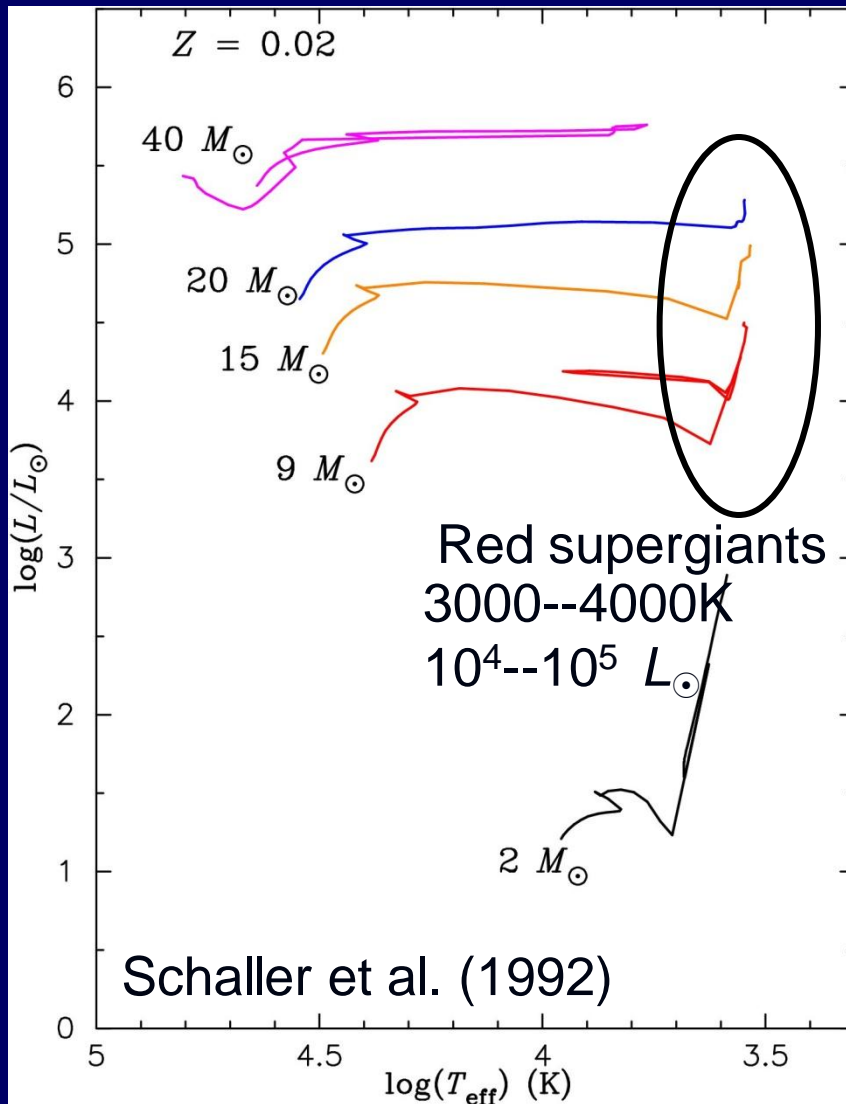


1-D imaging of the dynamical, inhomogeneous
atmosphere of the red supergiant Betelgeuse in
the $2.3 \mu\text{m}$ CO lines with VLT / AMBER

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Max Planck Institute for
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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...

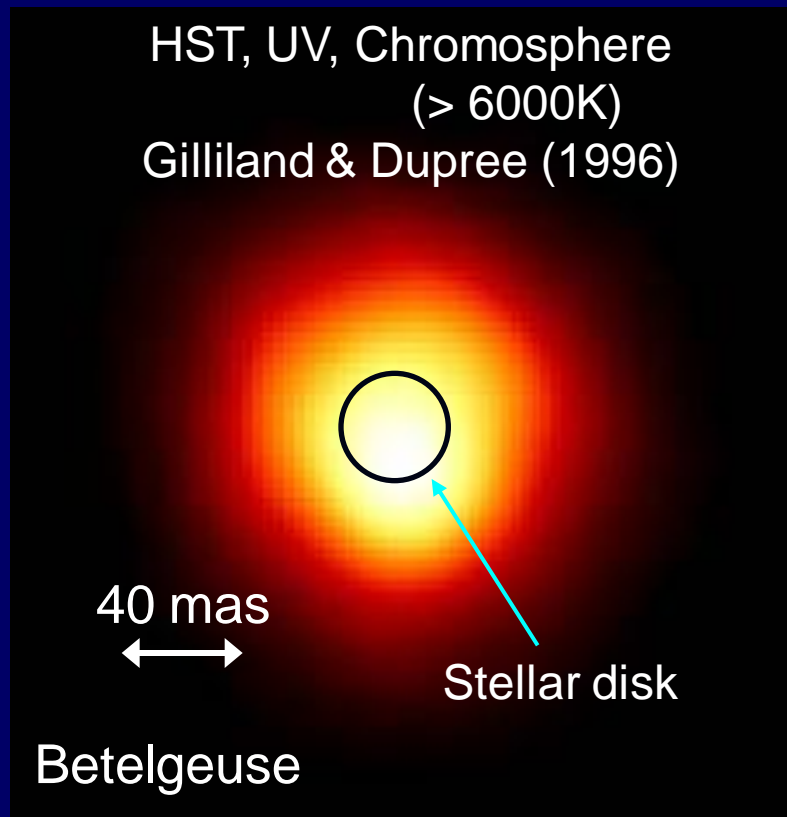
✓ UV ionizing radiation sources

✓ Strong winds, SN explosion
→ Mechanical energy input

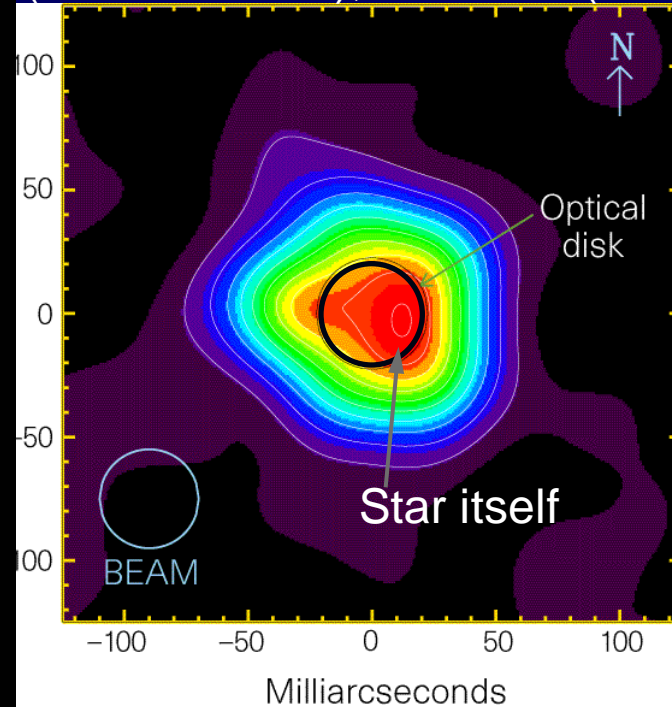
✓ Chemical enrichment of ISM

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

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)

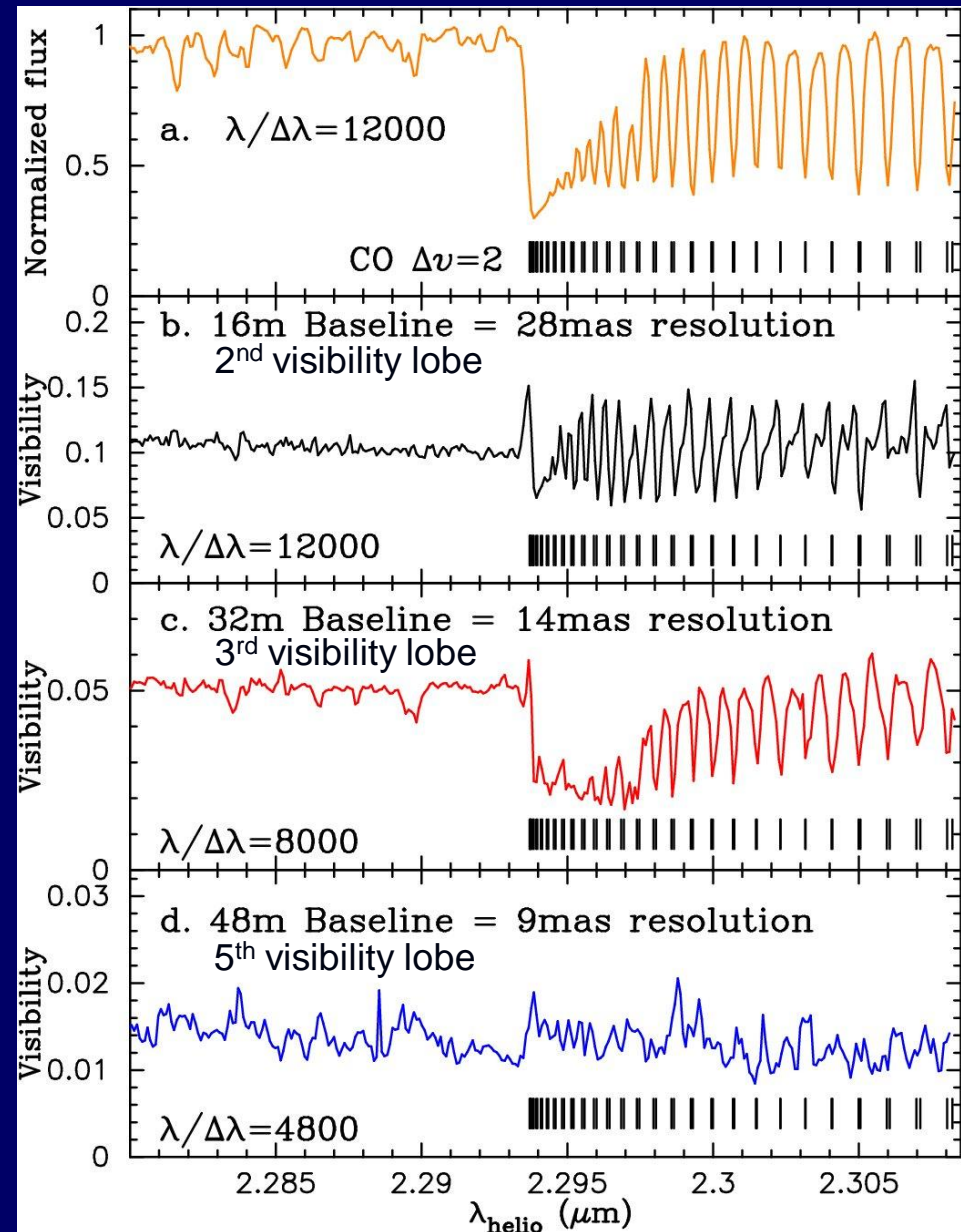
Strong IR molecular lines form in the outer atmosphere

- High spectral & spatial resolution observations
- Long-Baseline Spectro-Interferometry

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

Results

- 1) Fringes in the 2nd, 3rd, and 5th lobes
Spectral resolution up to 12000
- 2) 48m baselines = 9.8 mas resolution
→ Highest resolution on Betelgeuse

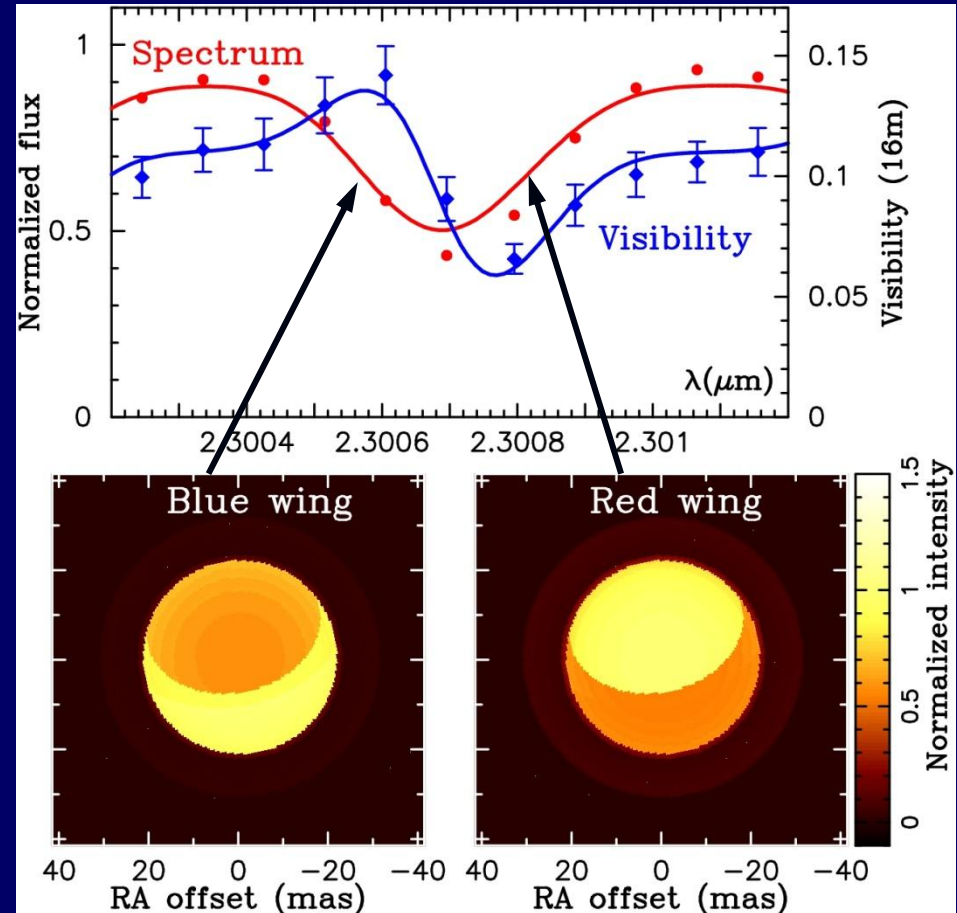


Ohnaka et al. (2009)

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

Results

- 1) Fringes in the 2nd, 3rd, and 5th lobes
Spectral resolution up to 12000
- 2) 48m baselines = 9.8 mas resolution
→ Highest resolution on Betelgeuse
- 3) Visibility & Closure phase asymmetric with respect to the line center
→ The star looks different in the red & blue wings
- 4) Gas motions in a stellar photosphere spatially resolved for the first time other than the Sun
Velocity amplitude = 10—15 km/s



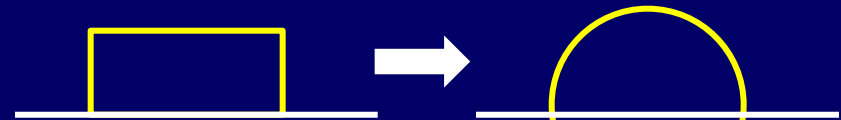
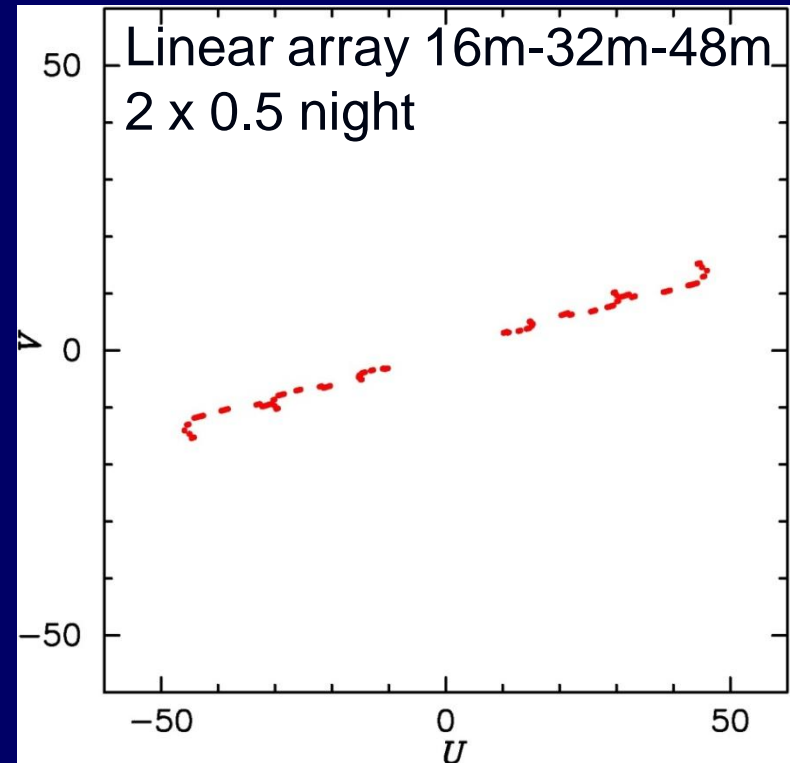
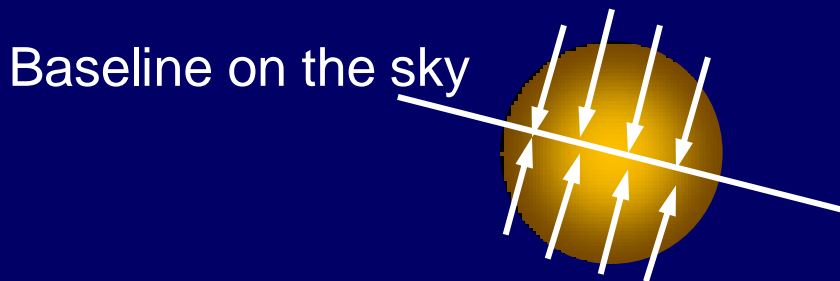
Ohnaka et al. (2009)

AMBER observations of Betelgeuse (2009)

1-D aperture synthesis imaging in the CO lines

Observations

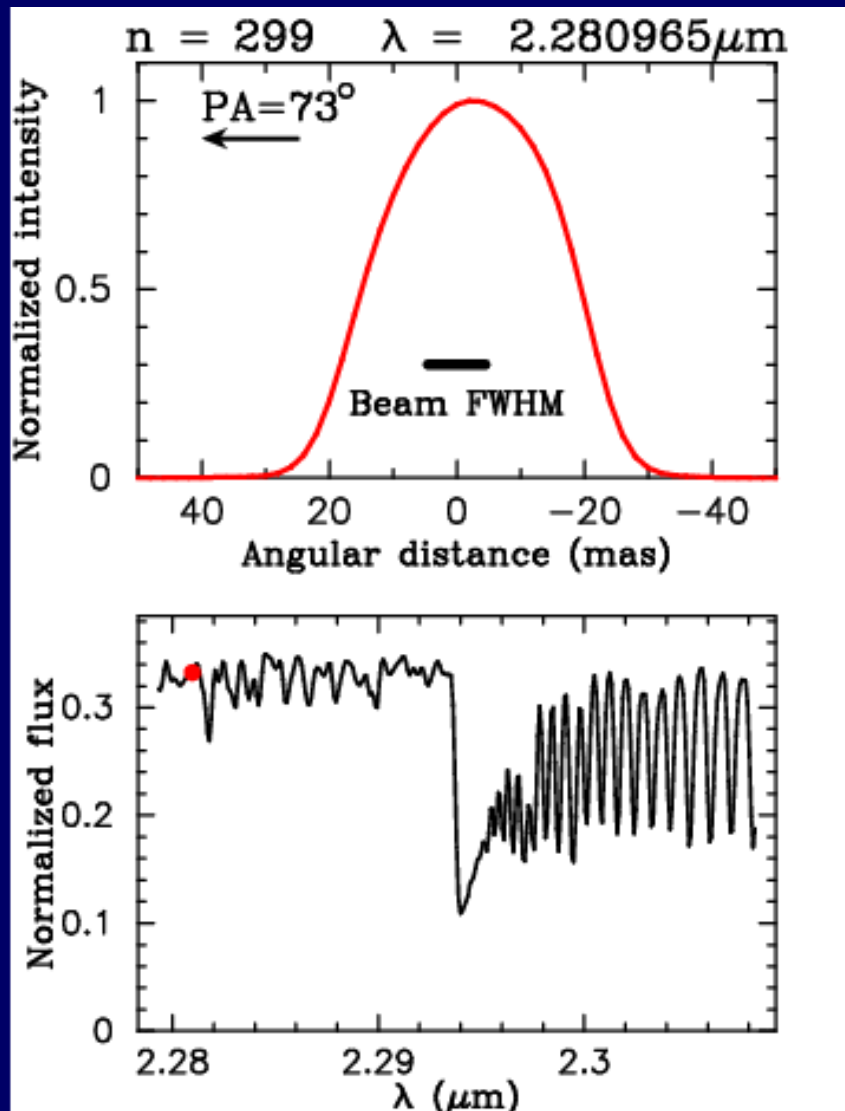
- ✓ CO lines, 2.28 – 2.31 μm
- ✓ Dense, linear uv coverage
Spatial resolution = 9.8 mas
→ 1st to 5th visibility lobes
- ✓ 1-D projection image =
“squashed” onto the baseline vector



- ✓ MiRA image reconstruction software (Thiébaud 2008)
+ self-calibration technique using differential phases

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

Movie available at <http://www.mpifr.de/staff/kohnaka>

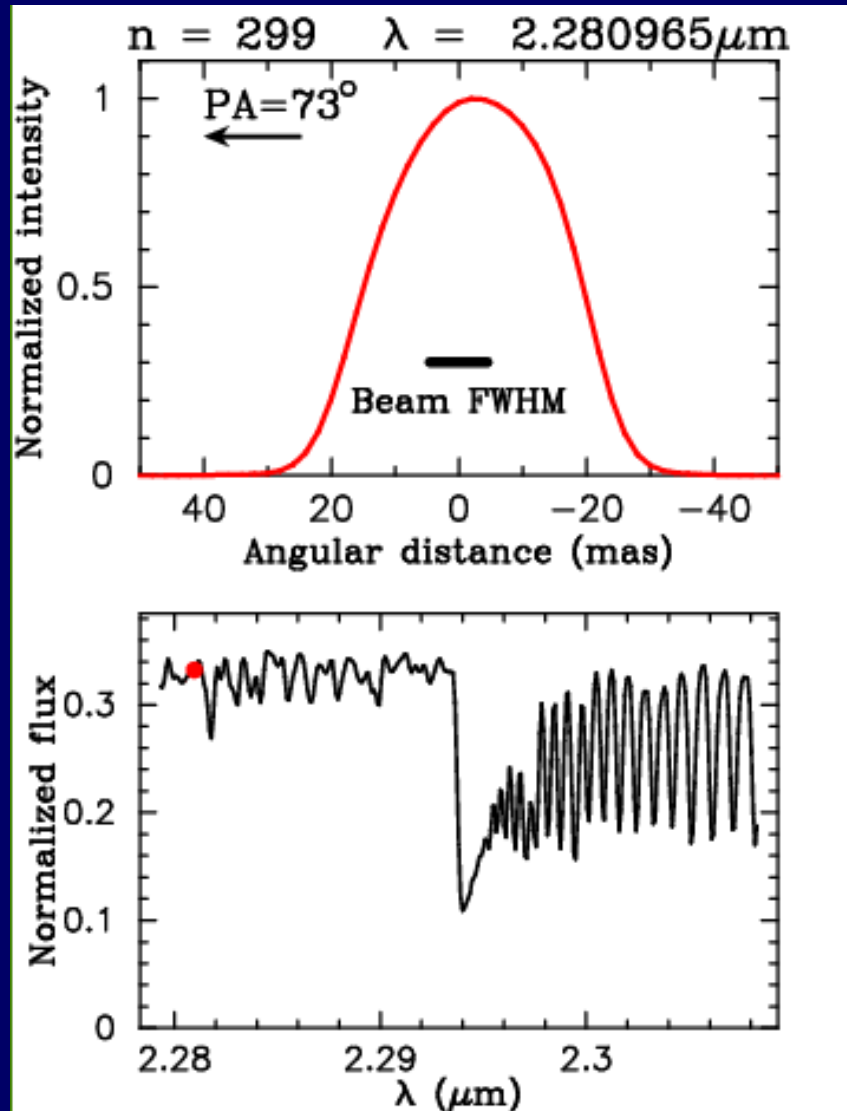


Spectral resolution
= 6000

Ohnaka et al. (2011)

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

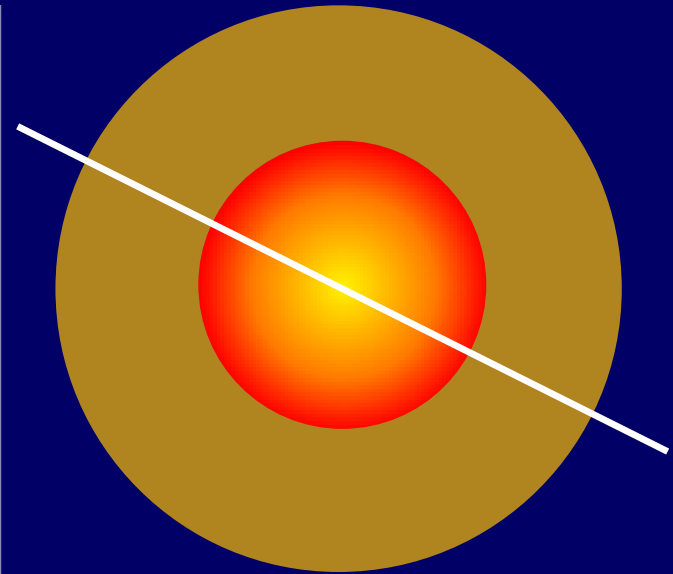
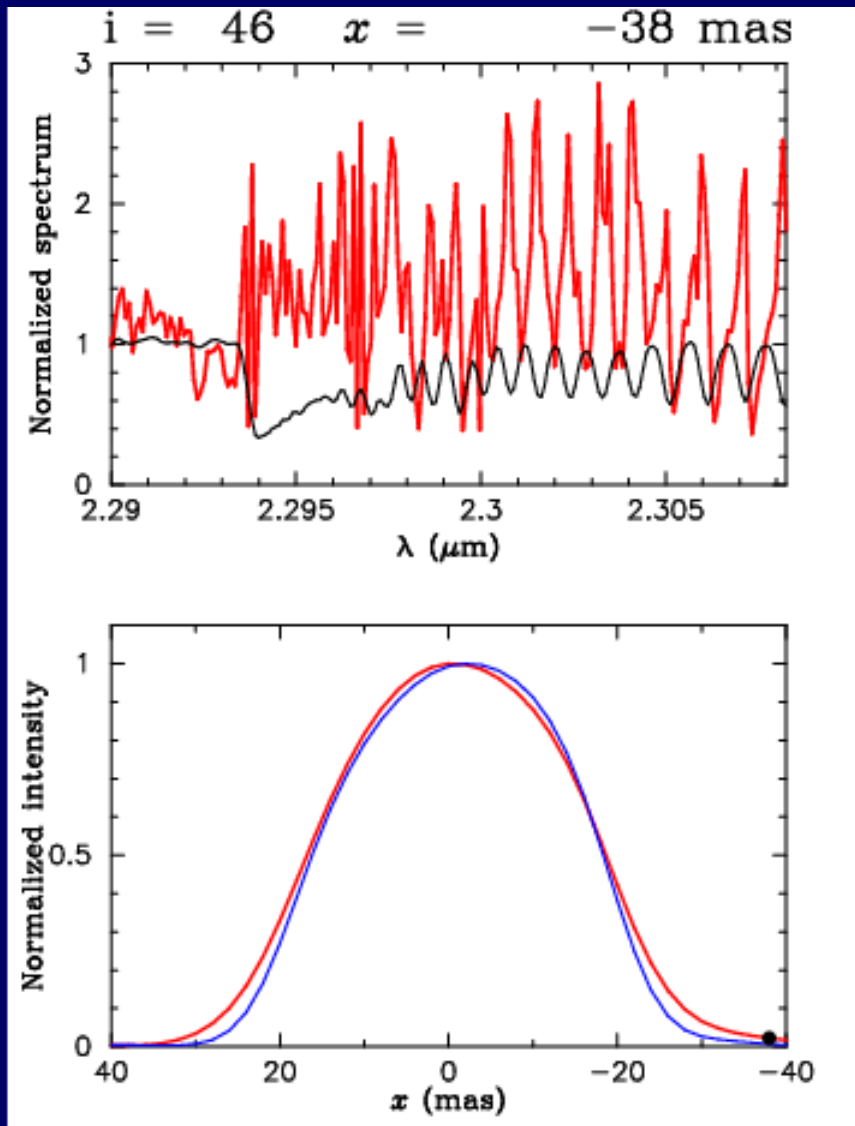
Movie available at <http://www.mpifr.de/staff/kohnaka>



Spectral resolution
= 6000

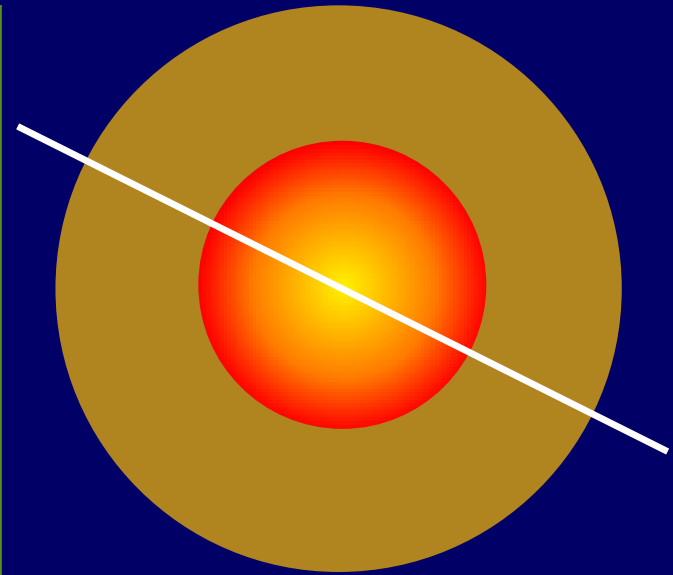
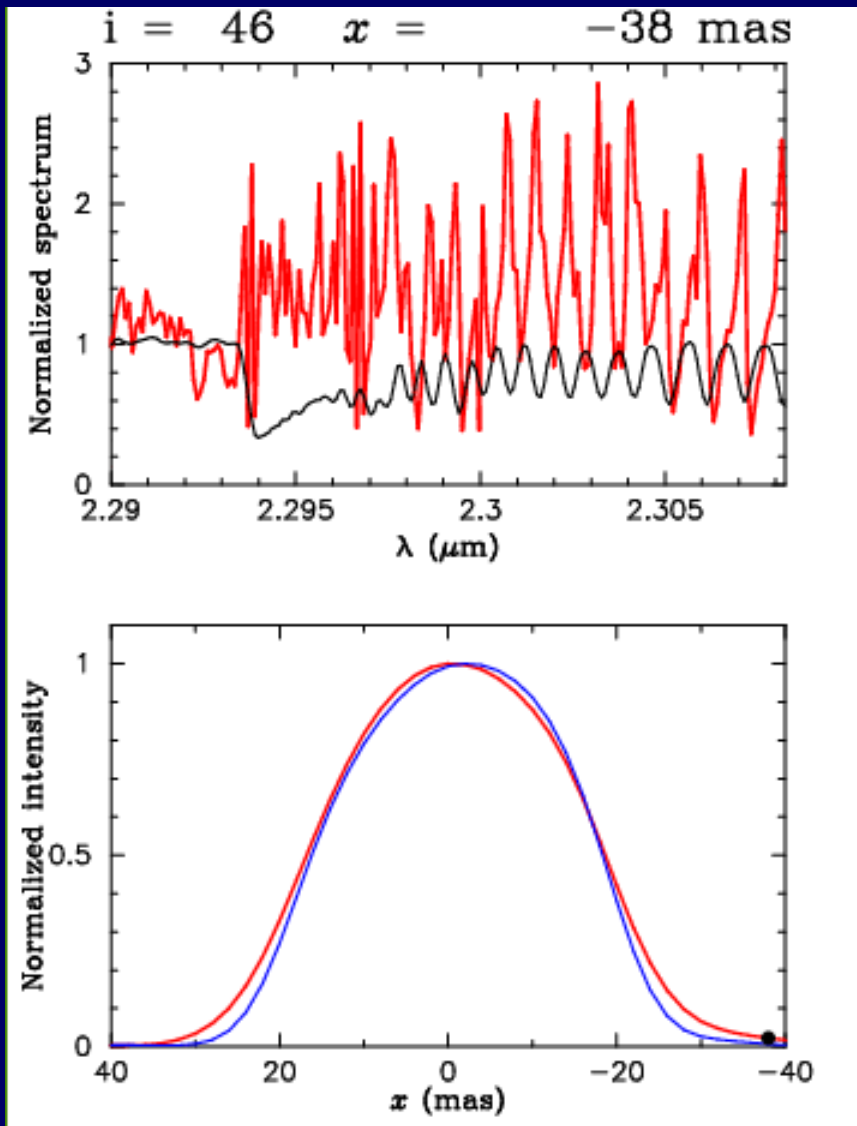
Ohnaka et al. (2011)

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



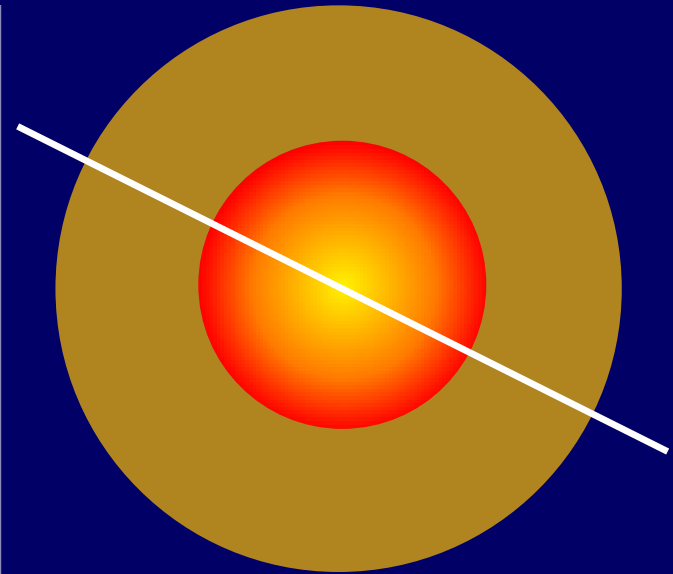
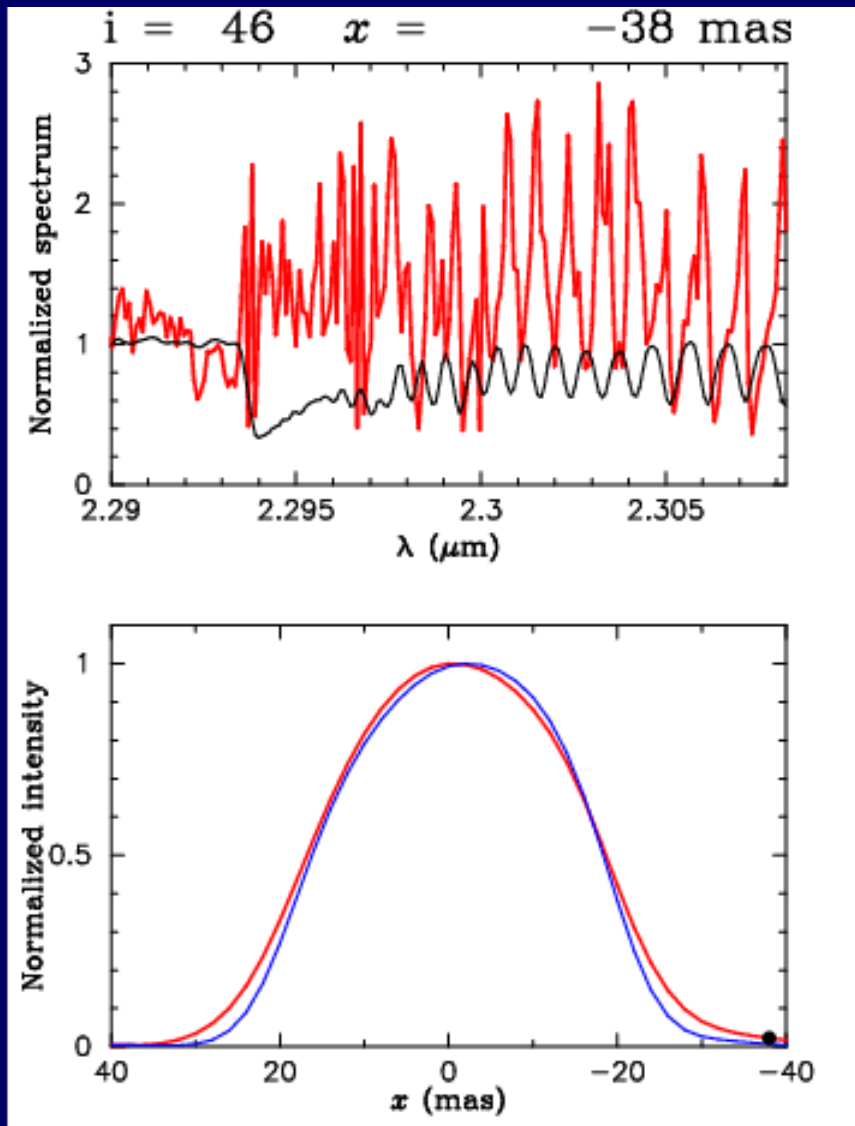
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1-D imaging of Betelgeuse: Spectrum of the CO lines at each spatial position



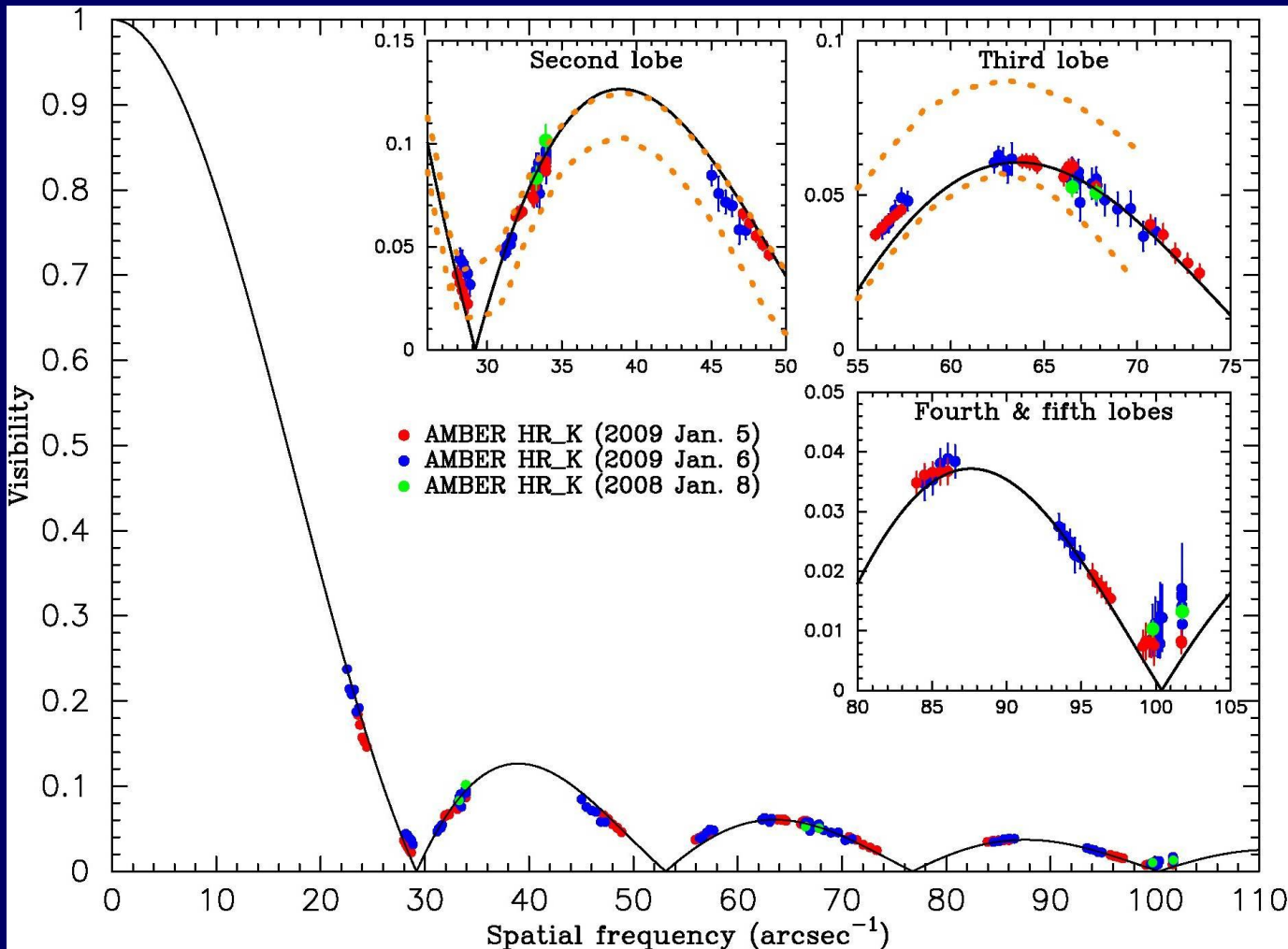
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1-D imaging of Betelgeuse: Spectrum of the CO lines at each spatial position



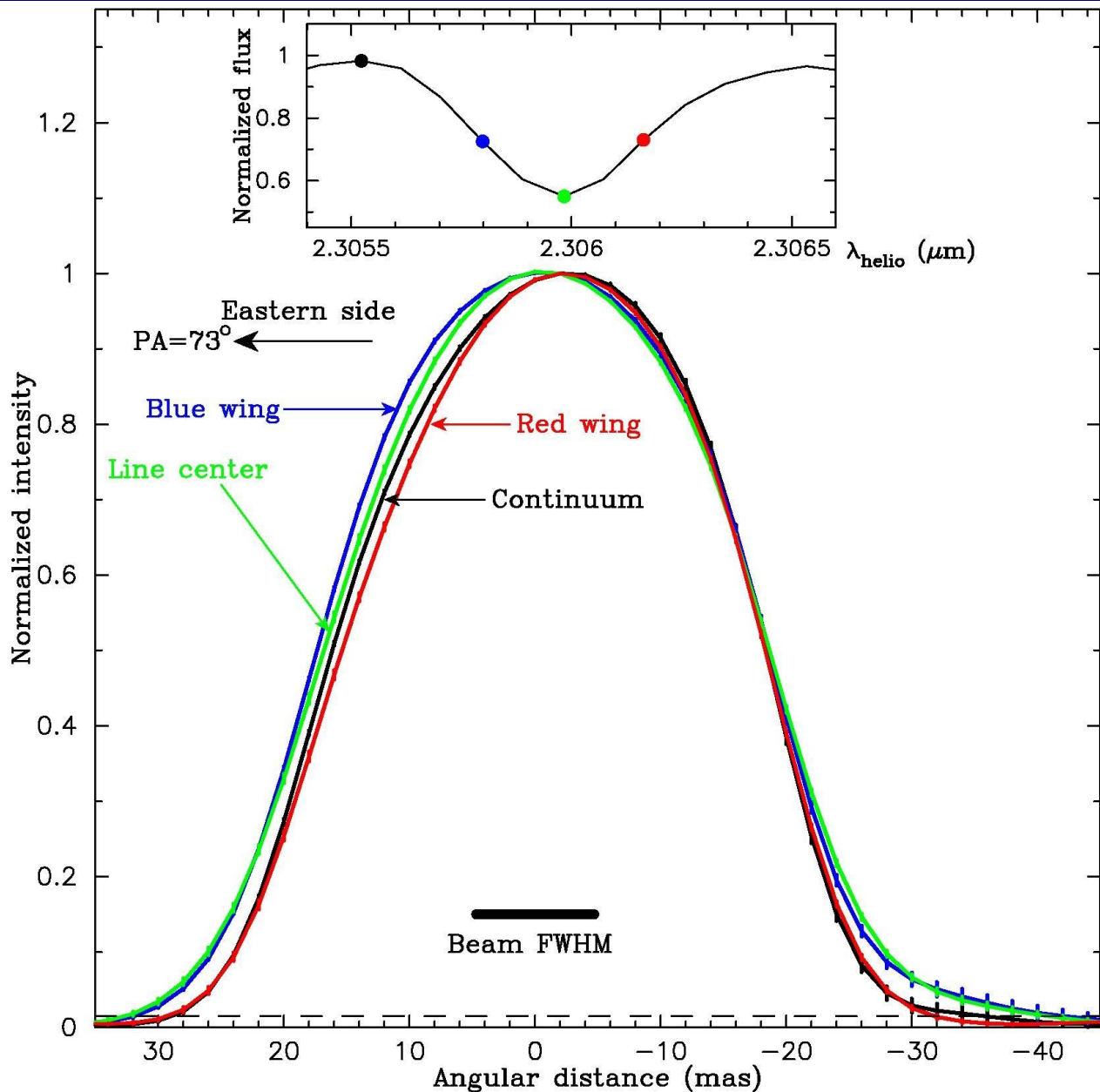
Movie available at
<http://www.mpifr.de/staff/kohnaka>

Betelgeuse in the *K*-band continuum: No or only marginal time variation between 2008 and 2009

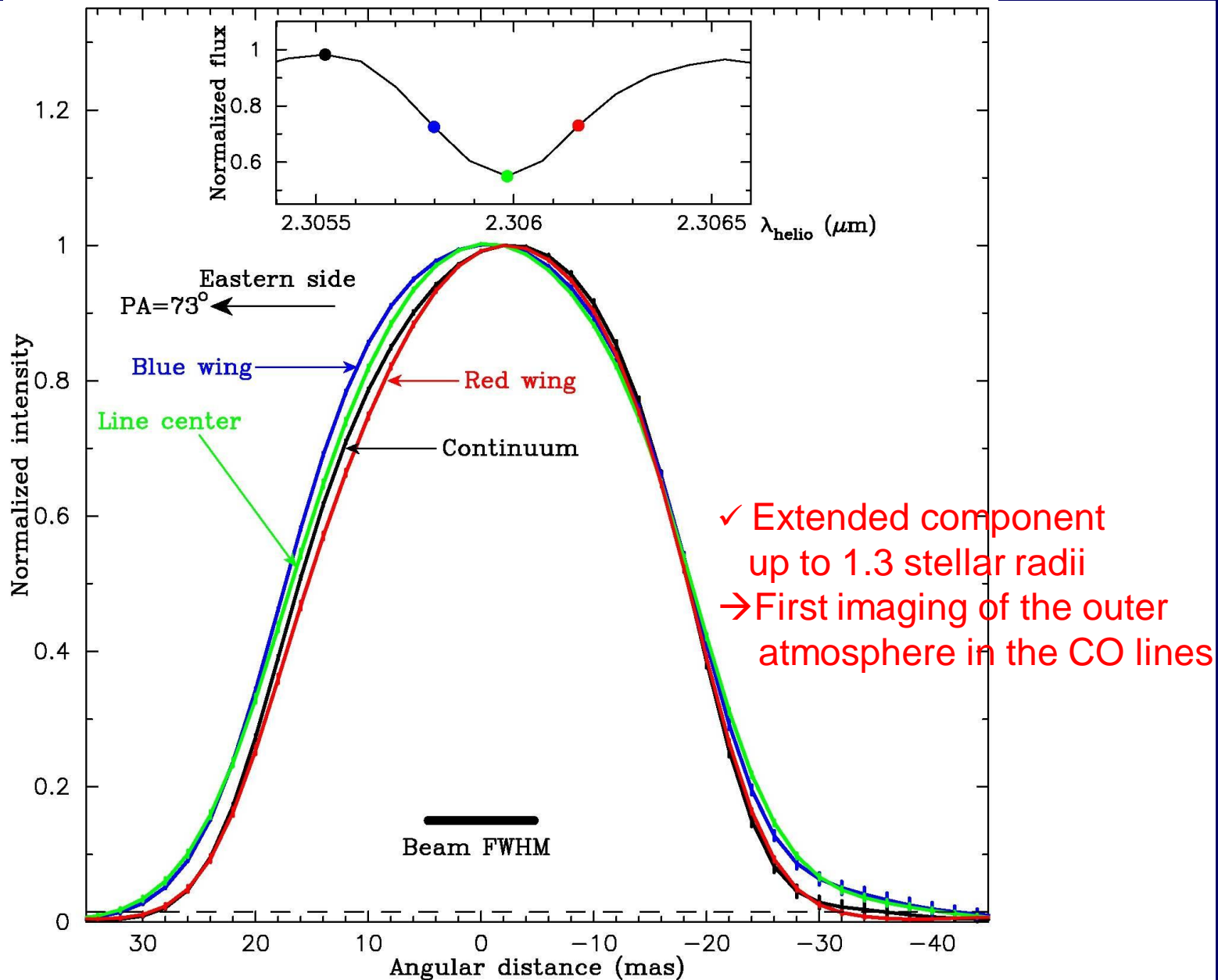


Time variation is much smaller than the maximum variation predicted by 3-D convection simulation (Chiavassa et al. 2009).
→ 3-D model predicts too pronounced inhomogeneities(?)

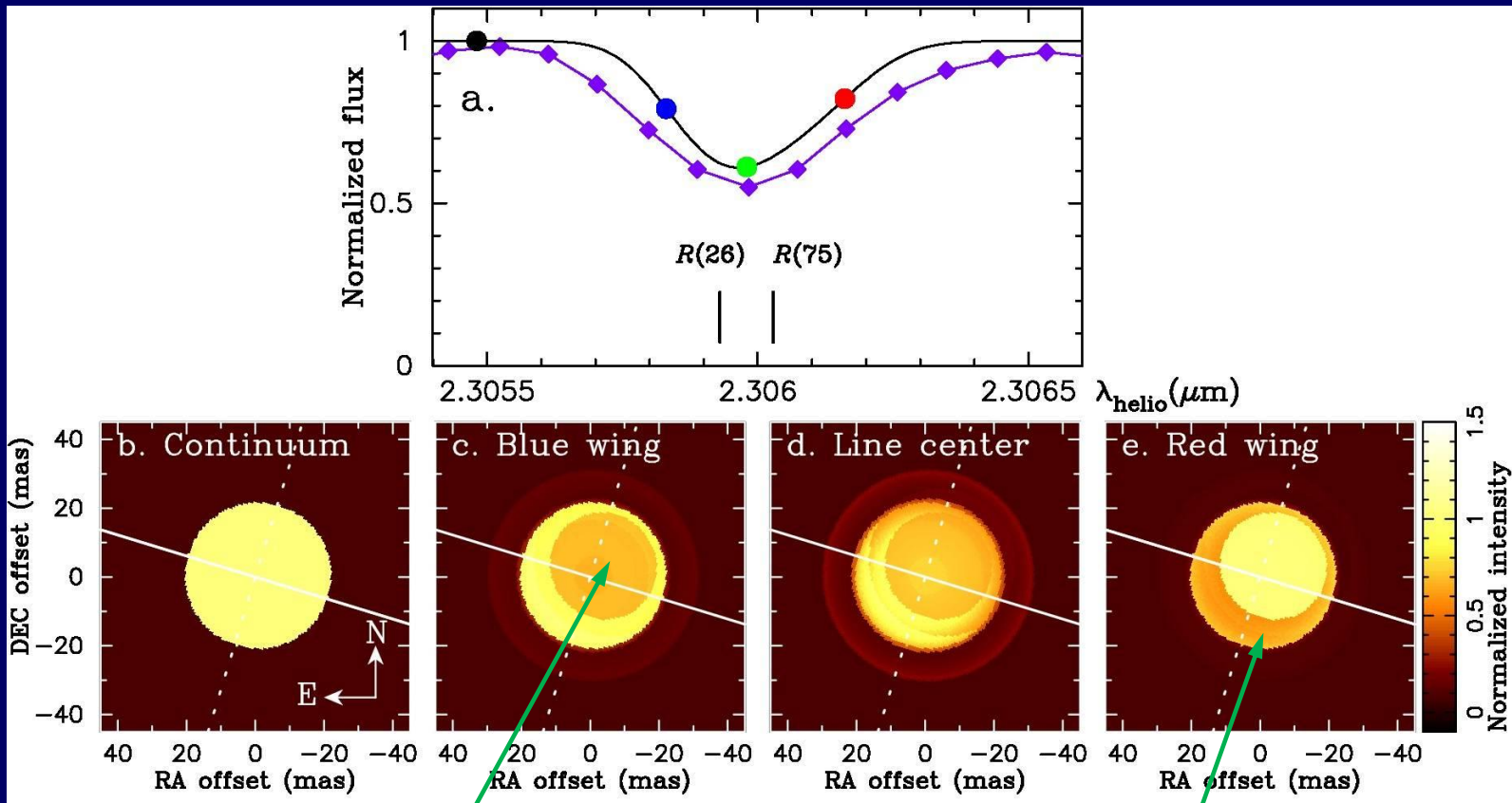
AMBER 1-D imaging of Betelgeuse in the CO lines



AMBER 1-D imaging of Betelgeuse in the CO lines



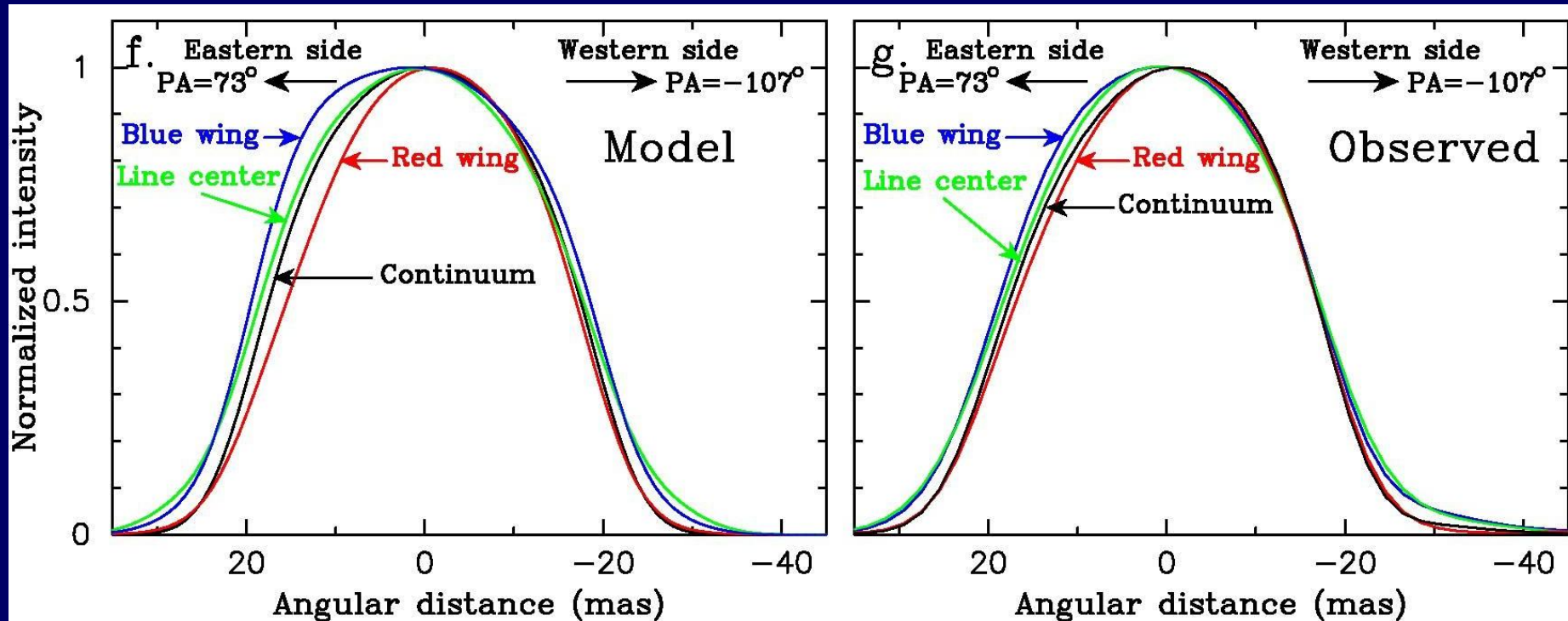
Modeling the inhomogeneous velocity field



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

Origin of the inhomogeneous velocity field

✓ Convection

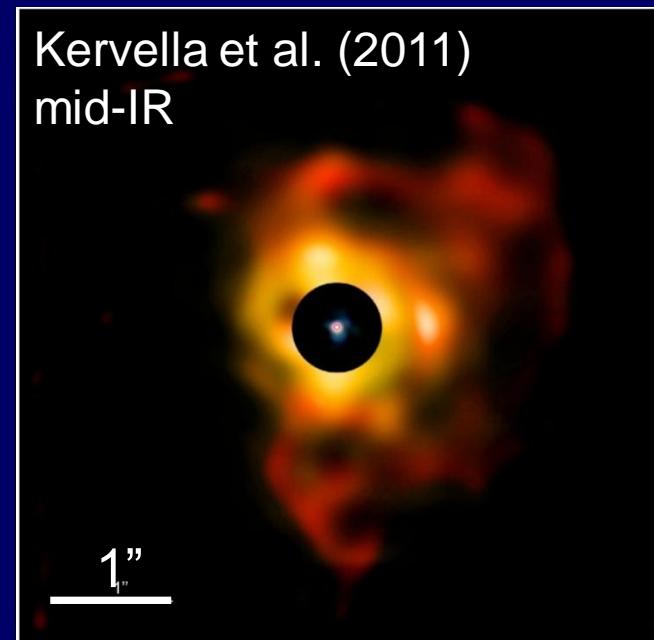
Extended component up to 1.3 stellar radii
→ Can convection overshoot so high?

✓ Driven by MHD processes

MHD simulations for red giants show strong variation from +40 km/s (outward) to -40 km/s (inward) at a few stellar radii (Suzuki 2007)
→ But no simulation yet for red supergiants

✓ Clumpy mass loss

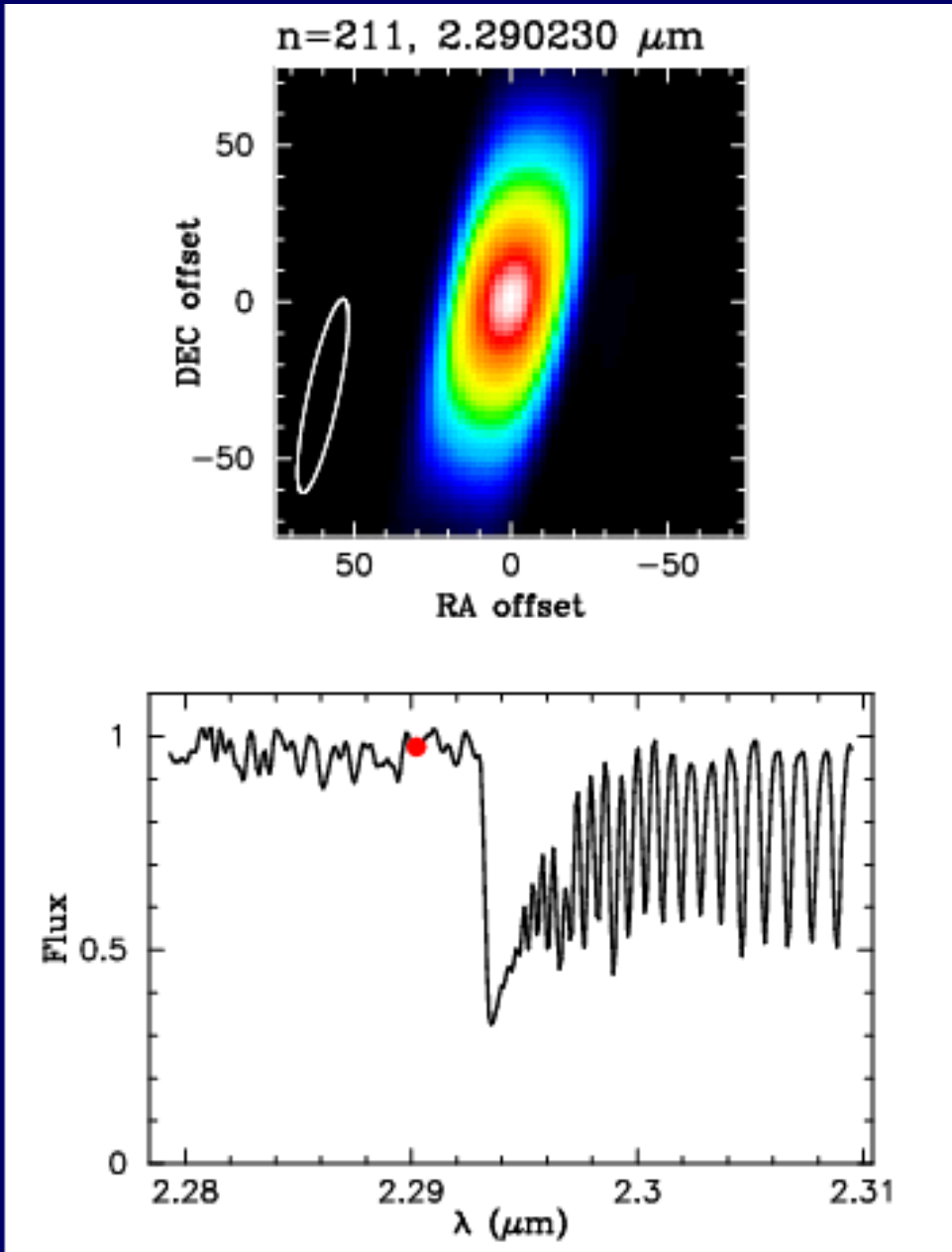
Temporally variable,
inhomogeneous velocity field
→ Clumpy mass loss(?)



Conclusion & Outlook

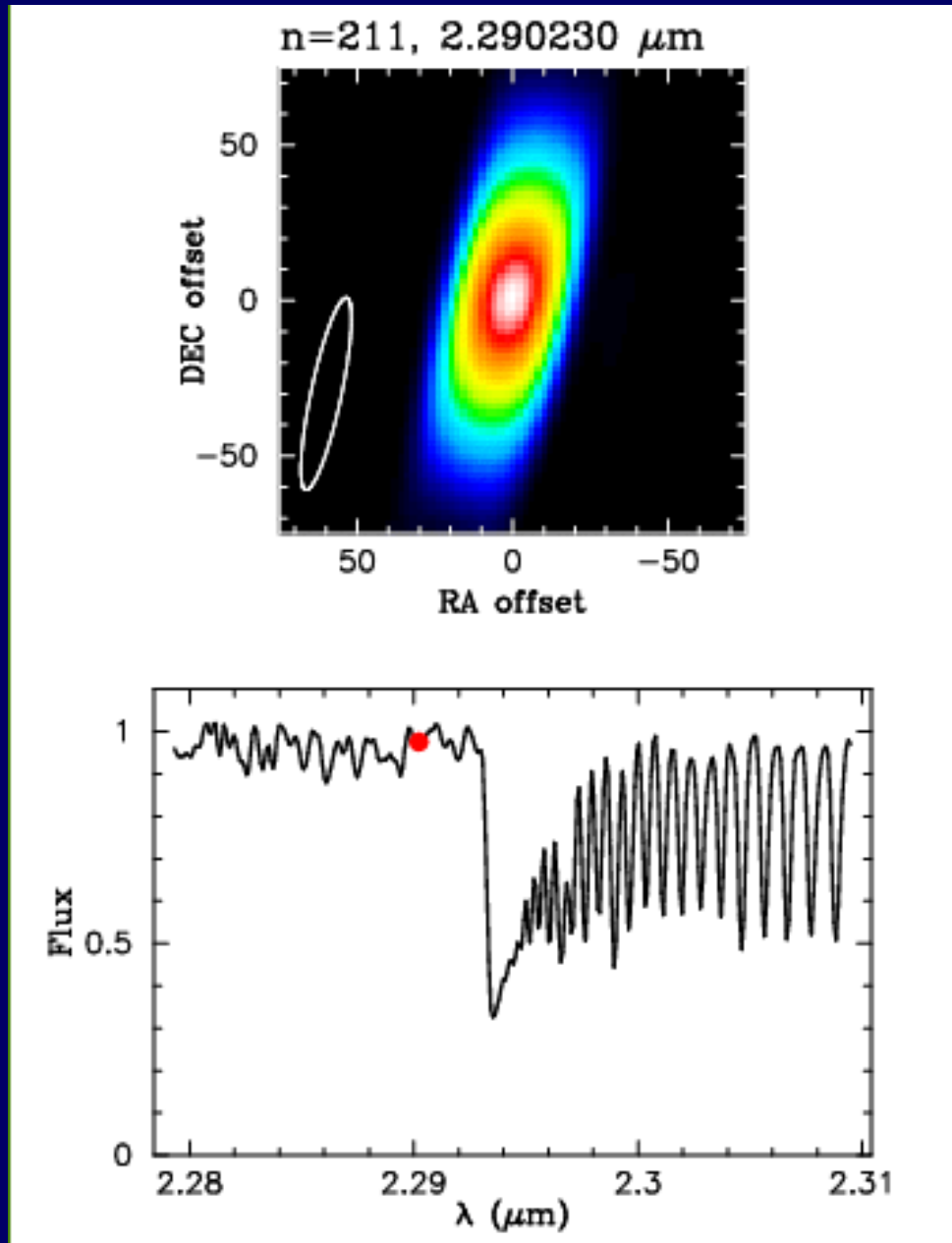
- ✓ 1-D imaging at high-spatial and high spectral resolution
- ✓ Betelgeuse appears different in the blue and red wings
- ✓ Stellar surface gas motions spatially resolved
- ✓ Long-term monitoring to follow the dynamics of the outer atmosphere
E.g., Episodic, strong outward motion?
- ✓ 2-D imaging

Image reconstruction of the red supergiant Antares

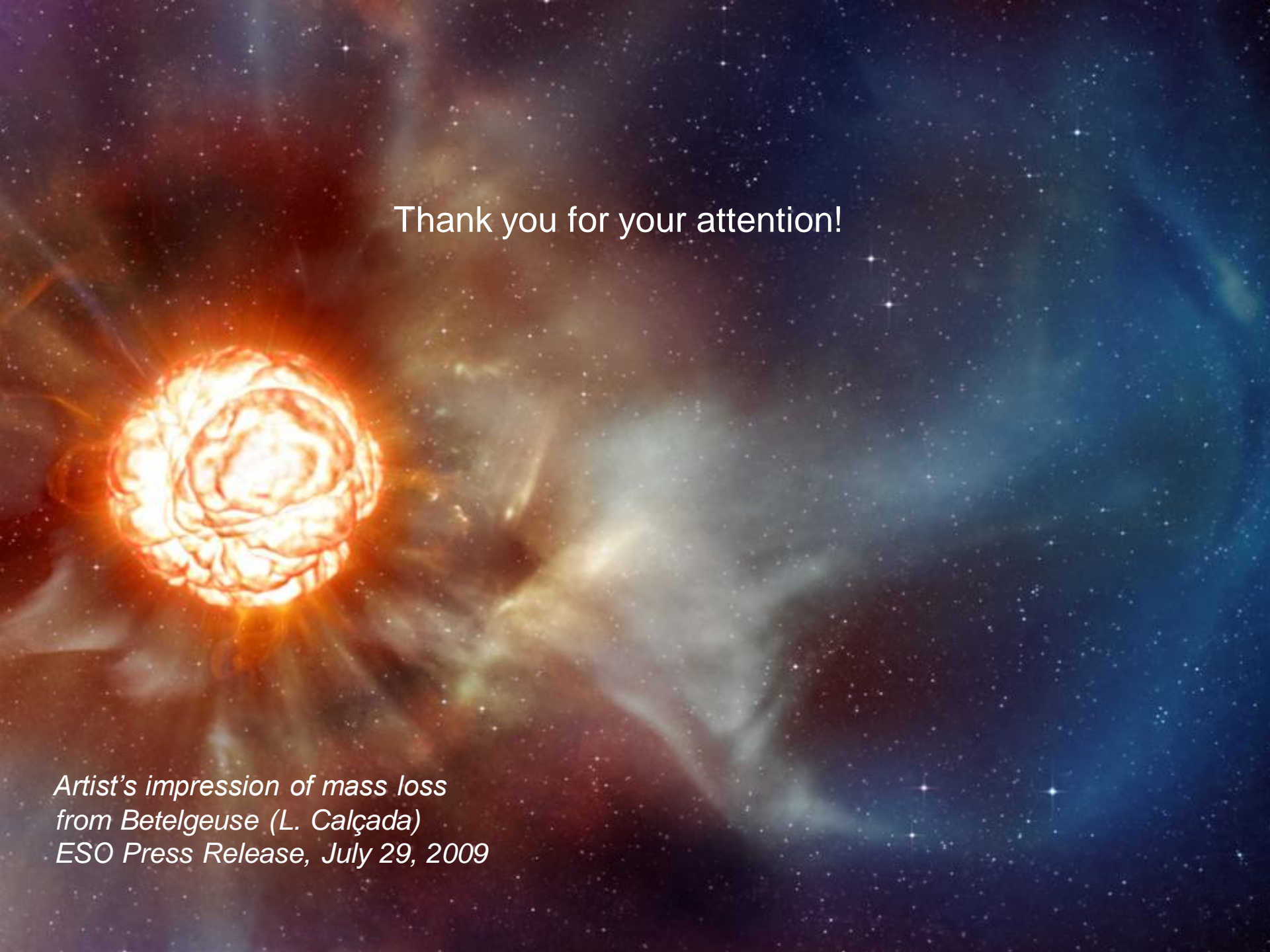


Movie available at
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Image reconstruction of the red supergiant Antares



Movie available at
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An artist's impression of the star Betelgeuse, showing a bright, textured orange-red sphere on the left. From the star, a large, diffuse, and multi-layered cloud of gas and dust extends to the right, appearing in shades of blue, white, and yellow. The background is a dark, star-filled space with a blueish tint on the right side.

Thank you for your attention!

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