High-spatial and high-spectral resolution 1-D imaging of the atmosphere of Betelgeuse in the 2.3 μm CO lines with VLTI / AMBER

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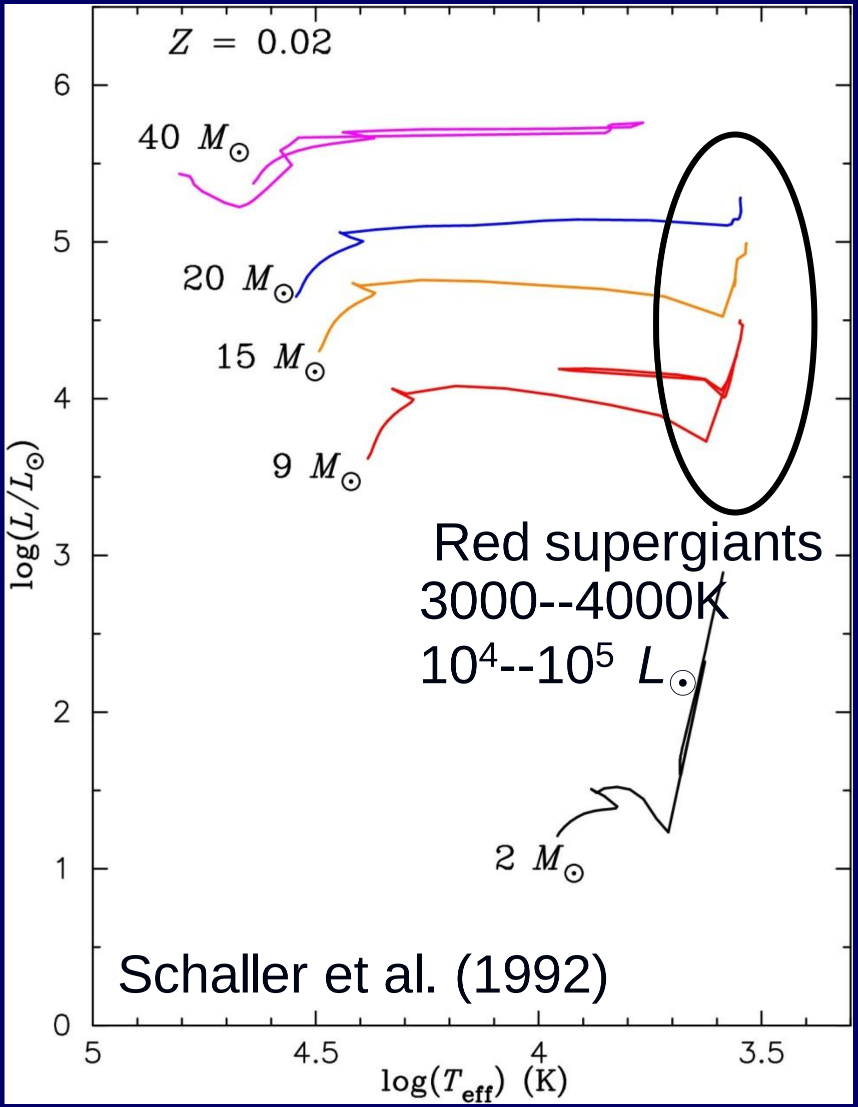
Photo: G. Weigelt

Introduction: Massive star evolution



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

✓ Rare in number, short-lived

However, great impact on their surrounding environment…

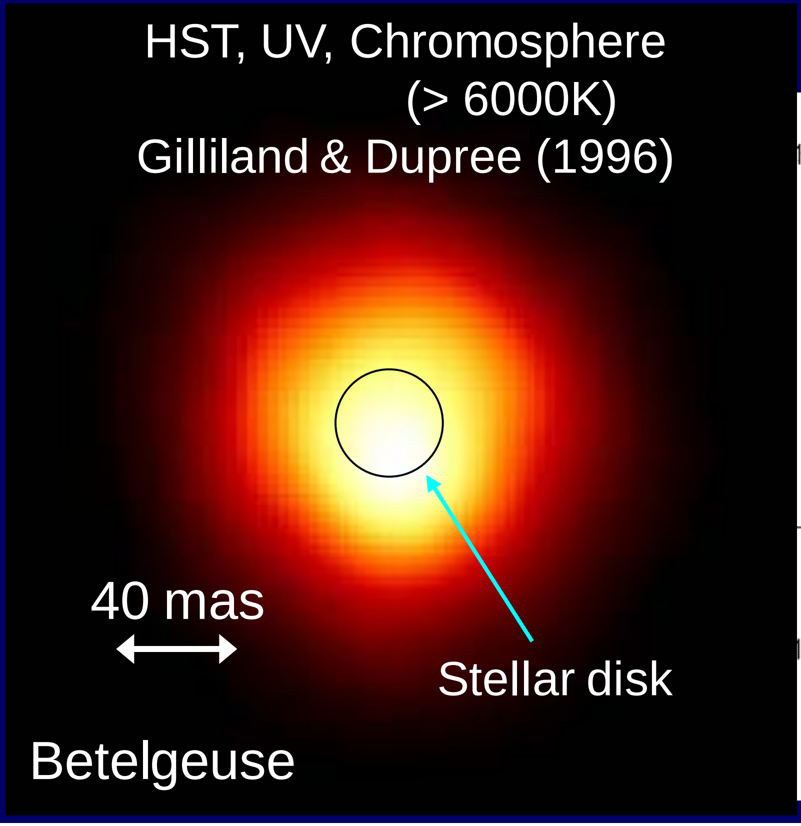
✓ UV ionizing radiation sources

✓ Strong winds, SN explosion
→ Mechanical energy input

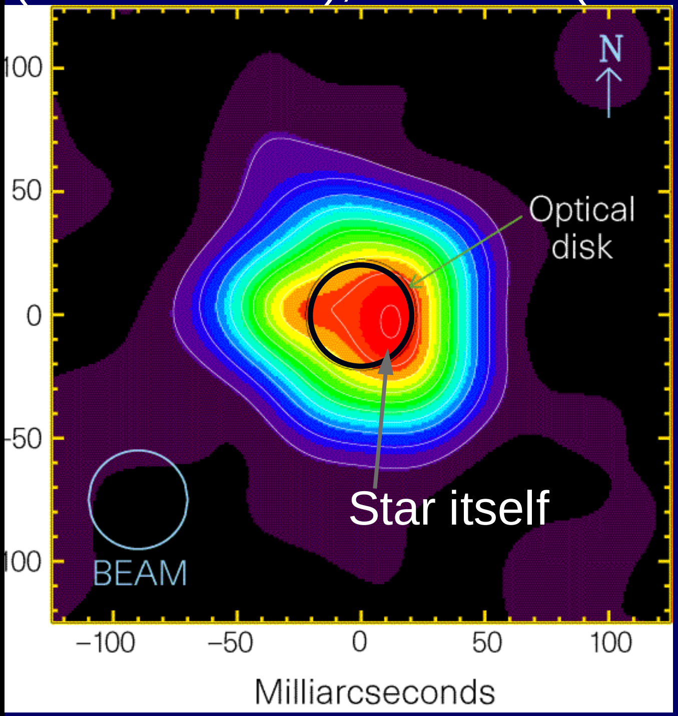
✓ Chemical enrichment of ISM

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

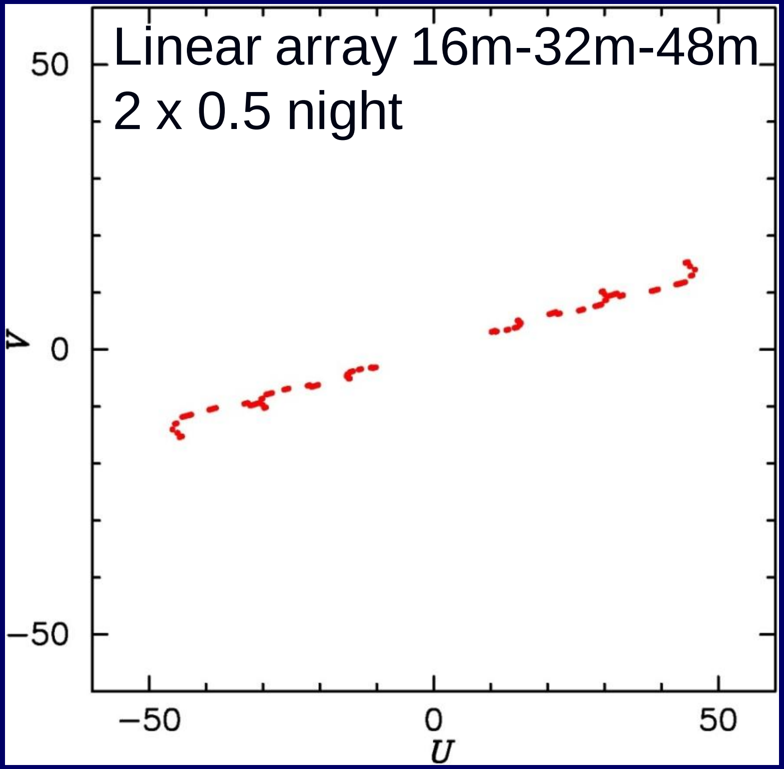
→ High spectral & spatial resolution observations

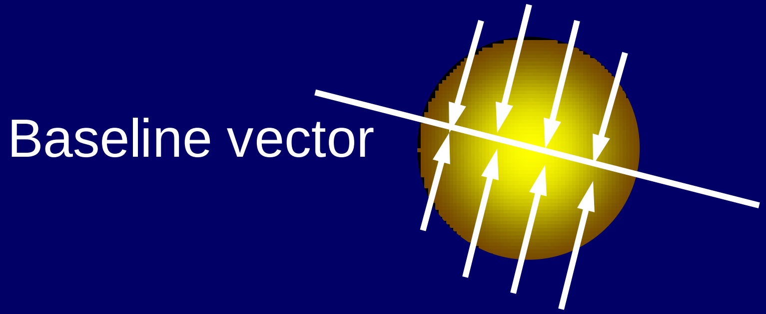
→ Long-Baseline Spectro-Interferometry

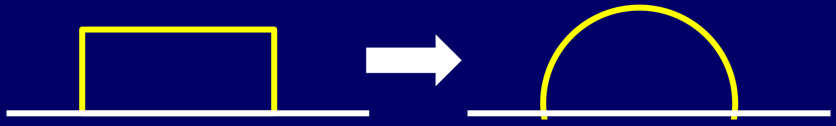
AMBER observations of Betelgeuse : 1-D aperture synthesis imaging in the CO lines

Observations

- ✓ 16-32-48m (resolution = 9 mas)
  Beam = 1/5 x star's size (highest)
  Spectral resolution = 12000
  Binning → 8000 (improve SNR)
- ✓ Dense (u,v) coverage at PA = 70°
  from 1st to 5th visibility lobes
  162 Visibilities, 54 closure phases
- ✓ Intensity profile "squashed"
  onto the baseline vector







- ✓ MiRA (Thiébaut 2008)

AMBER 1-D imaging of Betelgeuse: continuum

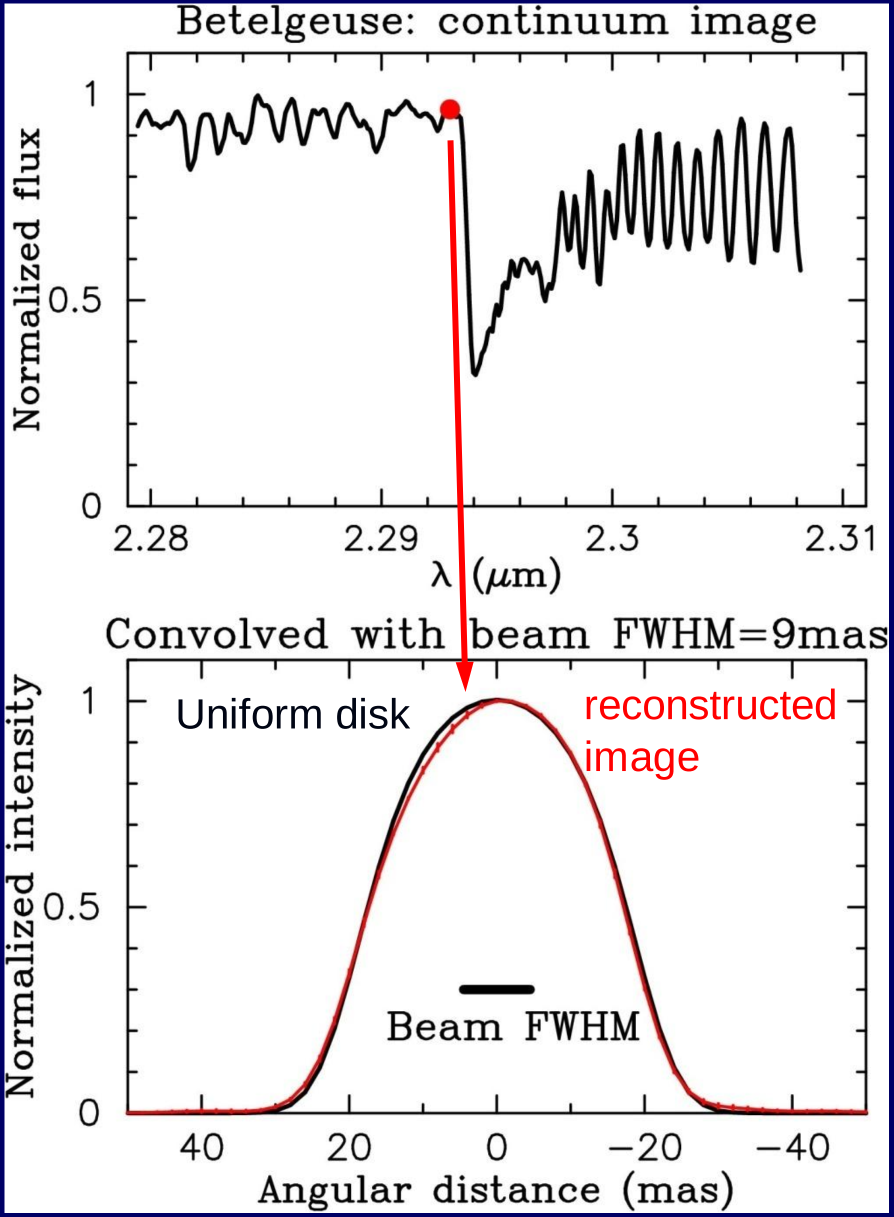
Results

✓ Betelgeuse appears rather homogeneous in the continuum
Only small deviation from a uniform or limb-darkened disk

✓ Significant bright spots in the IOTA *H*-band images (Haubois et al. 2009)

→ IOTA *H*-band: Broadband = continuum + molecular features

AMBER: (almost) continuum only



AMBER 1-D imaging of Betelgeuse: CO lines

Self-calibration using differential phase (Millour et al. 2010)

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

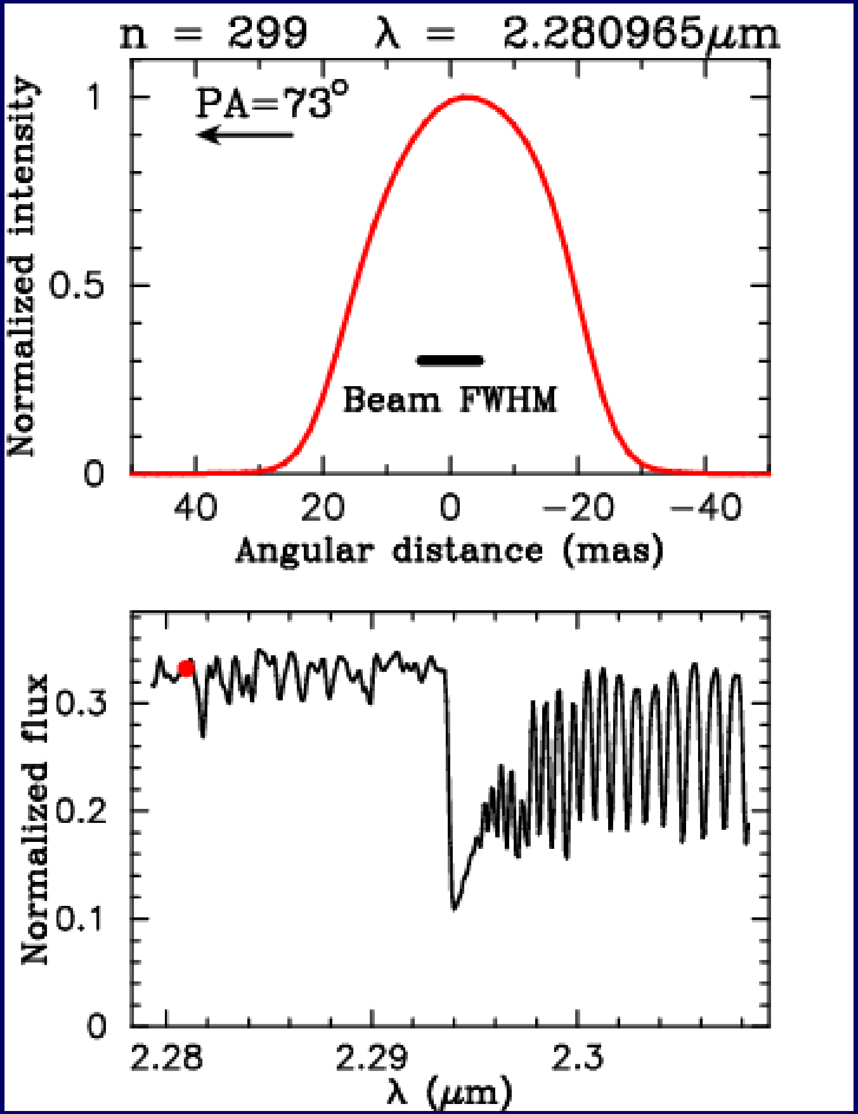
⬇

2) Compute the phase in the continuum. Interpolate for CO lines

⬇

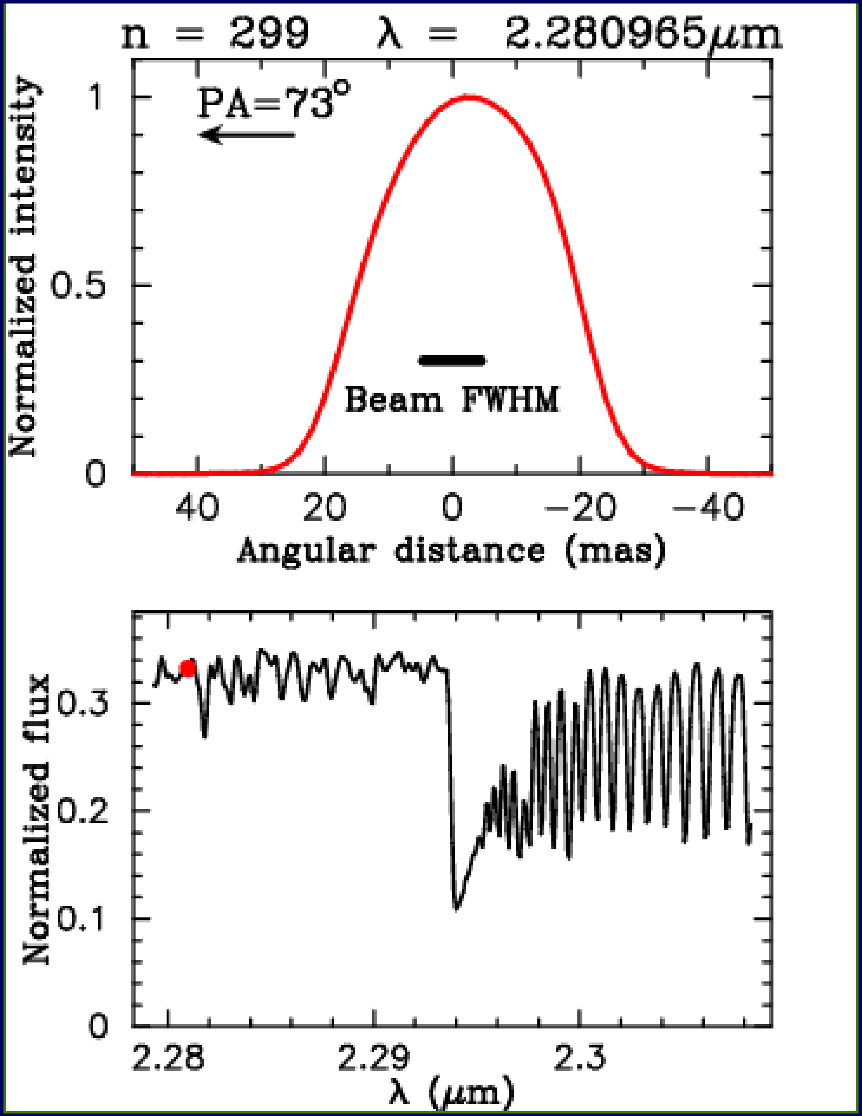
3) Phase(CO lines)
= Phase(continuum) + Observed Diff. Phase
→ Complex visibility restored

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



Ohnaka et al. (2010)

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

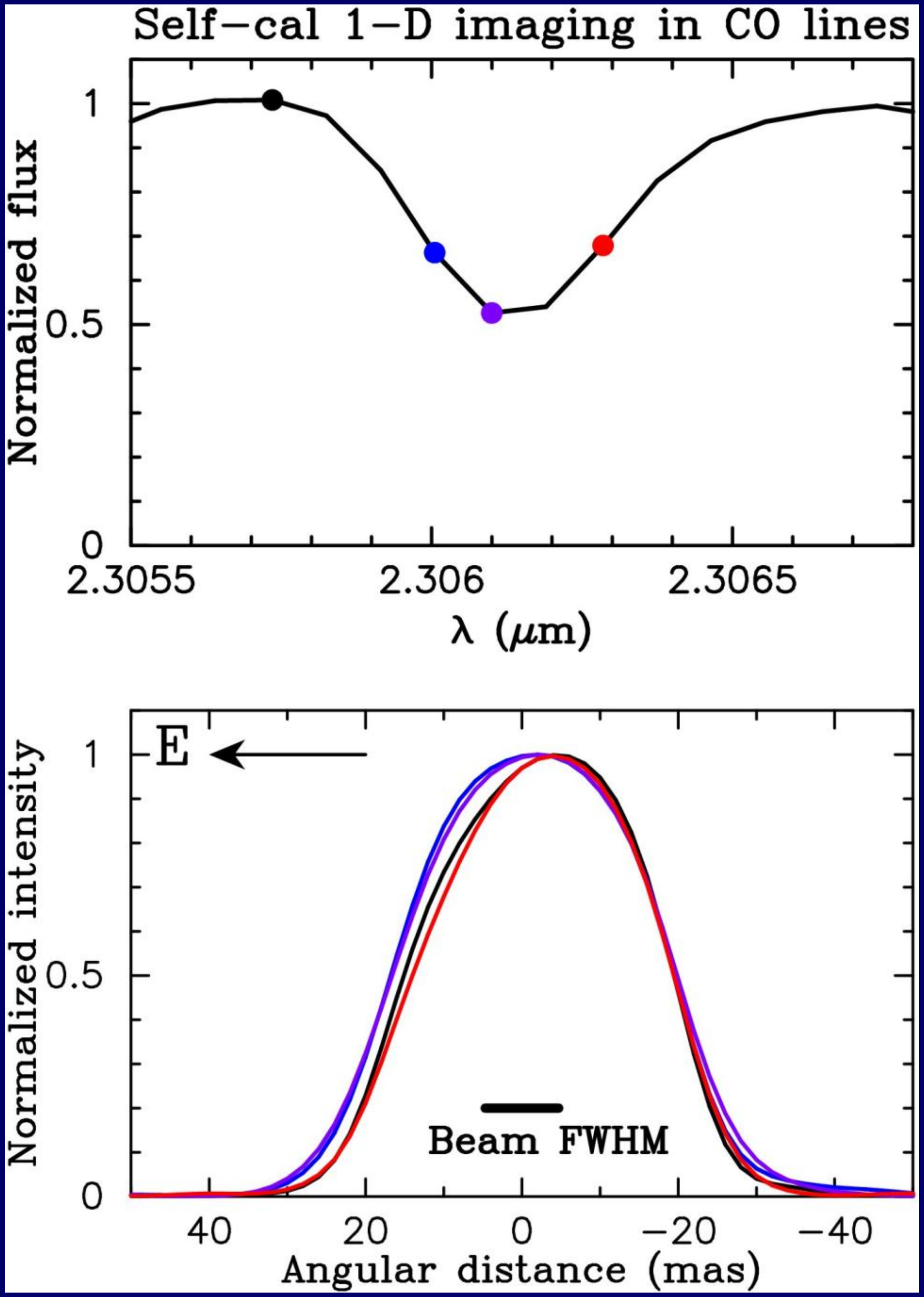


Ohnaka et al. (2010)

AMBER self-cal 1-D imaging of Betelgeuse

- ✓ Blue wing & line center images more extended than red wing or continuum images
- ✓ Extension is asymmetric: more pronounced on Eastern side
- ✓ Intensity profiles dominated by smooth, large-scale asymmetry. No fine structures > 9 mas

  But also due to the “squashing” onto the baseline vector.



What can be learned for future interferometers?

1) High-spatial AND high-spectral resolution is powerful
   → Probes not only spatial but also dynamical structures

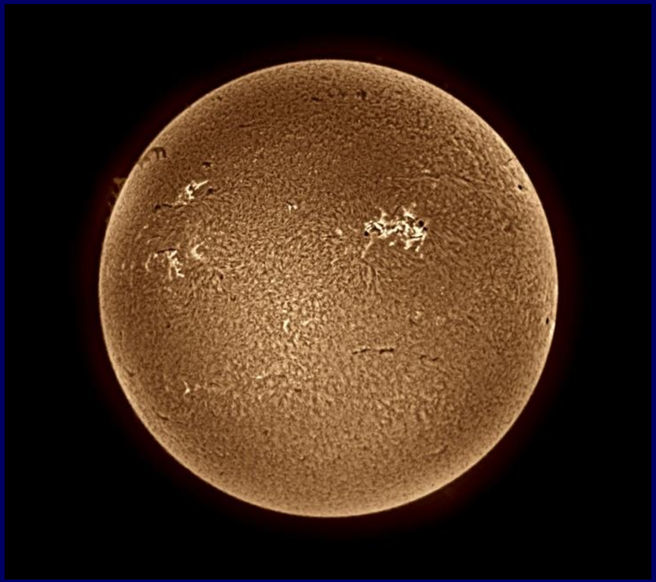
2) Self-cal imaging with differential phase is effective or necessary for imaging complex stellar surfaces
   --- The reconstructed 1-D images in the CO lines do not appear so complex. Still self-cal was necessary.

3) Need to go to even longer baselines (> 5^{th} visibility lobe) to image the surface of giants or main-sequence stars

Science cases with high-resolution imaging

✓ Convective cells expected to be smaller on giant stars and main-sequence stars

~0.001 x stellar radius (Sun)
~0.1 x stellar radius (Red Giant)



✓ 3-D model atmospheres are more and more used for chemical composition analyses in main-sequence / giant stars:

For example,

1) Extremely metel-poor stars to probe the galaxy formation
2) Li abundance to test the Big Bang Nucleosynthesis

However, how reliable are 3-D model atmopsheres?

✓ Mode identification of non-radial oscillations (e.g., roAp stars)

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3) Need to go to even longer baselines (> 5^{th} visibility lobe) to image fine structures
   - ✓ 20 x 20 pixel image (10 x 10 resolution elements)
     Visibility (10^{th} lobe) < 0.01
   - ✓ 100 x 100 pixel image (50 x 50 resolution elements)
     Visibility (50^{th} lobe) < 0.001
   - ✓ Fringe tracking requires even higher sensitivity.
     E.g., VLTI / FINITO @ H band → Visibility(H) < Visibility (K)

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 for the first time
- ✓ Long-term monitoring to measure temporal fluctuations in visibility and phase is a MUST for testing 3-D convection simulations !!!