First IR interferometric mapping of the gas motion in the atmosphere of evolved stars

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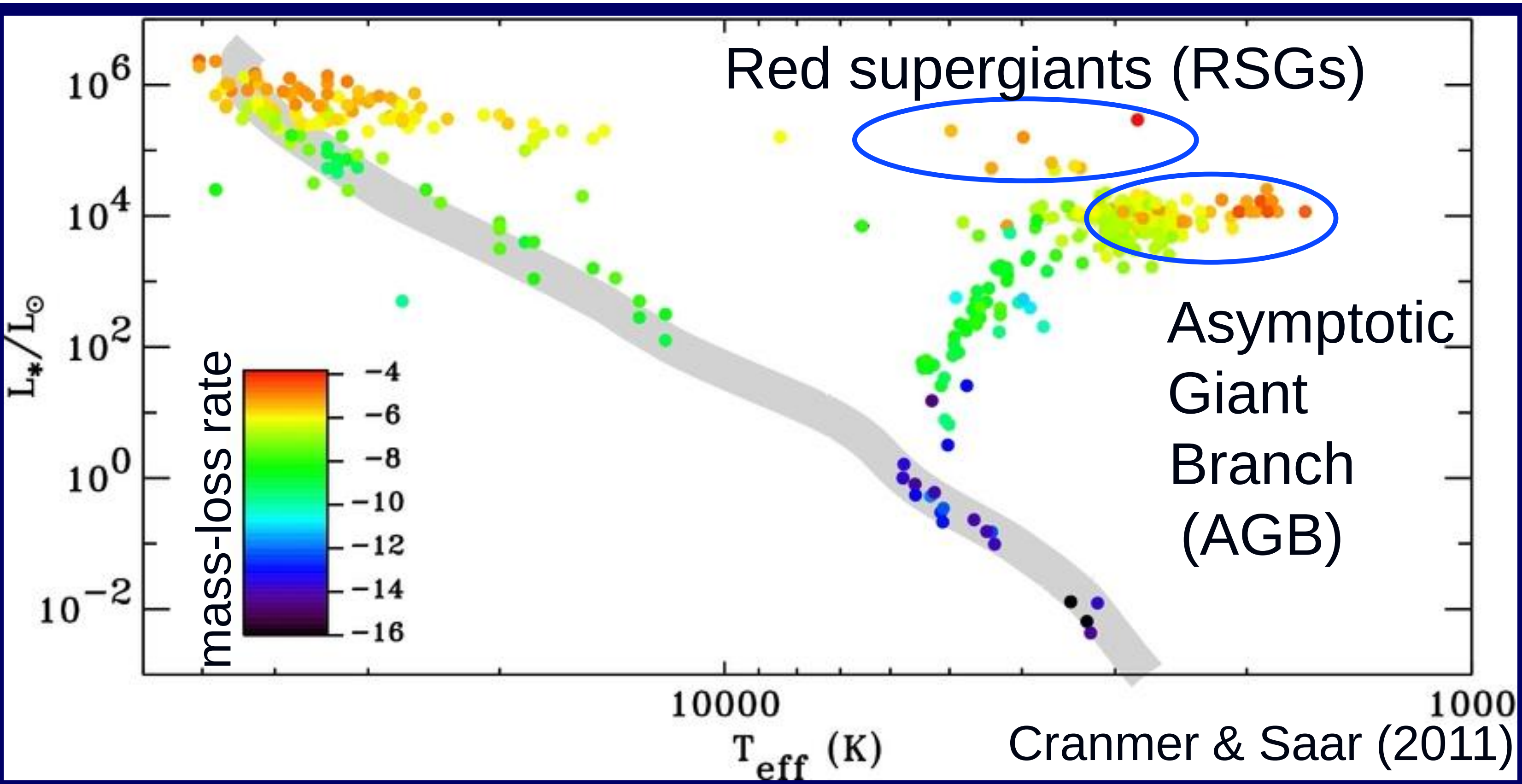
Introduction: Mass loss across H-R diagram

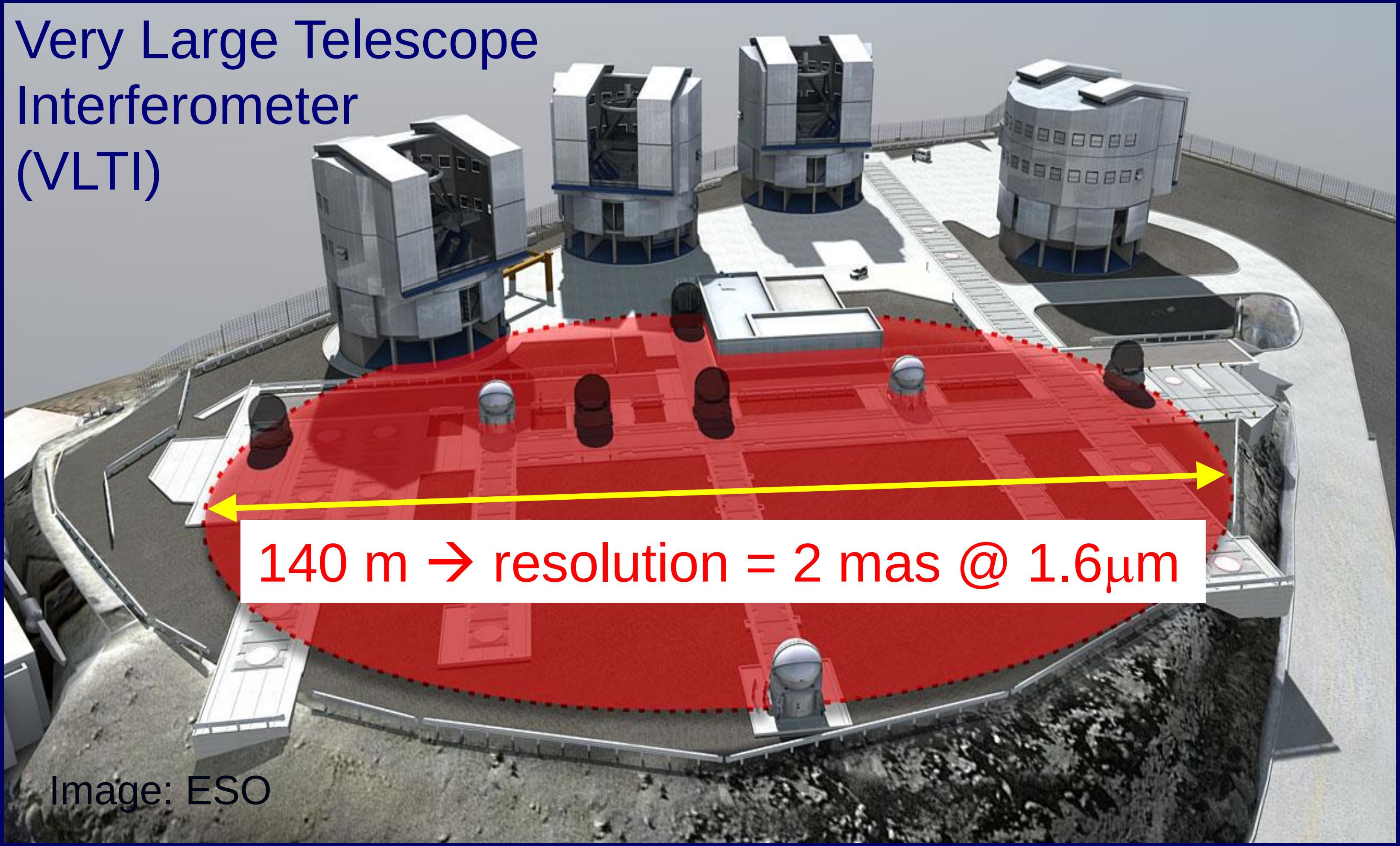


- ✓ Significant influence of mass loss on Stellar evolution & chemical enrichment of ISM
- ✓ Spatially resolving the region < 10 $R_\star$ where the stellar winds are accelerated

Spatially resolving stars — like observing the Sun

Milliarcsecond spatial resolution needed.

→ Optical / infrared long-baseline interferometry



Spatially resolving the dynamics of the atmosphere

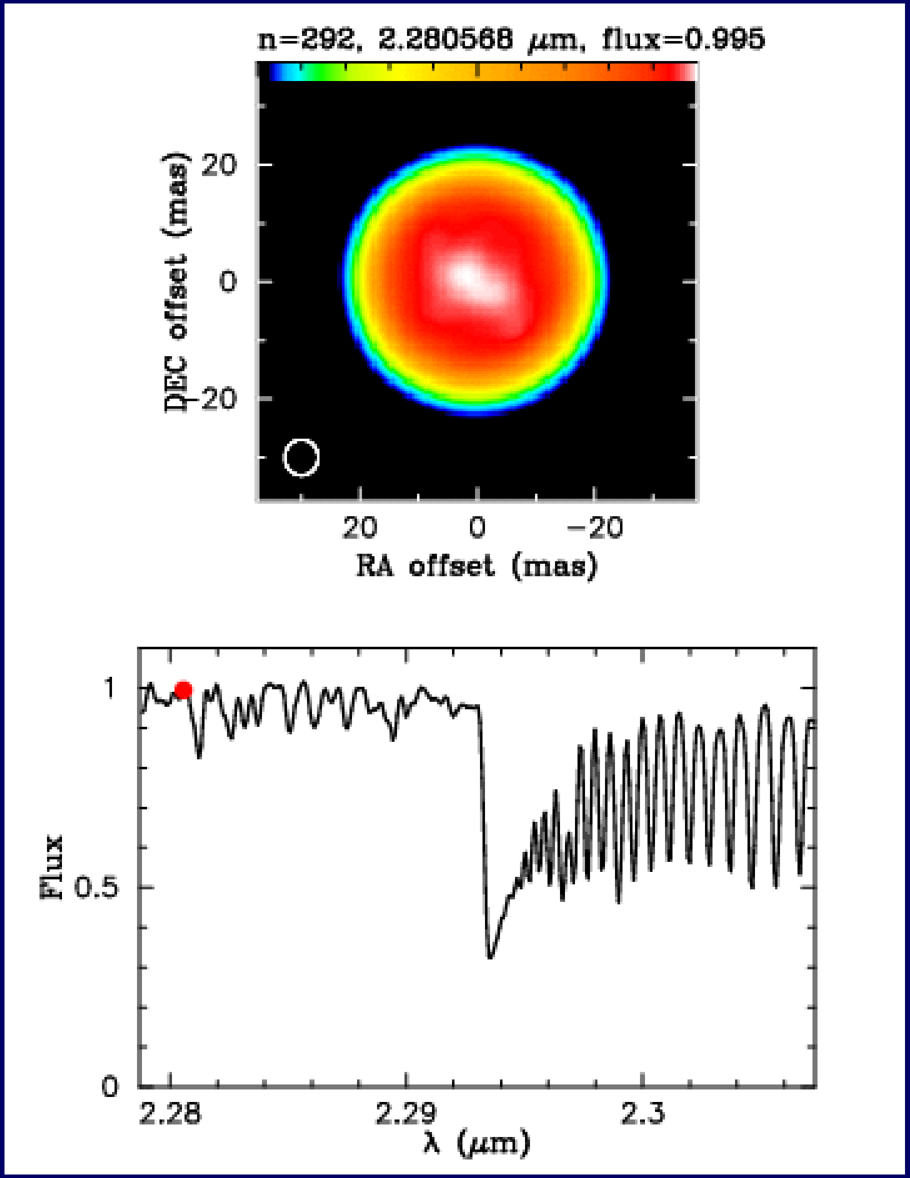
- ✓ Combining high spatial and high spectral resolution
  → Spatially resolve atmospheric gas motion

- ✓ VLTI / AMBER instrument
  Spatial resolution of down to 2 mas
  Spectral resolution of up to 12000
  → Individual molecular & atomic lines resolved

- ✓ CO first overtone lines near 2.3 μm
  → Probing the dynamics of the upper photosphere & outer atmosphere

Velocity-resolved imaging of the surface of Antares

- ✓ Baseline = 4.6 – 82 m
  4 different array config.
  on 5 full nights
- ✓ Spatial resolution (λ/B)
  = 5 mas
  Star's size = 37 mas
  → 1/7 × stellar size
- ✓ VLTI / AMBER
  Spectral resolution
  = 8000



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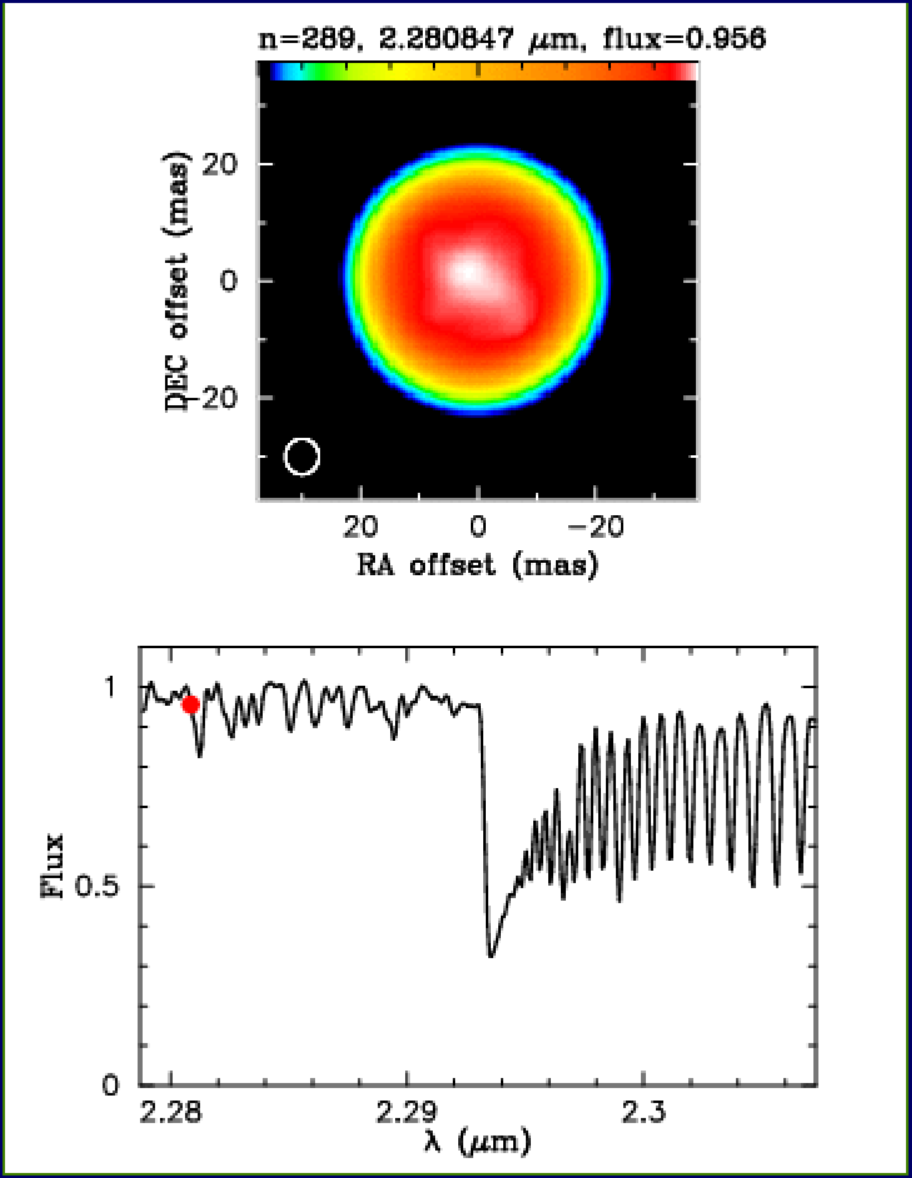
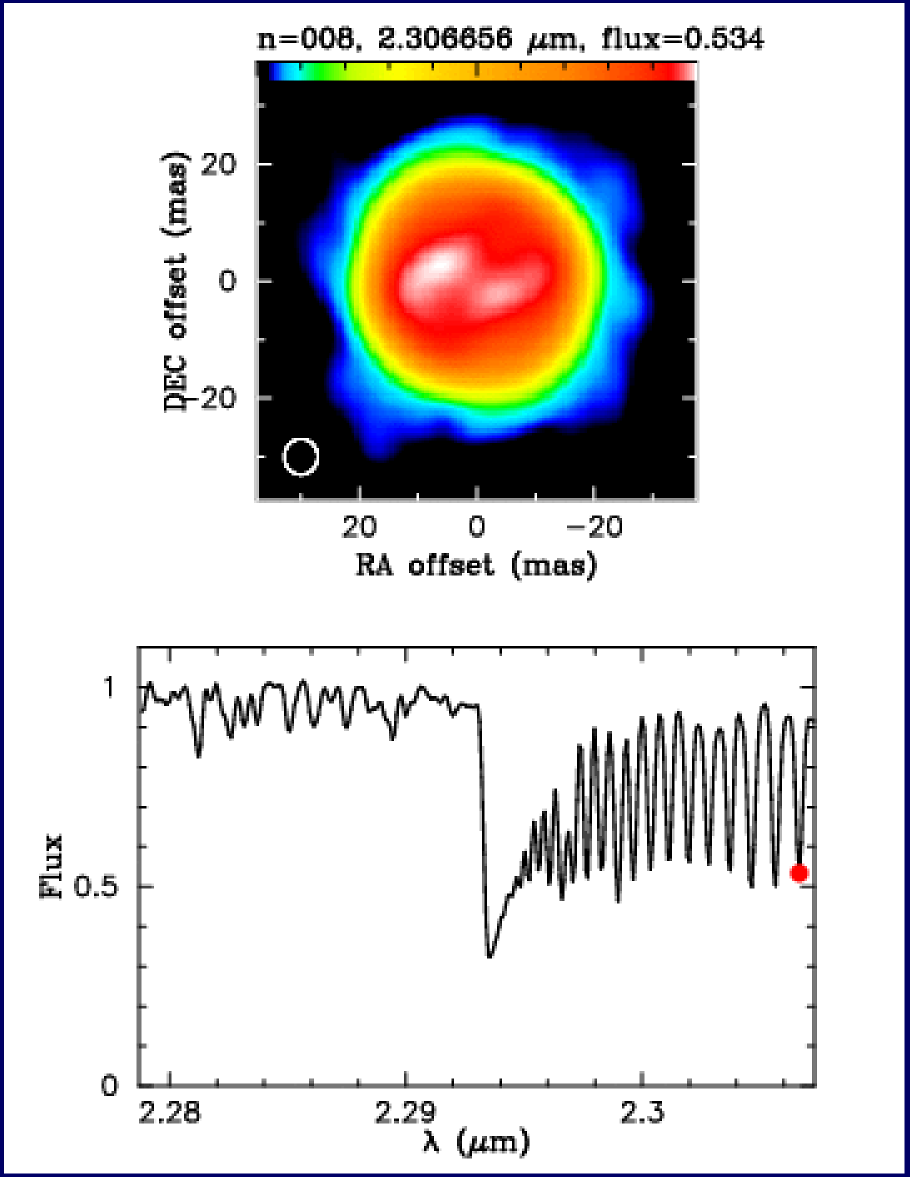


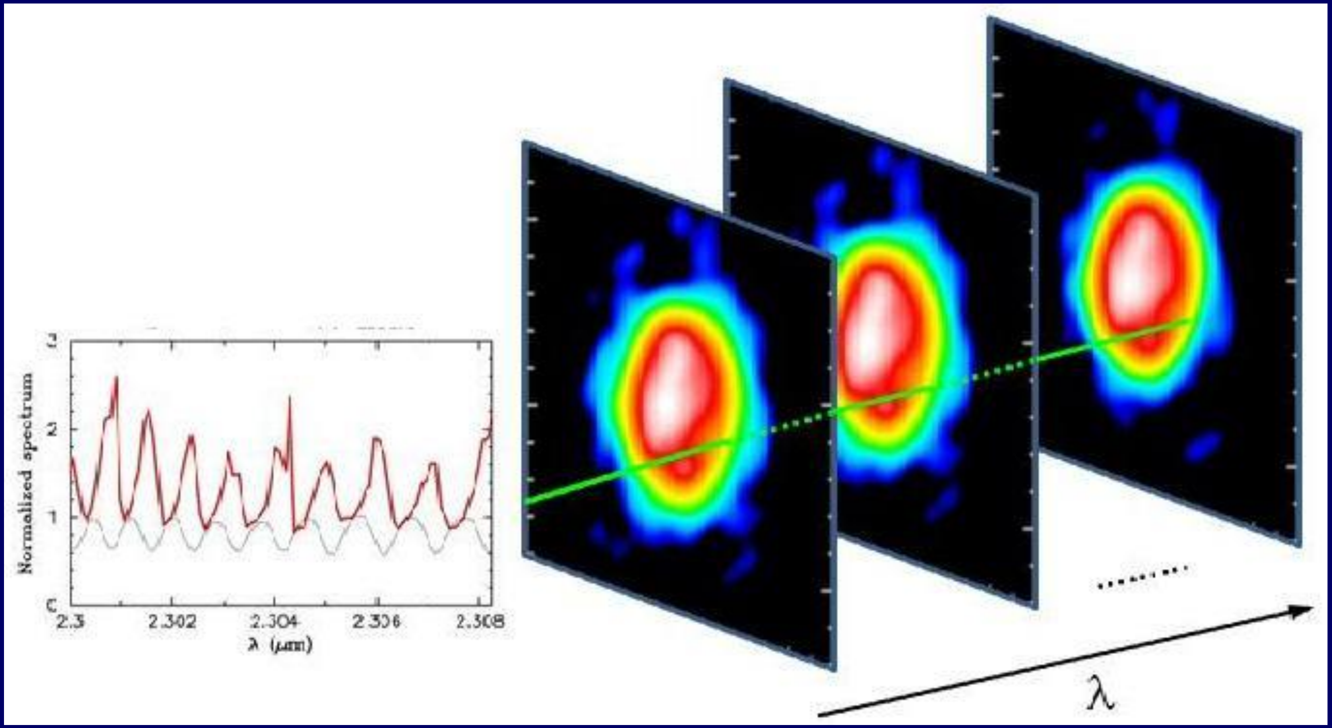
Velocity-resolved imaging of the surface of Antares

- ✓ Weak, large spot in the continuum
  contrast = 3–4 %
- ✓ Two bright spots in CO lines → Holes?
- ✓ Asymmetrically extended atmosphere in CO lines ~1.7 stellar radii



Spatially resolved spectroscopy of the atmosphere

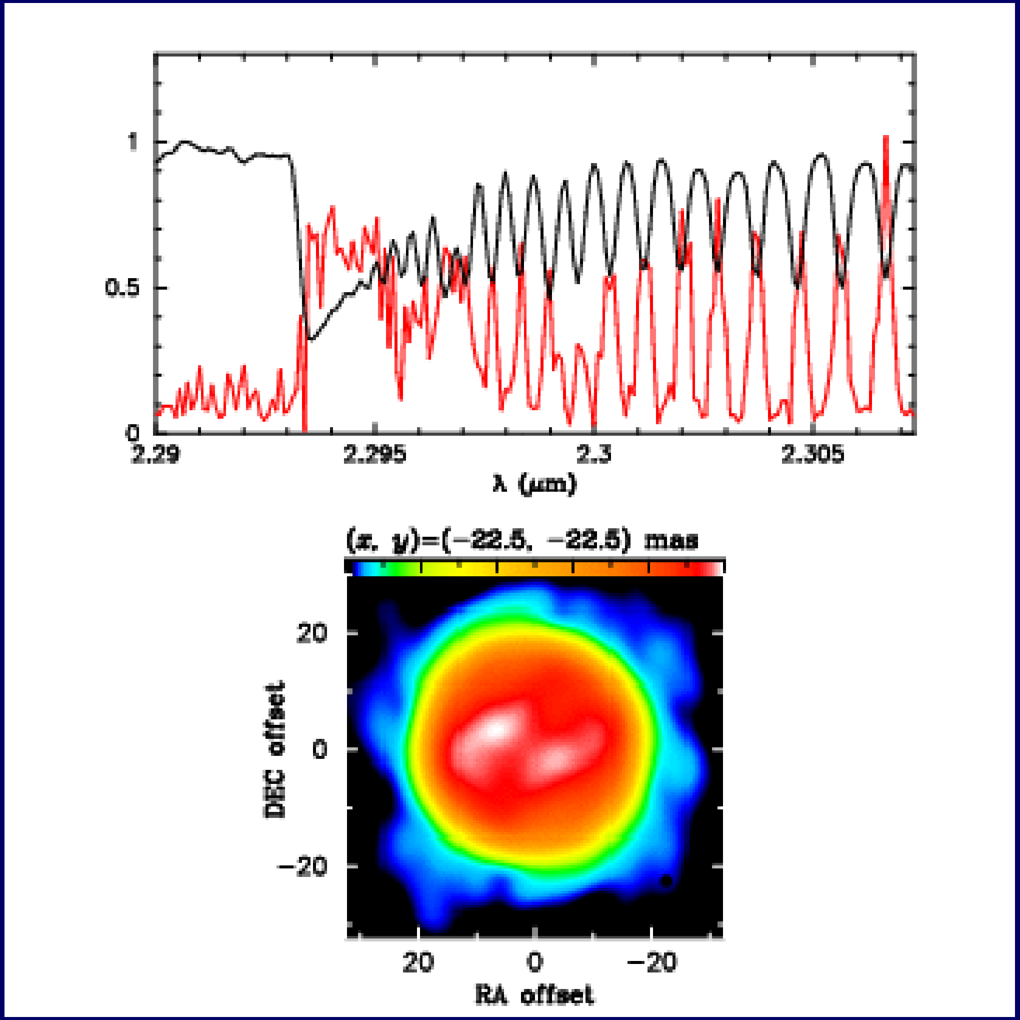
✓ Extract the spatially resolved spectrum at each position



Spatially resolved spectroscopy of Antares

- ✓ Emission lines from the extended atmosphere
- ✓ Absorption lines over the stellar disk

→ Stellar astrophysics a few steps closer to solar physics



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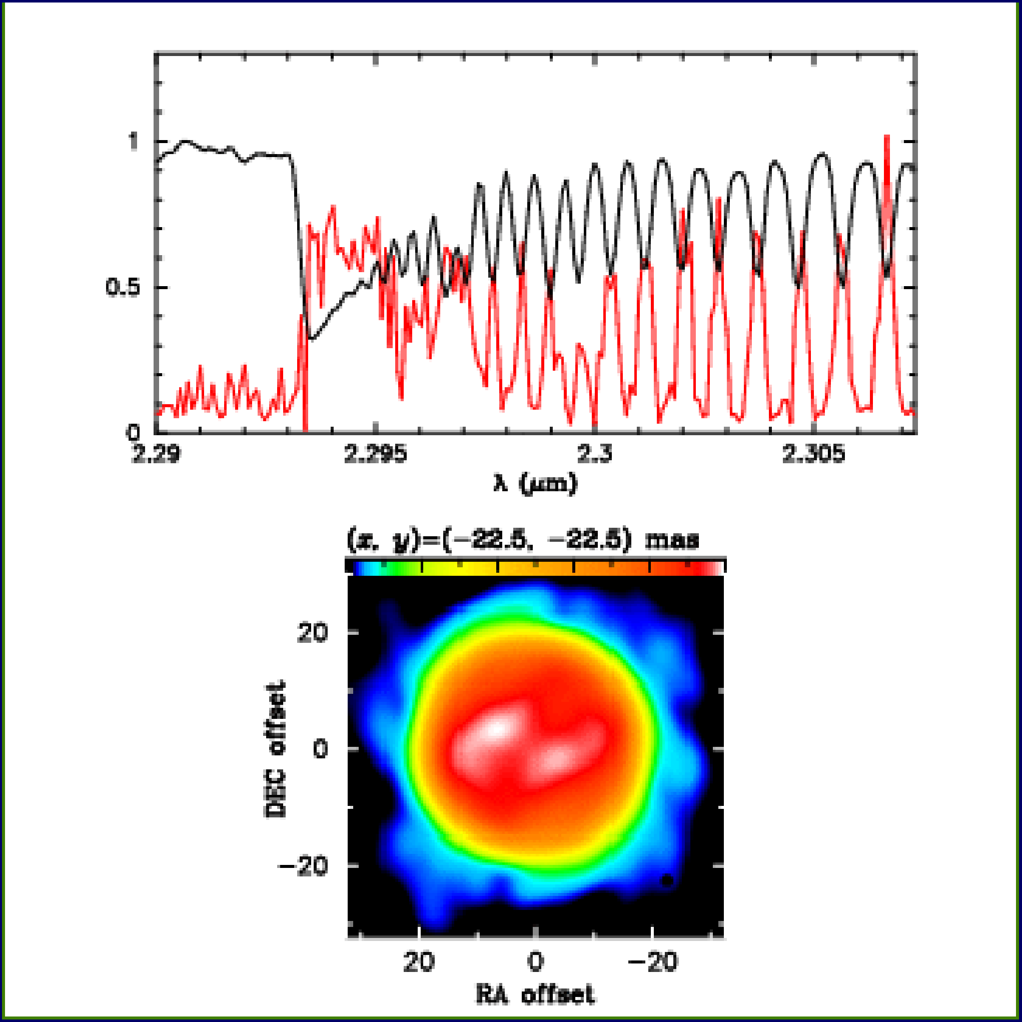

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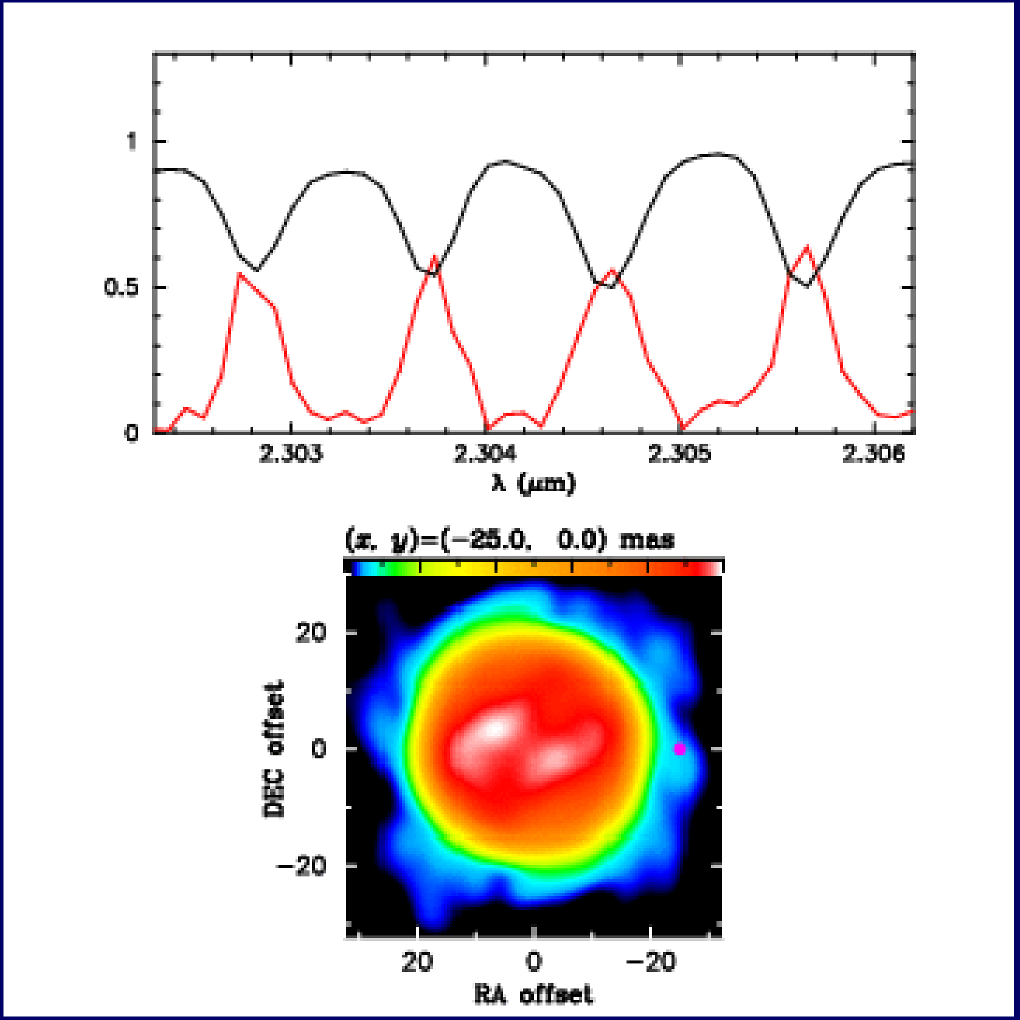
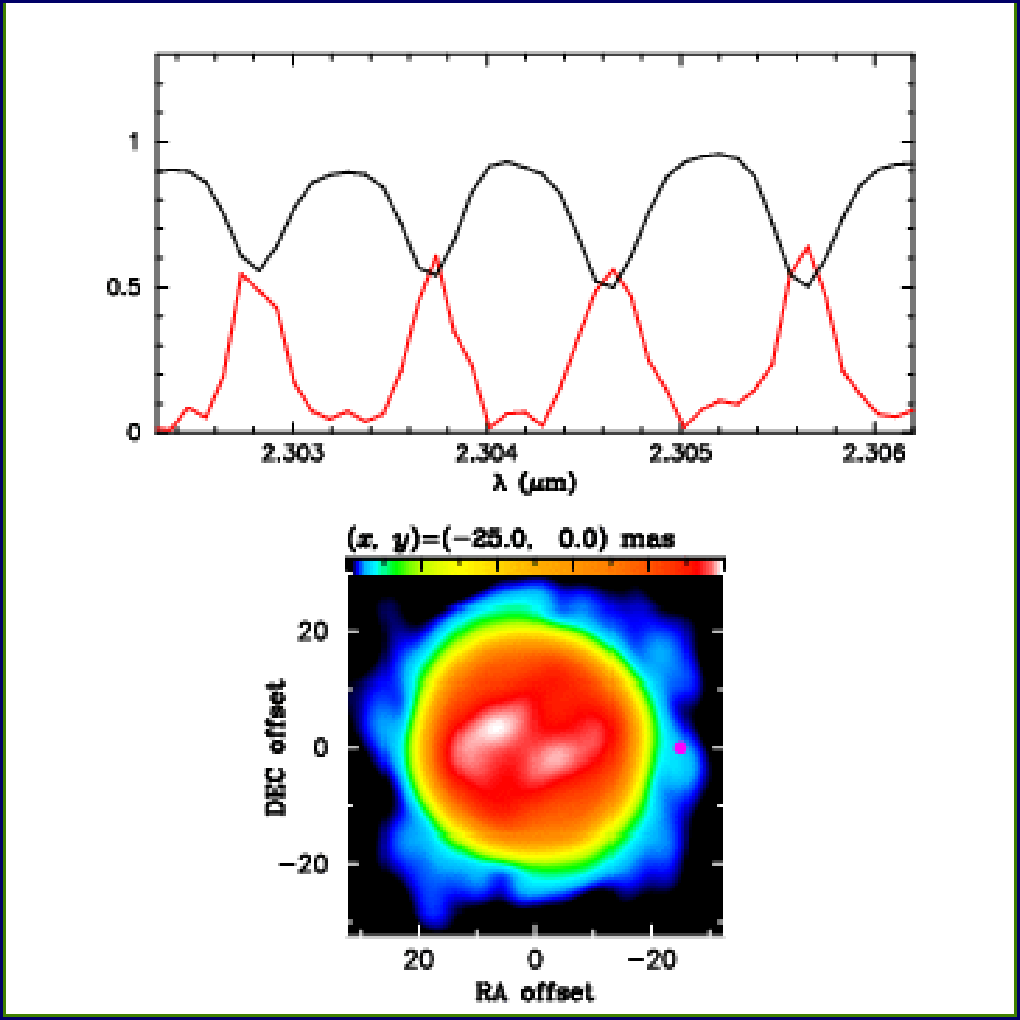
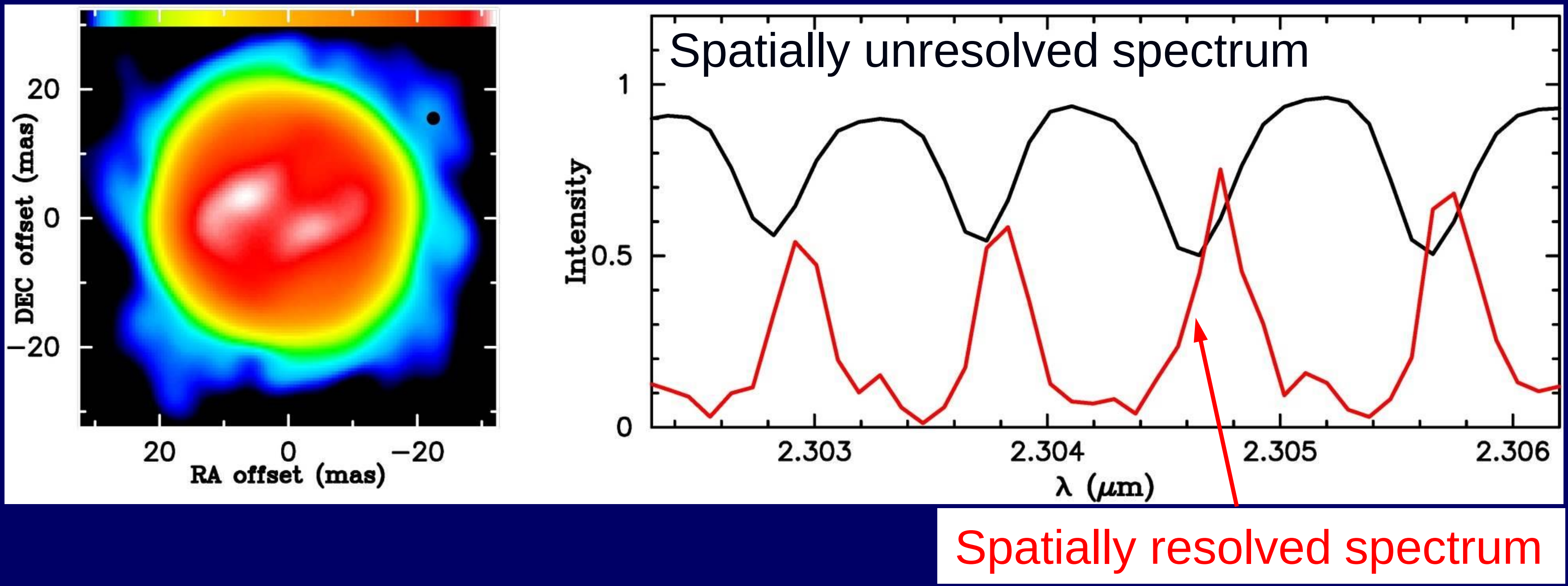


Spatially resolved spectroscopy of Antares

- ✓ Emission lines from the extended atmosphere
- ✓ Absorption lines over the stellar disk
- ✓ Blueshifted at some points, redshifted at other points



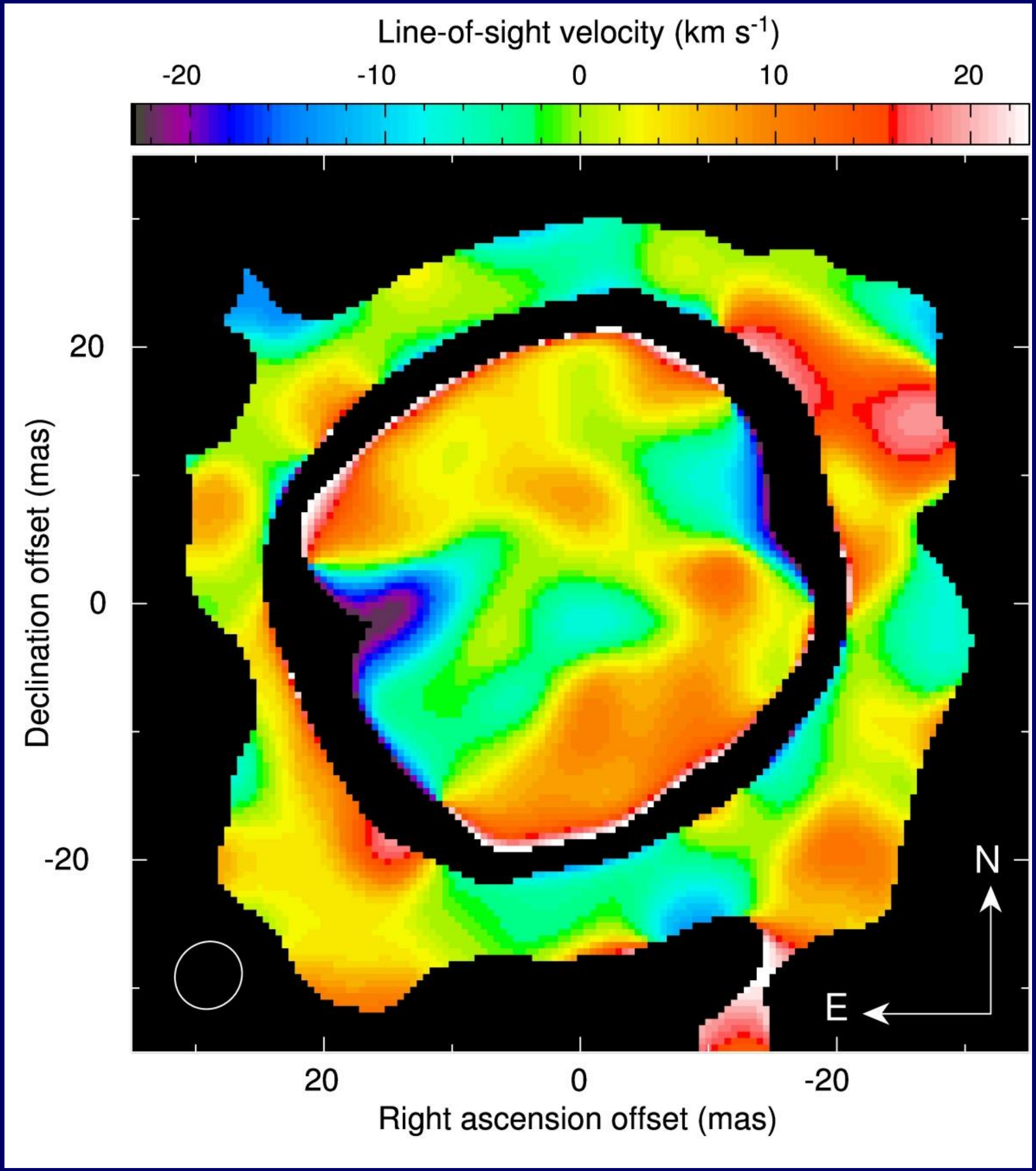
Spatially resolved spectroscopy of Antares



✓ Emission lines from the extended atmosphere are redshifted

→ This clump is moving away from us at ~20 km/s.

Spatially resolved spectroscopy of Antares



- ✓ 2-D velocity map of the atmosphere of a star other than the Sun
- ✓ Turbulent motion of large gas clumps within 1.7 stellar radii
- ✓ No systematic outflow

Ohnaka et al. (2017)

Origin of the inhomogeneous velocity field

✓ Convection – unlikely (Ohnaka et al. 2011, 2013)

Observationally estimated density ~ 10^{-14} g/cm^3 at 1.3 $R_\star$
3-D convection model < 10^{-20} g/cm^3 at 1.2 $R_\star$
(Chiavassa et al. 2011)

✓ Radiation pressure on molecules?
(Arroyo-Torres et al. 2015; Wittkowski et al. 2016)

✓ Driven by MHD processes?
Magnetic field detected on Betelgeuse ~1 G
(Aurière et al. 2010)
→ But self-consistent modeling not yet available

Going to 3D: Tomographic velocity-resolved imaging

✓ Tomographic velocity-resolved imaging

Probing the velocity field at different atmospheric heights using different molecular and atomic lines

Strong lines → Upper layers
Weak lines → Deep layers

Conclusions & Prospects

✓ Velocity-field mapping over the atmosphere

→ Vigorous turbulent motion in Antares

✓ Tomographic velocity-resolved imaging

→ Little motion in deep layers, upwelling motion in R Dor

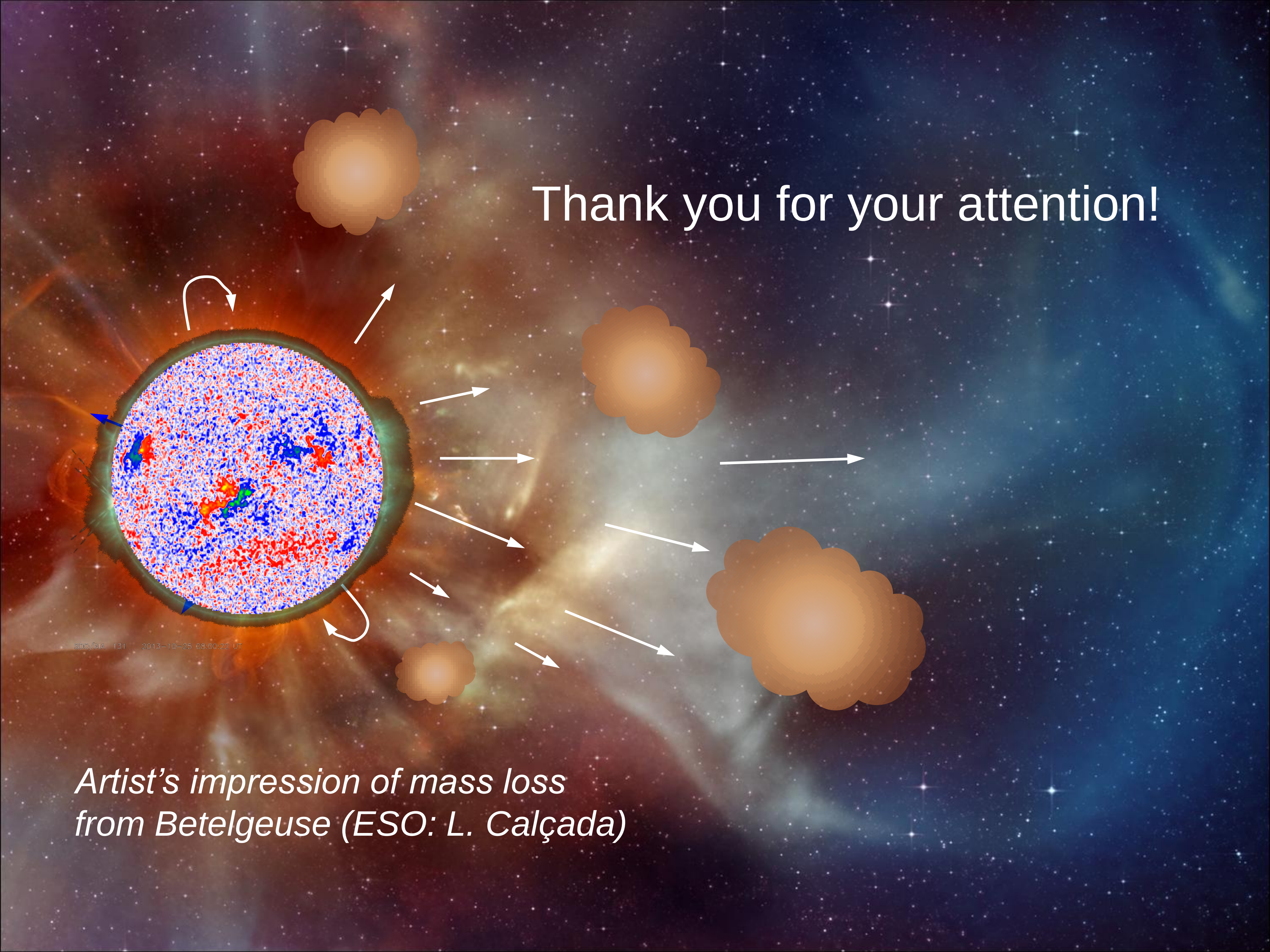
✓ Spatially resolving the magnetic fields over the surface

→ Zeeman-broadening in spatially resolved spectra

✓ VLTI 2nd generation instruments

- GRAVITY (2–2.4 μm) → Better sensitivity, efficient imaging
- MATISSE (3–13 μm) → Imaging dust formation zone.

Thank you for your attention!



Artist's impression of mass loss from Betelgeuse (ESO: L. Calçada)