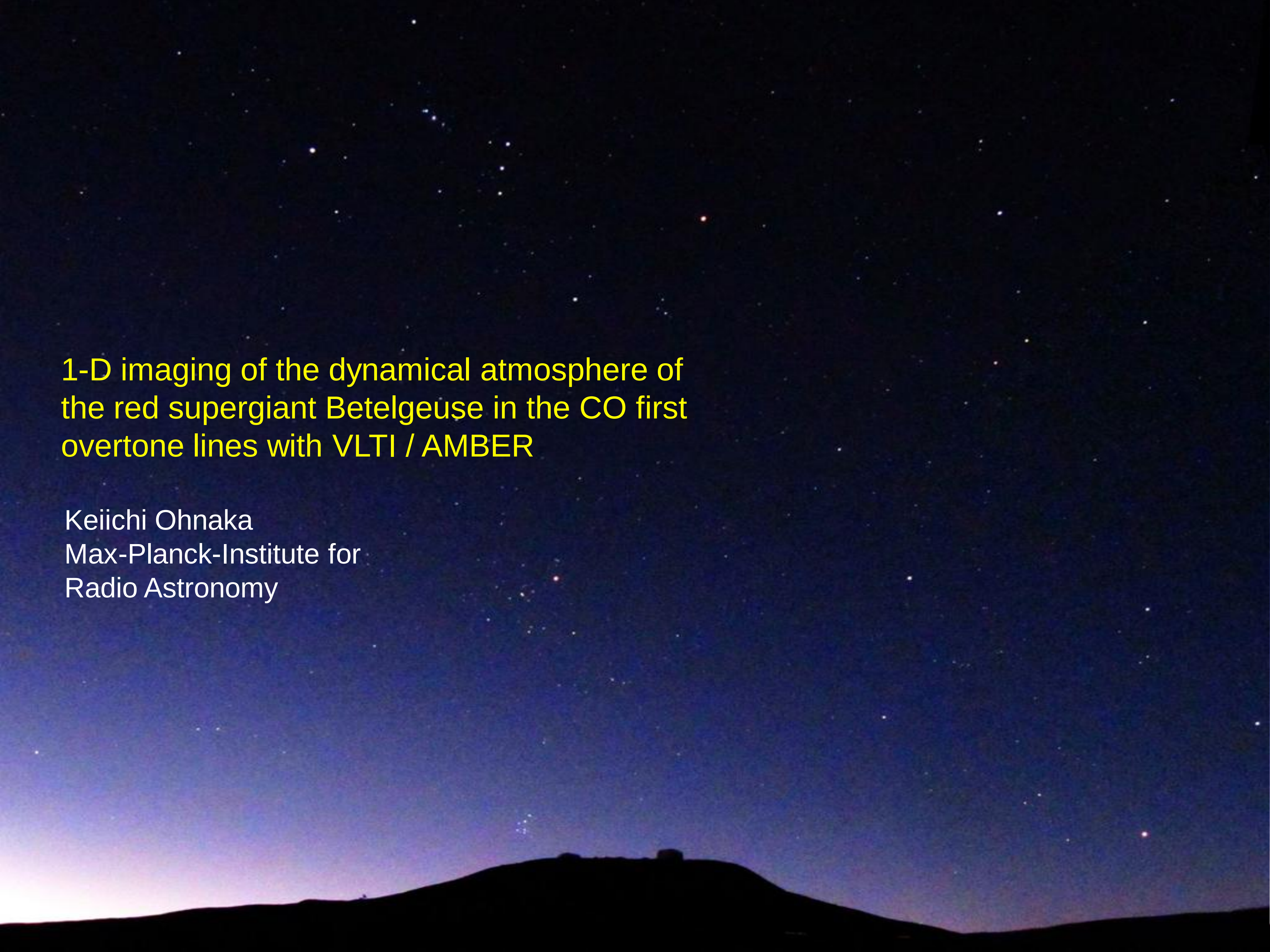

1-D imaging of the dynamical atmosphere of the red supergiant Betelgeuse in the CO first overtone lines with VLTI / AMBER

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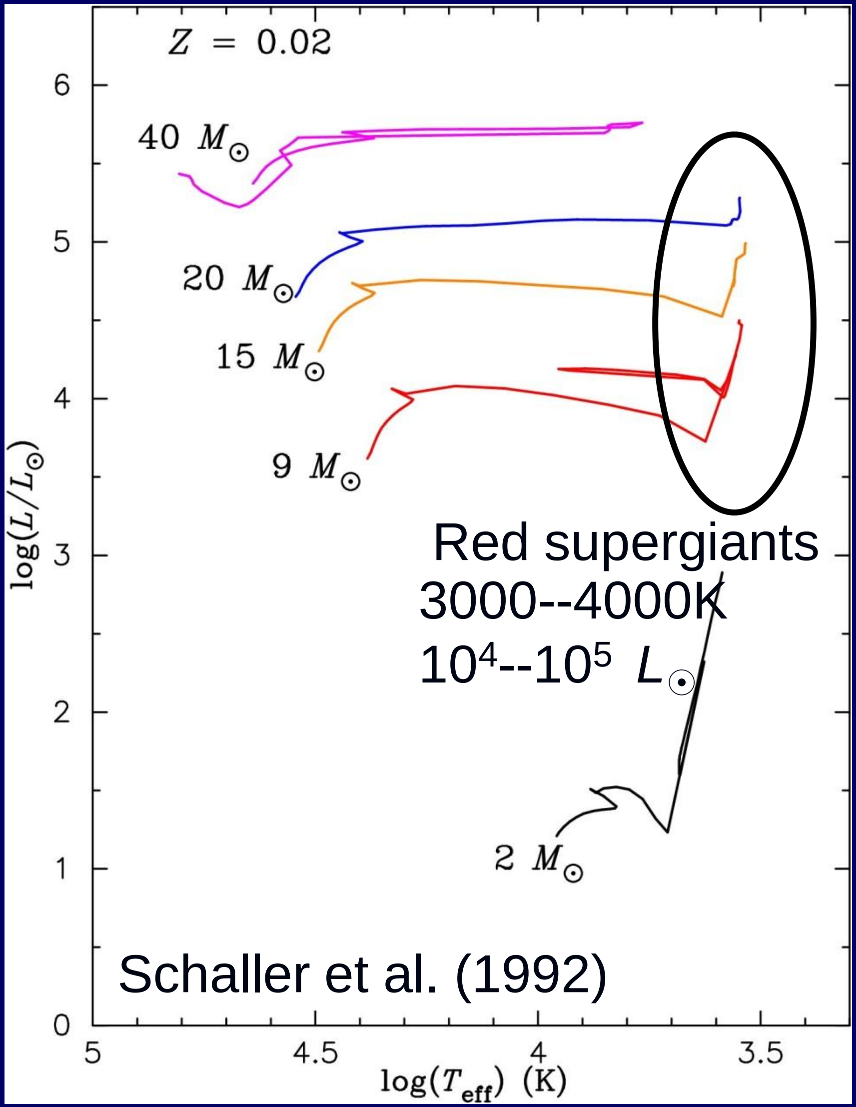
Introduction: Massive star evolution



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

✓ Rare in number, short-lived

However, great impact on their surrounding environment…

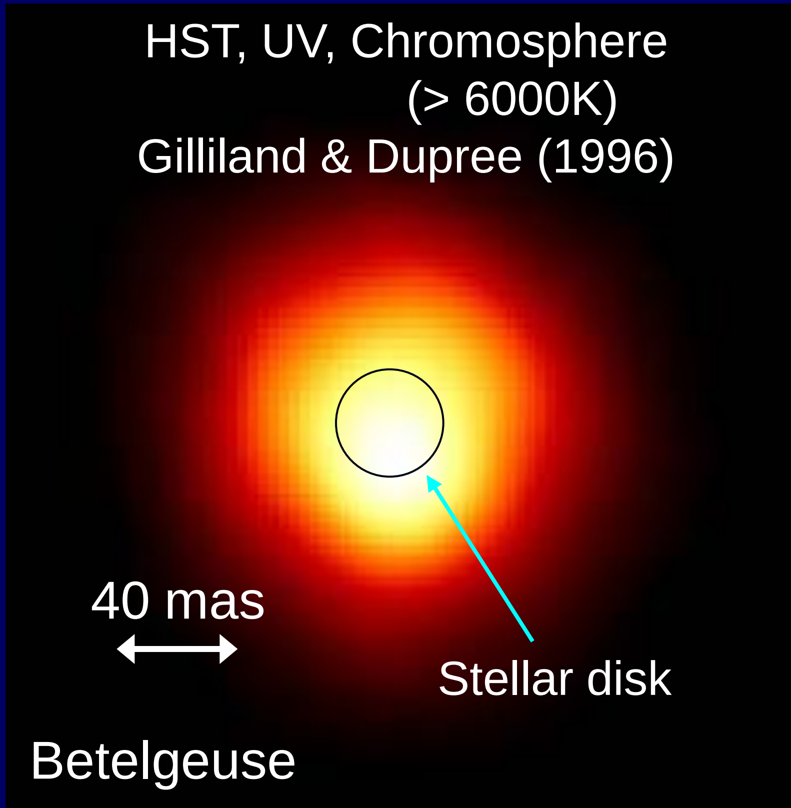
✓ UV ionizing radiation sources

✓ Strong winds, SN explosion
→ Mechanical energy input

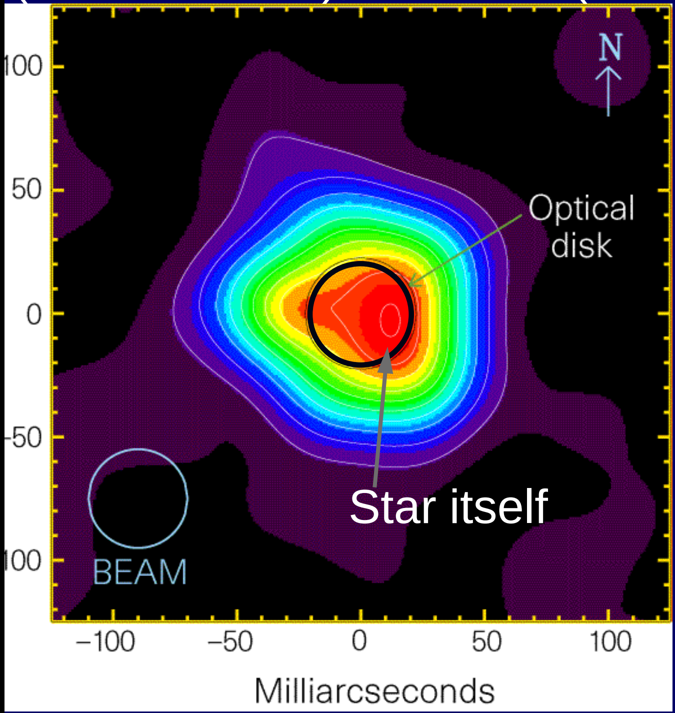
✓ Chemical enrichment of ISM

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

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

AMBER observations of Betelgeuse (2008)

AMBER HR_K observations

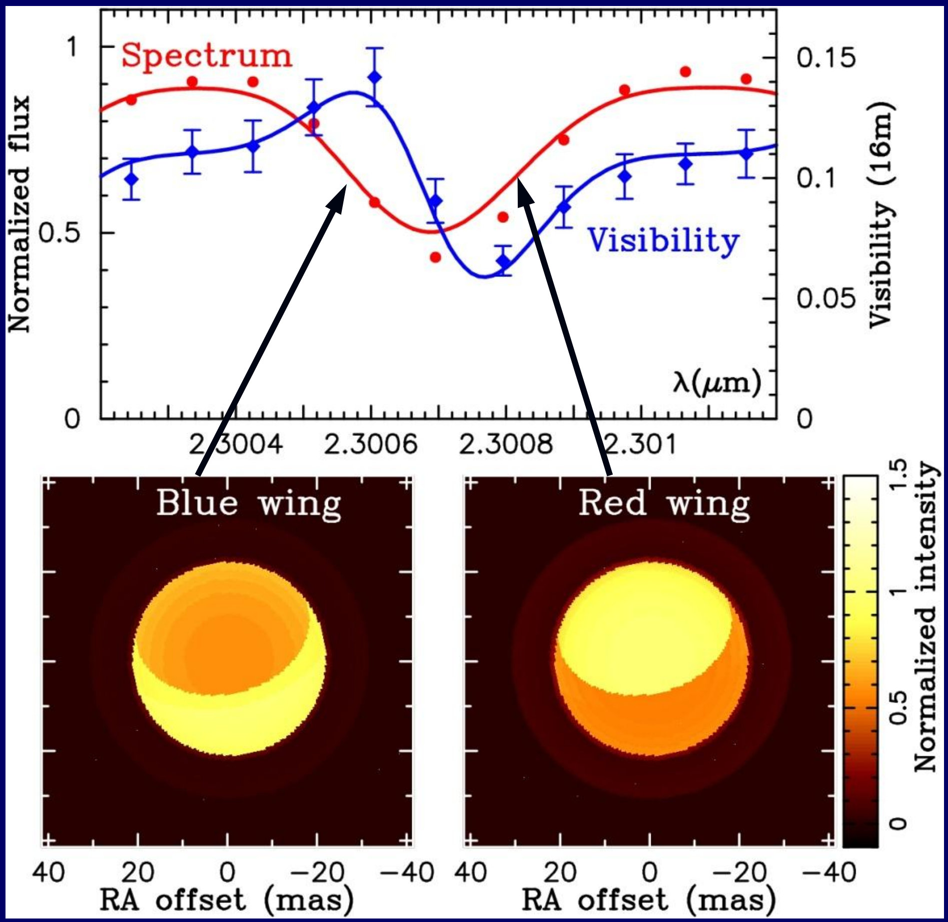
✓ Very bright (*K* = -4.4),
but very big (43 mas)
→ Strongly resolved at
16—32—48m baseline

Results

✓ Fringes detected in the
2nd, 3rd, and 5th visibility lobe
→ Highest spatial resolution on
Betelgeuse

✓ Spatially resolving gas motions
in a stellar photosphere for the
first time other than the Sun

Velocity amplitude = 10—15 km/s



Ohnaka et al. (2009)

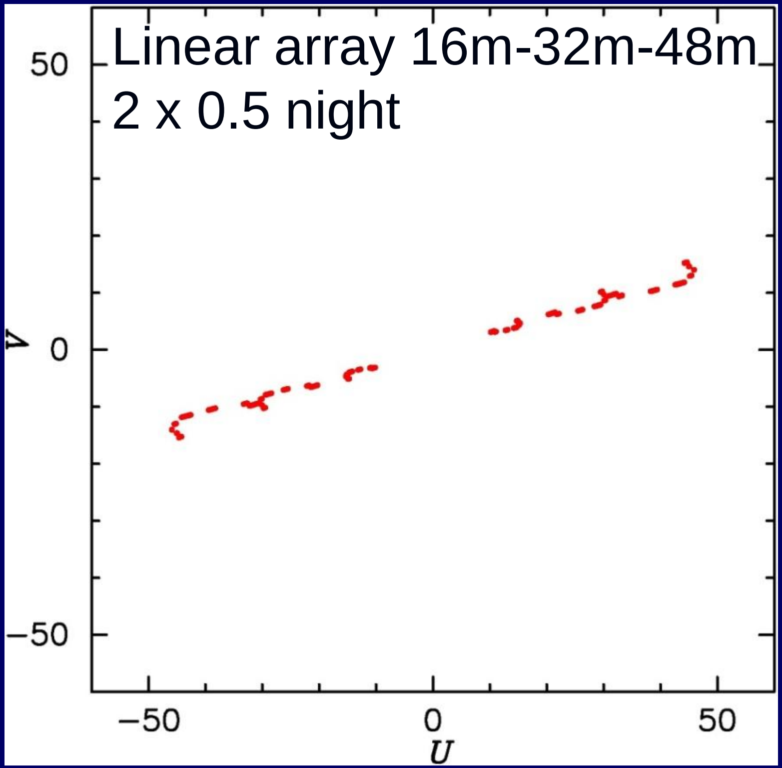
AMBER observations of Betelgeuse (2009)
1-D aperture synthesis imaging in the CO lines

Observations

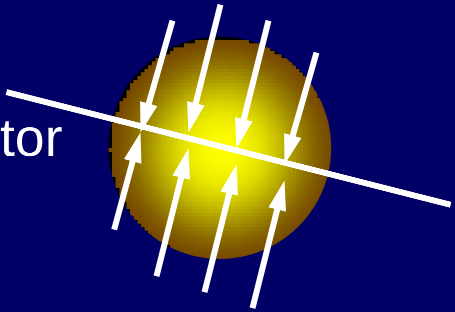
✓ 16-32-48m (resolution = 9.8 mas)
Beam = 1/4 x star's size
Spectral resolution 12000 → 6000

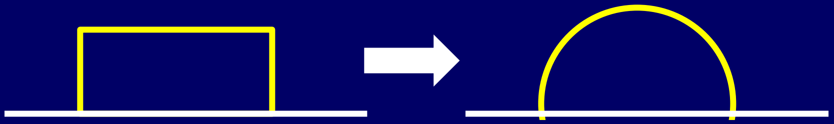
✓ Dense *uv* coverage at PA = 73°
from 1st to 5th visibility lobes
162 Visibilities, 54 closure phases

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



Baseline vector





✓ MiRA (Thiébaut 2008)

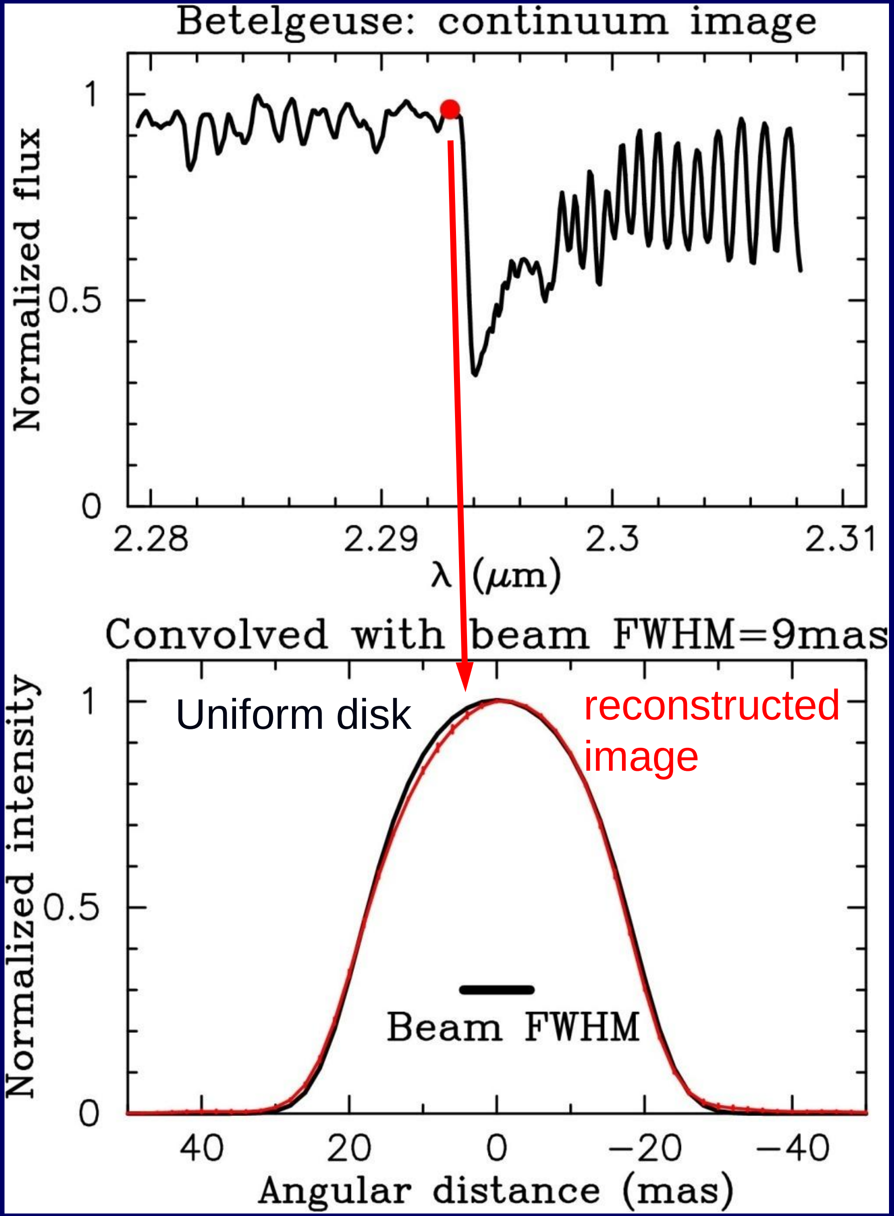
AMBER 1-D imaging of Betelgeuse: continuum

Tests with simulated data

- ✓ Determine the appropriate initial models, prior, & regularization scheme

Results

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



AMBER imaging of Betelgeuse: CO lines

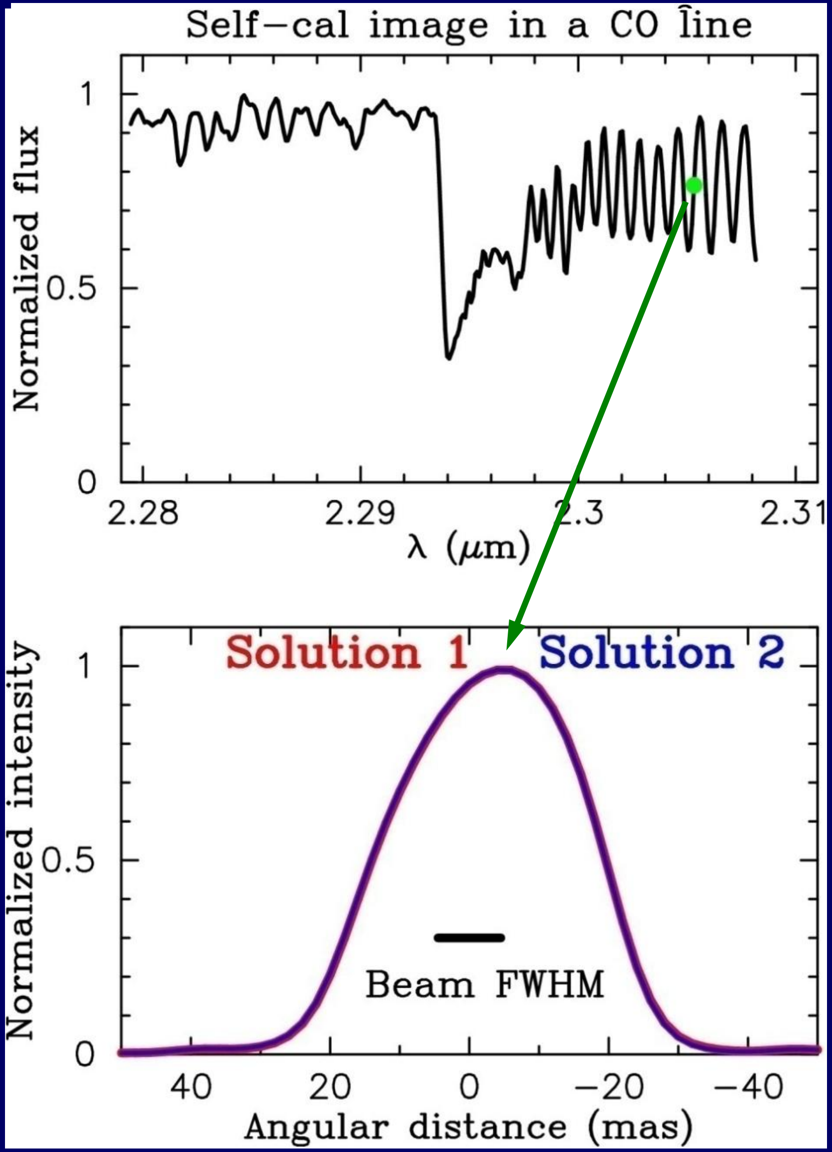
✓ Image reconstruction with
V^2 + Closure phase is not unique!
(Fit to the data is equally good.)

Self-calibration using differential phase (Millour et al. 2011)

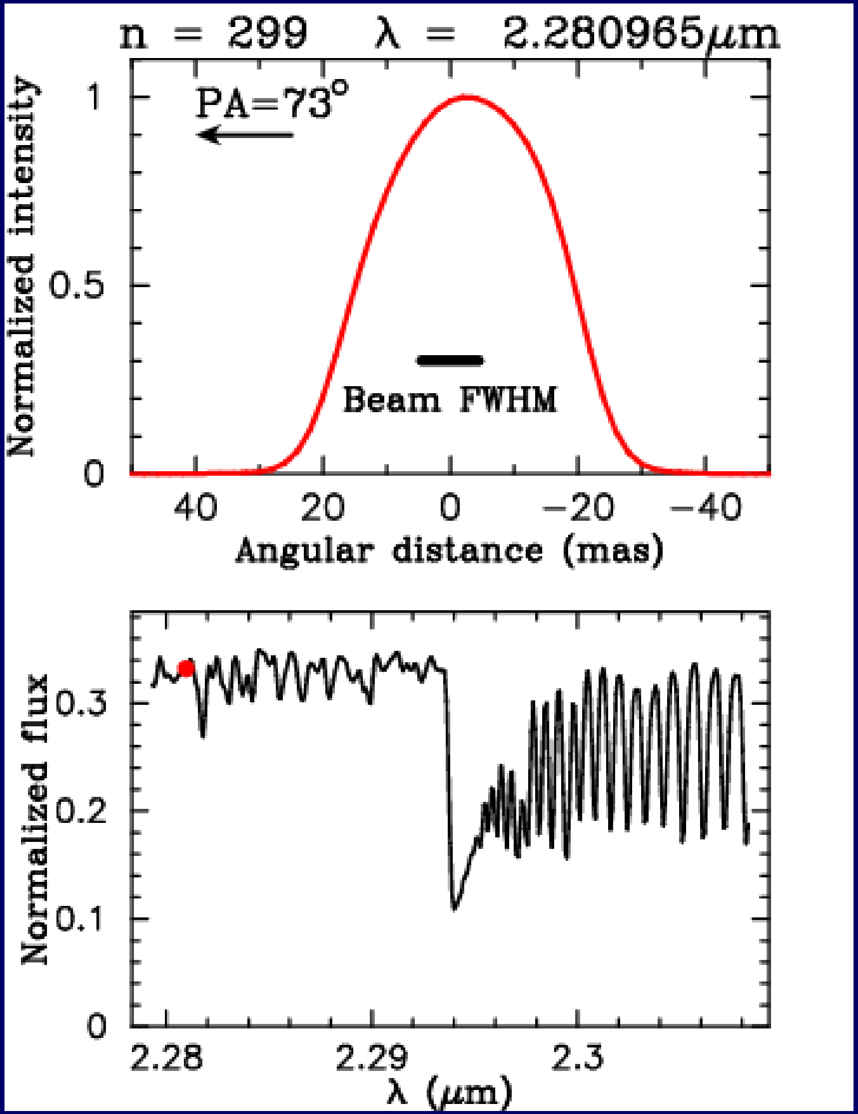
1) Phase from reconstructed images at all continuum spectral channels

2) Interpolate for CO line spectral channels

3) Phase(CO lines)
= Phase(cont) + Diff. Phase
→ Complex visibility restored

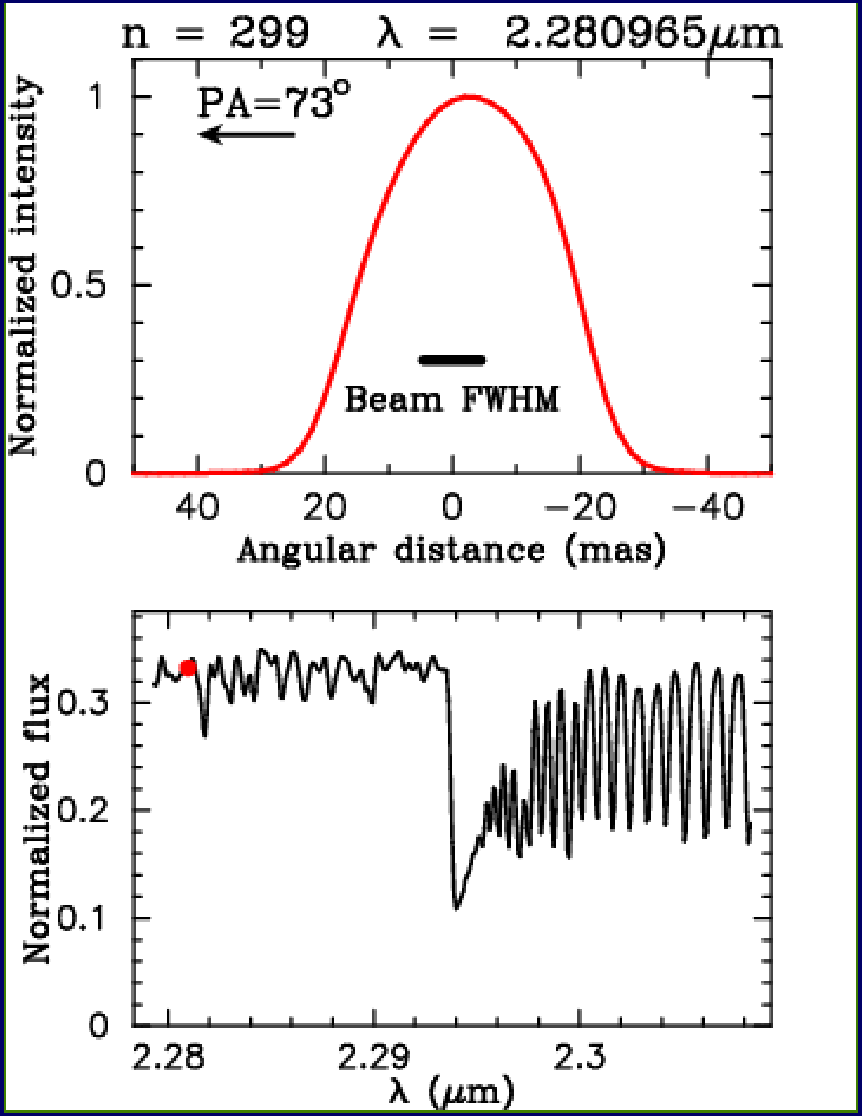


Self-cal 1-D imaging of Betelgeuse: First aperture synthesis imaging in CO lines



Ohnaka et al. (2011, A&A, in press)

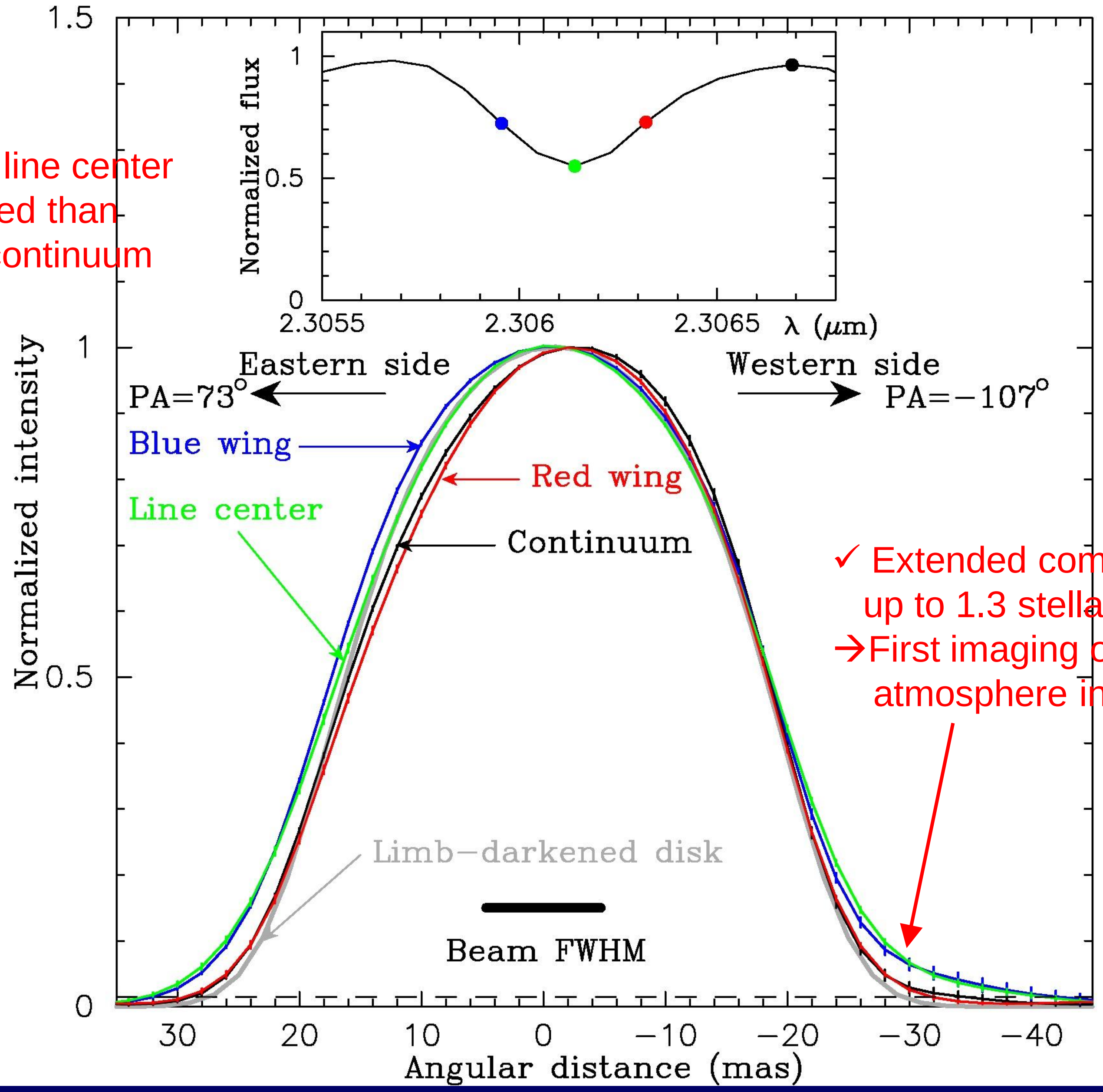
Self-cal 1-D imaging of Betelgeuse: First aperture synthesis imaging in CO lines



Ohnaka et al. (2011, A&A, in press)

AMBER self-cal 1-D imaging of Betelgeuse

✓ Blue wing & line center more extended than red wing or continuum



✓ Extended component up to 1.3 stellar radii

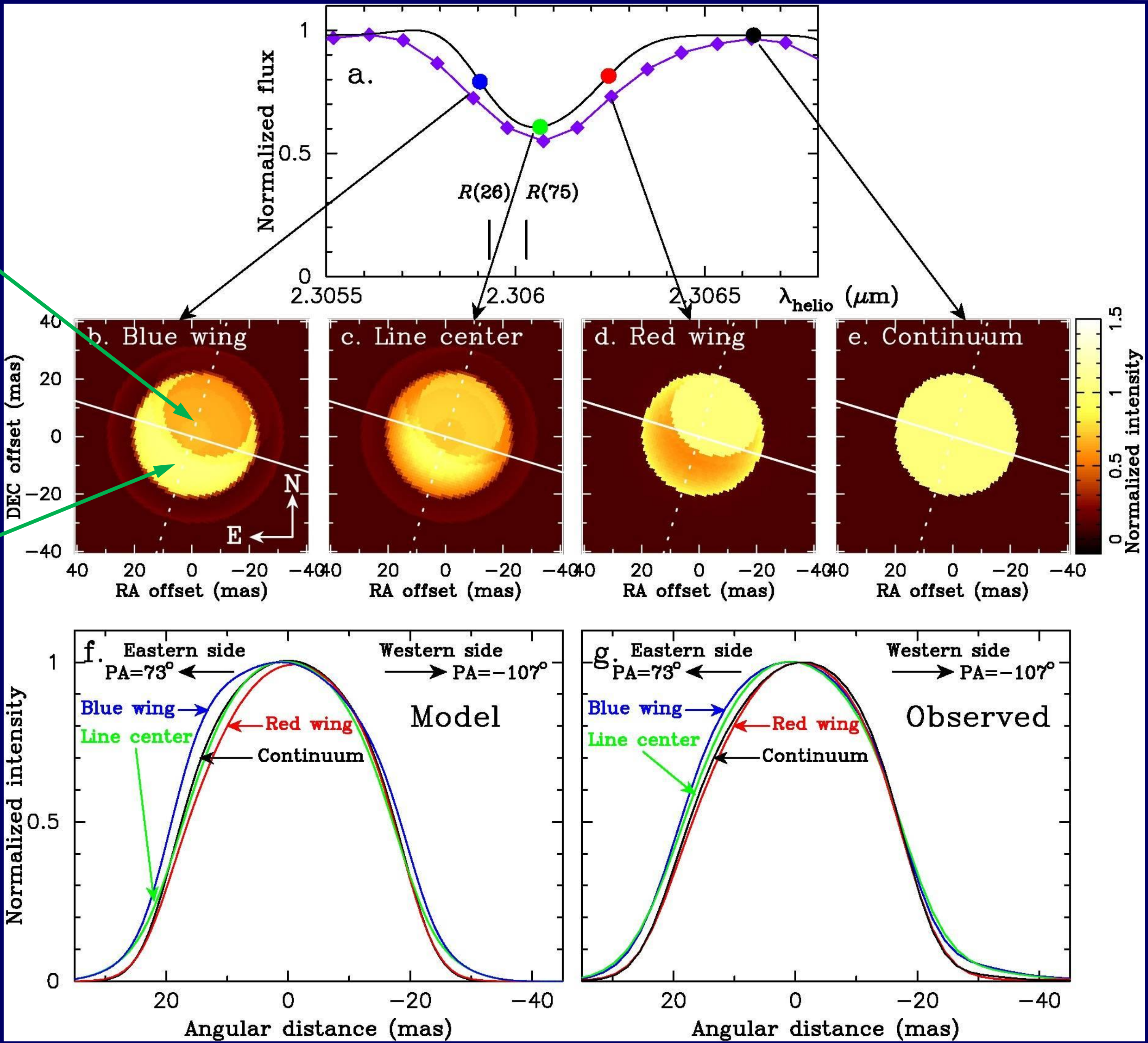
→First imaging of the outer atmosphere in the CO lines

Modeling the inhomogeneous velocity field

Infalling with 0—10 km/s

Strong downdraft with 30—40 km/s

No systematic outflow



Origin of 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: Dominated by downdrafts with up to 30—40 km/s

- ✓ 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

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?