Atmosphere analysis through interferometry

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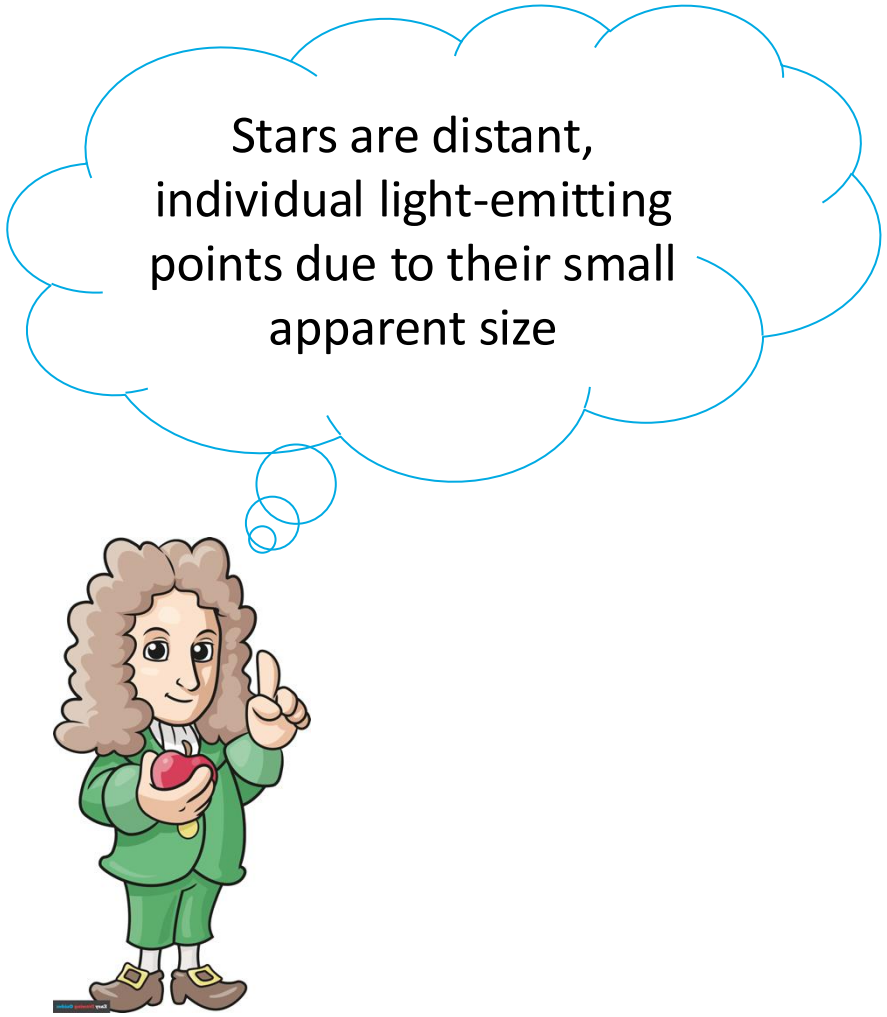
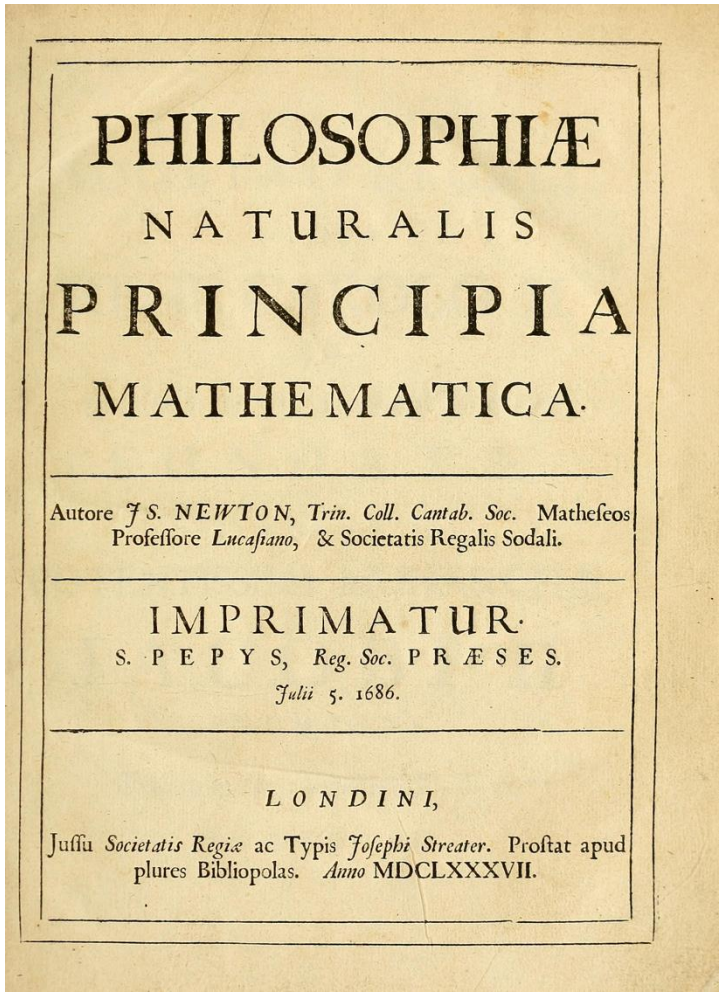
Today's story

Biased view on asymtotic giant branch (AGB) stars and a bit of red supergiants (RSG)

- How we went from point sources to resolved stellar surfaces
- Principle of interferometry
- What's on the market nowadays
- Beyond stellar diameters
- Constraining convection

Stars defined as point-sources due to observational limits



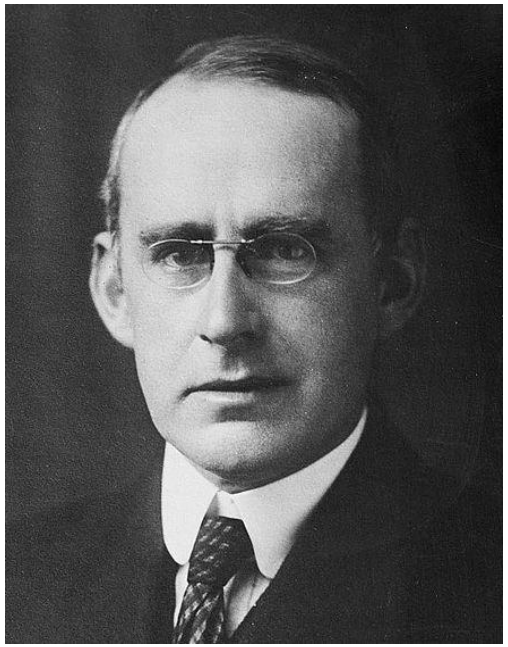

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano,* & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater.* Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Stars defined as point-sources in the early 20th century



Eddington 1924

E. Milne 1930

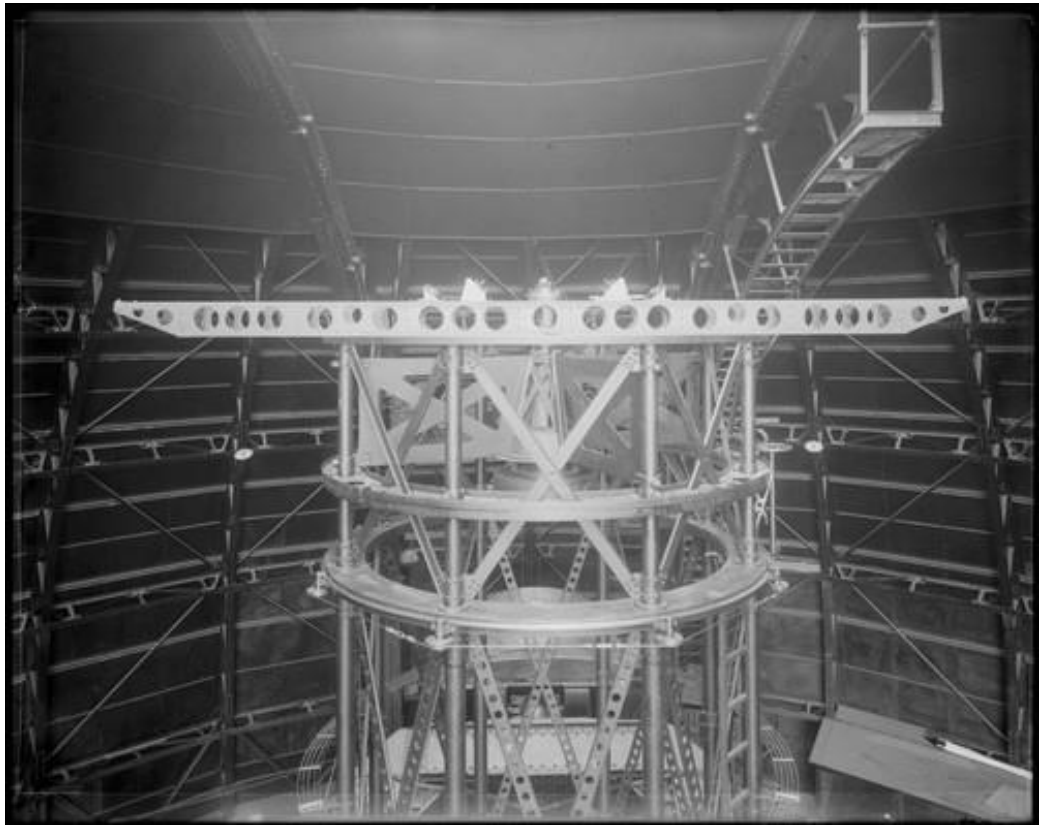
Eddington (1924) and Milne (1930s) referred to stars as point sources for calculation purposes.

These definitions were foundational, as treating stars as point sources helped simplify early models of stellar energy and radiation

These historical definitions helped lay the groundwork for more detailed and nuanced models in modern astrophysics.

Spectroscopy & Interferometry

- **1930s-1940s**: The advent of better spectroscopic techniques enabled astronomers to study the atmospheres and composition of stars, leading to a clearer understanding of their extended nature.
- **Post-1950s**: With the development of high-resolution imaging and the application of interferometry, astronomers could directly observe the extended nature of some stars (e.g., supergiants) and better model their sizes.
  - Michelson & Pease December 13, 1920 measured for the first time the diameter of Betelgeuse

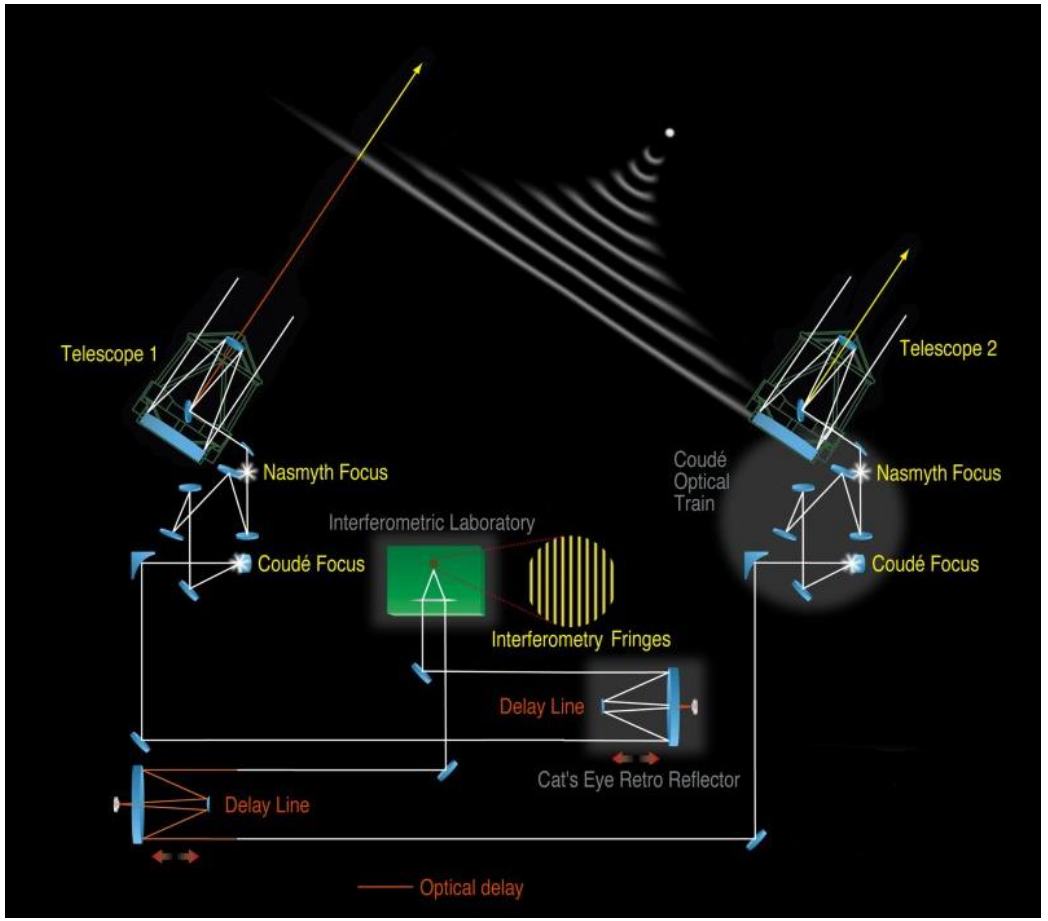


Hooker telescope, Mount Wilson, California.

Basics of interferometry

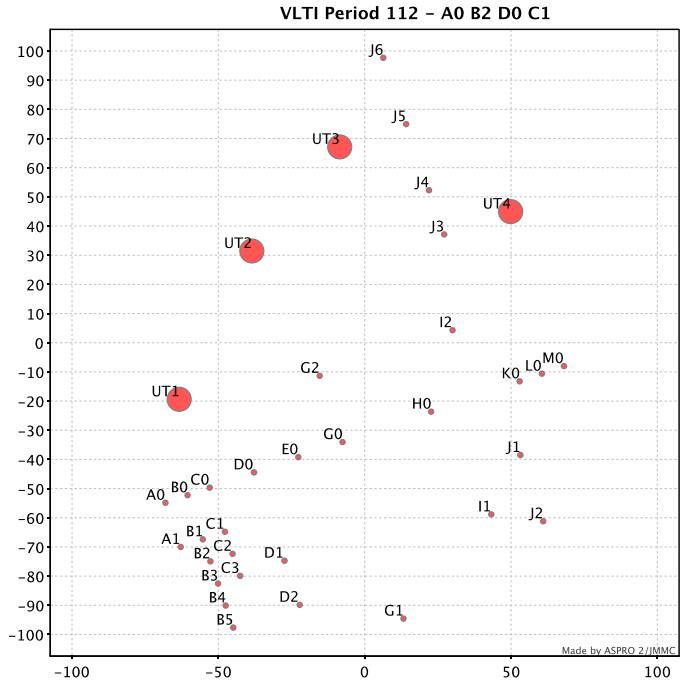
- Not a single dish Telescope but 2, 3, 4…6...
- We observe an interference pattern
- We measure “fringes”: Visibility, Phase
- We derive: sizes, degree of symmetry

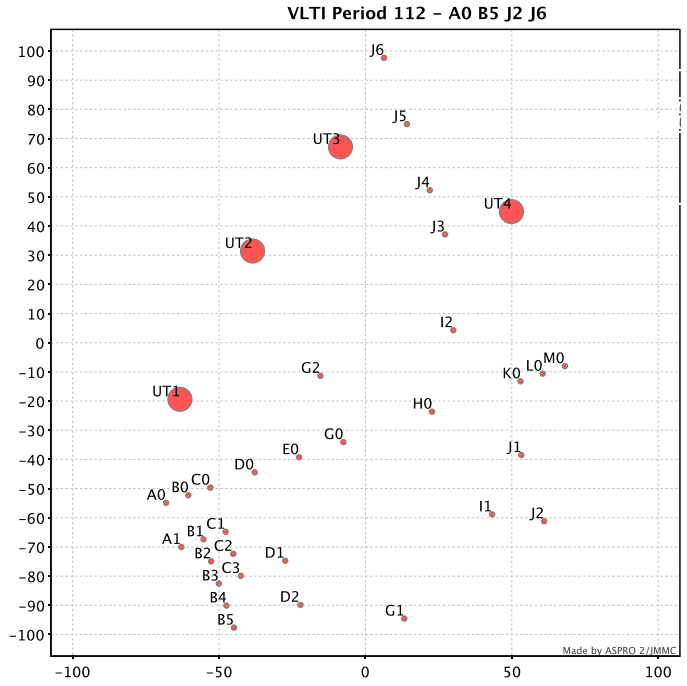
and IMAGES! (with 3+ Telescopes)

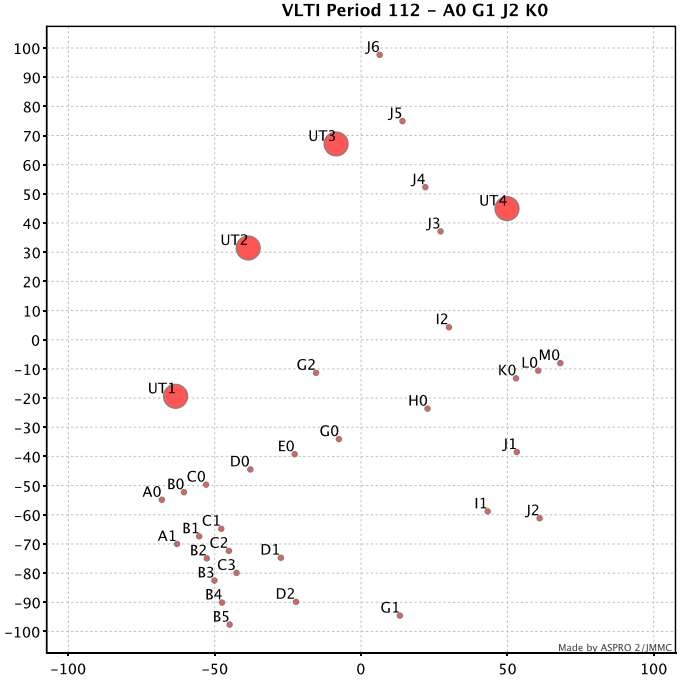


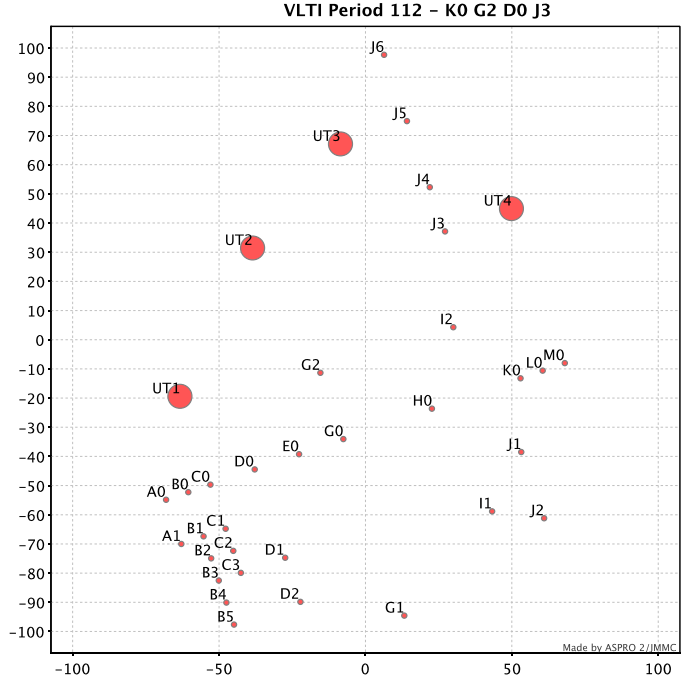
VLTI acts like a virtual 200 m telescope

- Combining 4UTs (8m telescope), maximum baseline 130 m, resolution ~2 mas at 2 micron
- Combining 4ATs (1.8m telescope), maximum baseline 200 m *(from October 2023), resolution ~0.8 mas at 1.5 micron*


VLTI Period 112 – A0 B2 D0 C1
Stations
A0-B2
A0-D0
A0-C1
B2-D0
B2-C1
D0-C1
Made by ASPRO 2/JMMC


VLTI Period 112 – A0 B5 J2 J6
Stations
Made by ASPRO 2/JMMC


VLTI Period 112 – A0 G1 J2 K0
Stations
Made by ASPRO 2/JMMC


VLTI Period 112 – K0 G2 D0 J3
Stations
Made by ASPRO 2/JMMC

VLTI today

Auxiliary Telescopes equipped with NAOMI Adaptive Optics

- R~15 mag in excellent conditions
- R <= 12.5 in standard conditions

Unit Telescopes equipped with

- GPAO + Natural guide star Adaptive Optics V = 12.5
- GPAO + Laser Guide star from 2026 will improve limits by 5 mag
- CIAO Adaptive Optics GRAVITY only, K <=10

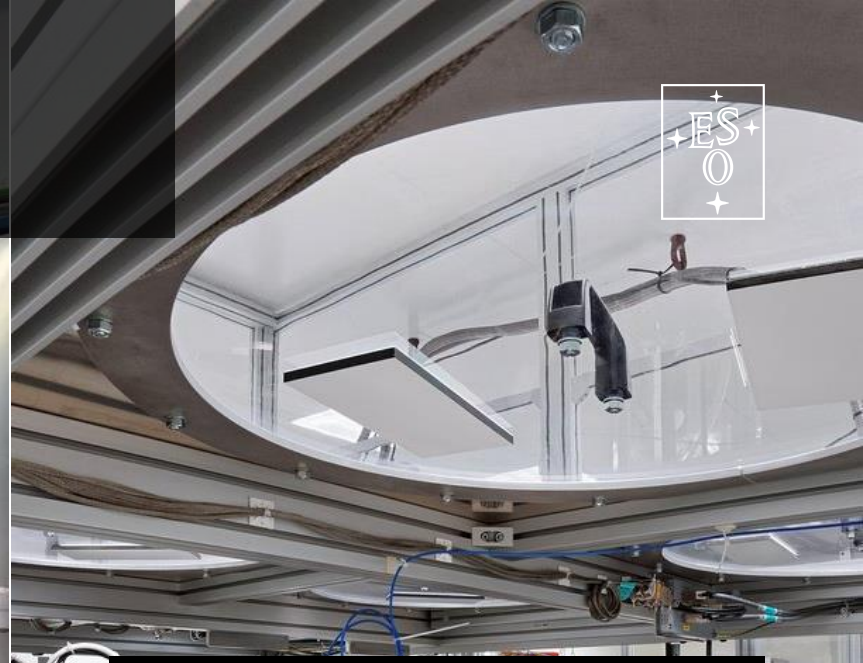
VLTI today

PIONIER

- 1 mas angular resolution
- H band (λ~1.6μm)
- R~50
- ATs limit H ~ 9 mag

GRAVITY

- 2 mas angular resolution
- K band (λ~2.2μm),
- R~20, 500 and 4000
- Fringe tracker (up to 2” off-axis)



MATISSE

- 3 mas angular resolution
- L,M,N bands (λ~3 to 12μm),
- R~30, 500, 1000 and 3500
- GRAVITY as a fringe tracker

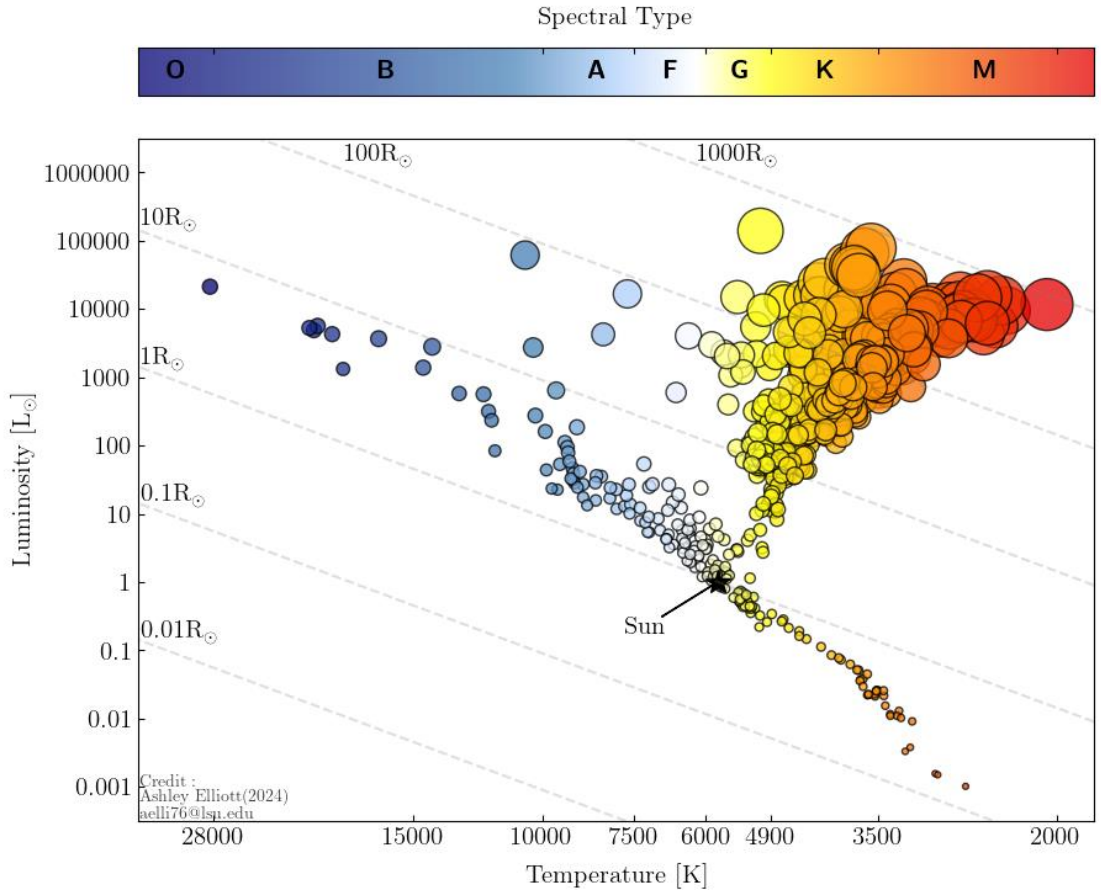
For many years we measured diameters…

Boyajian et al. 2012, ApJ, 746, 101

Boyajian et al. 2012, ApJ, 757, 112

Boyajian et al. 2013, ApJ, 771, 40

von Braun & Boyajian 2017, in Extrasolar Planets and Their Host Stars, Springer

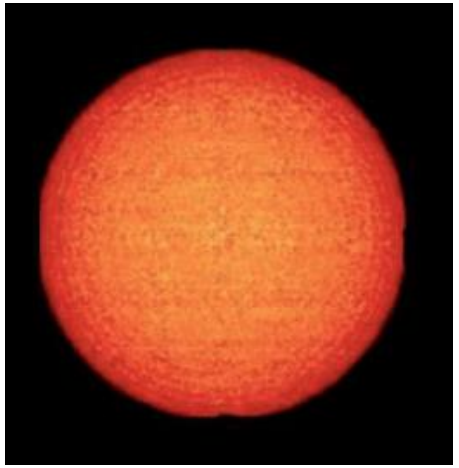


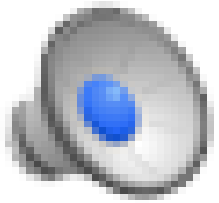

Beyond stellar diameters:
probing stellar surfaces

The surface of our Sun

- R ≈ 700,000 km
- Geometrically thin Photosphere: 300 km
- Convective granules: 1,000 km, few millions
- Dark spots related to magnetic field
- Corona, flares

Credit: Solar simulation @B. Freytag



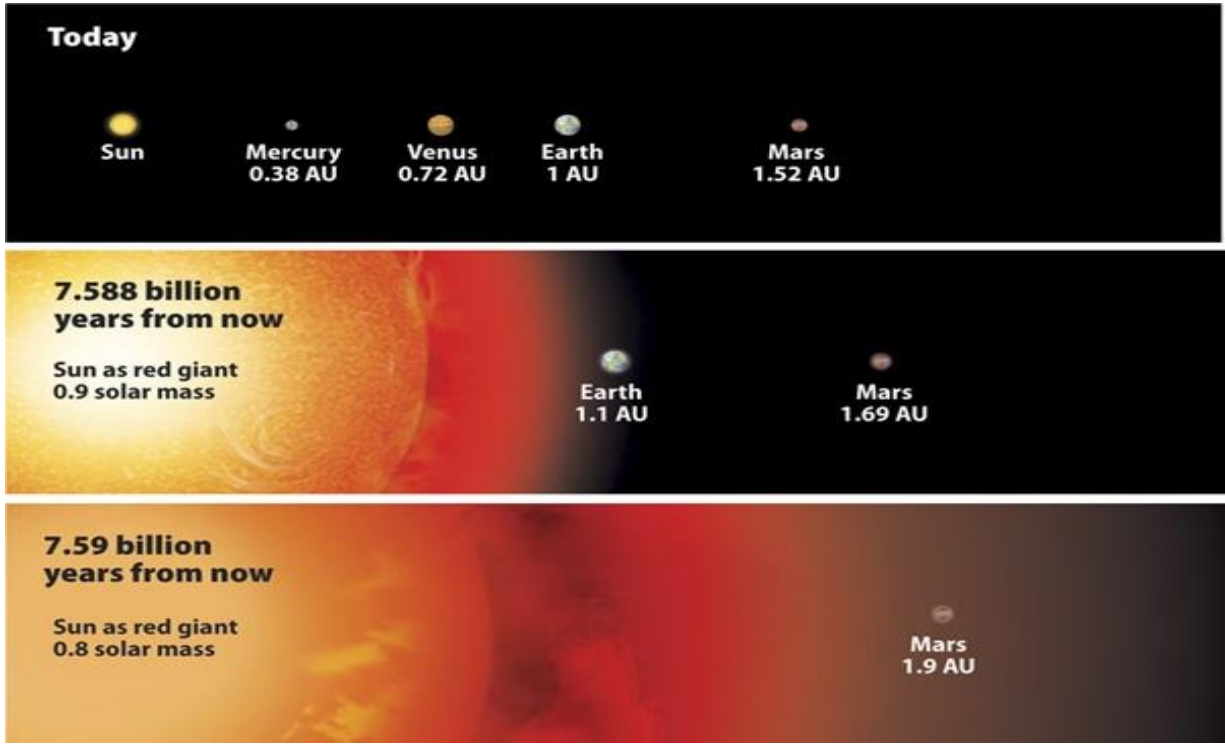


Credit: @SungrazerComets

Asymptotic Giant Branch Stars

- R ≈ 10^6 km
- Diluted photosphere of the order of the star radius plus extended envelope

Convection? Magnetic field?
Chromosphere?



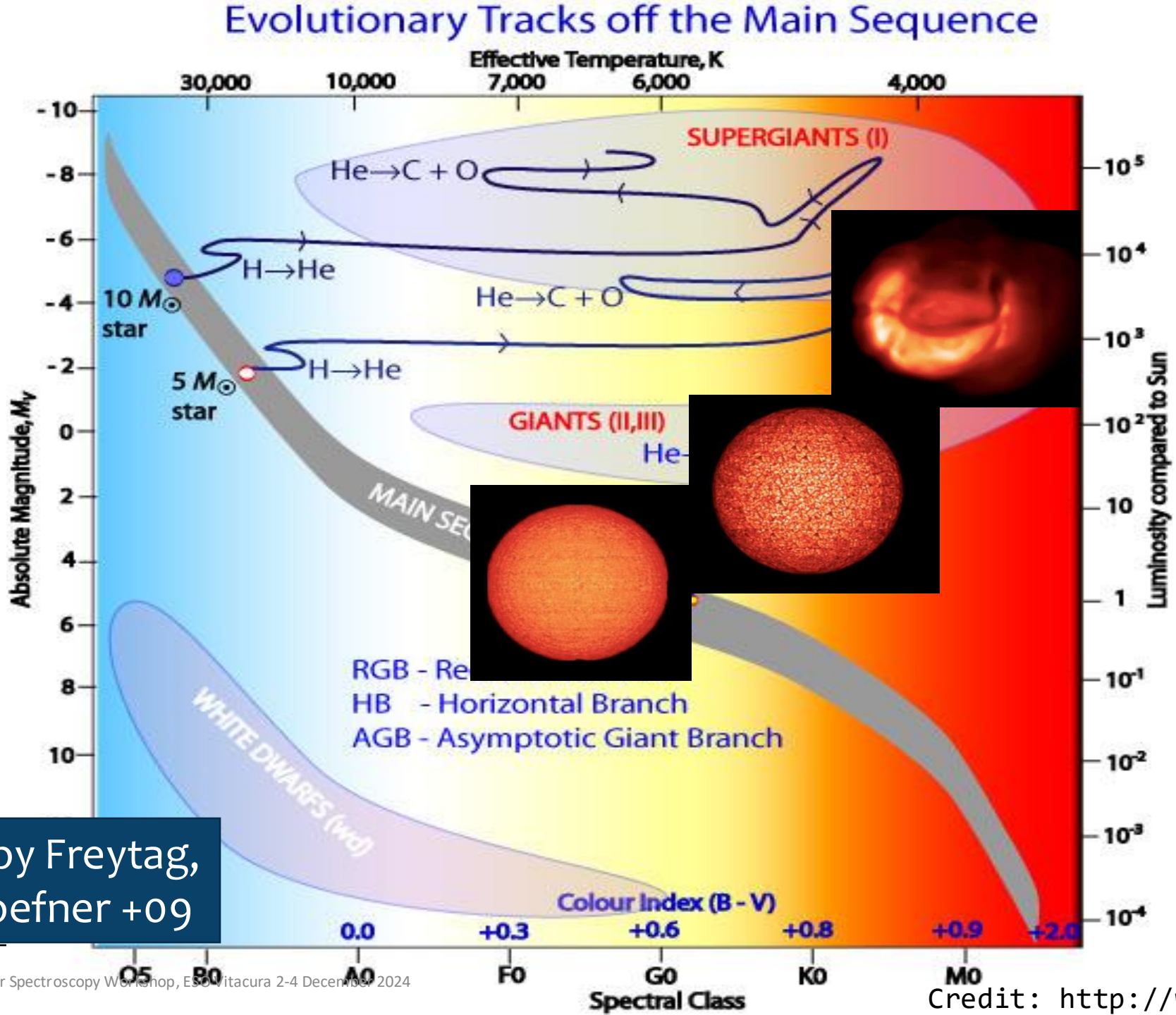
ON THE SCALE OF PHOTOSPHERIC CONVECTION IN RED GIANTS AND SUPERGIANTS

MARTIN SCHWARZSCHILD
Princeton University Observatory
Received 1974 June 21

ABSTRACT

An attempt is made to estimate the sizes of the convective elements which dominate the brightness variations on the photospheres of red giants and supergiants. The data assembled permit the extreme hypothesis that these dominant convective elements are so large that only a modest number of them exists at any one time on the entire surface of such a star—in contrast with two million granules on the Sun.
Subject headings: convection — interiors, stellar — late-type stars

Schwarzschild (1975)



Simulations by Freytag, Freytag & Hoefner +09

Credit: http://www.atnf.csiro.au/

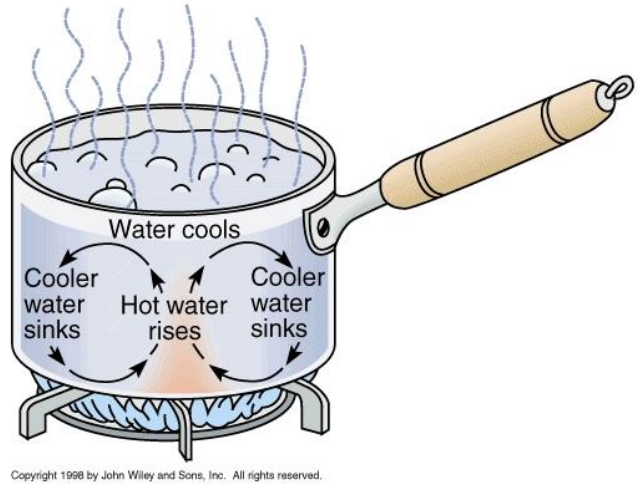
Convection studies in Fourier space

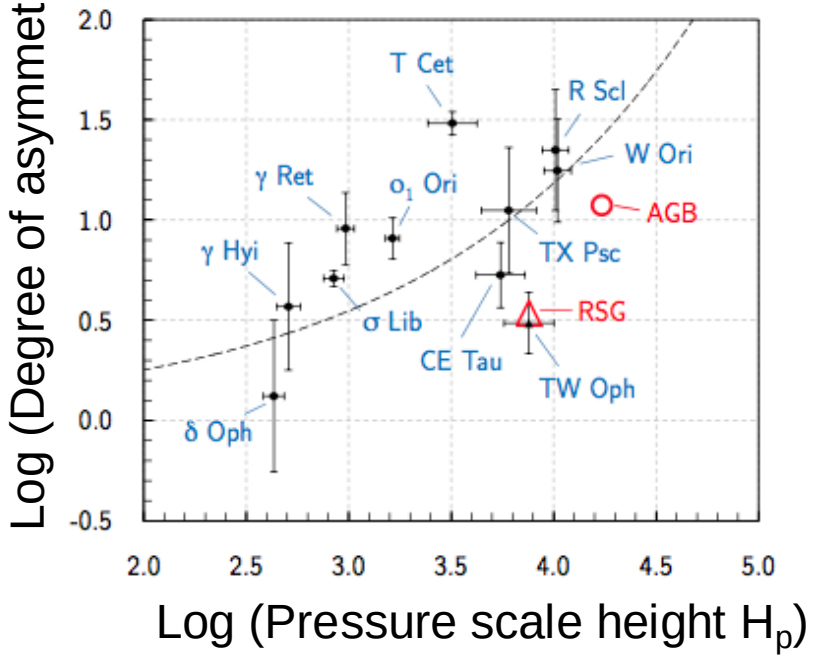
Cruzalebes++2014 found asymmetric signatures with VLTI/AMBER for many AGB

- Asymmetry increase following the sequence

  K giants -> RSG -> AGB

- Qualitative agreement with photocentric motion relation predicted by 3D-RHD (Chiavassa++2011)



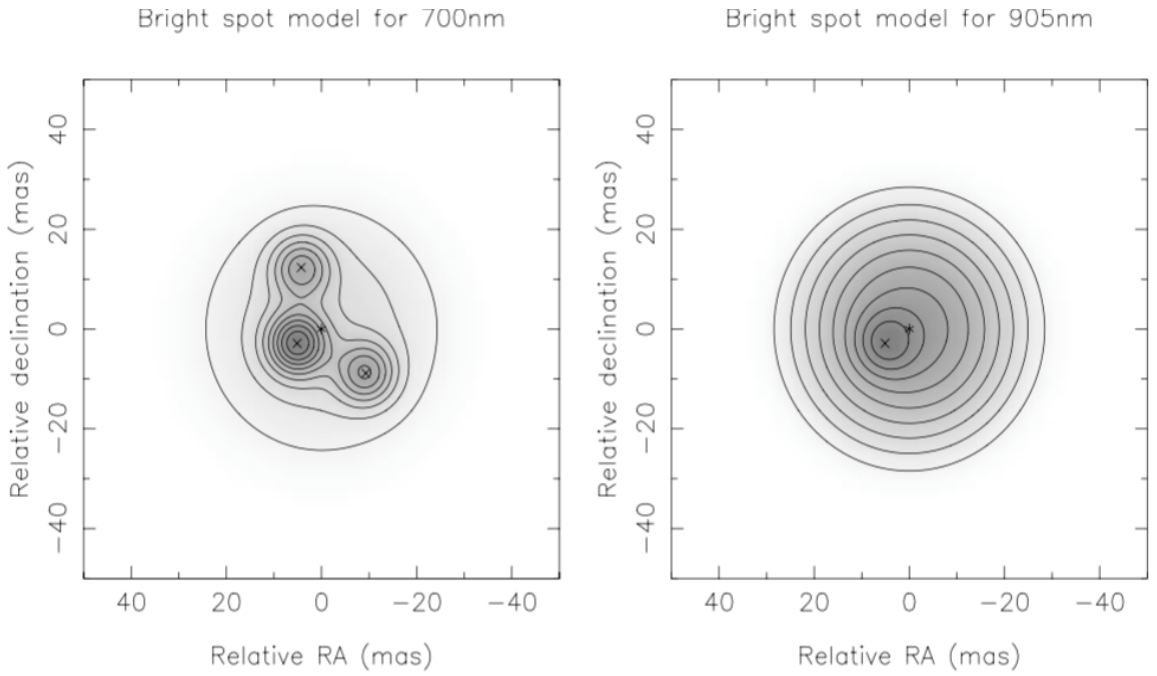


Spots on Betelgeuse

If you anticipate the presence of spots, you can include them in your model.

Parametric study, not images

- *"hot spots" of convective nature*
- *1.2 micron no features, perhaps not enough resolution*
- *Constrast increases at short λ*
  - *Probably dust*



Parametric studies are highly degenerate

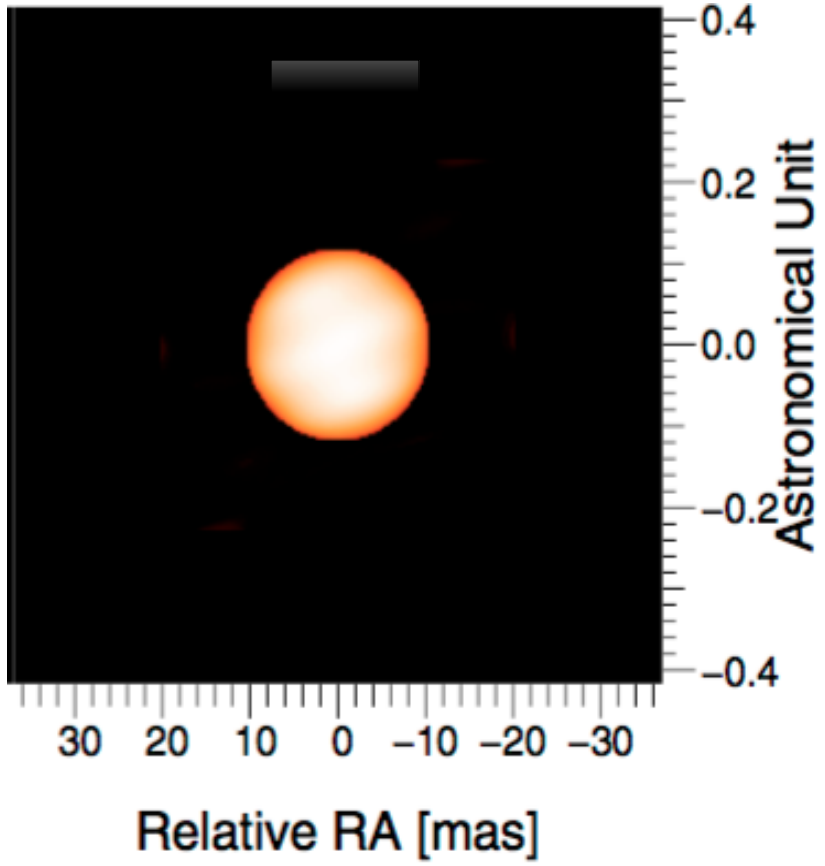
Young++2000 @COAST

First images with 3 telescopes: Arcturus

- 3 Telescope H-band parametric imaging
  - A prior model is applied
  - Grey reconstruction
- No spots observed
- Limit ~ 10^{-3} of the total flux

Limits in angular resolution,
images still heavily dominated by models

Lacour++2008 @ IOTA



Betelgeuse… again

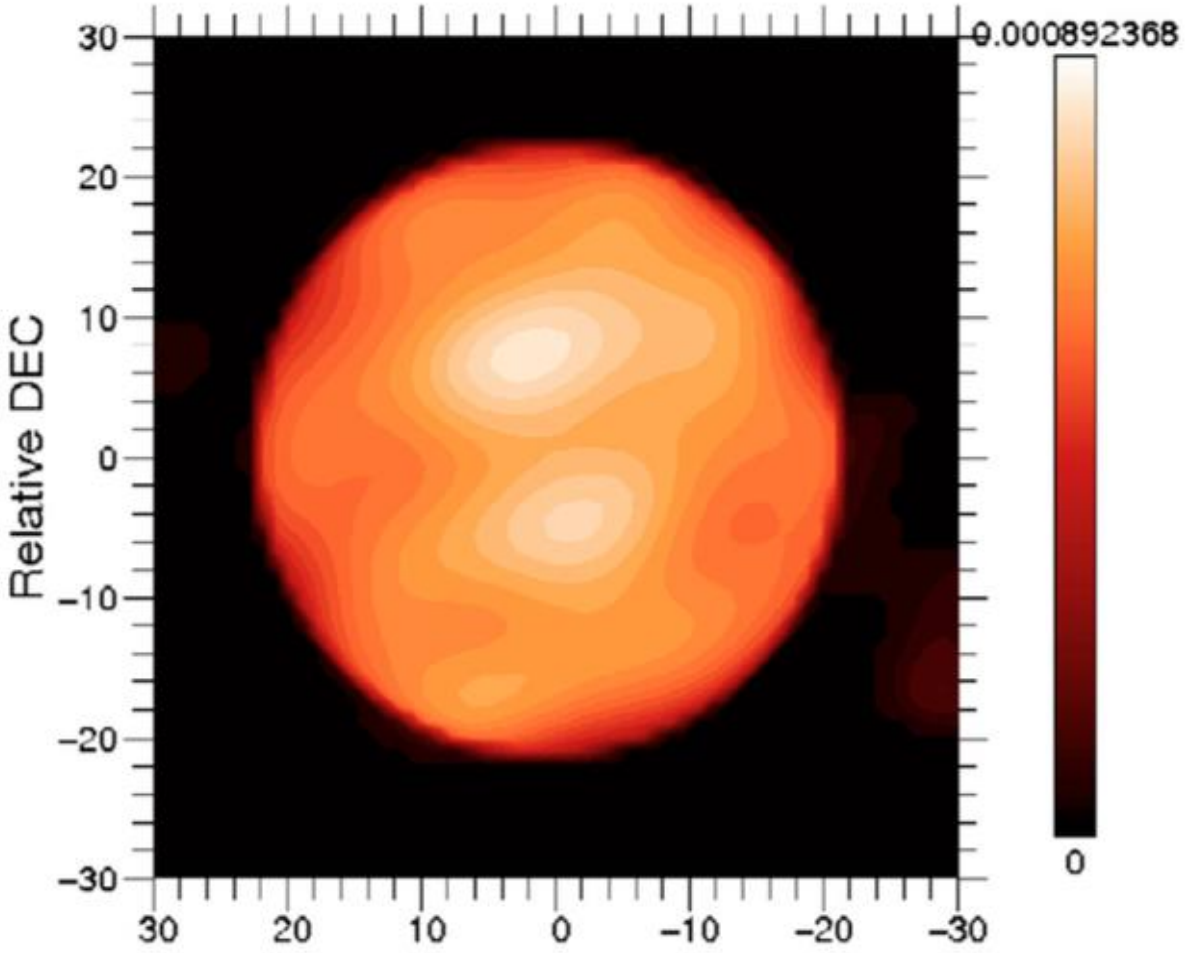
3 Telescope H-band parametric imaging

- A prior model is applied
- Grey reconstruction

2 spots ~1000 K hotter than surface

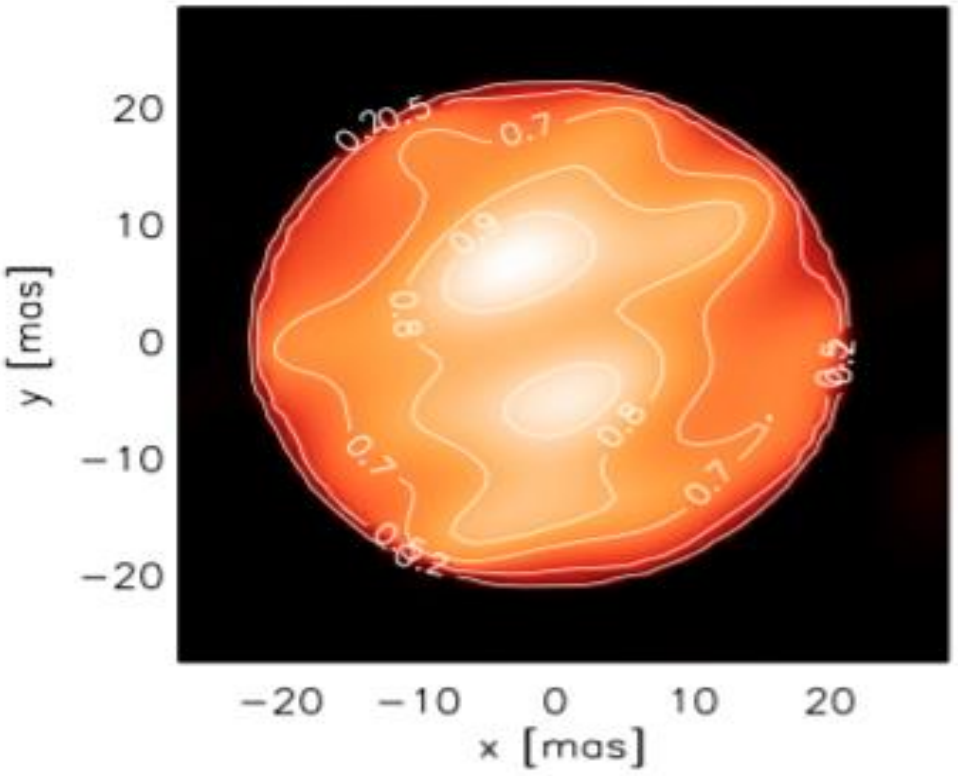
Contribute to ~10% of the flux

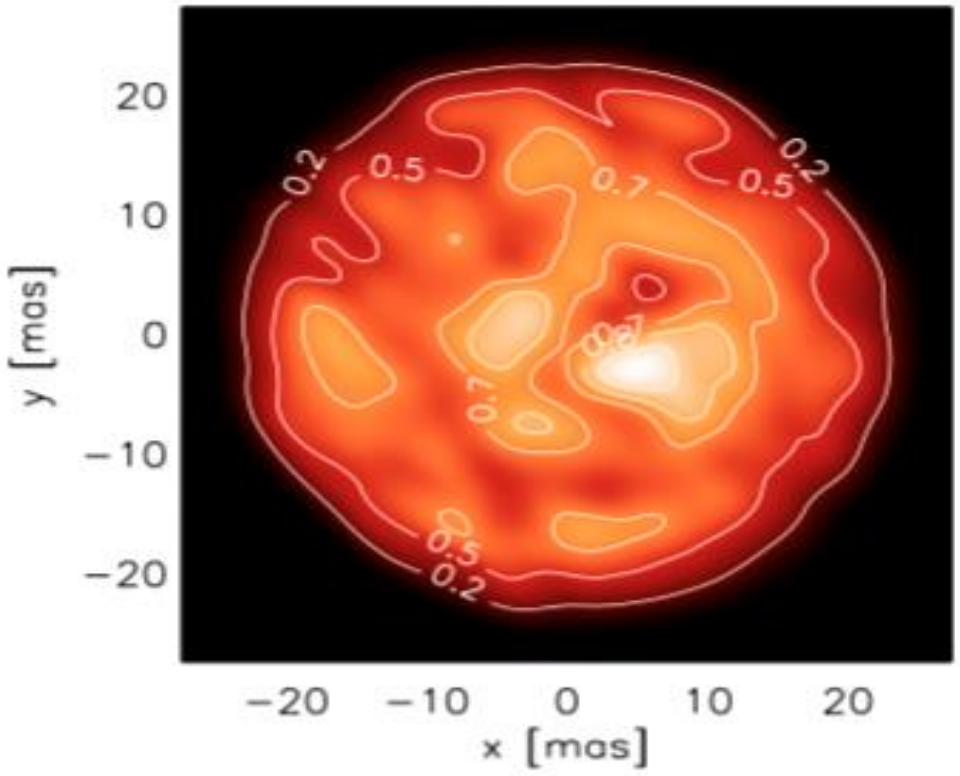
Structures smaller than angular resolution (~10 mas) expected



Haubois++2009 @ IOTA

Model comparison





Chiavassa++2009 @ IOTA

VX Sgr

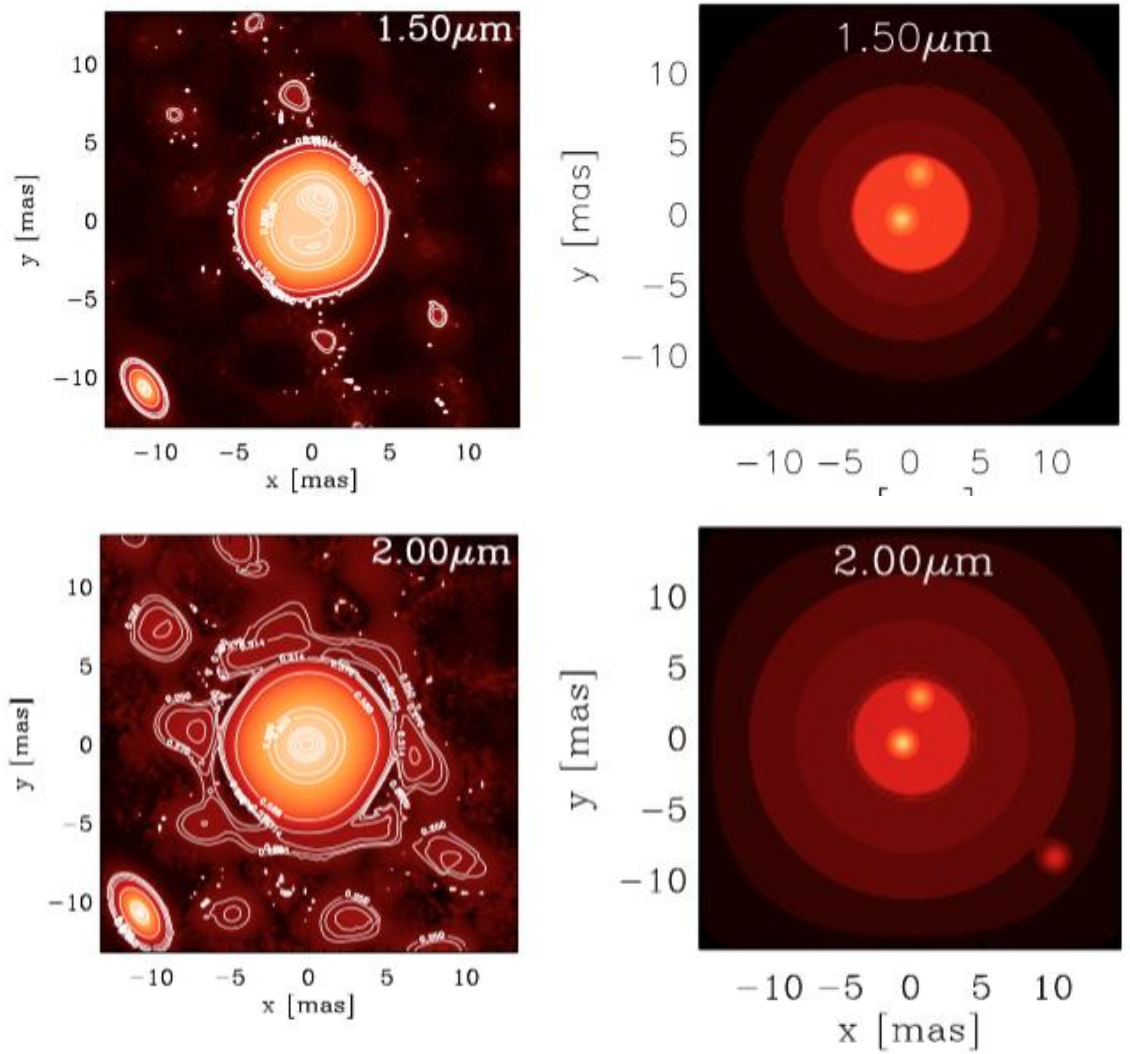
3 Telescope H & K-band parametric imaging

- A prior model is applied
- Chromatic reconstruction

•At least 2 spots present on the surface

•Spots (clumps?) outside the disc

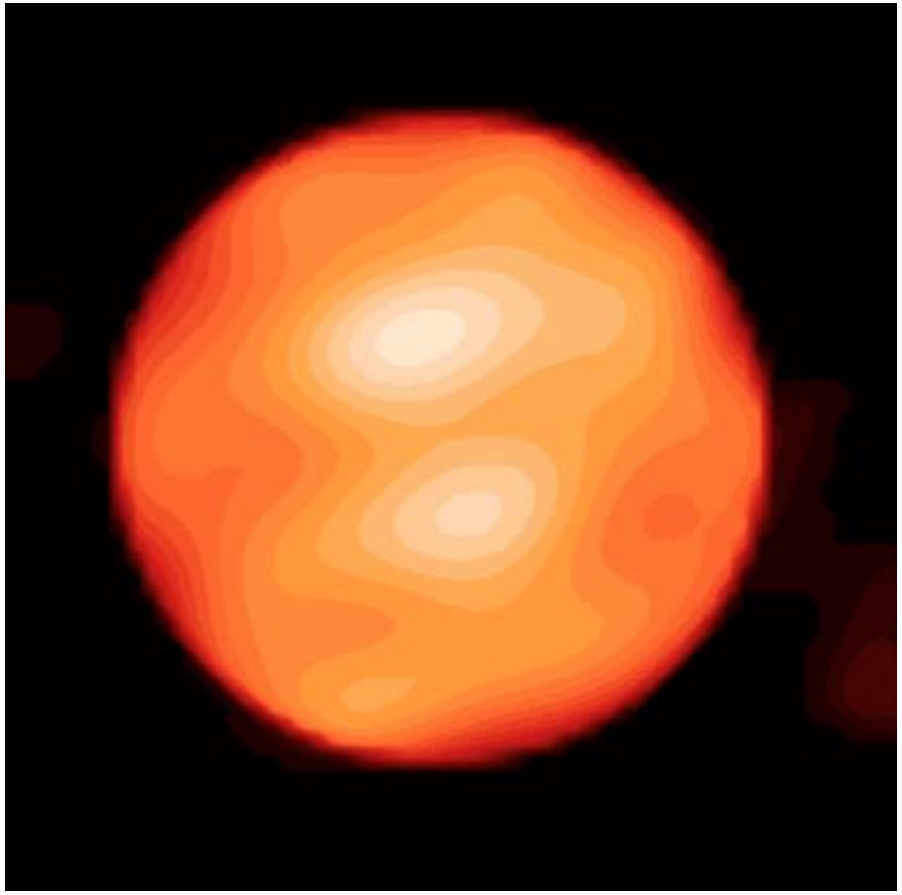
•Spots present at all λ



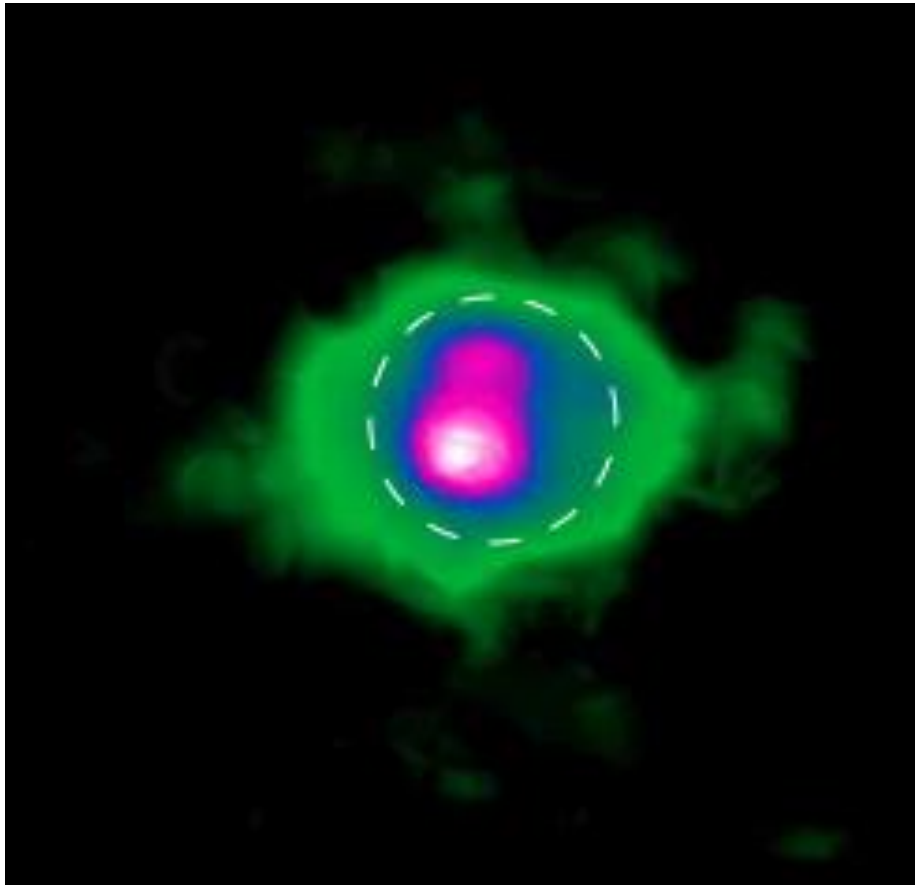
Chiavassa++2009@VLTI/AMBER

Impact of Adding an Additional Telescope

3 telescope image: sharp edge due to mask



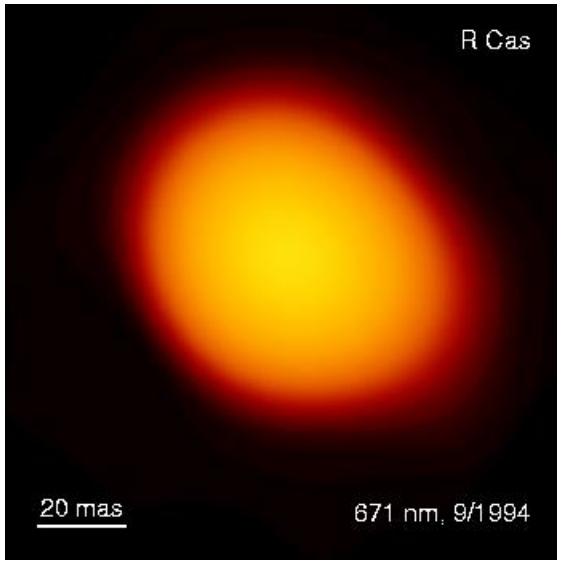
4 telescope image, no model added



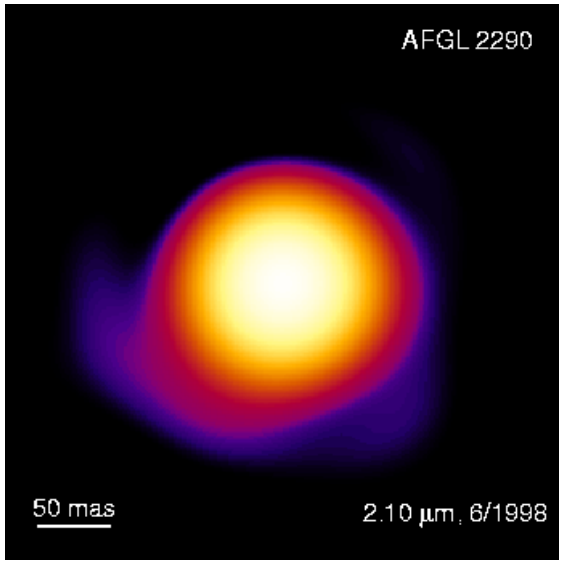
Monnier++2014
@VLTI/PIONIER

First images of AGB stars

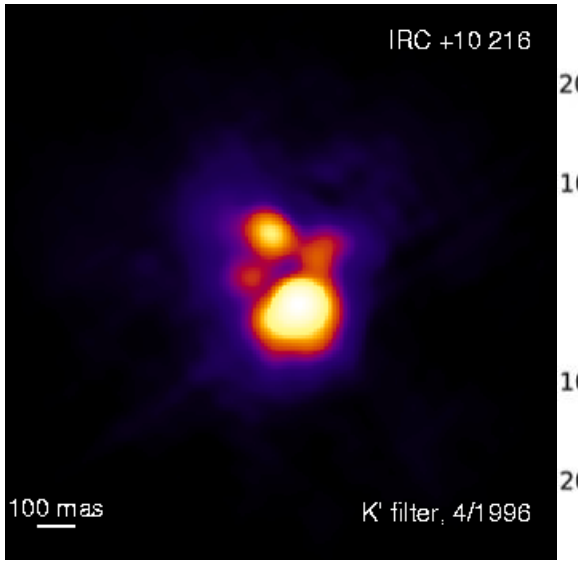
Focused on detecting photosphere-adjacent shells using prior knowledge.



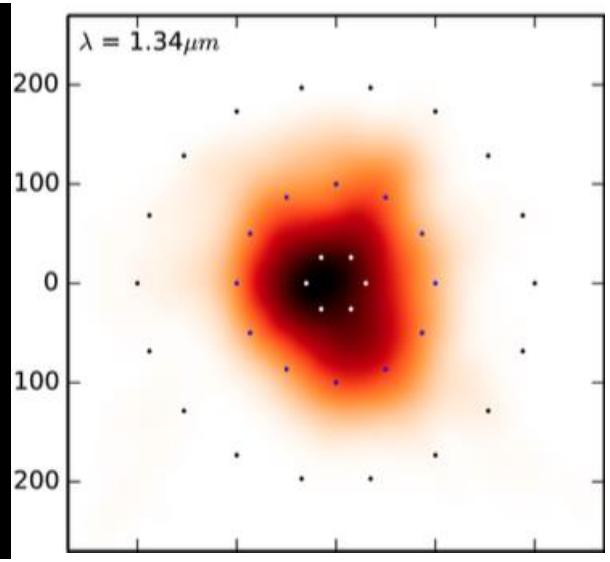
Mira star R Cas
Weigelt++1996



AFGL 2290
Gauger++1999

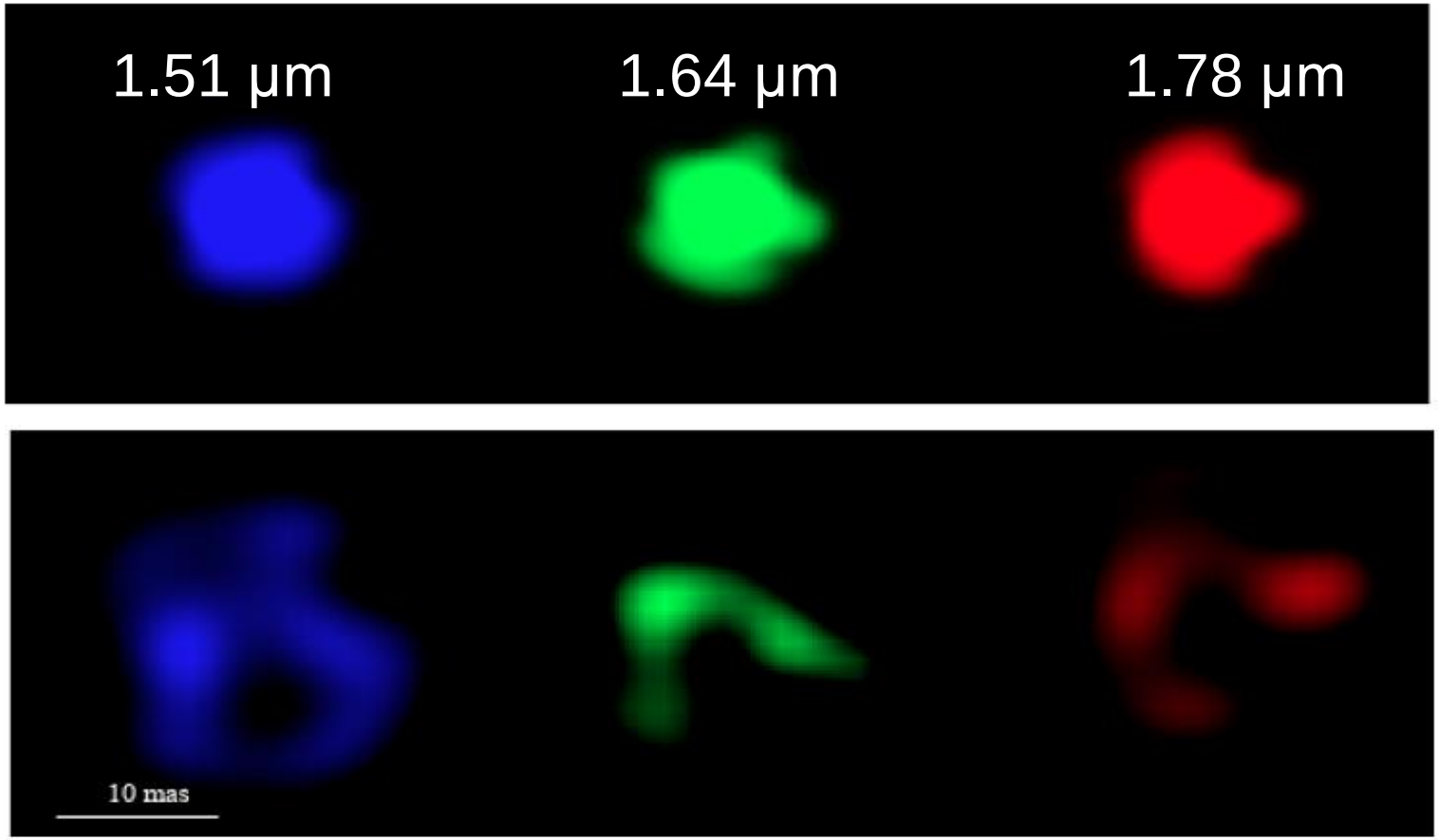


IRC+10216
Weigelt++1998



Mira
Stewart++2016

Asymmetric shell around R Aqr

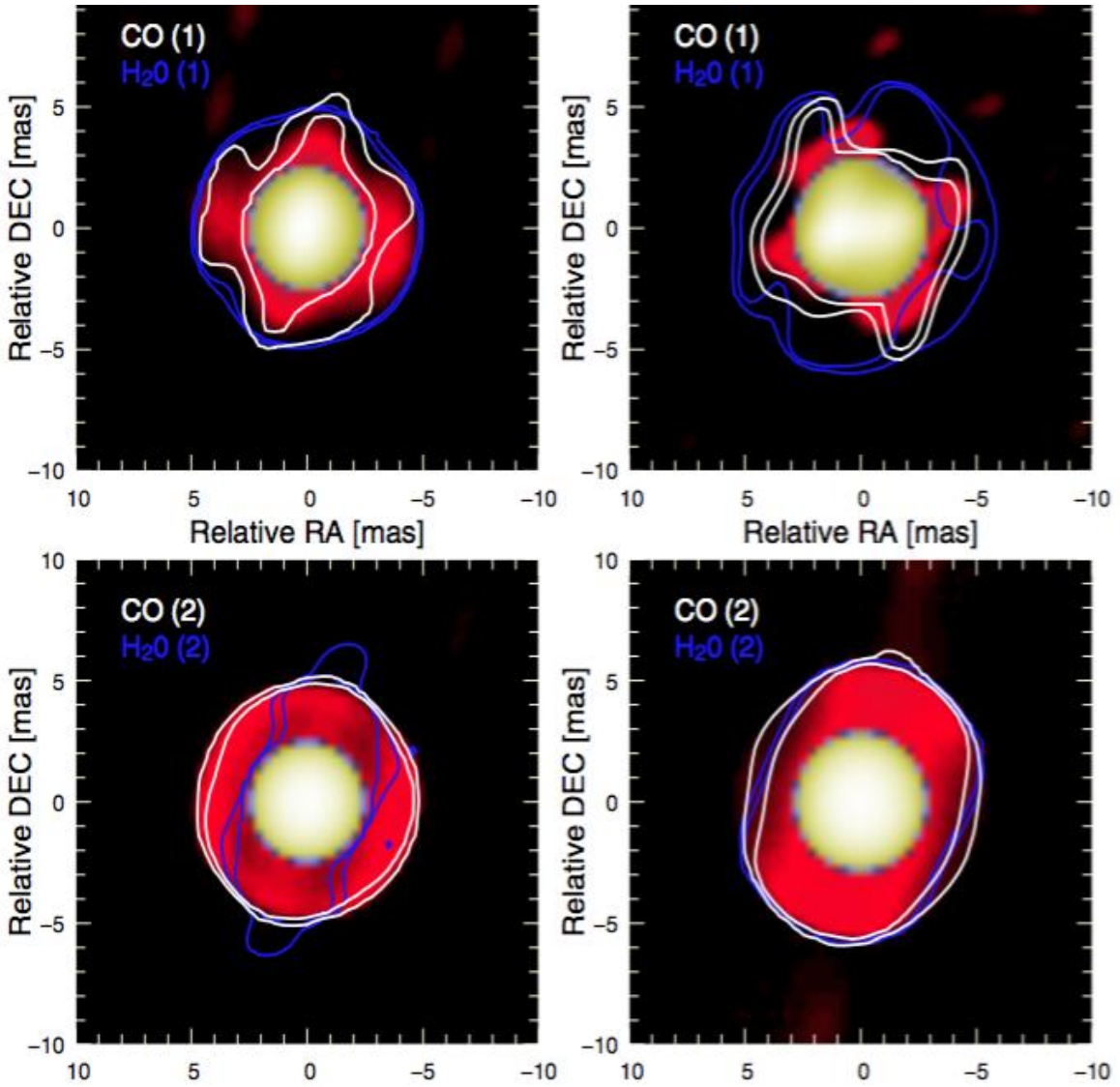


Ragland++2008@IOTA

Variability

- 3T H & K Bands
- Model dependent reconstruction

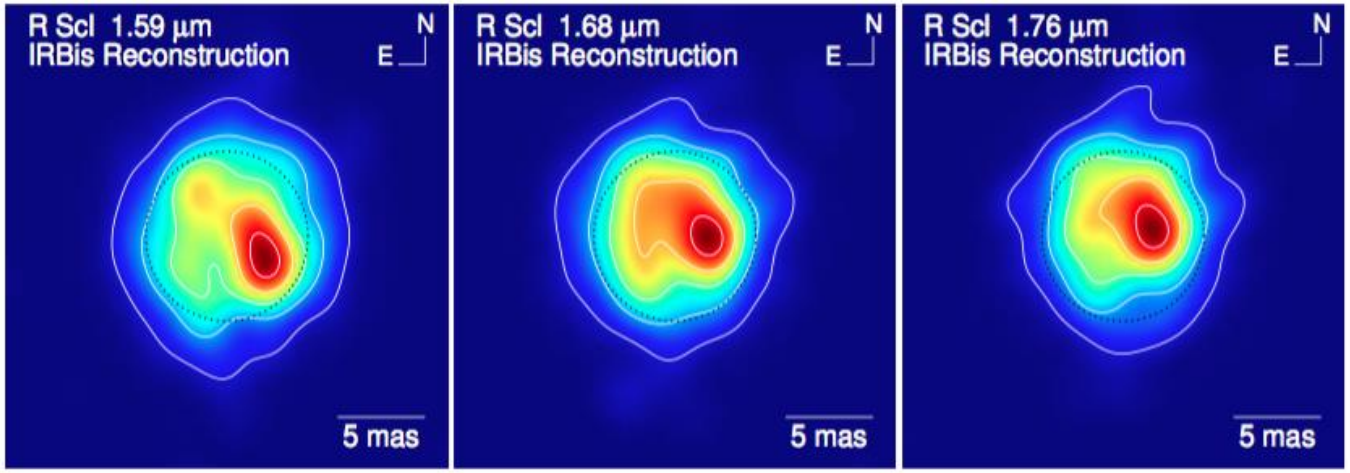
- Asymmetric signatures more pronounced after maximum
- No discontinuity between surface and shell (Le Bouquin++2009)
- Unresolved spots, 2-3% total flux



Haubois++2016@VLTI/AMBER

The surface of R Scl

- 4Telescopes H-Band
  - Model independent reconstruction
  - Wavelength independent
  - Contrast 40-60%
- Estimated using cut-off radius
  - Comparison with 1D models
  - Stellar parameter estimation

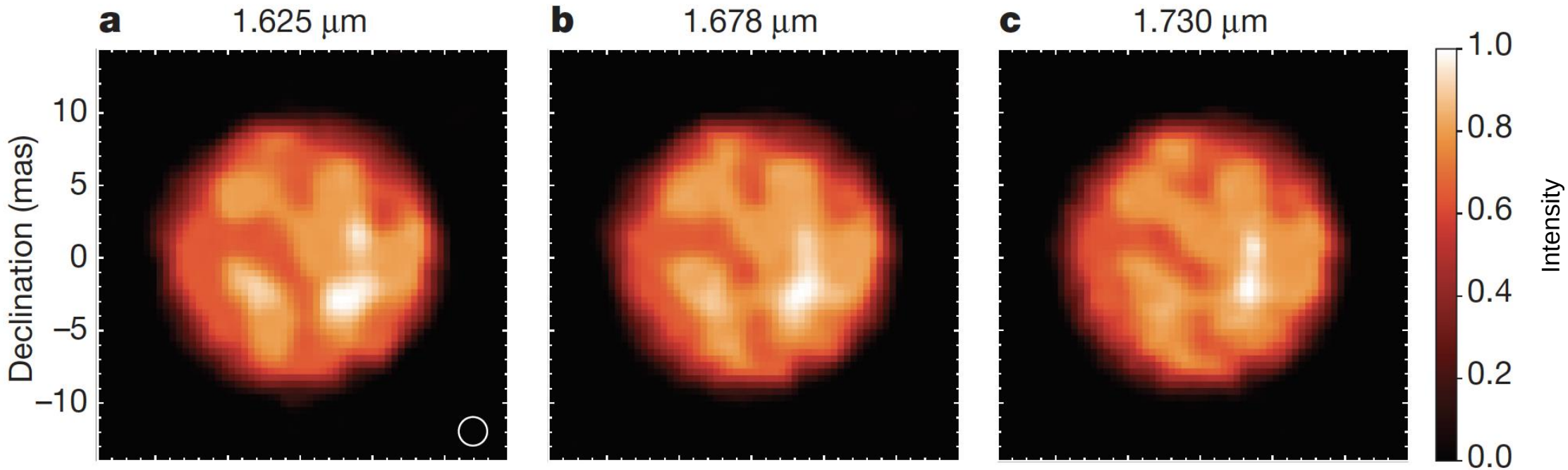


RScl is a carbon star, the spectrum is contaminated by molecules and dust. Hard to see the stellar photosphere

Wittkowski ++ 2017@VLTI/PIONIER

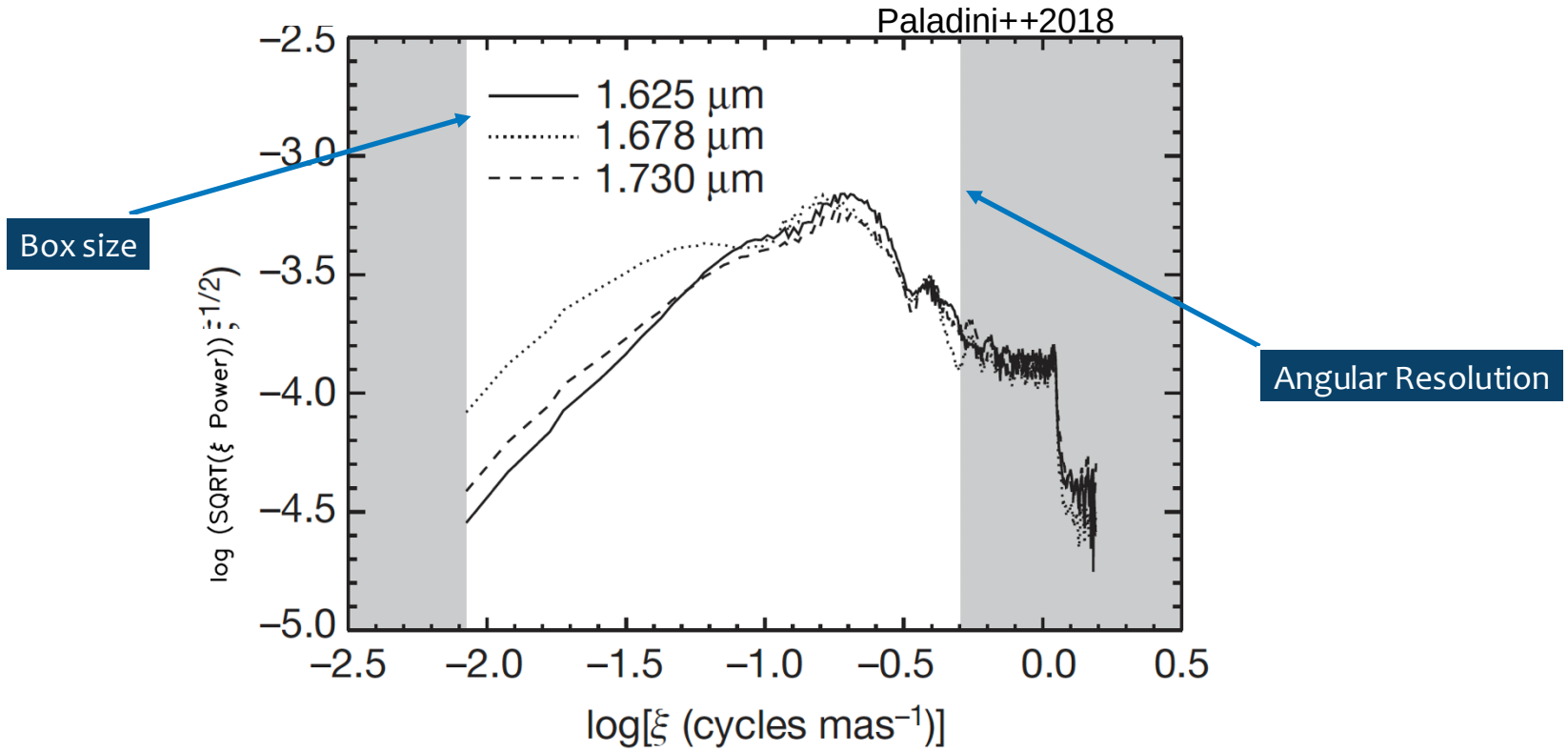
Constraining convection theory

The surface of pi[1] Gru @PIONIER



Paladini++2018

Granulation size from power spectrum density

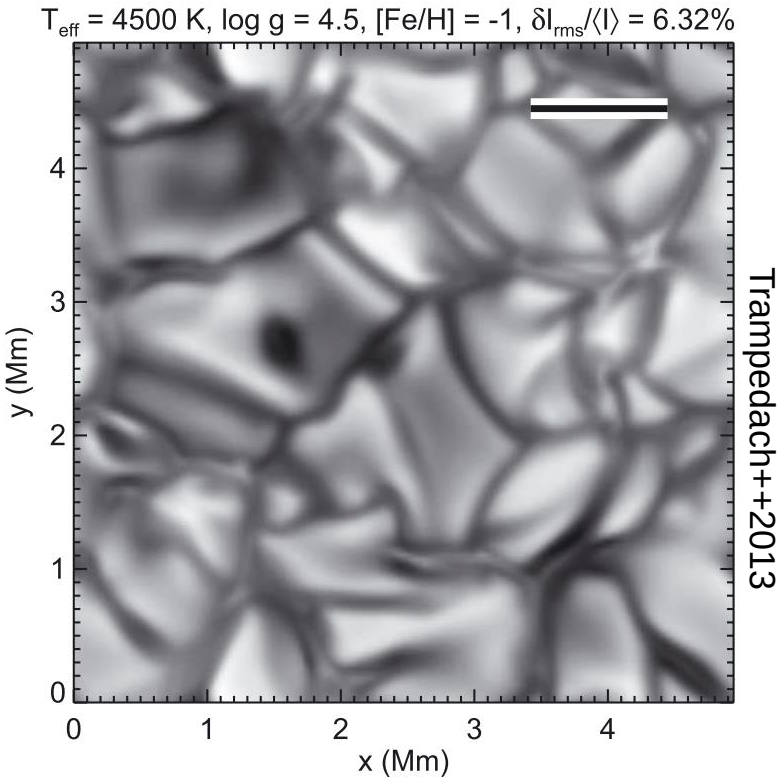


Granulation size = $5.3 \pm 0.5\ mas$ = 1.2 x 10^{11} m

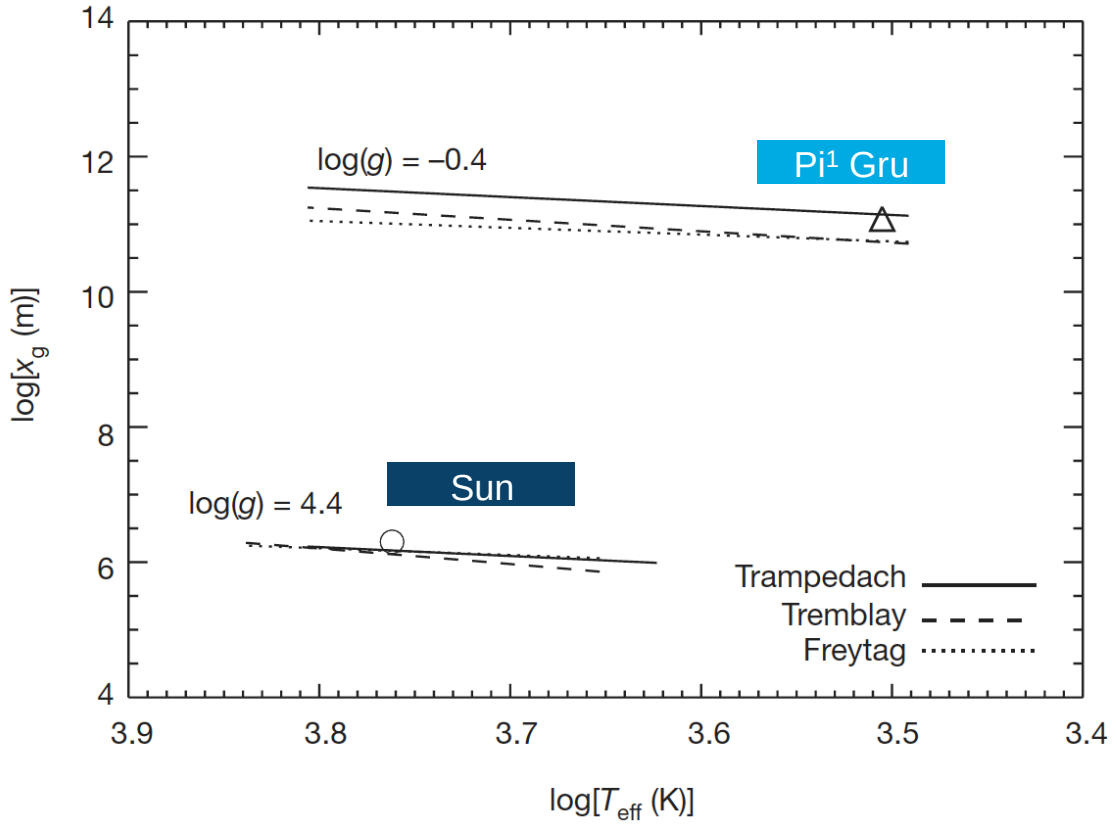
Granulation size across the HR-diagram

Model grids of convection NOT covering pi[1] Gru parameter space

Freytag++1997, Trampedach++2013, Tremblay++2013 provide parametric formulas relating the granulation size to the stellar parameters



Granule scale vs. stellar parameters

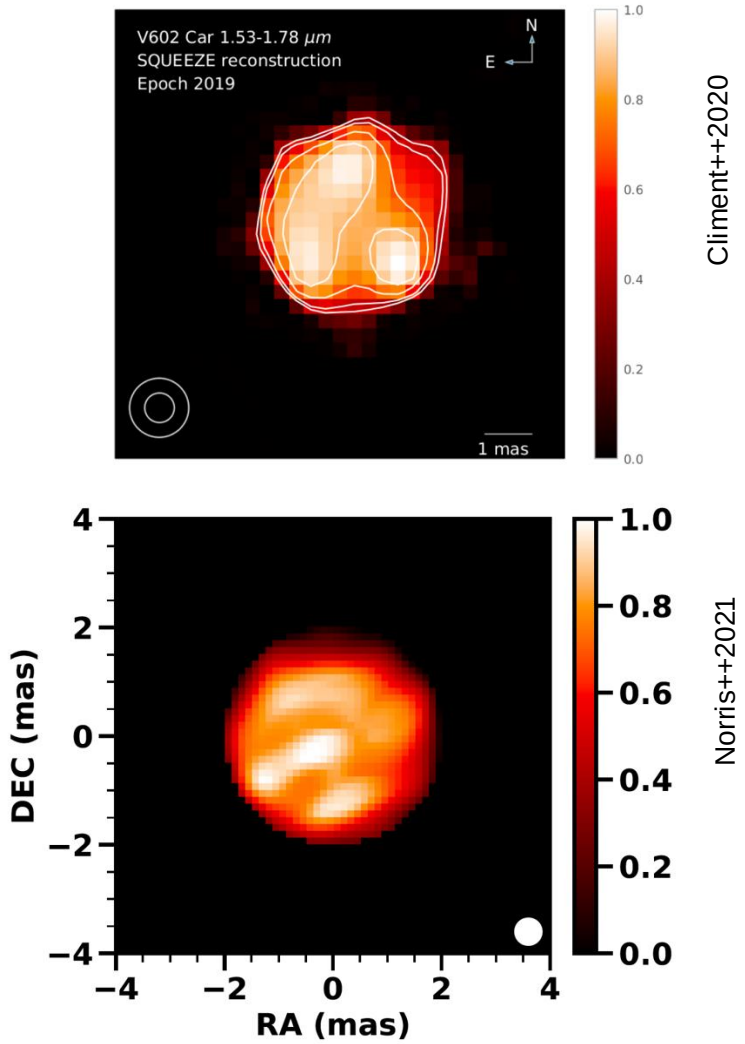


Paladini++2018

The case of Red Supergiants (RSG)

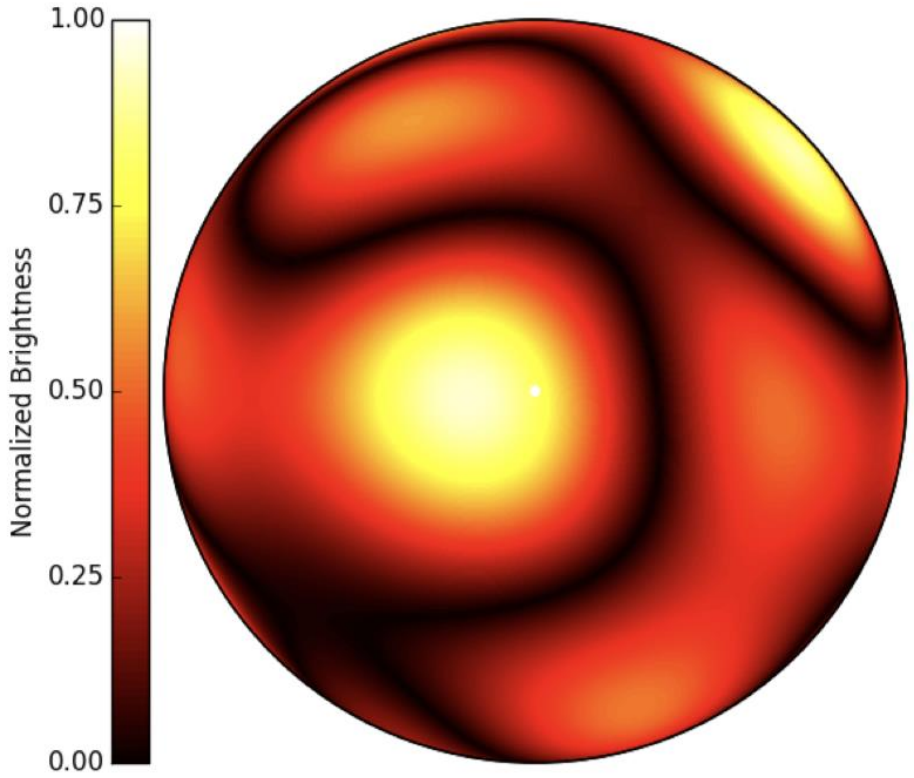
Red Supergiants do not fit the model predictions

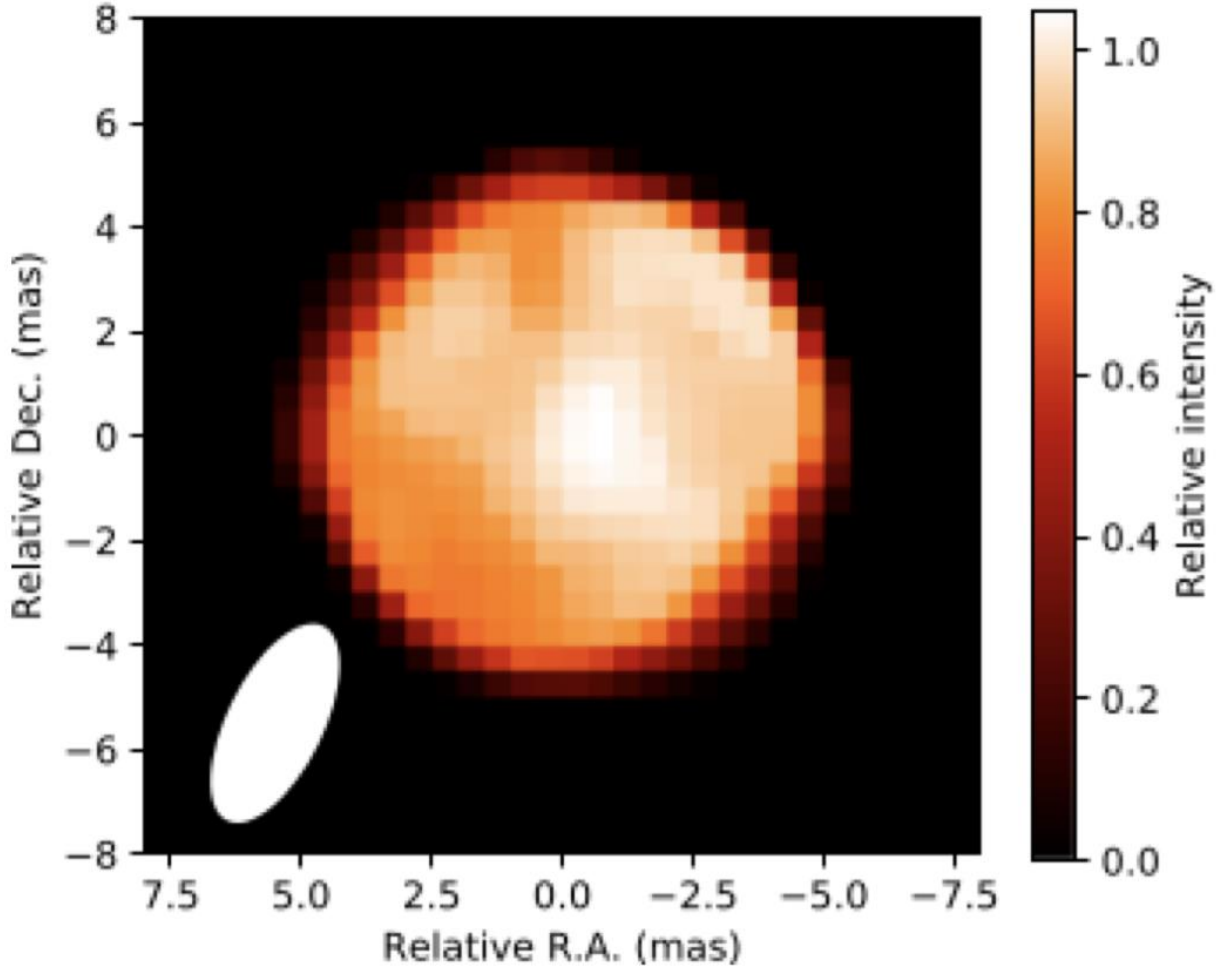
- Size measured are larger than predictions by factor of 5
- Physical limitation of the observations or underlying physical difference of processes for AGB vs RSG?



Convection & magnetic field in RSG

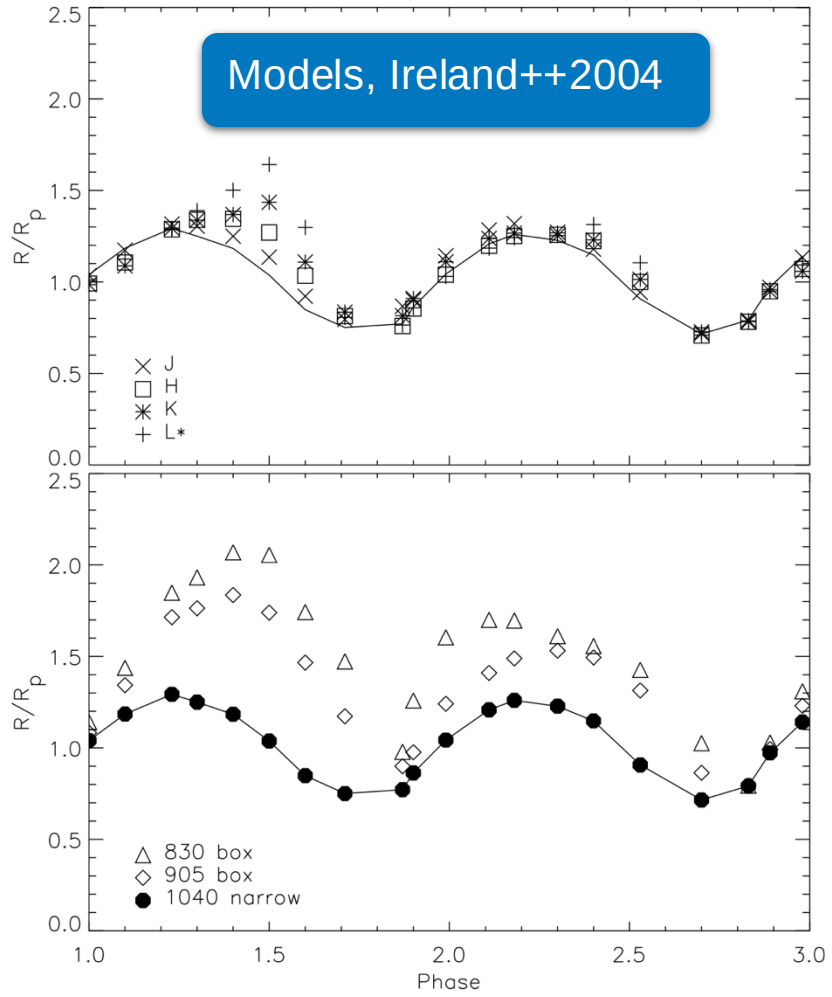
Lopez-Ariste ++2018

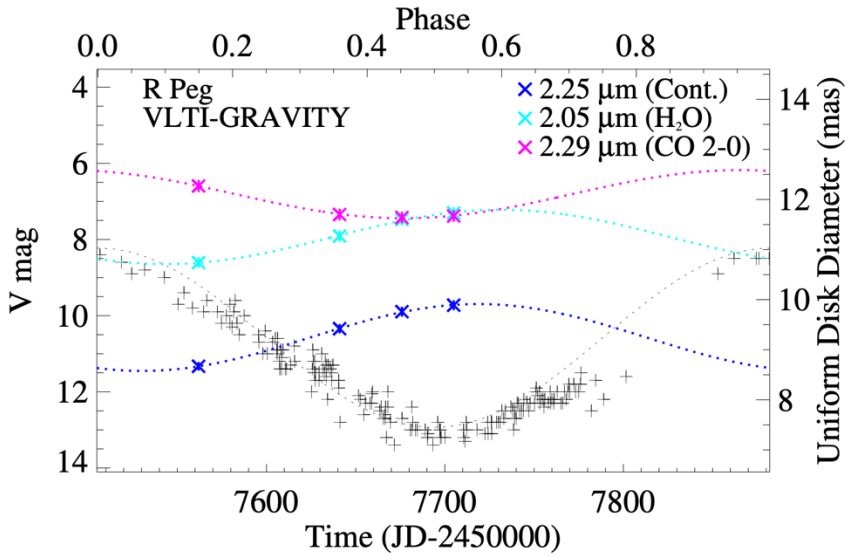




Not so obvious for AGBs

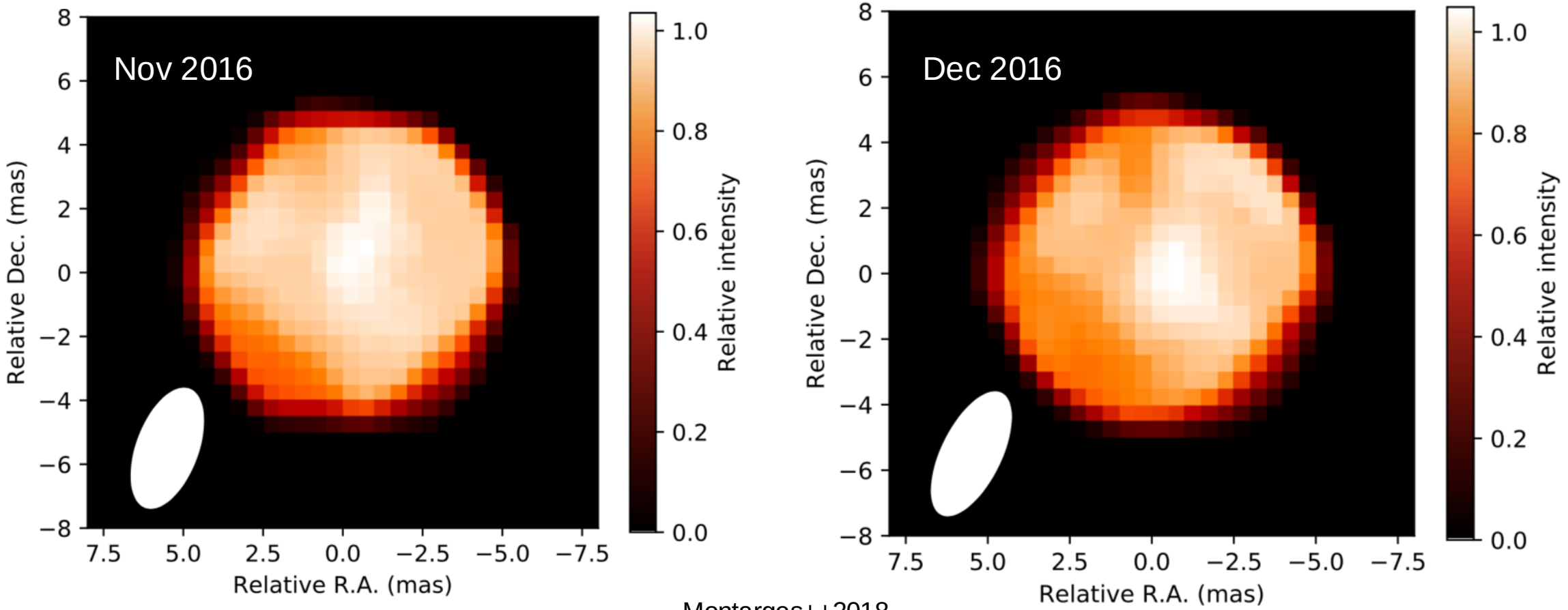
Time domain: diameter changes with pulsation





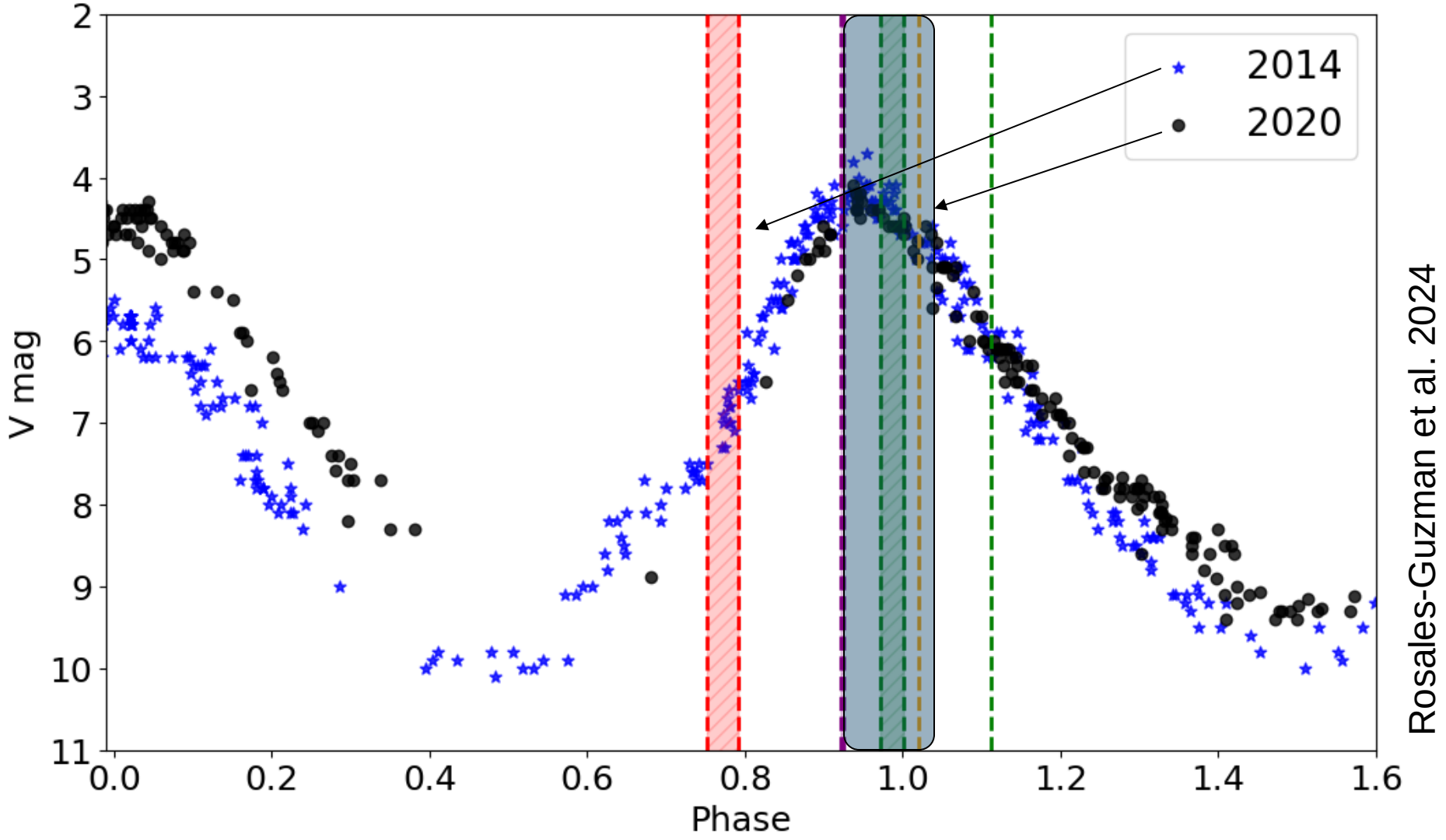
GRAVITY results Wittkowski++2018: anticorrelation between diameter and lightcurve

Time domain: convection time scales in RSG



Montarges++2018

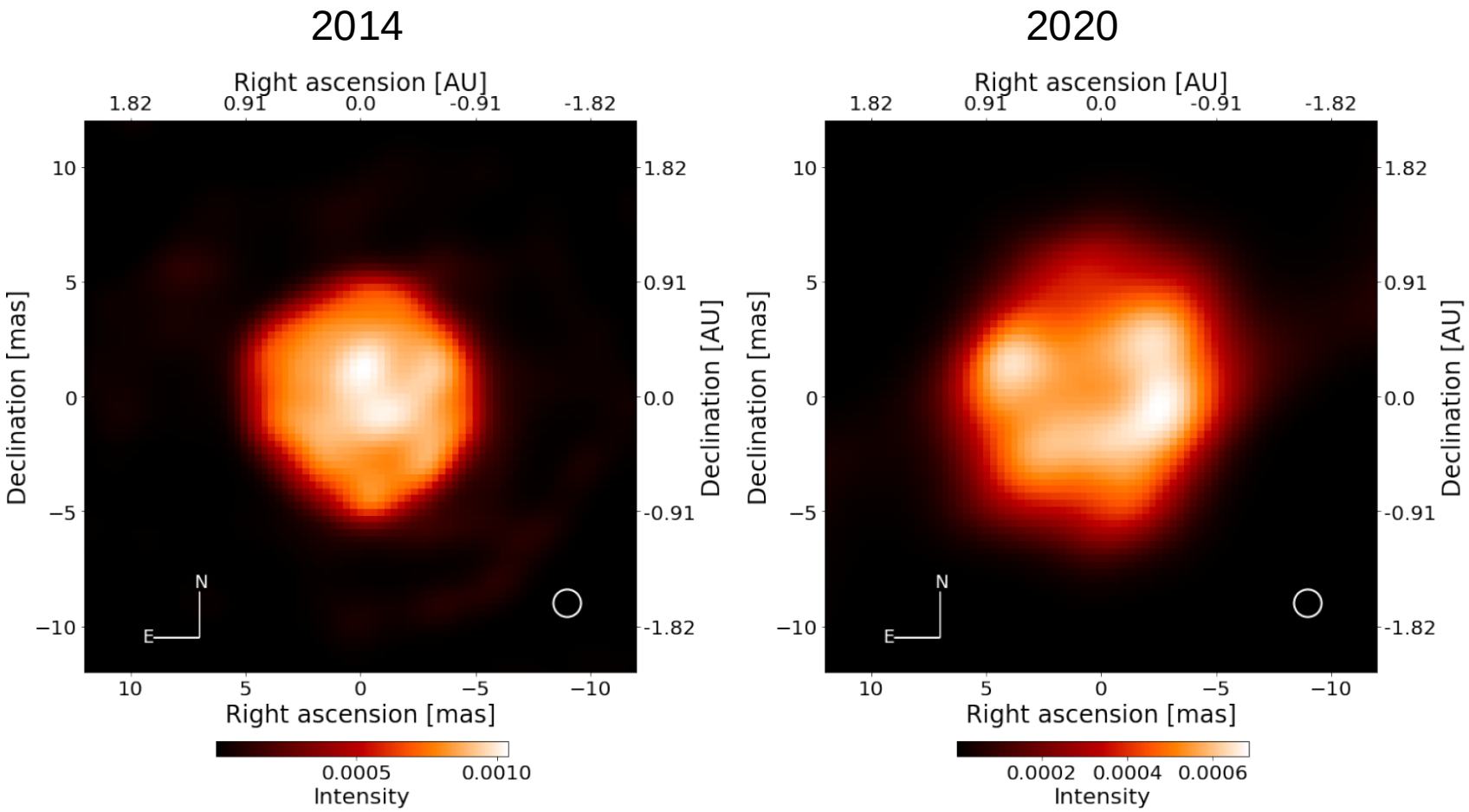
Necessity is the mother of invention



Rosales-Guzman et al. 2024

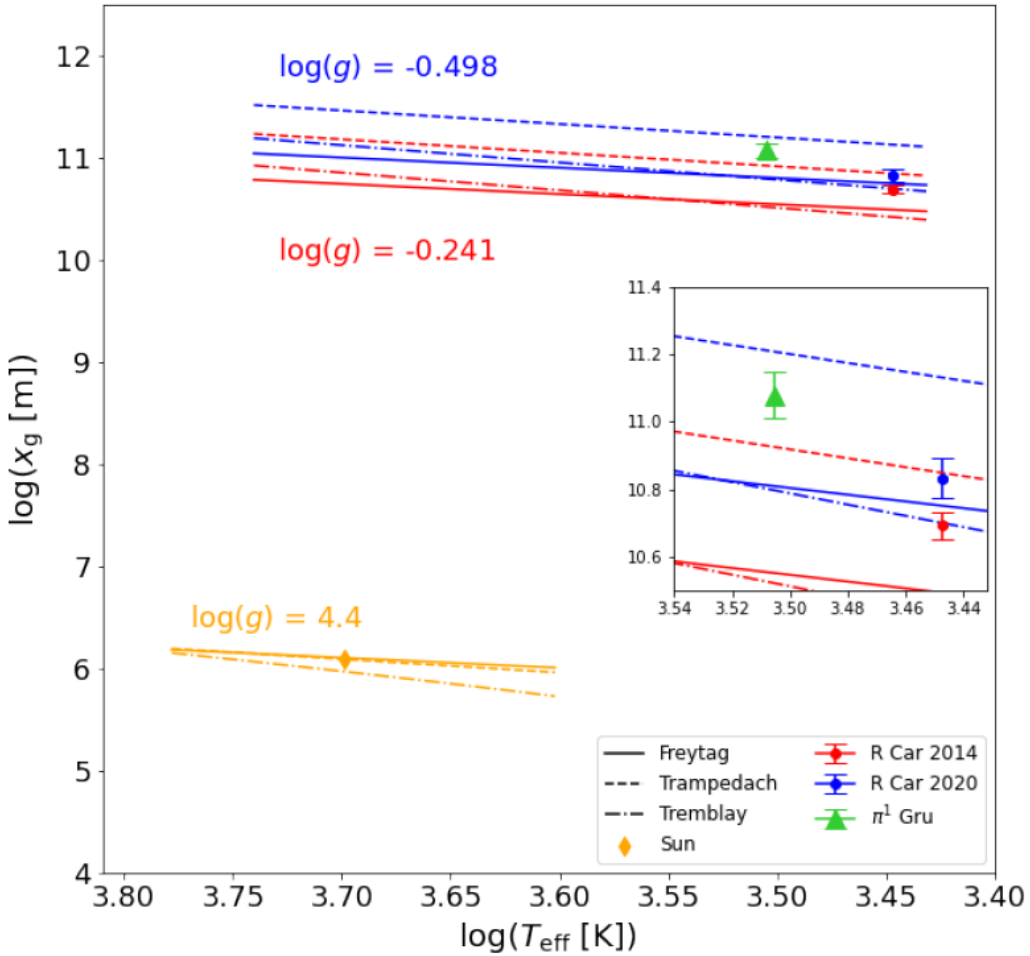
Variation in Star Diameter and Convection Scale

(Rosales-Guzman et al. 2024)

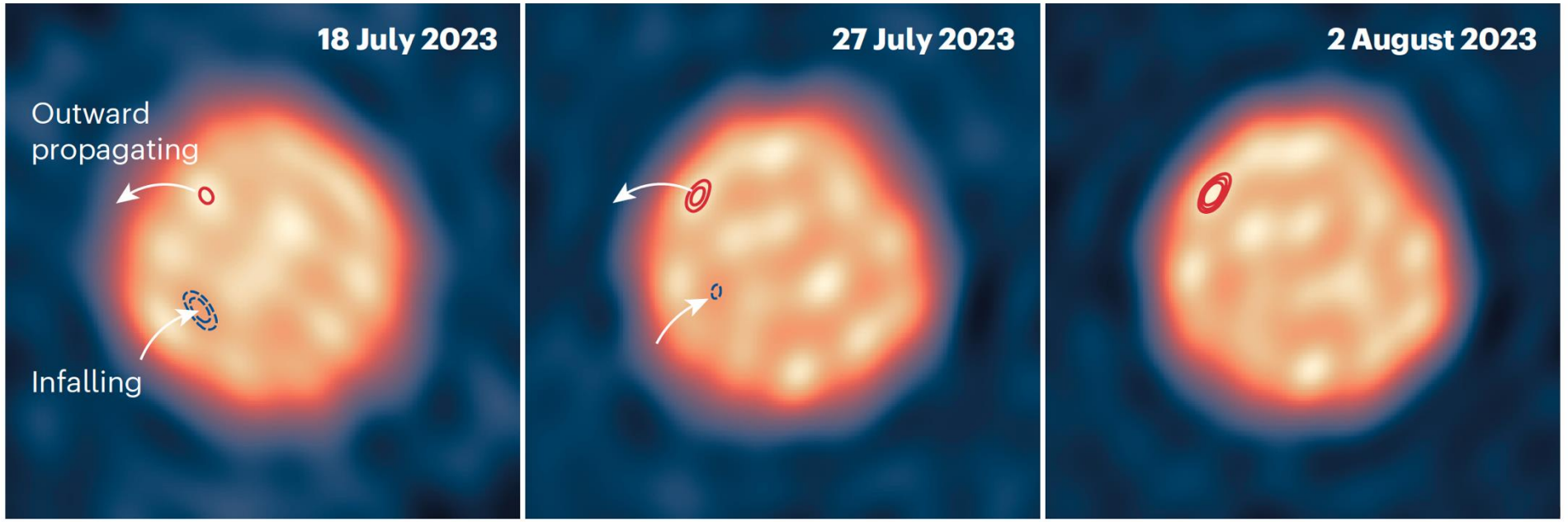


Star is smaller pre-maximum phase (2014)
and larger after the maximum (2020) confirming models

R Car versus the literature



ALMA sharpest eye unveil the face of R Dor



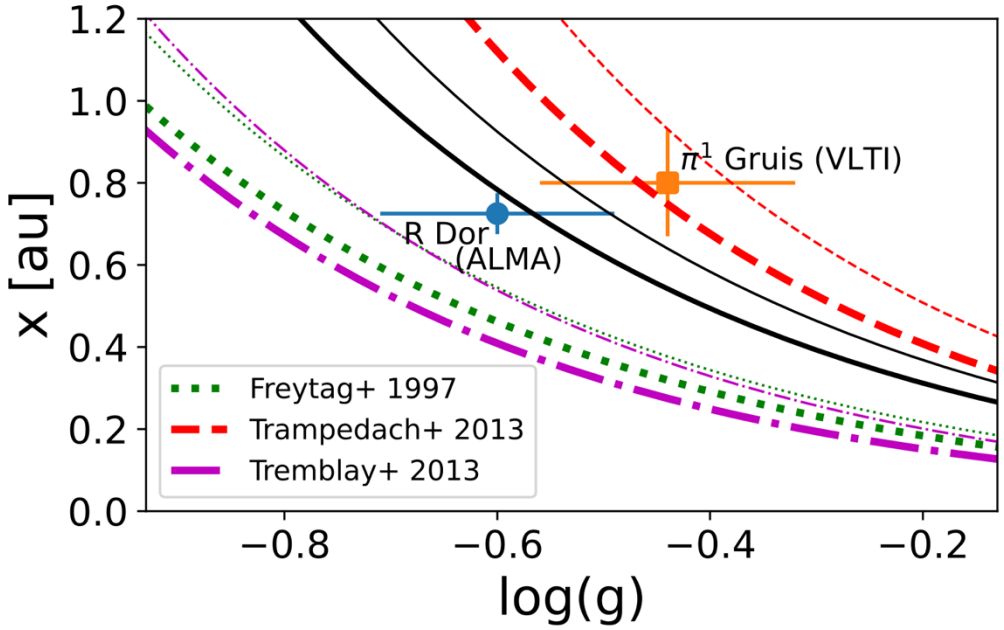
Vlemmings et al. 2024

Constraining convection theory

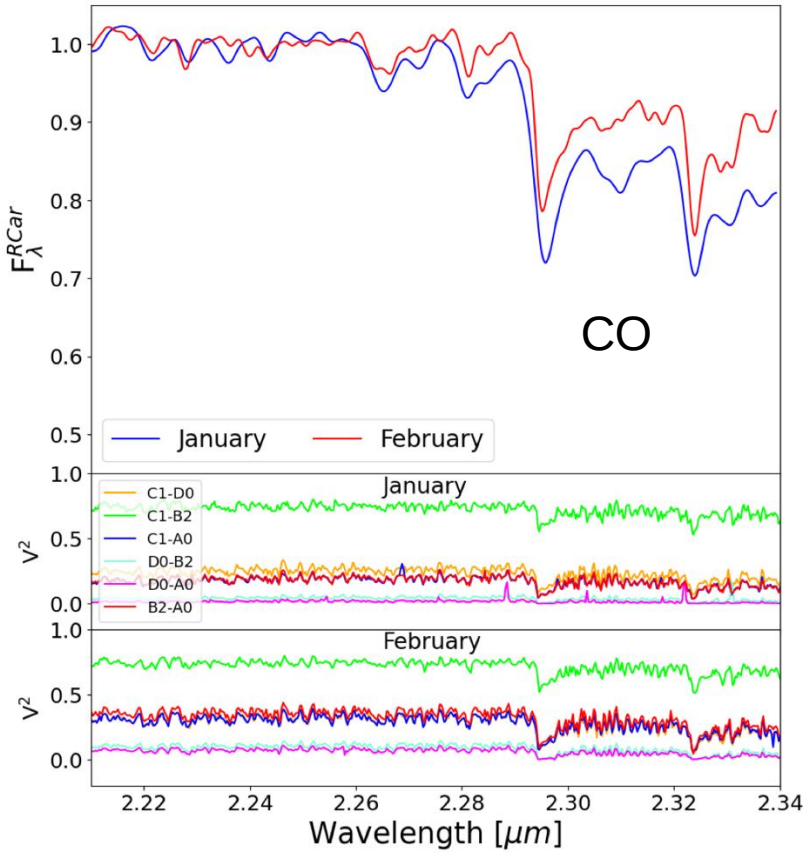
- The size of the granulation scales with the pressure scale height Hp immediately below the photosphere

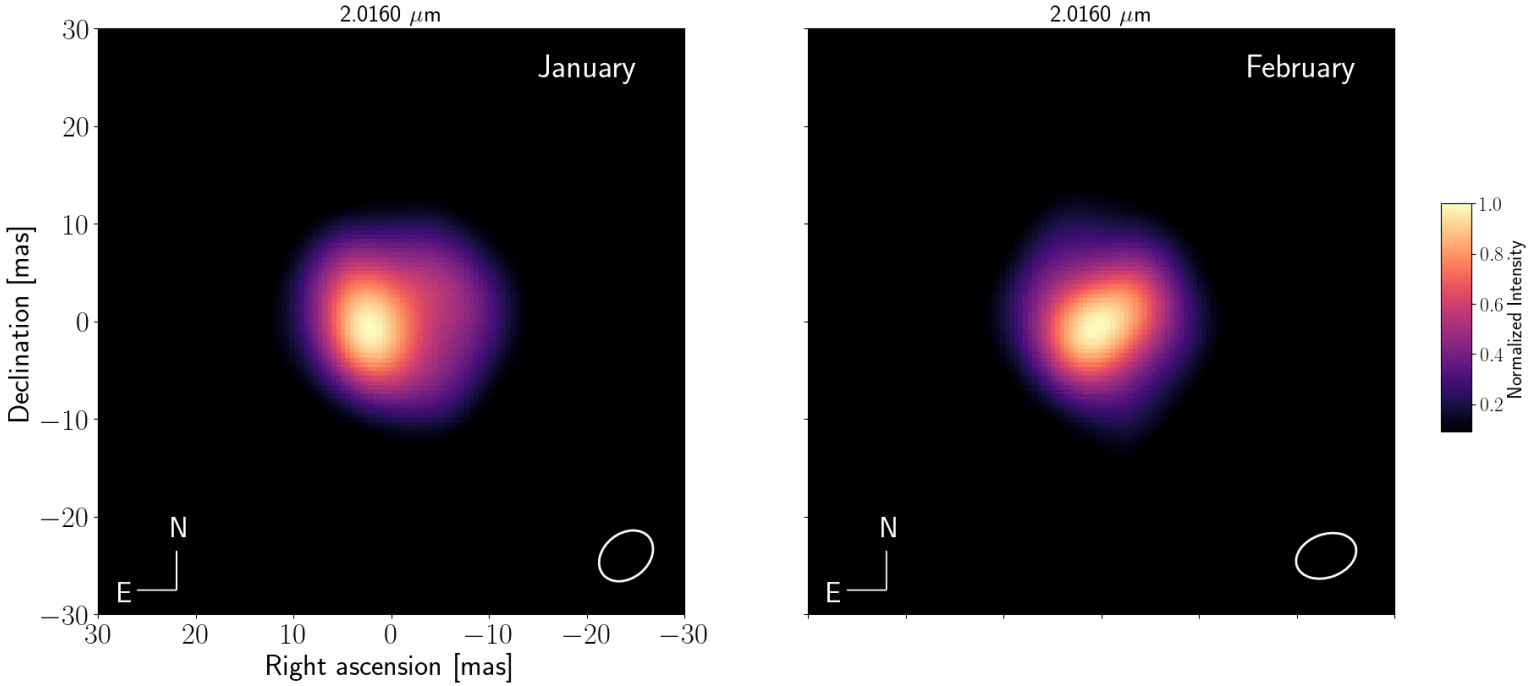
$$x = \alpha H_p$$

- α is parametrised in stellar evolutionary codes. Assumed to be 1 for the Sun, 10 for AGBs.
- By fitting the measured values there is evidence that the value for AGBs is ~ 17 (Vlemmings++2024).
- Red Super Giants have values going up to 30 or 50… pending confirmation from angular resolution
- Recently convection spatially resolved on the surface of a Cepheid (Evans++2024)



Adding spectral and angular resolution

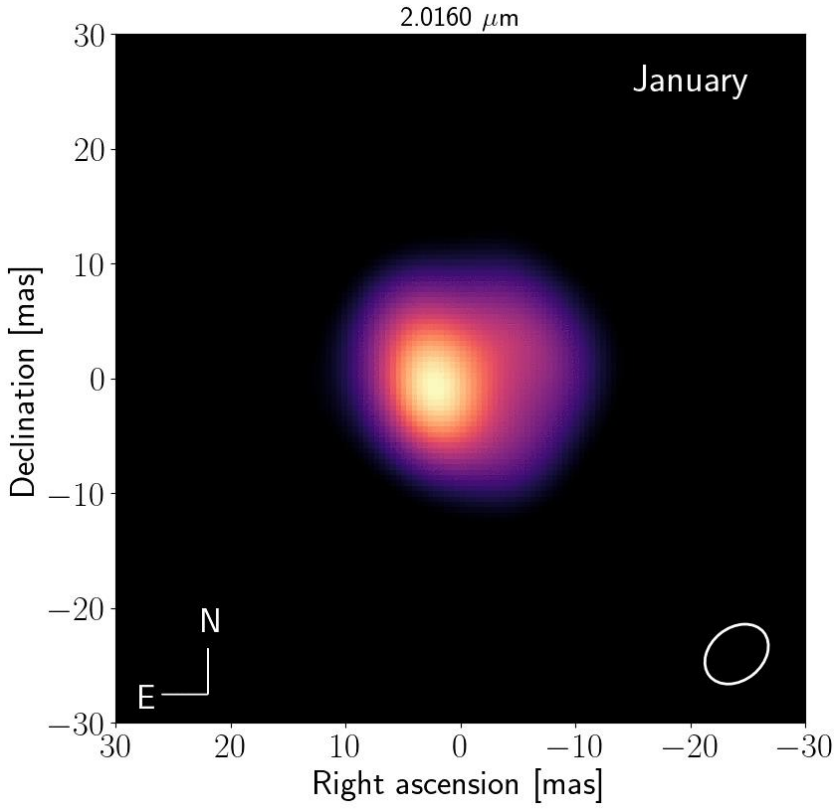




Rosales-Guzman et al. 2023

Take home messages

- Nowadays studies of stellar surfaces are going beyond diameter measurements
- Potential to constraint the mixing length theory & do asteroseismology from interferometric images
- Convection studies on RSG limited by angular resolution
- Connection between magnetic field and convection in RSG is detected
- Future: adding the spectral resolution dimension to study the vertical stratification (molecules, atoms, dust)



Rosales-Guzman et al. 2023

Thank you!

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