Perspectives on evolved stars

Astrophysical Masers: Unlocking the Mysteries of the Universe
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7 September 2017

Scope/oultine of the talk

Overview of some recent results in the field based on:

- long baseline infrared interferometry
- adaptive optics and/or aperture masking in the visible and near-infrared
- ALMA
- spectro-polarimetry

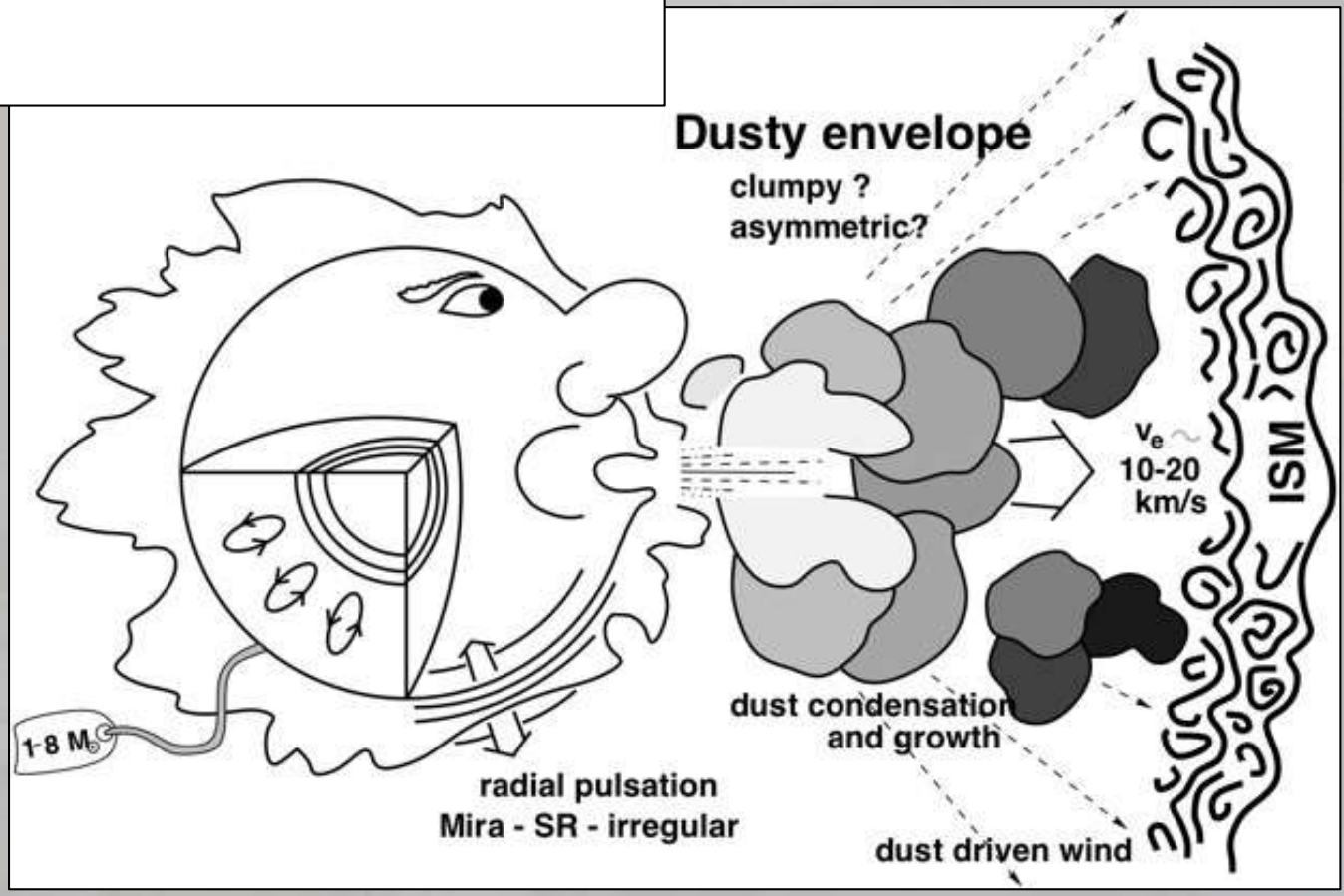
For AGB and RSG stars

Connection with masers

Draw a few perspectives and conclusions

Mass loss in AGB stars

role of convection? how can it be detected (spots, timescale?)
where does the dust form?
what kind of dust?
origin of asymmetries of post-AGBs and PNs?
binarity?
…



http://kaze.physics.iastate.edu/mmarengo/agb.html

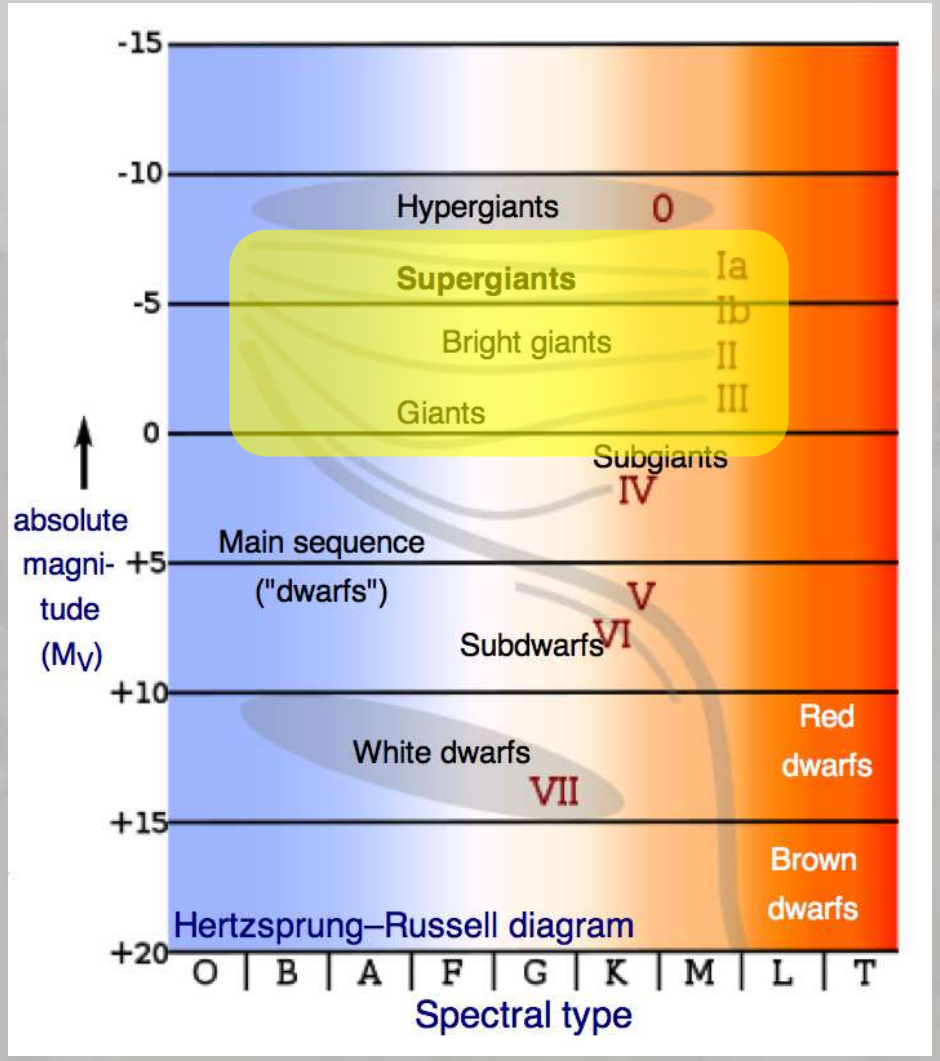
Mass loss in Red Super Giant stars

A still elusive mechanism:

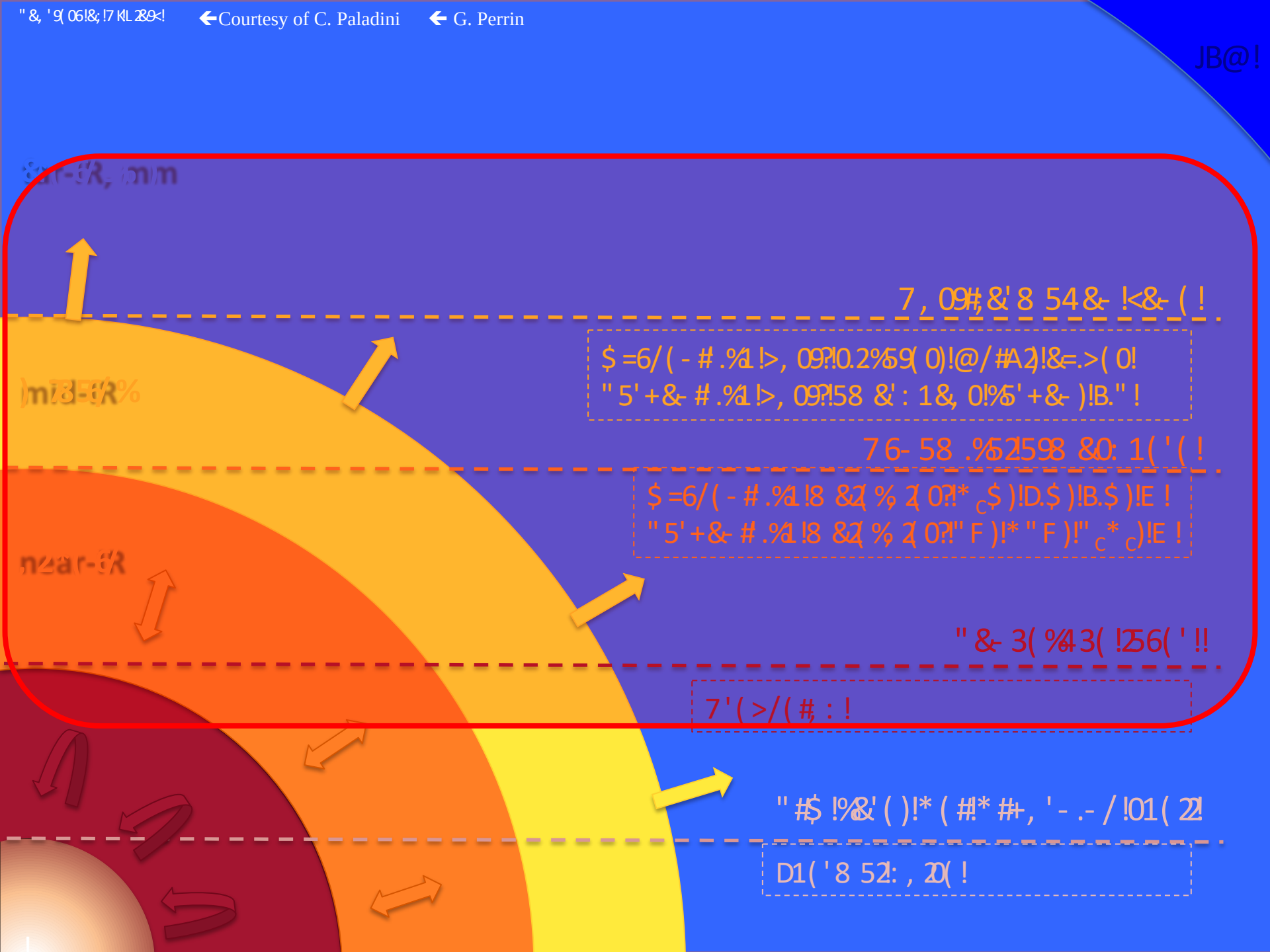
- the physical process remains unknown (no large pulsations)
- Josselin & Plez (2007) suggested a convection triggered mass loss
- Airapetian et al. (2000): Alfvén-wave triggered outflow

- → Study of the photosphere + circumstellar environment + magnetic field

We are lucky: AGBs and RSGs are big and bright



High Angular Resolution techniques needed to resolve stars to ~1/10th R* (convection, dust clumps, B …)


←Courtesy of C. Paladini
← G. Perrin
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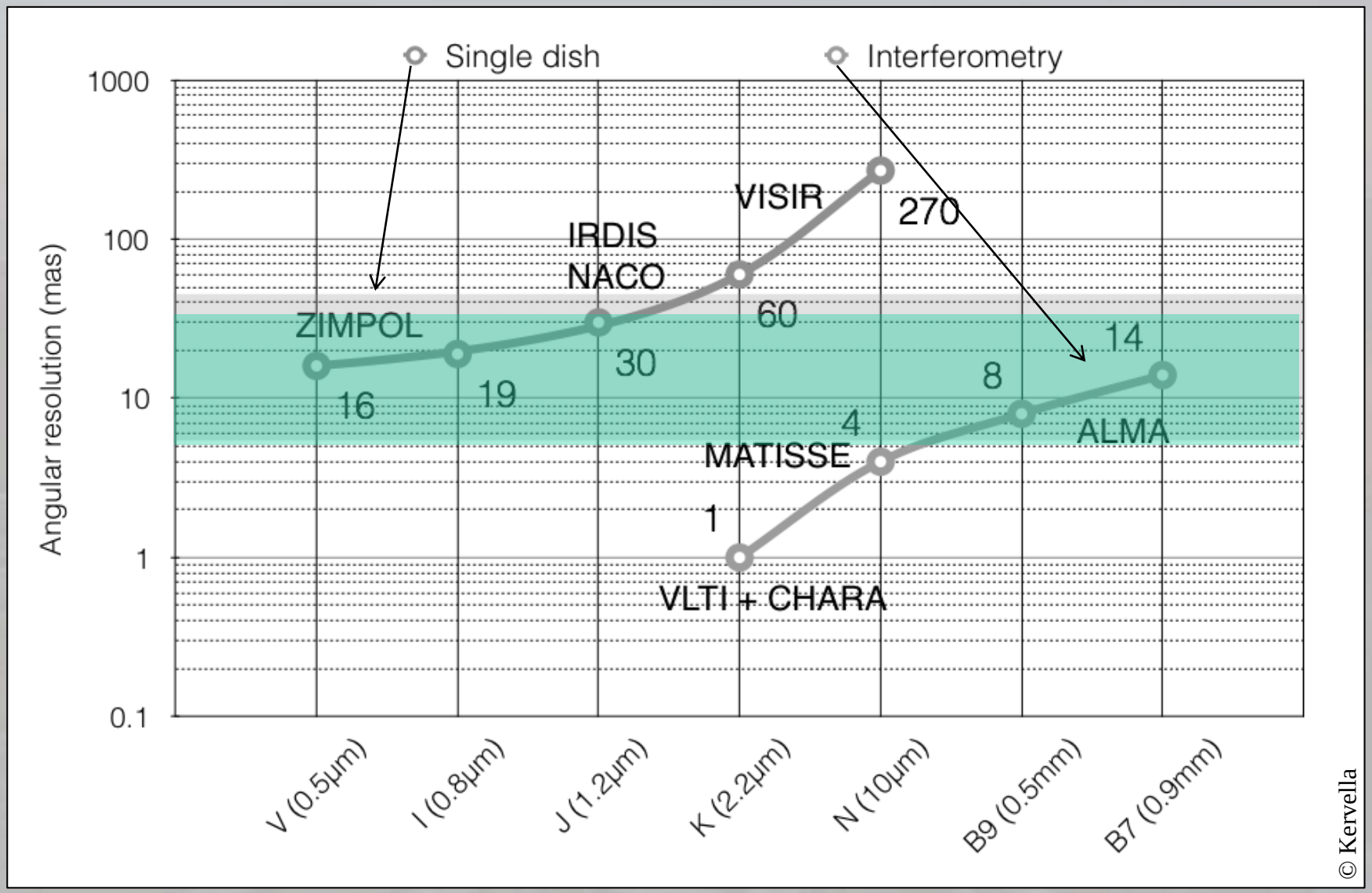
Angular resolutions



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Observations with long baseline interferometers at infrared wavelengths

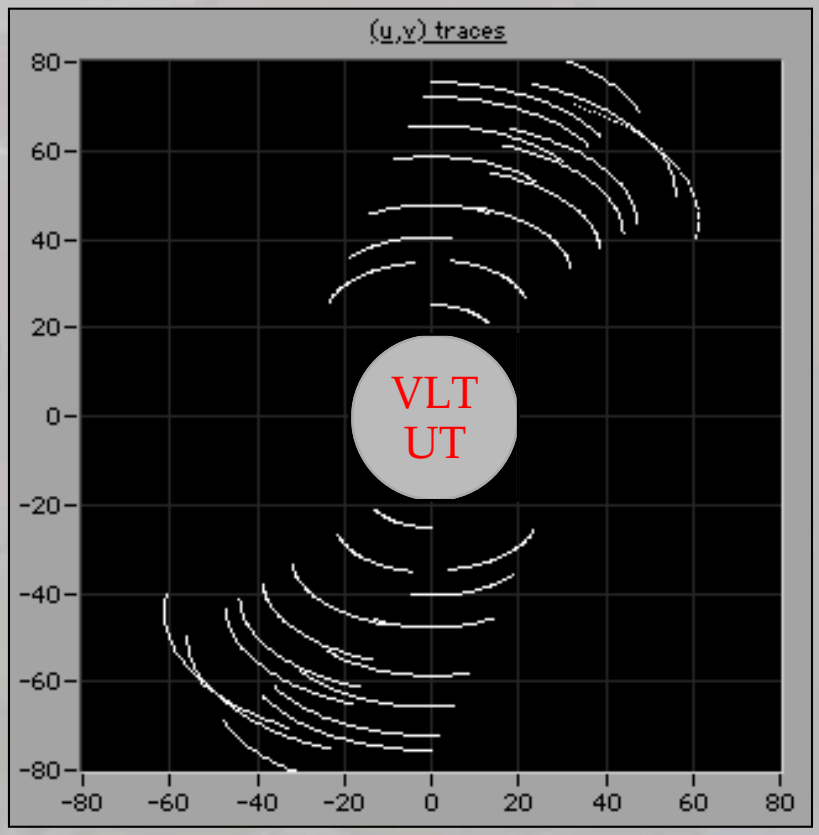
(no imaging first)



Mont Hopkins
Arizona

IOTA

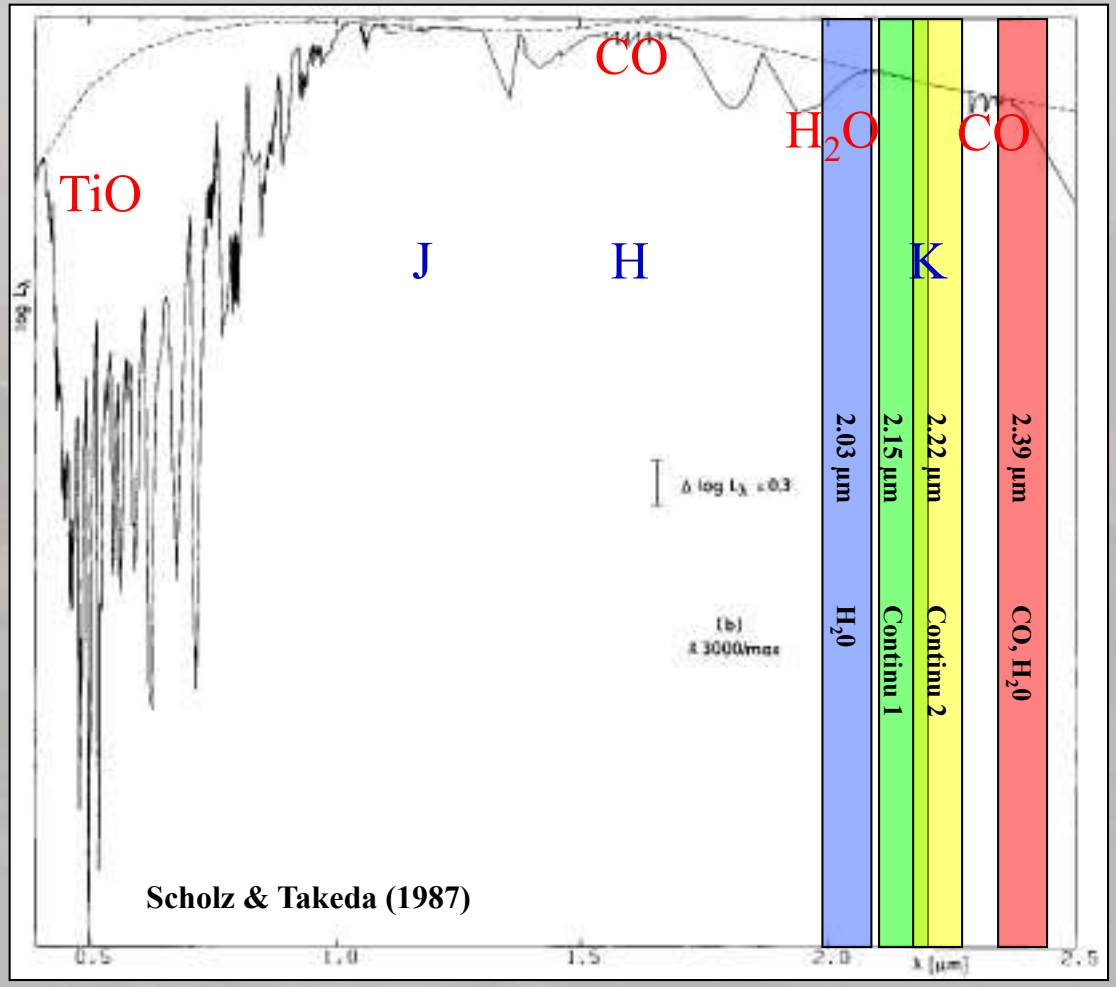
Infrared and Optical Telescope Array



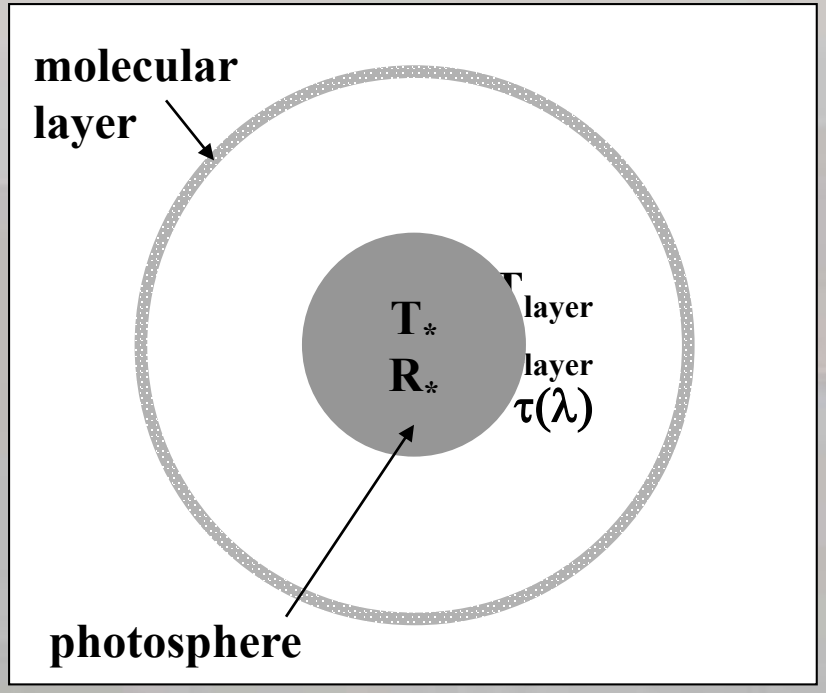
- 3 movable 45 cm siderostats
- Minimum baseline: 5 m
- Maximum baseline: 38 m
- Resolution in K band: 12 mas

- Passed away in July 2006!

Observations of Mira stars in narrow bands in K

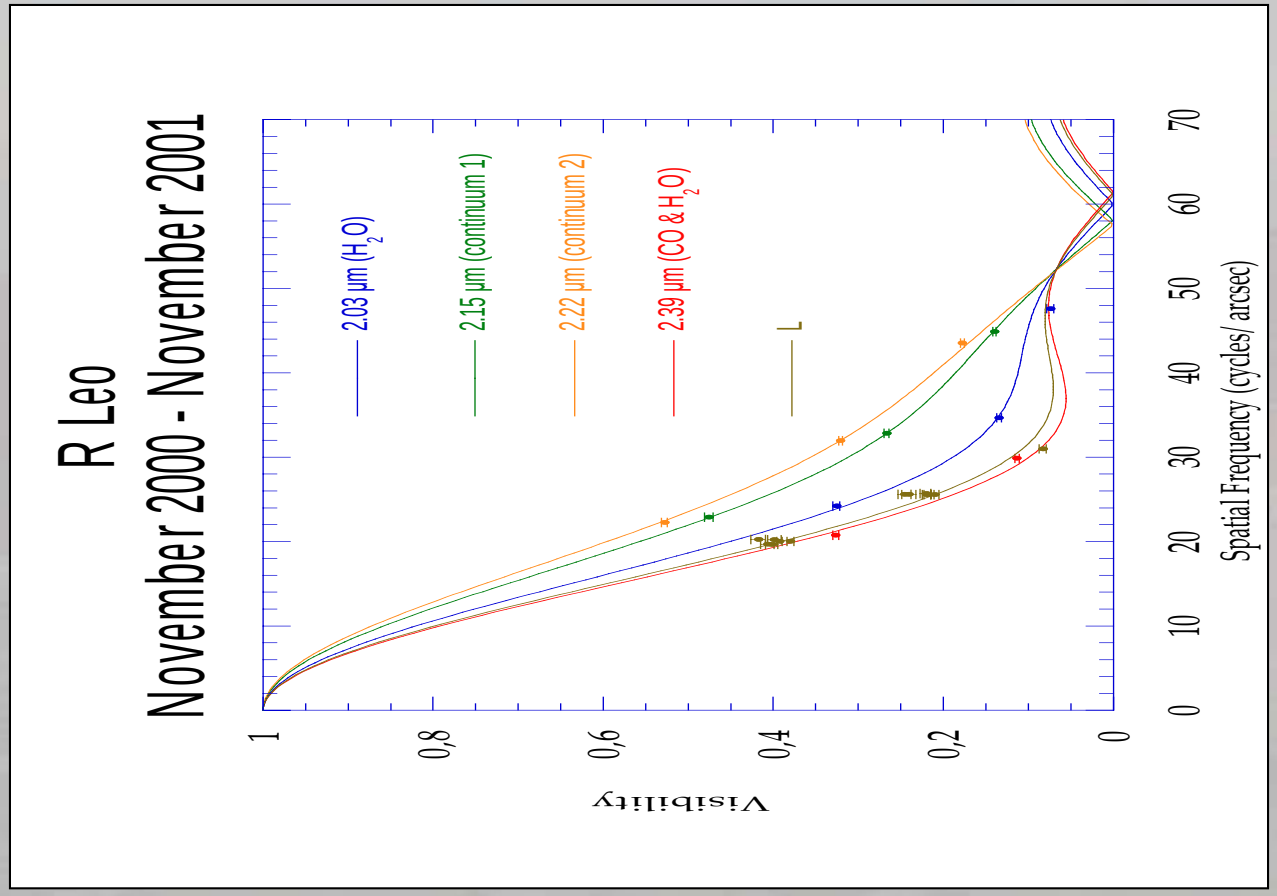


Simple toy model: photosphere + molecular shell



R Leo in L band and K narrow bands

(Perrin et al. 2004, A&A 426, 279)



$\tau_{2.03\mu m} = 1.19 \pm 0.01$

$\tau_{2.15\mu m} = 0.51 \pm 0.01$

$\tau_{2.22\mu m} = 0.33 \pm 0.01$

$\tau_{2.39\mu m} = 1.37 \pm 0.01$

$\tau_{L} = 0.63 \pm 0.01$

$R_{layer}/R_* = 2.4$

R_* = 10.94±0.85 mas **R_{layer} = 25.00±0.17mas**

T_* = 3856±119 K **T_{layer} = 1598±24 K**

Phase K: 0.79

Phase L: 0.64

Type: M0-M1

VLTI

First generation (2T): MIDI N & (3T): AMBER (J)HK with up to R=12000

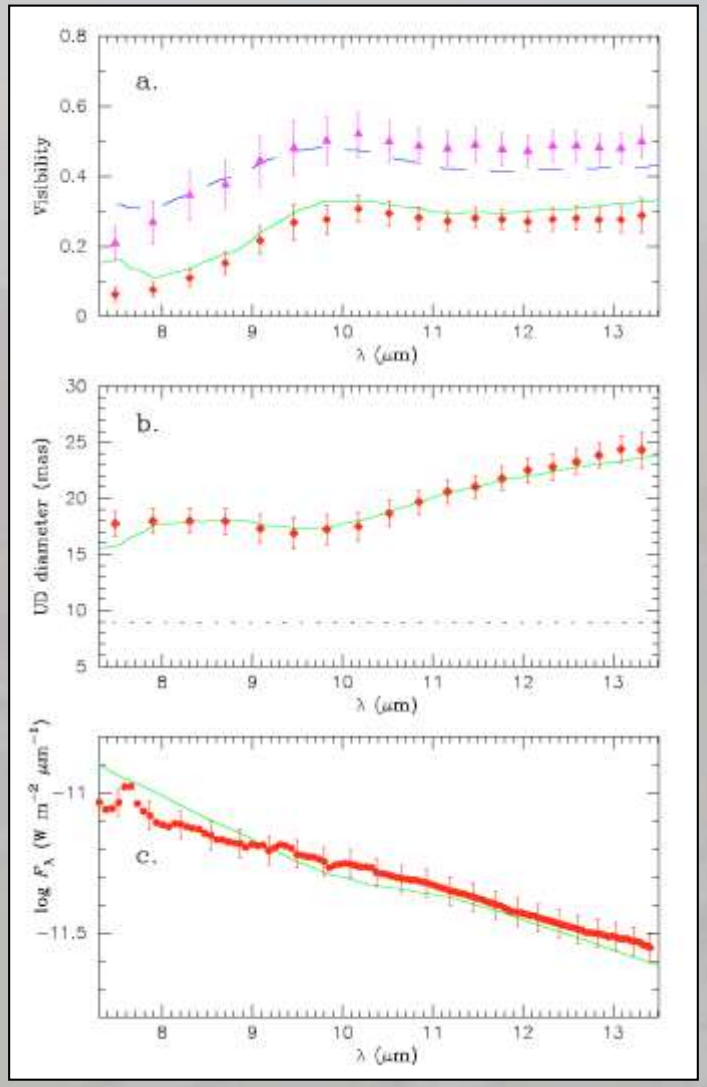
Second generation (4T): PIONIER HK, GRAVITY K, MATISSE LMN

Maximum baseline = 200 m





The contents of the molecular layer of RR Sco with MIDI (VLTI)



H_2O+SiO layer

T_{layer} = 1400 K
R_{layer} = 2.3 R_*

N_{H2O} = 3x10^{21} cm^{-2}
N_{SiO} = 1x10^{20} cm^{-2}

Ohnaka et al. (2005, MIDI)

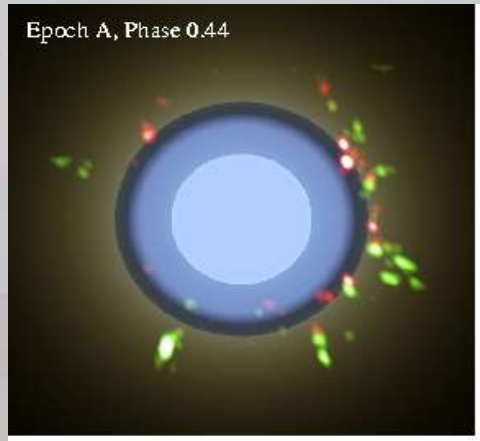
MIDI (VLTI) and VLBA measurements of the O-rich Mira S Ori

(Wittkowski et al. 2007, A&A 470, 191)

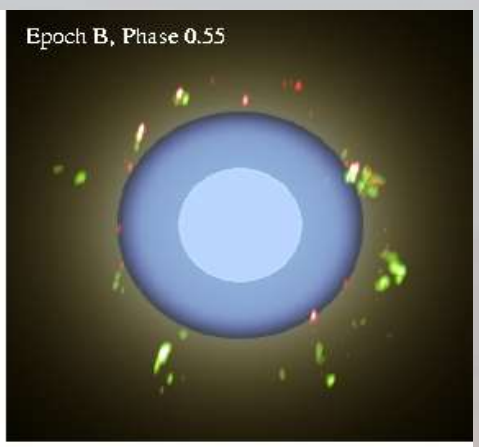
A

Al_2O_3 grains
τ_V=2.5
R_{in}=1.8 R_*

θ_*=9.0 mas



B



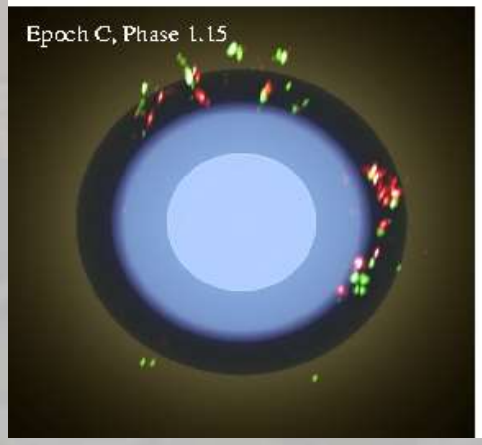
Al_2O_3 grains
τ_V=2.5
R_{in}=2.0 R_*

θ_*=7.9 mas

C

Al_2O_3 grains
τ_V=1.5
R_{in}=2.2 R_*

θ_*=9.7 mas





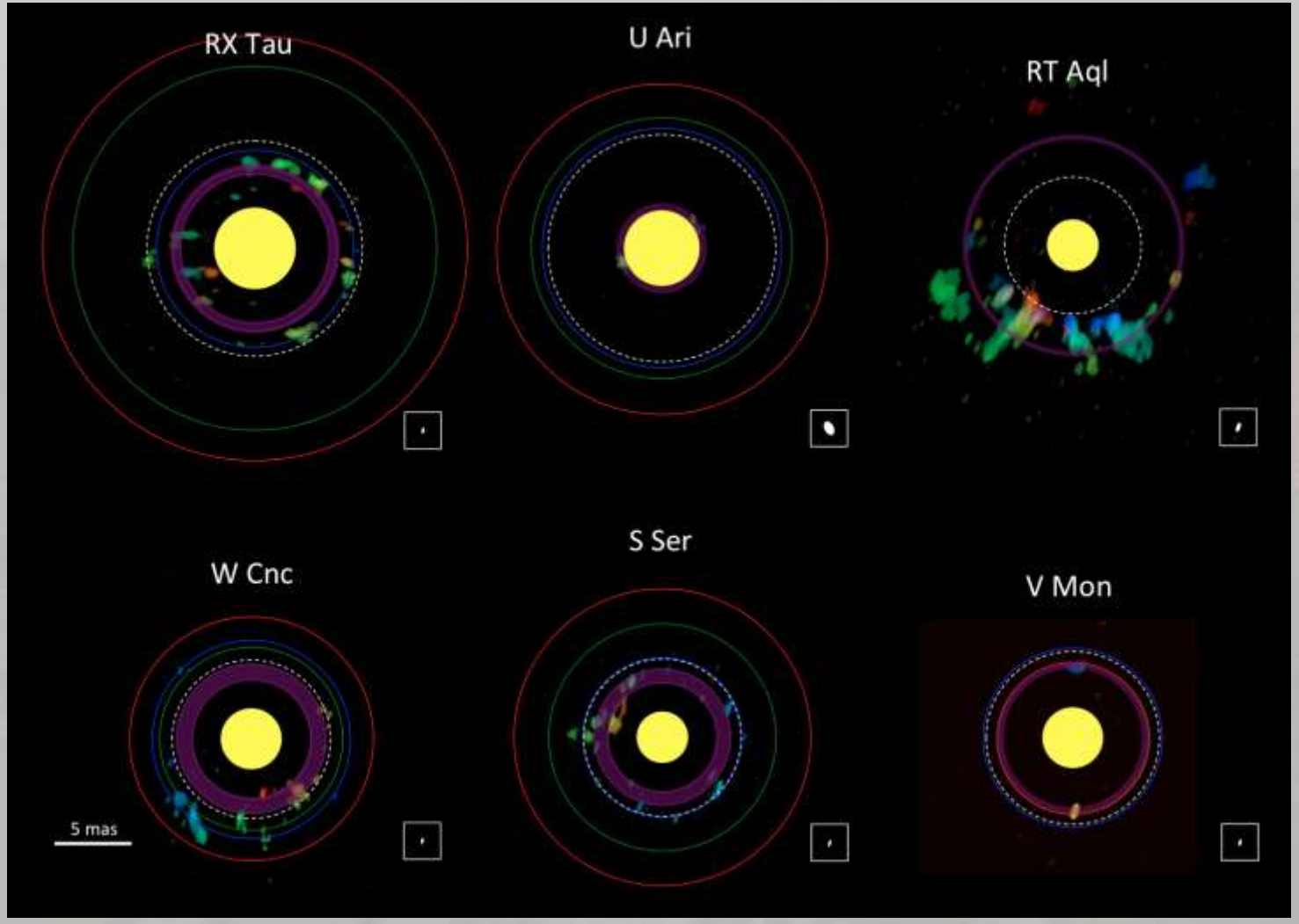
D

Al_2O_3 grains
τ_V=1.5
R_{in}=2.4 R_*

θ_*=9.5 mas

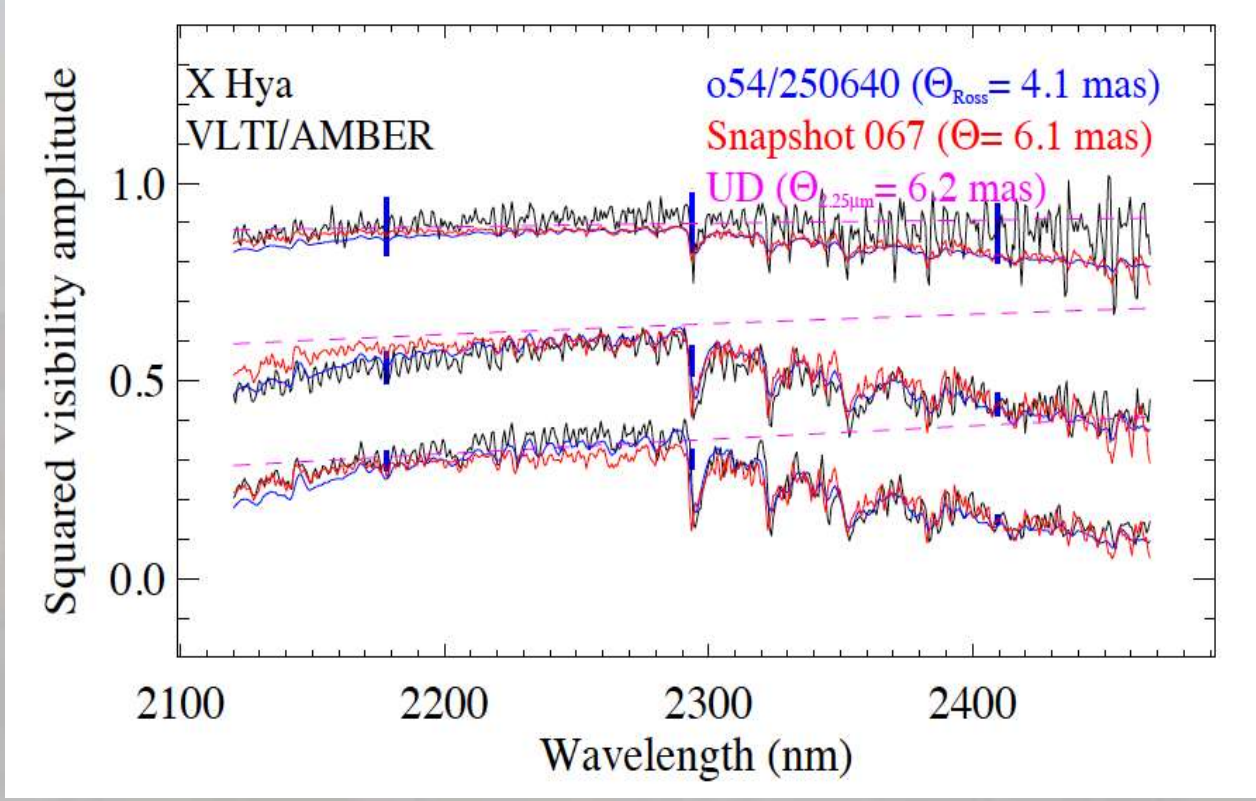
Masers, dust and molecular shells in AGB stars

(Perrin et al. 2015, A&A 576, A70)



No SiO (blue circle) found beyond the SiO maser rings

Agreement with 1D and 3D models
(Wittkowski et al. 2011, 2016)



Spectro-interferometric observations of AGB stars are consistent with both
3D AGB models (Freytag & Höfner 2008) and 1D CODEX models (Ireland, Scholz & Wood 2008, 2011)

self-excited pulsation models including molecular layers

pulsations + convection and fomation of molecular layers

VLTI GRAVITY

(Abuter et al. 2017, A&A 602, A94)

- Specifications driven by the Galactic Center (Sgr A*)
- But: general purpose instrument
- Super PIONIER (4T) with high spectral resolution (R=4000) and high sensitivity (K=10 on axis), IR adaptive optics (red sources)



GRAVITY Science Verification observations of R Peg

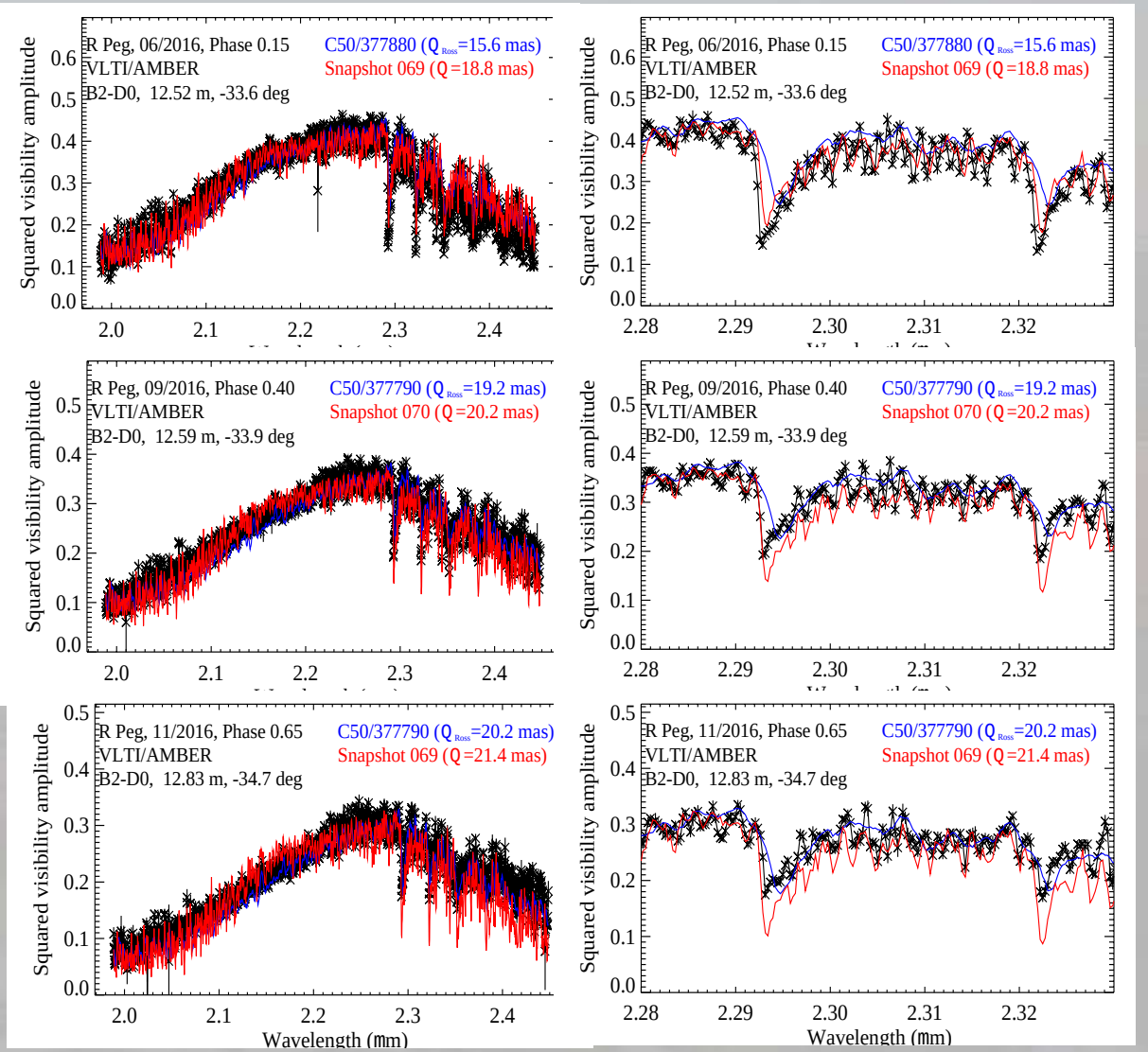
Full K-band at a resolution of R~4000

6 baselines simultaneously

Time series of photospheric and envelope sizes

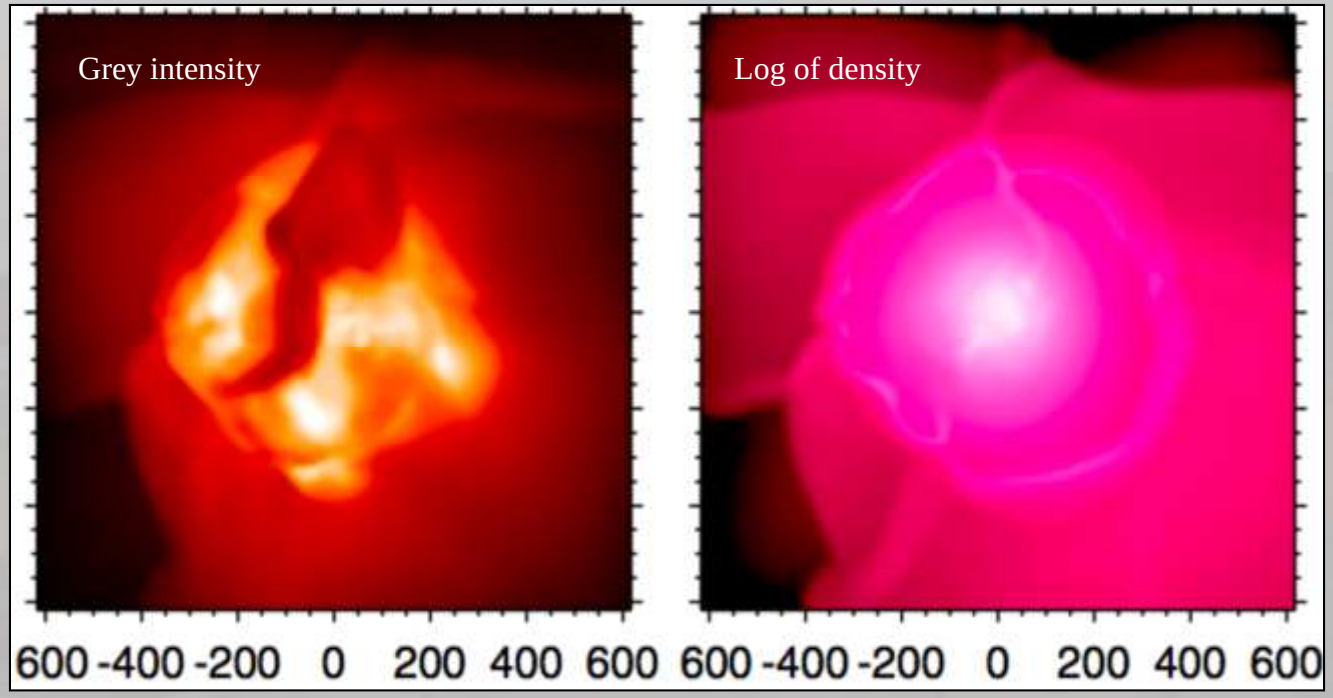
Imaging at many wavelength in continuum and across lines

Observations during SV in 2016 with the aim to obtain time series snapshots



Rau/Wittkowski et al., in progress

Hydrodynamical model of convection and pulsation of an AGB star

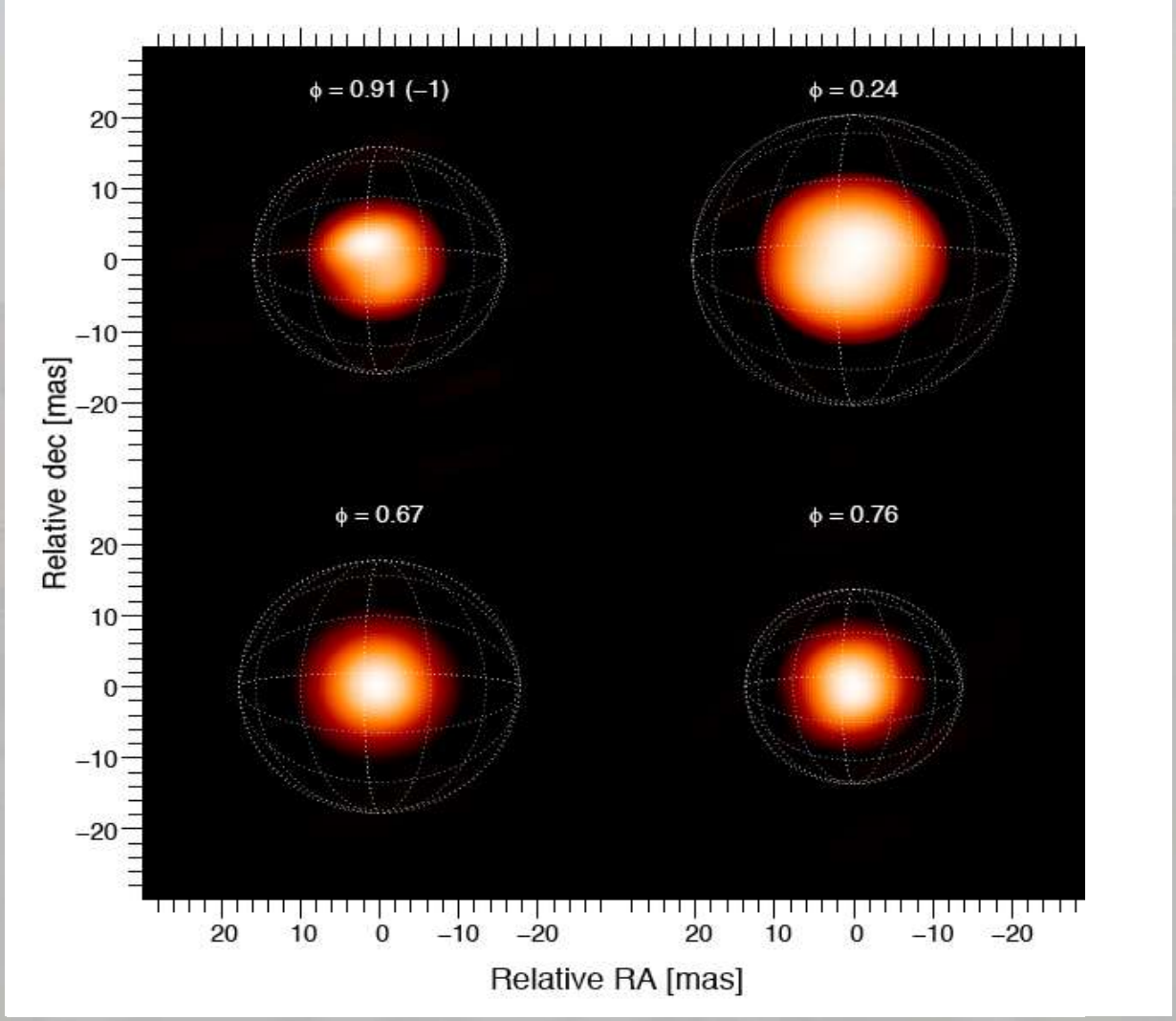


(Freytag & Höfner, 2008, A&A **483**, 571)

Snapshot of a hydrodynamical model of an AGB star with both convection and pulsation.

χ Cyg (IOTA/IONIC, H)

(Lacour et al. 2009, ApJ 707, 632)



VLTI/AMBER two-epoch imaging of the Mira X Hya

(Haubois et al. 2015, A&A 582, A71)

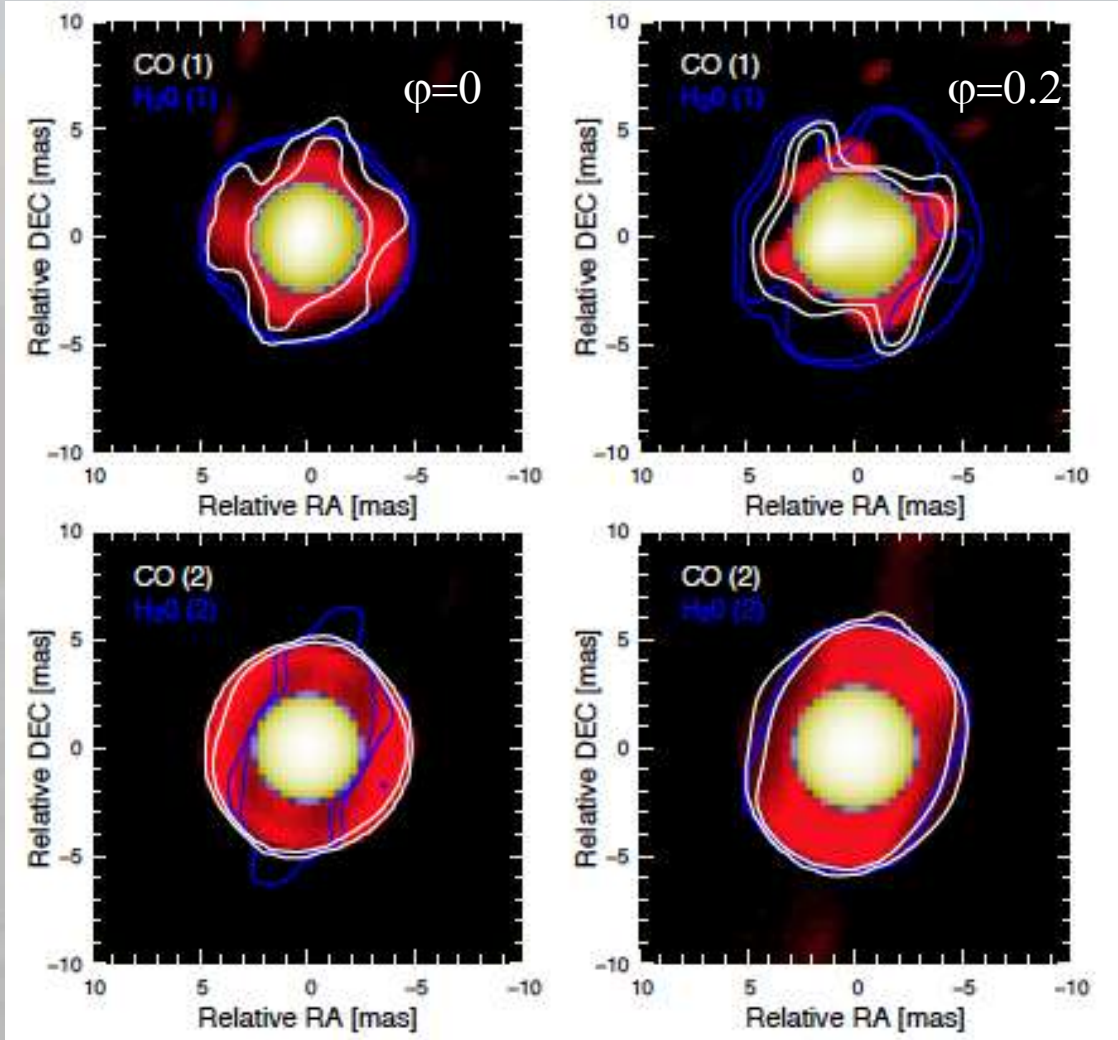


Fig. 16. Continuum images overplotted (Fig. 13) with H_2O (blue) and CO (white) intensity contours (from Figs. 14 and 15). Intensity contour levels represent 2% and 5% of the maximum intensity of each image and allow to compare the extension and shape of the environment between spectral bands for Epoch A (left panels) and B (right panels). Upper panels represent the Cont (1), $H_2O(1)$ and CO(1) bands whereas the lower panels represent the Cont (2), $H_2O(2)$ and CO(2) bands.

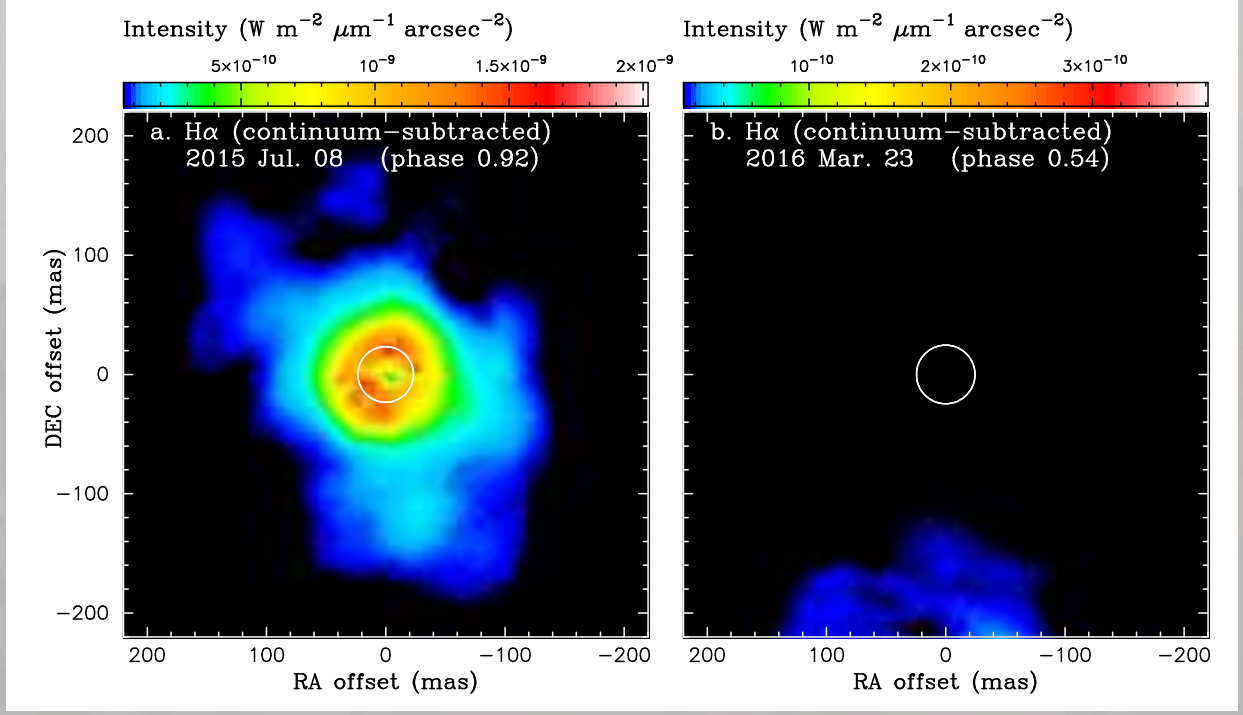
- Angular scale change between phase 0.0 and 0.2
- Reconstructed model-dependent images reproduce closure phase, showing phase-dependent material inhomogeneities located in the atmospheric molecular layers

Going to shorter wavelengths with 8m-class telescopes with adaptive optics and/or aperture masking

(better imaging quality but lower angular resolution)

Dust clumps in the atmosphere of W Hya

(Ohnaka et al. 2017, A&A 597, A20)



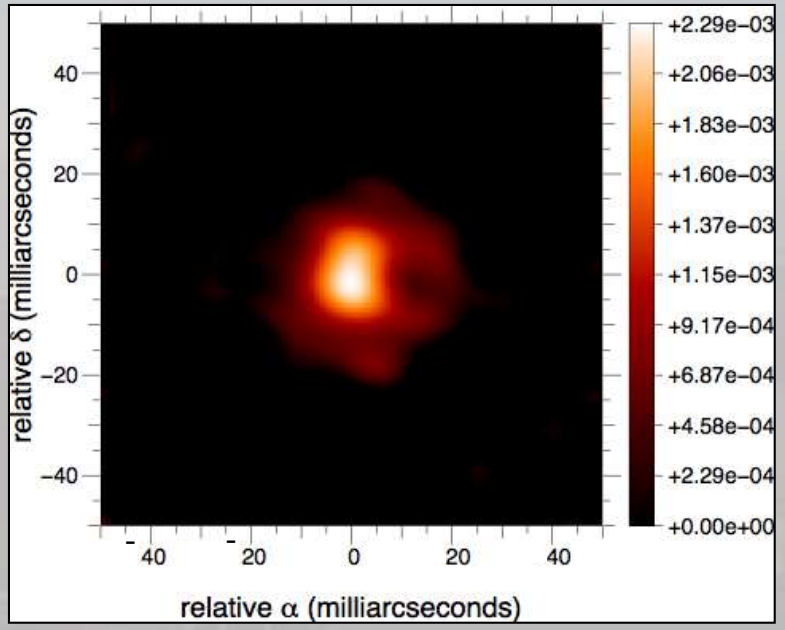
Ohnaka et al. A&A 597, A20 (2017)

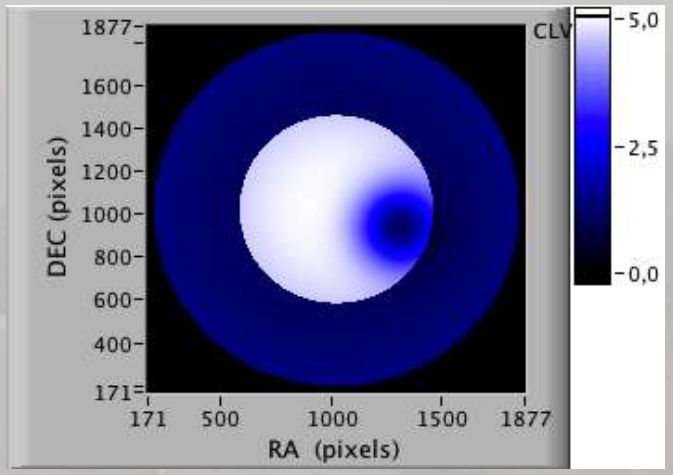
SPHERE images at two epochs + diameters from AMBER:
shell of 0.1 μm grains of Al_2O_3, Mg_2SiO_4, and $MgSiO_3$
inner and outer radii of 1.3 R⋆ and 10±2 R⋆

Formation of a new dust cloud (W) at φ=0.54 and
disappearance of the SW dust clouds of φ=0.92

A potential dust cloud found in Mira's atmosphere

(IOTA/H Perrin et al., to be submitted)





Model fitting with a photosphere + shell+ gaussian absorbing dust cloud

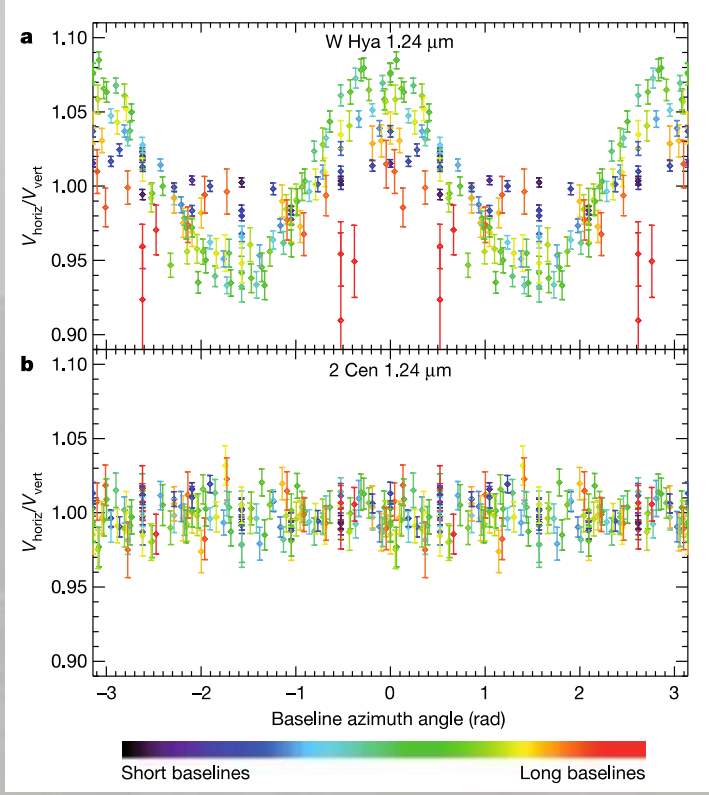
Star + shell characteristics:

R_*	10.55 mas
R_{shell}	20.00 mas
T_*	3400 K
T_{shell}	2000 K
τ_{shell}	0.70

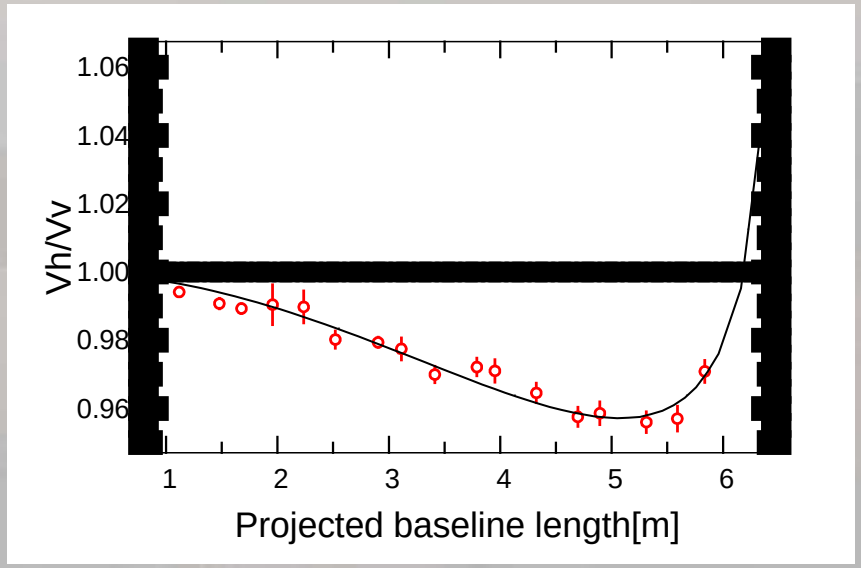
Cloud characteristics:

FWHM	7.50 mas
α	7.00 mas
δ	-2.00 mas
grain sizes	5-400 nm
type	$MgSiO_3$, Mg_2SiO_4
mass	10^{-8} $M_\odot$

Dust grain sizes from polarimetry in molecular shells
VLT/NACO/SAMPol (1.04-2.42 μm)



Norris et al. 2012, Nature 484, 220



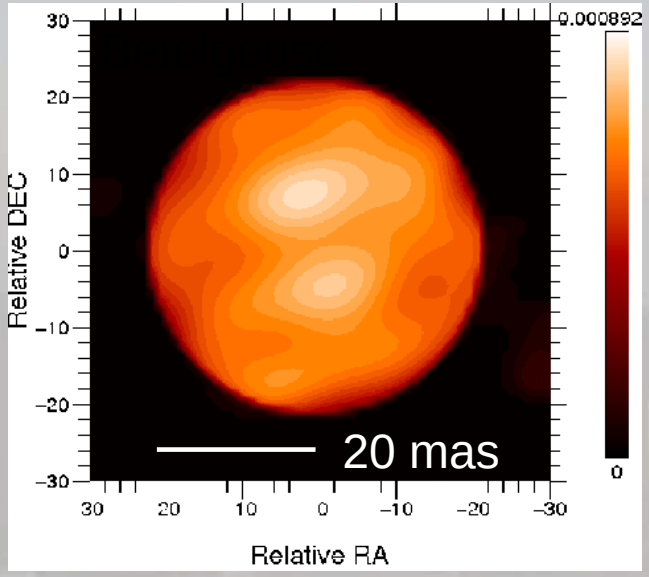
Haubois et al. 2017, A&A, submitted

W Hya, R Dor, R Leo
300 nm Corundum (Al_2O_3) grains at less than 2 R*
Grains are transparent
Acceleration mechanism: photon scattering (rather than absorption)

Betelgeuse
300 nm grain sizes at 1.5 R*
Type of dust : enstatite ($MgSiO_3$) or forsterite (Mg_2SiO_4) rather than corundum.

Red Super Giants

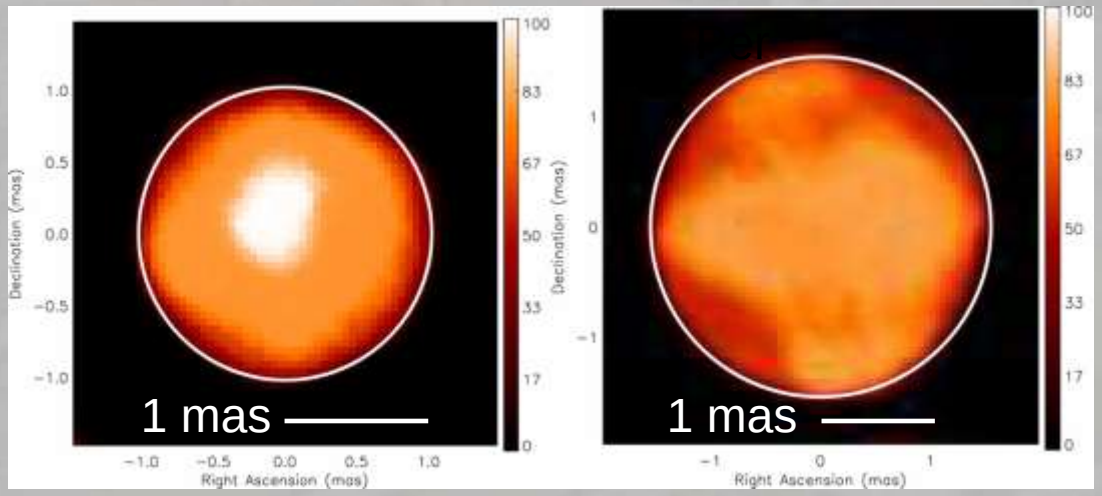
Images of red supergiants with interferomerters



✓ Betelgeuse (M1.5I) in the H band
IOTA array (Haubois et al. 2009, A&A 508, 923)

✓ 2 spots detected over the surface
✓ 4-9% contrast

✓ Comparison with 3-D convection models
(Chiavassa et al. 2009, A&A 506, 1351)



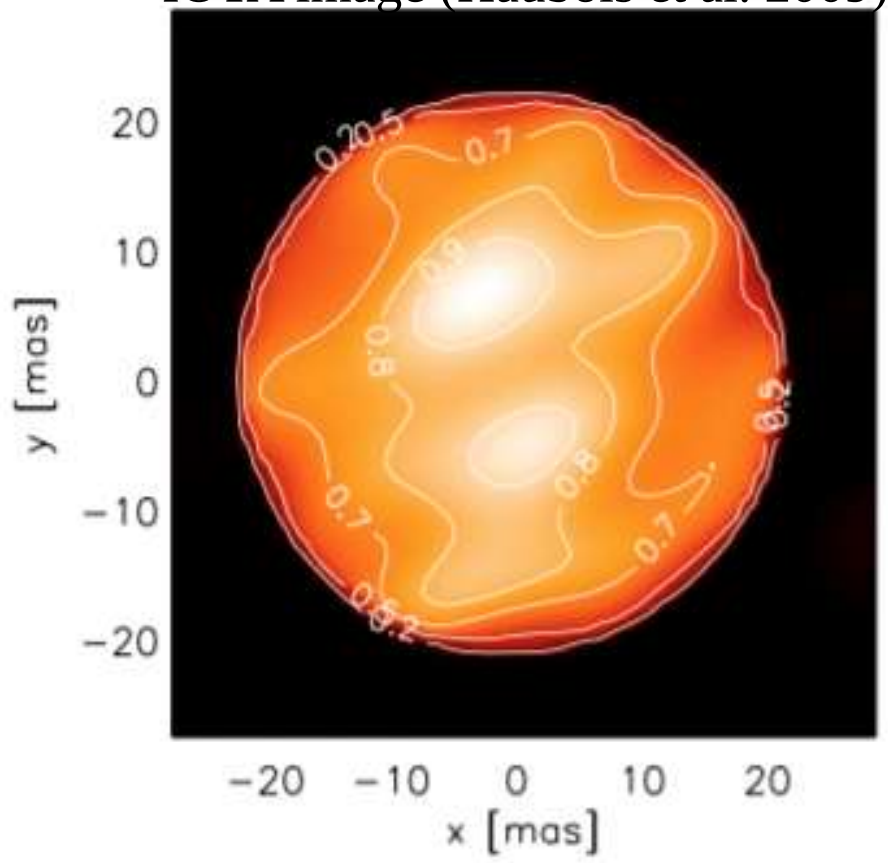
T Per (M2I) & RS Per (M4I)
1.6 μm
CHARA array
(Baron et al. 2014, ApJ 785, 46)

✓ Bright spot on T Per
✓ Dark regions on RS Per
✓ Contrast ~ 25%

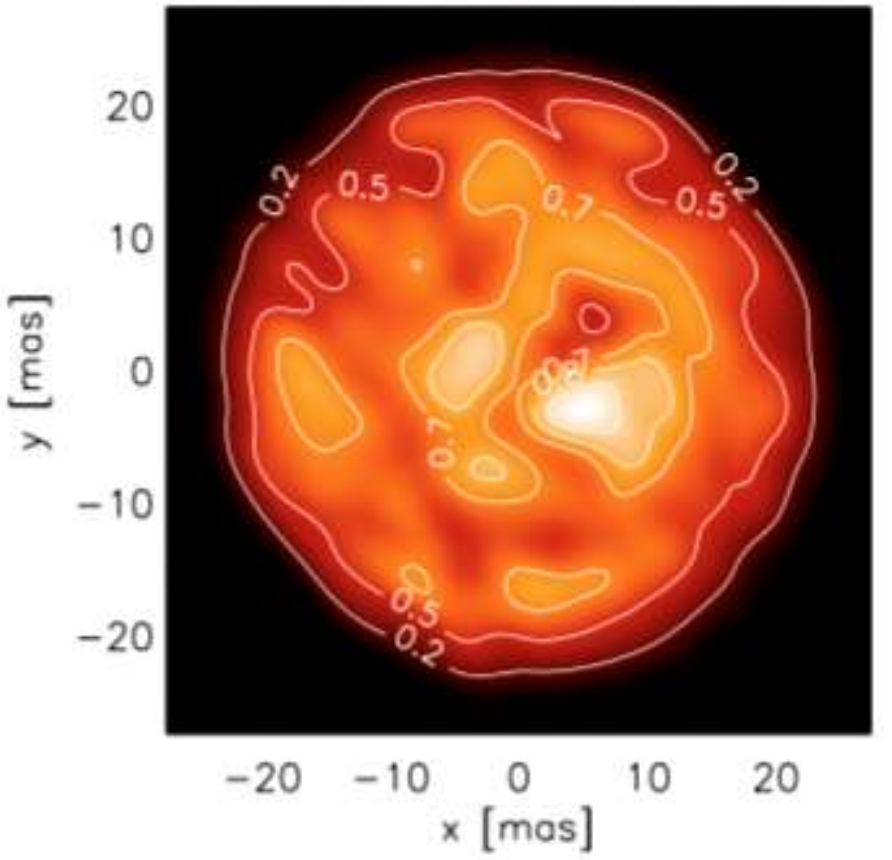
Comparison with RSG convective model

(Chiavassa et al. 2009, A&A 506, 1351)

IOTA image (Haubois et al. 2009)



Simulation

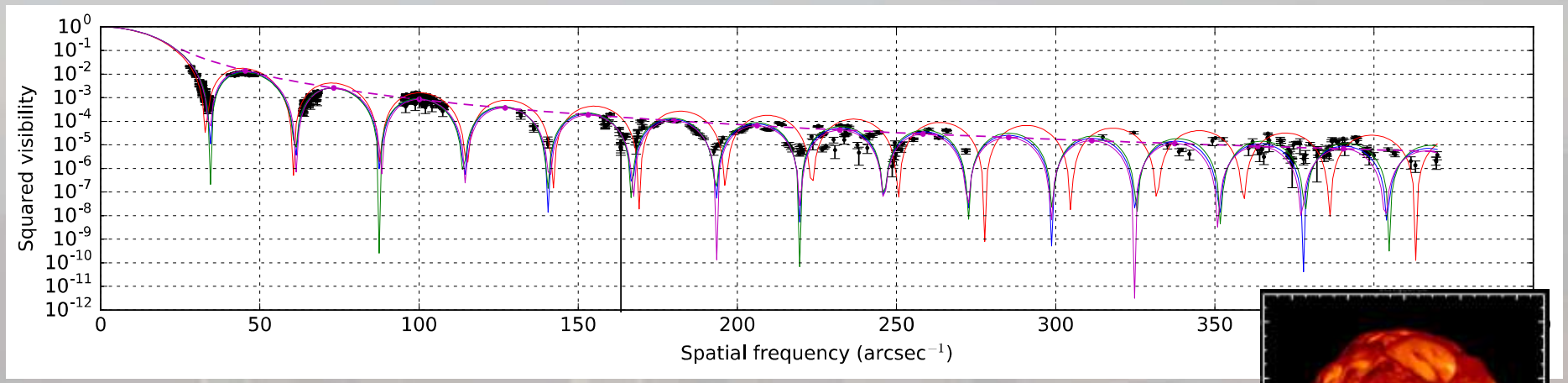


Stellar surface is compatible with the RSG convective model.

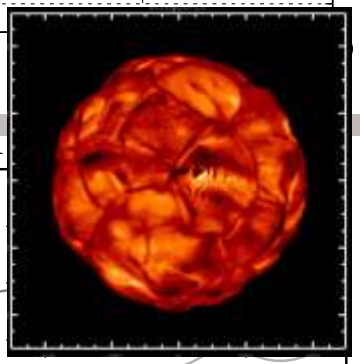
Size distribution through Fourier analysis : 5-15 mas and 1 large convective cell ~ 30 mas

Antares with VLTI/PIONIER at H

(Montargès et al. 2017, submitted)



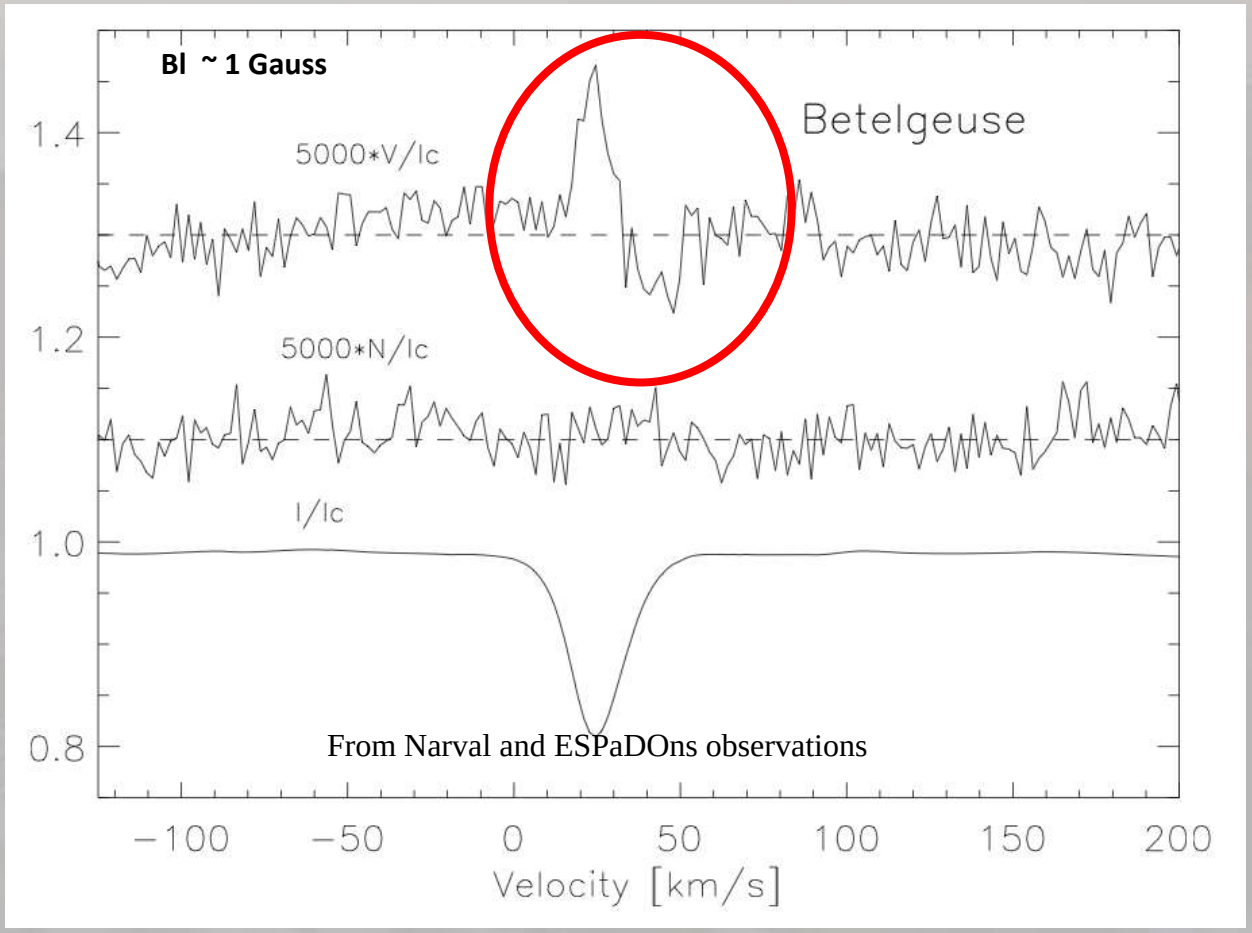
Best matching simulation



Magnetic fields of RSGs from spectro-polarimetry

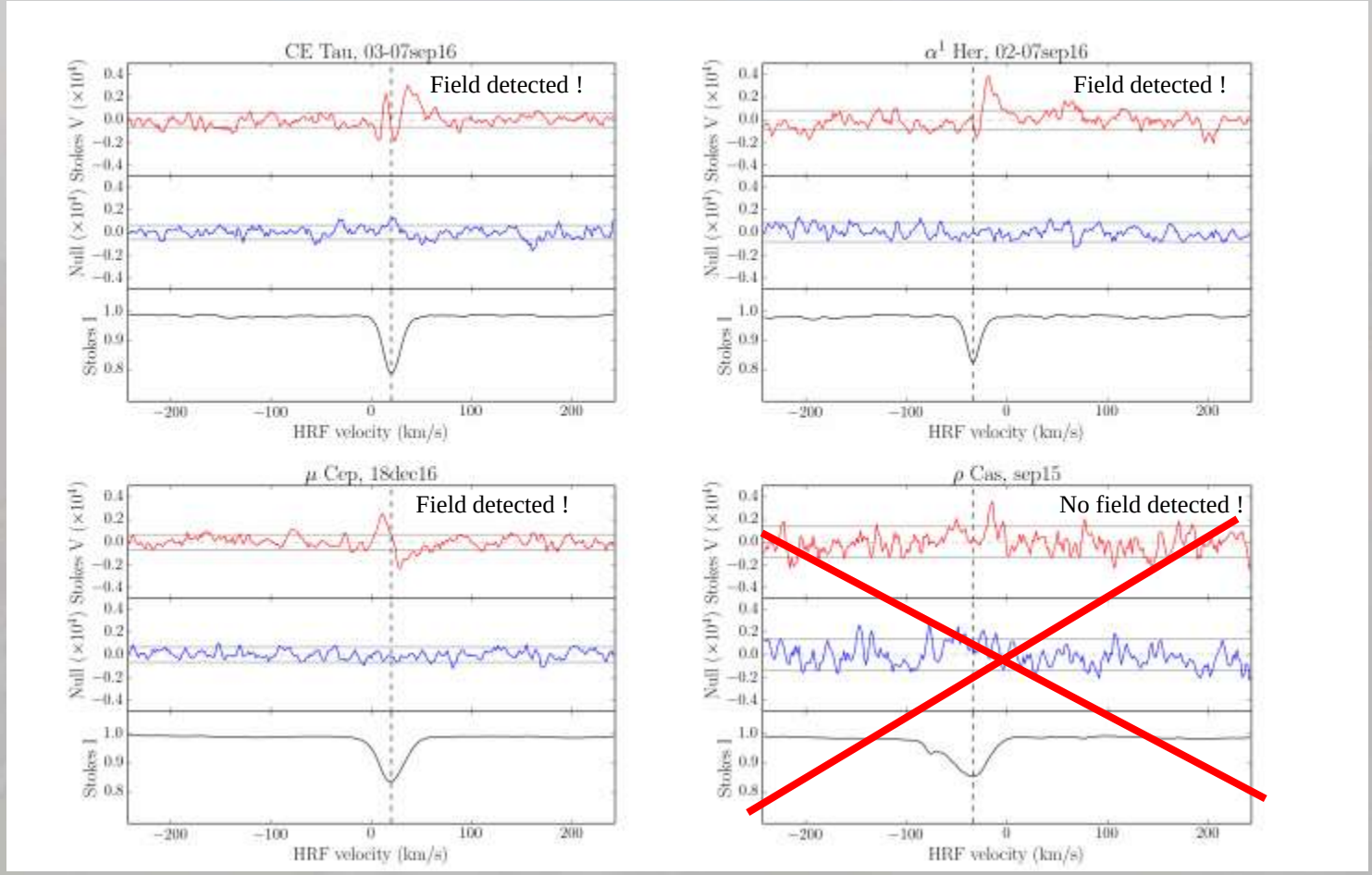
Detection of surface magnetic field in Betelgeuse
(Aurière et al. 2010 A&A 516, L2)

The large-scale convective motions can generate **small-scale dynamo action,** and thus transitory fields.



Search for surface magnetic fields in other M RSG

(Tessore et al. 2017, A&A 603, 129)

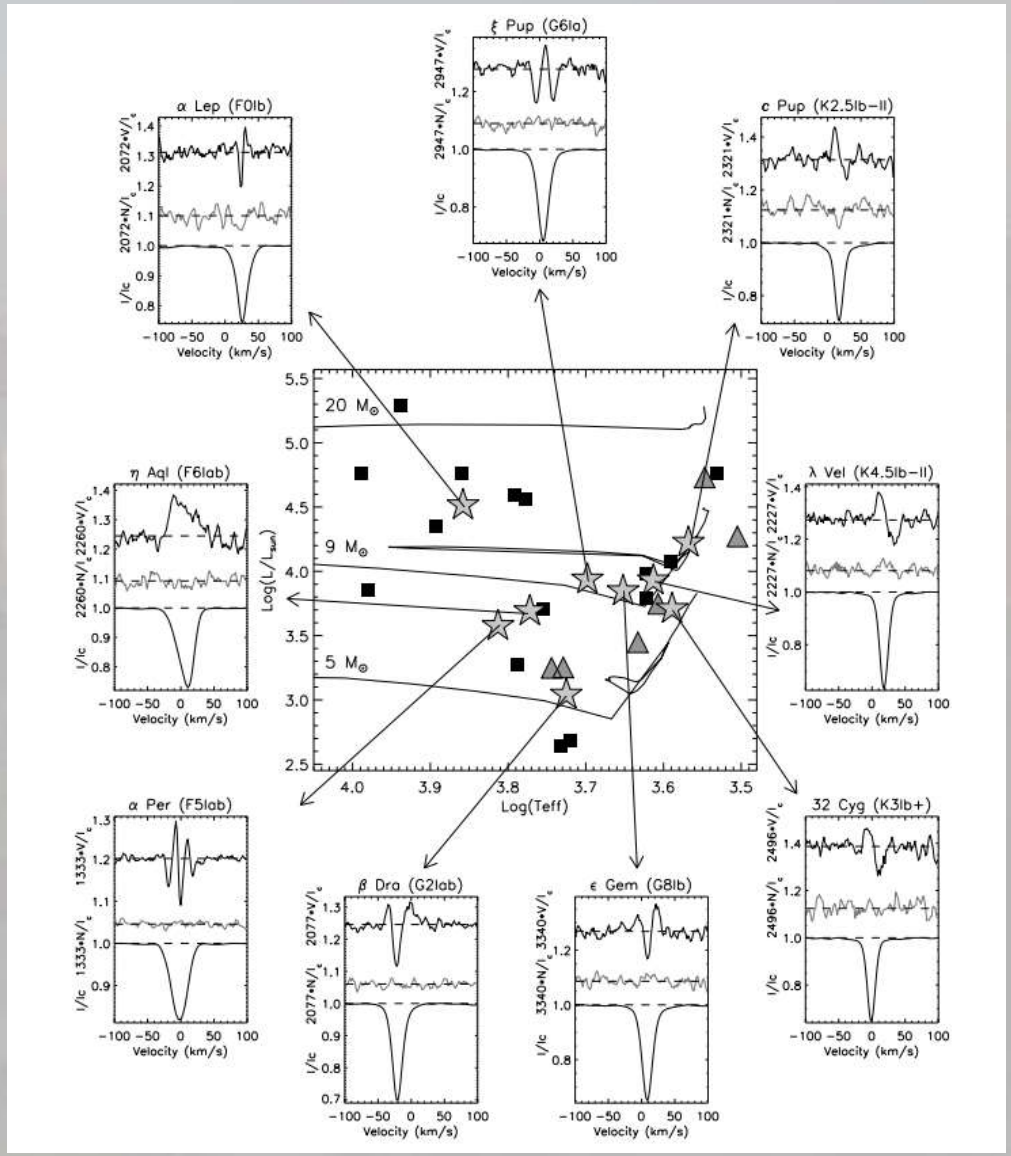


1 G level

Magnetic fields in F-K RSGs

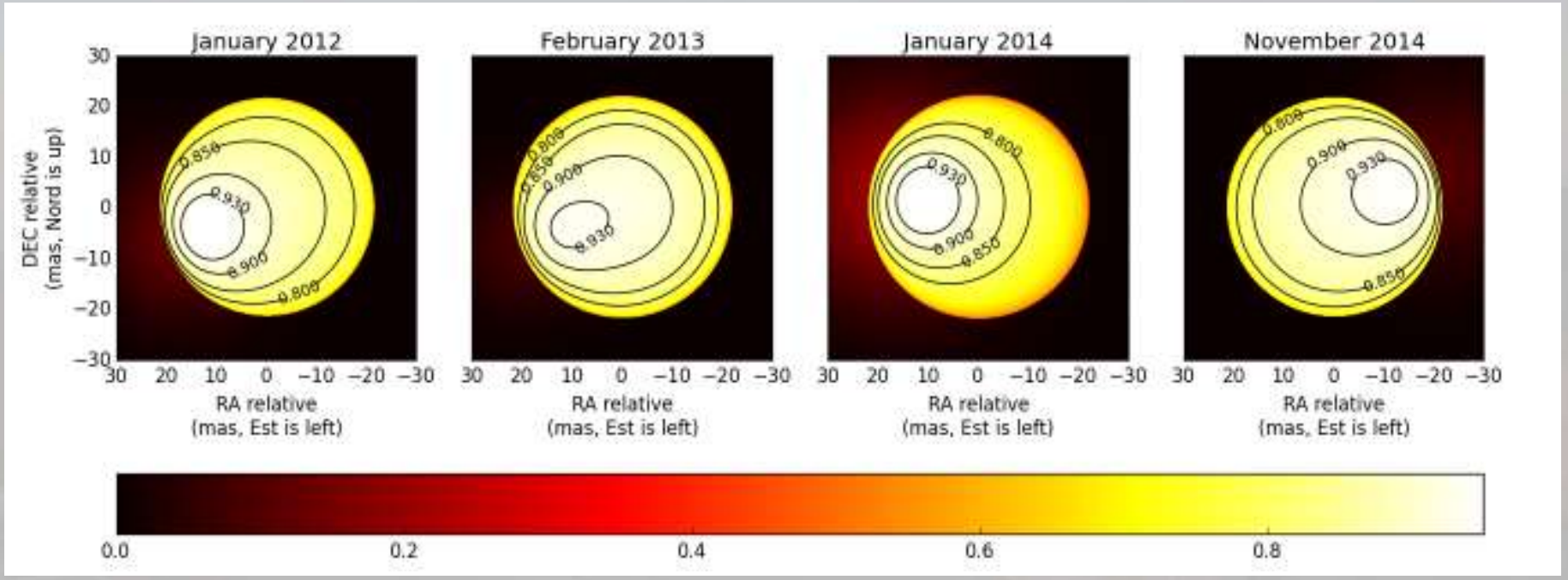
(Grunhut et al. 2010, MNRAS 408, 2290)

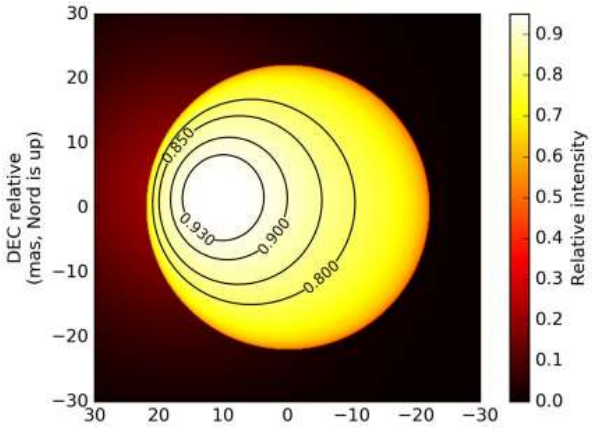
Magnetic fields at the Gauss level are common in F- to K-type RSG.

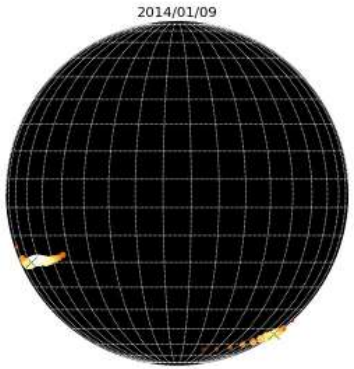


Monitoring Betelgeuse with VLTI/PIONIER at H

(Montargès et al. 2016, A&A 588, A130)







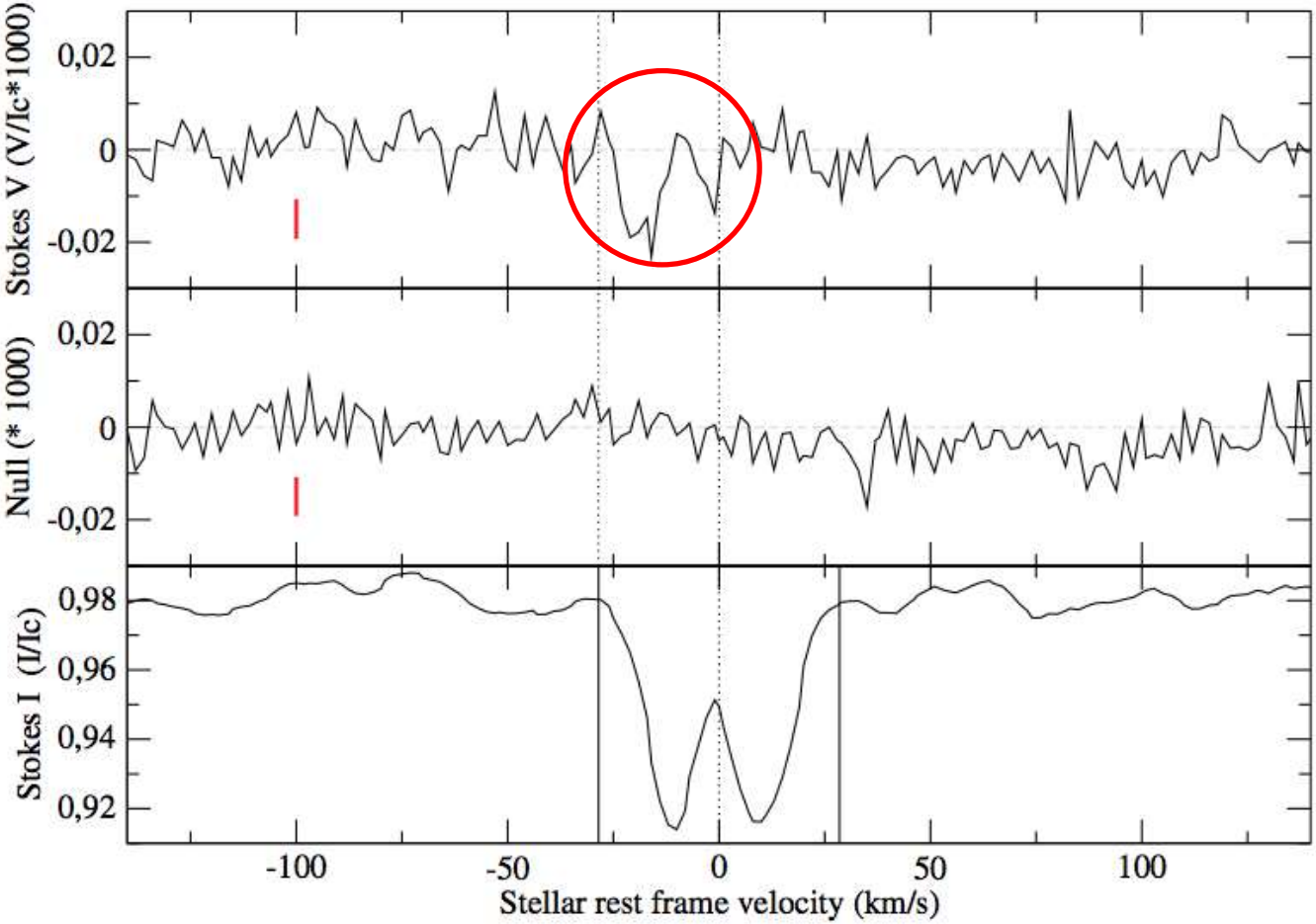
Spot could be linked to the magnetic field (linear polarization)

(Aurière et al. 2016, A&A 591, 119)

Magnetic fields of AGBs from spectro-polarimetry

First detection of surface magnetic field on a Mira star

(χ Cyg, Lèbre et al. 2014, A&A 561, 85)



Clear signature in Stokes V spectra : Definite Detection and stellar origin

a (magnetic) Zeeman effect origin

Surface field estimation : 2-3 G

Stokes I profile : typical line doubling of metallic lines due to **a shock wave** in the atmosphere.

Stokes V signal : associated to the blue component of the I profile

Magnetic field versus distance

(from Vlemmings 2012, IAUS 287, 31)

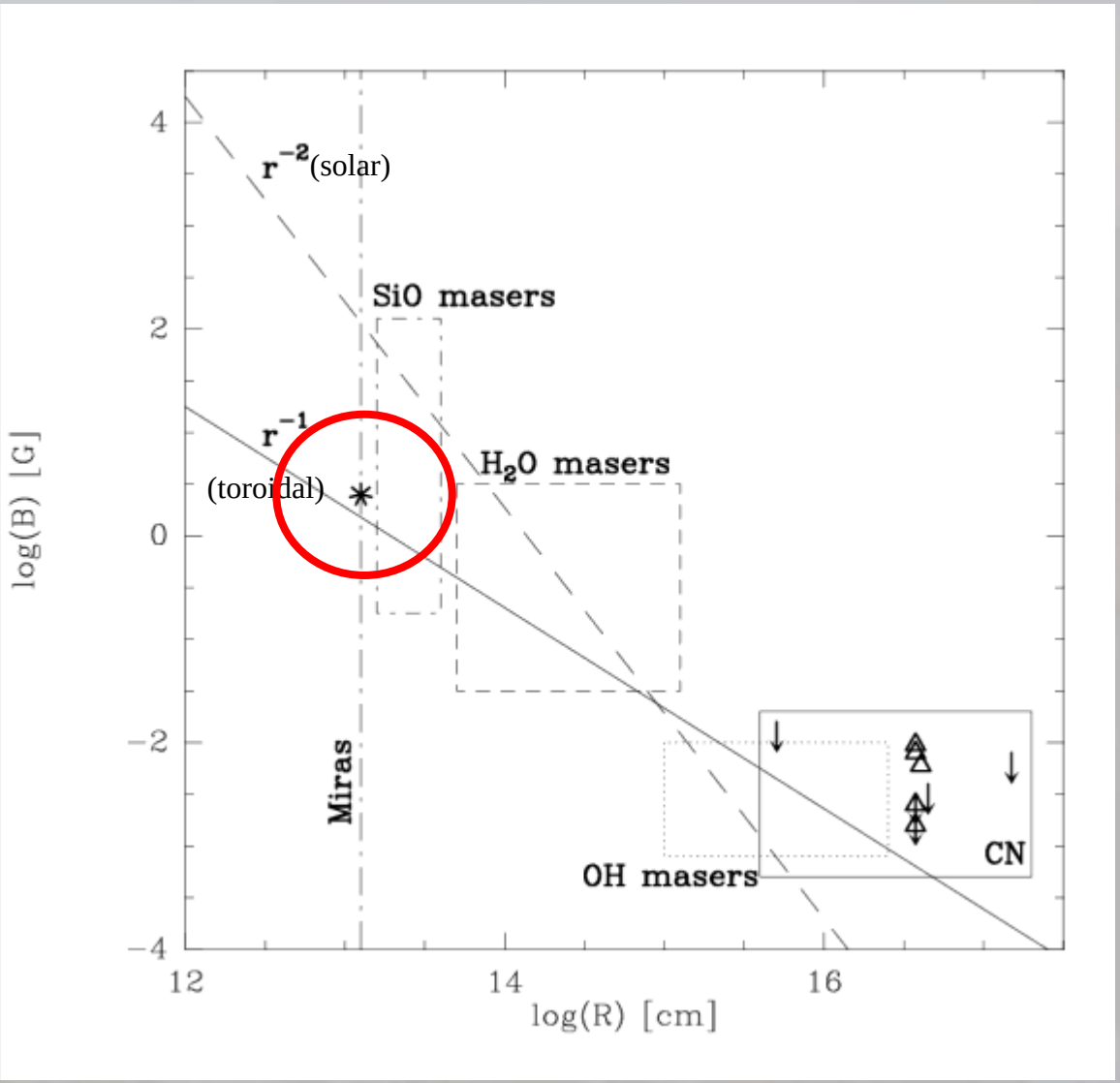
SiO masers: Kemball et al., 2009 ApJ698, 1721; Herpin et al., 2006, A&A 450, 667;

H_2O masers: Vlemmings et al., 2002, A&A 394, 589; Vlemmings et al., 2005, A&A 434, 1029;

OH masers: Rudnitski et al., 2010, AN 54, 400;

CN masers: Duthu et al., 2017 A&A, 604, A12

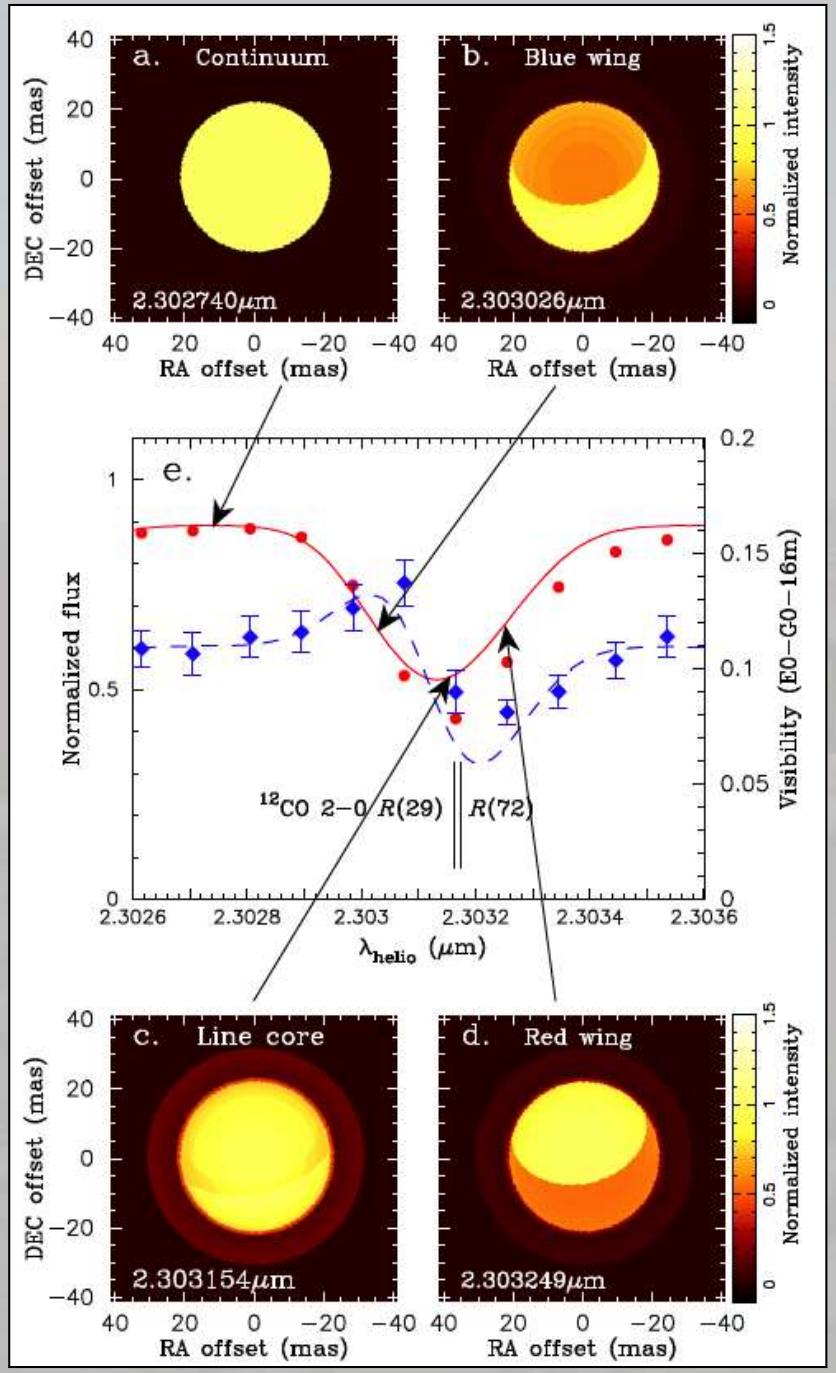
Optical: * χ Cyg by Lèbre et al. (2014)

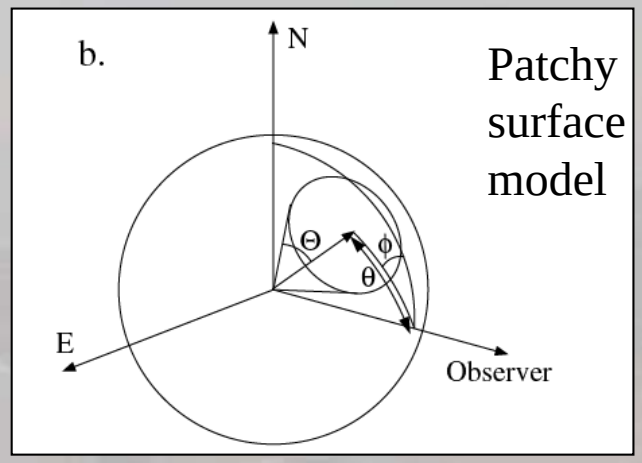


Surface velocity field mapping for RSGs

Convective motions at the surface of Betelgeuse

(Ohnaka et al. 2009 A&A 503, 183)





Date of observation: January 2008

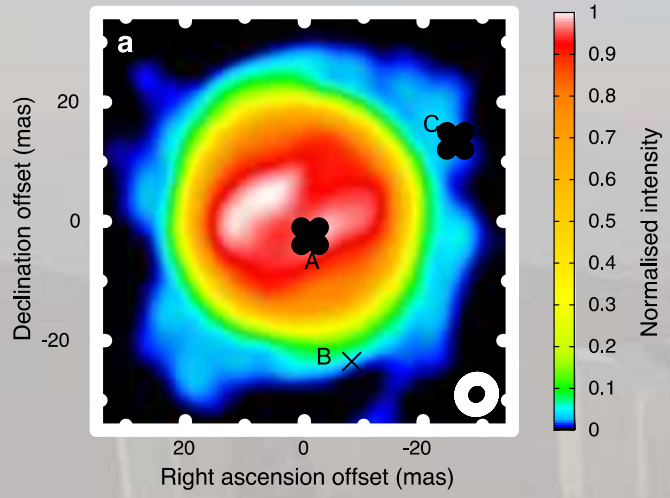
Large upwelling spot (≤ hemisphere, Θ=60˚)
10-15 km/s velocity

Detected in the blue and red wings of CO lines in K band with AMBER.

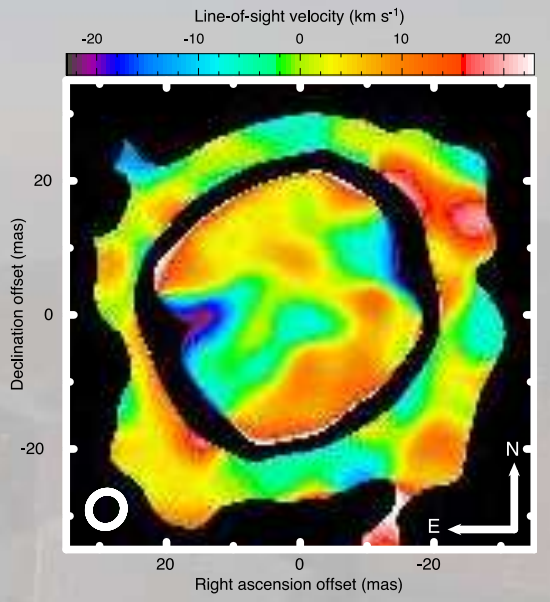
Atmospheric motions of Antares

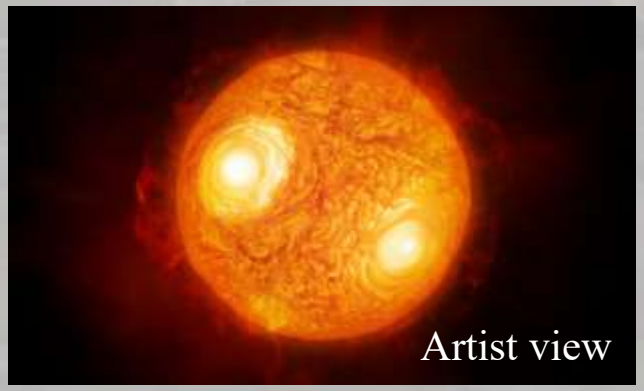
(Ohnaka et al. 2017, *Nature* **548**, 310)

Image at the centre of the CO line (2.30665 μm)



Velocity map





AMBER observations in CO lines between 2.28 and 2.31 μm

Velocity field ranges between -20 and + 20 km/s.

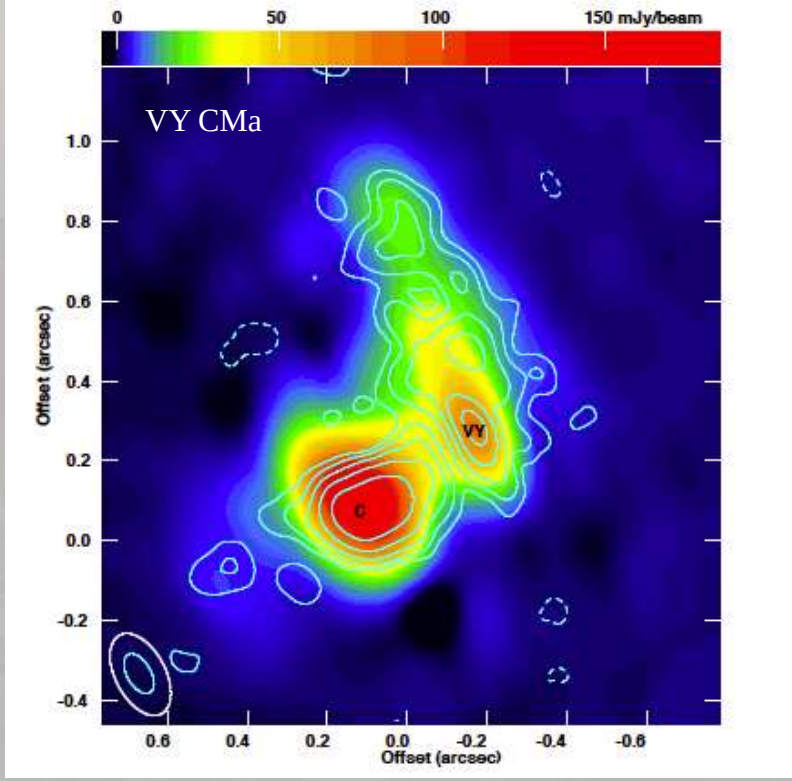
Atmosphere up to 1.7 R*
Very high density level

Convection alone cannot explain these facts -> what process ?

The revolution of sub-environment or sub-stellar resolution imaging with ALMA

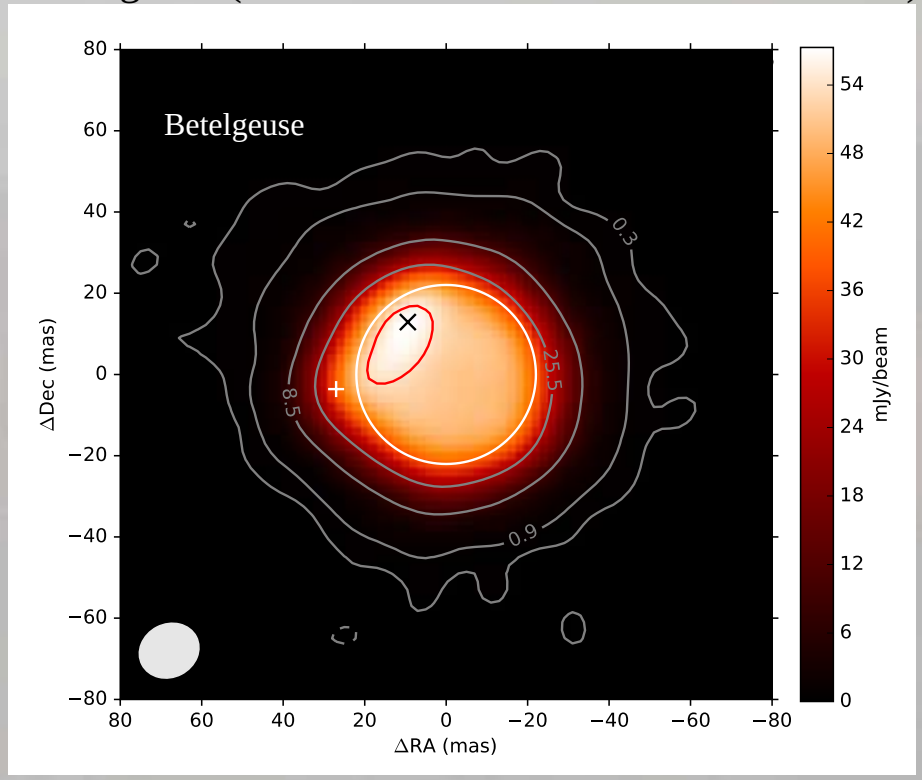
RSG stars with ALMA

VY Cma (O'Gorman et al. 2015, A&A, 573, L1)



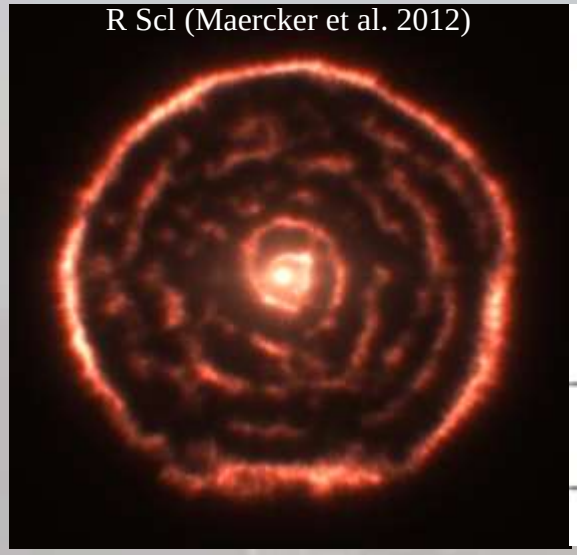
11 R* resolution
Continuum image (dust)
Very nons-spherical distribution is **not consistent with convection**

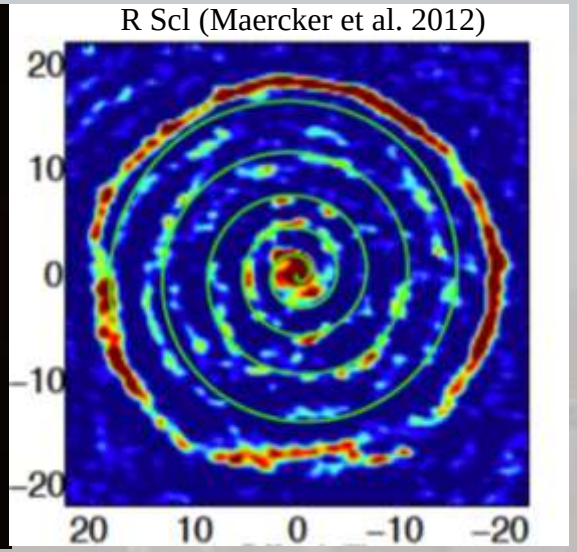
Betelgeuse (O'Gorman et al. 2017, A&A, 602, L10)

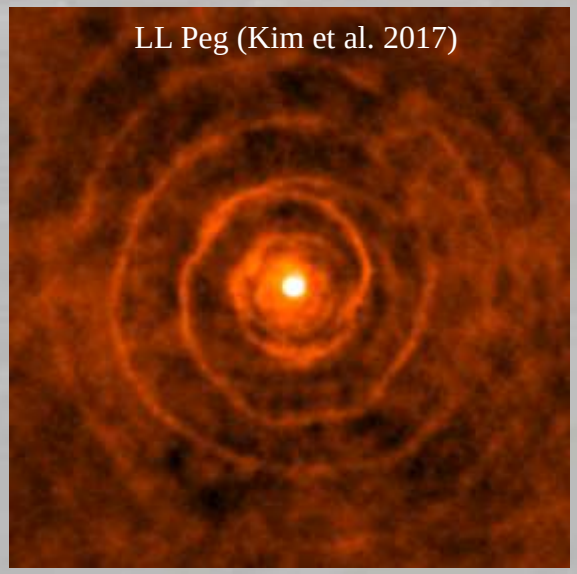


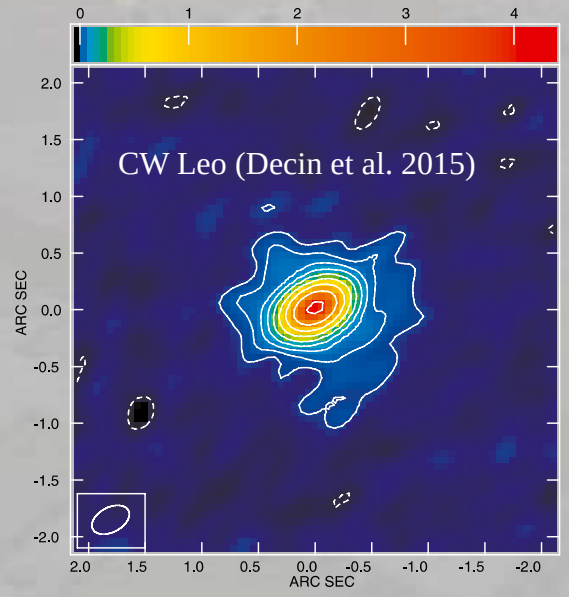
0.3 R* resolution
Continuum image (atmosphere)
Local hots spots linked to magnetic activity **generated by large-scale photospheric convection.**

Spiral mass loss streams in AGBs with ALMA







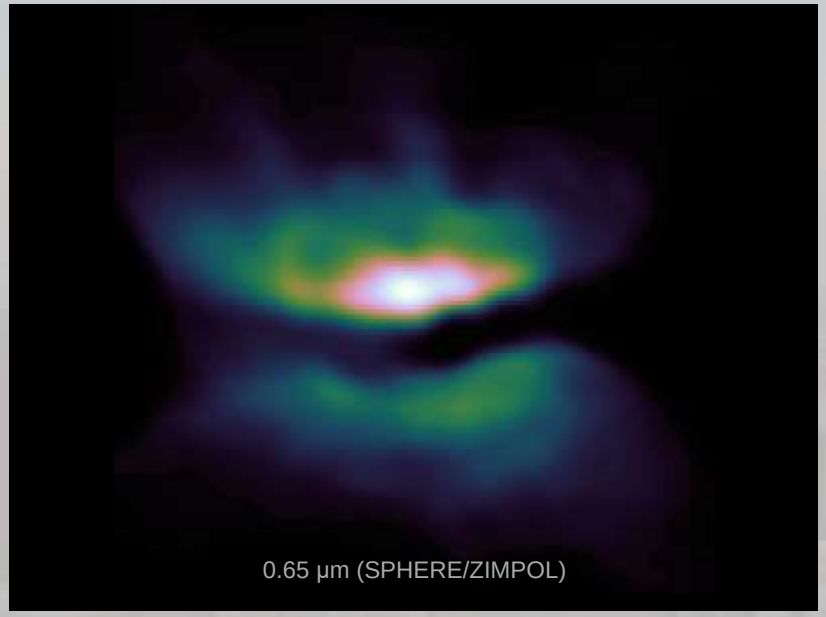


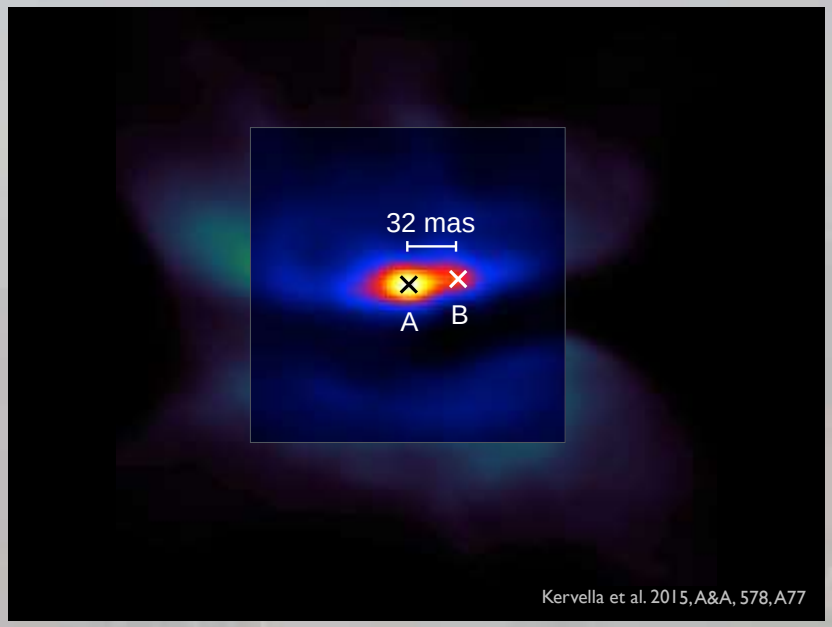
Companion ?

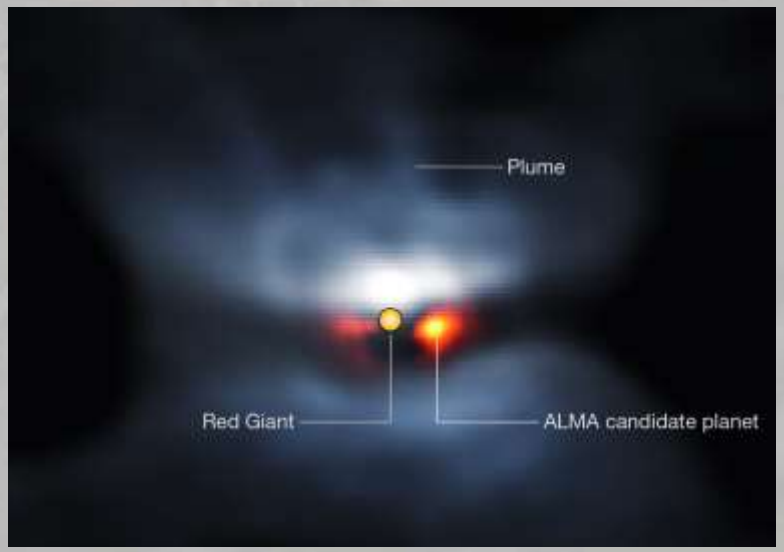
R Scl, LL Peg & CW Leo show evidences of companion disturbing the mass loss outflow into a spiral (edge-on spiral for CW Leo)

Evidence of binarity: the case of L2 Pup

(Kervella et al. 2016, A&A 596, A92)







$m_B = 12 \pm 16 M_{Jupiter}$

(offset between continuum and line)

Conclusions and prospects

- **Almost a golden age of instrumentation for the field from visible up to mm**
- **Imaging of stellar surfaces has made an impressive leap forward:**
  - asymmetries and spots at photospheric level
  - inhomogeneities in molecular shells
  - duts clumps → **but movies are needed for dynamics**
- **Progress have been made on the characteristics of shells where dust forms**
- **Small magnetic fields (~1-few G) detected in AGBs and RSGs + first B maps**
- **Masers are fantastic tools:**
  - they probe molecules in shells (edge of molecular envelope),
  - they probe dynamics (TX Cam, Diamond and Kemball 2003, ApJ 599, 1372)
  - they probe B
- **Convection is challenged:**
  - consistent with spotty surfaces, detection of magnetic fields, photospheric motions, molecular shells of AGBs
  - but challenged by motions in Antares atmosphere and inner dust shell of VY CMa

Conclusions and prospects

- **Binarity evidenced in 1 AGB star (L2 Pup) with ALMA and SPHERE (but no companion detected with PIONIER, Wittkowski et al. 2017, A&A 601, A3)**

The number of studied targets has increased but we still cite the names of the stars …

We are lacking earlier type stars (K giants): a few done with CHARA (4)+IOTA (1)

Some large programs have started (e.g. VLTI with MIDI, PIONIER, AMBER) but more systematic approach required as a complement to the very special cases.

Other instruments in the future ?

- high angular resolution on ELTs (AO, pupil masking) to image the surface of smaller objects
- interferometric imager (6-8T) with high spectral resolution (Ohnaka-like motion studies)
- visible interferometer for atmospheric and chromospheric structure/dynamics
- interfero-polarimetry for B mapping

Thank you!

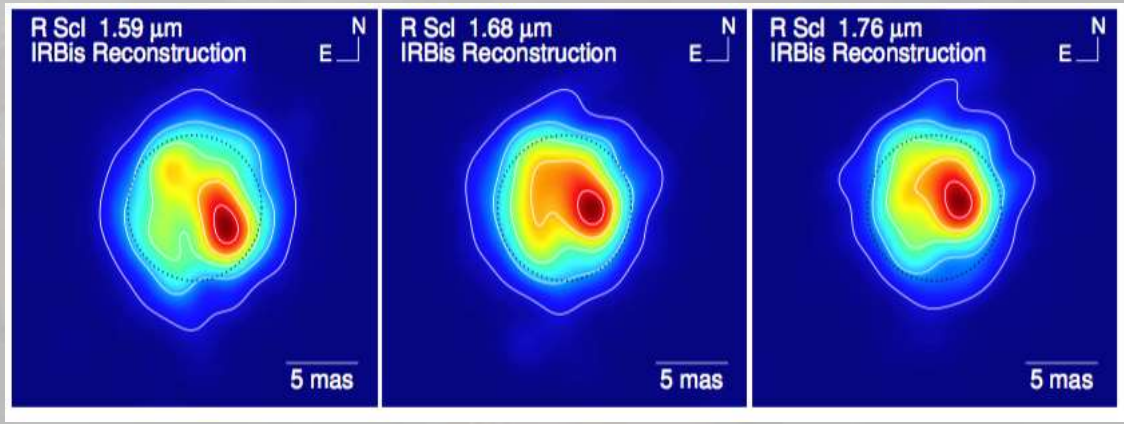
Special thanks to the organizers for the invitation

and to: A. Chiavassa, X. Haubois, P. Kervella. A. Lèbre, M. Montargès, C. Paladini, M. Wittkowski

The surface of R Scl

(Wittkowski et al. 2017, A&A 601, A3)

- 4T H Band images with PIONIER
- 40-60% contrast hot-spot
- consistent with convective and RHD models
- **No companion detected**



Adaptive optics

