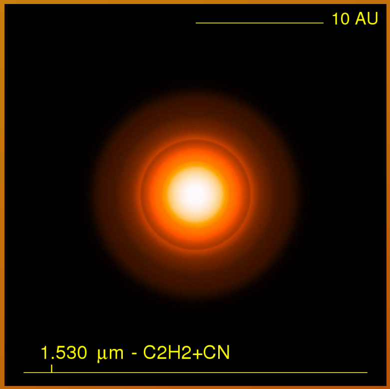
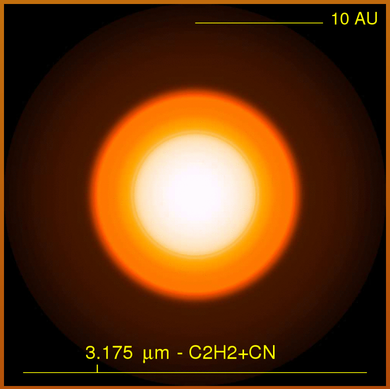
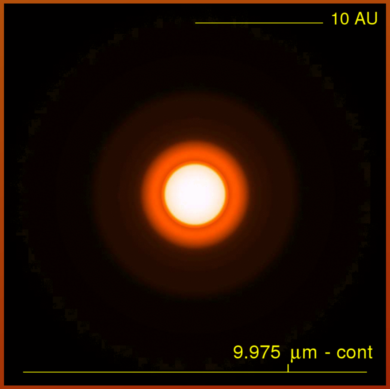



# Evolved stars
# Theory & interferometric view

ULB UNIVERSITÉ LIBRE DE BRUXELLES

fnrs FREEDOM TO RESEARCH

**Claudia Paladini**
Institut of Astronomy
and Astrophysics
Université Libre de Bruxelles

# Disclaimer

- Evolved stars are post main sequence objects

=> this talk will cover the Asymptotic Giant Branch

**AGB**

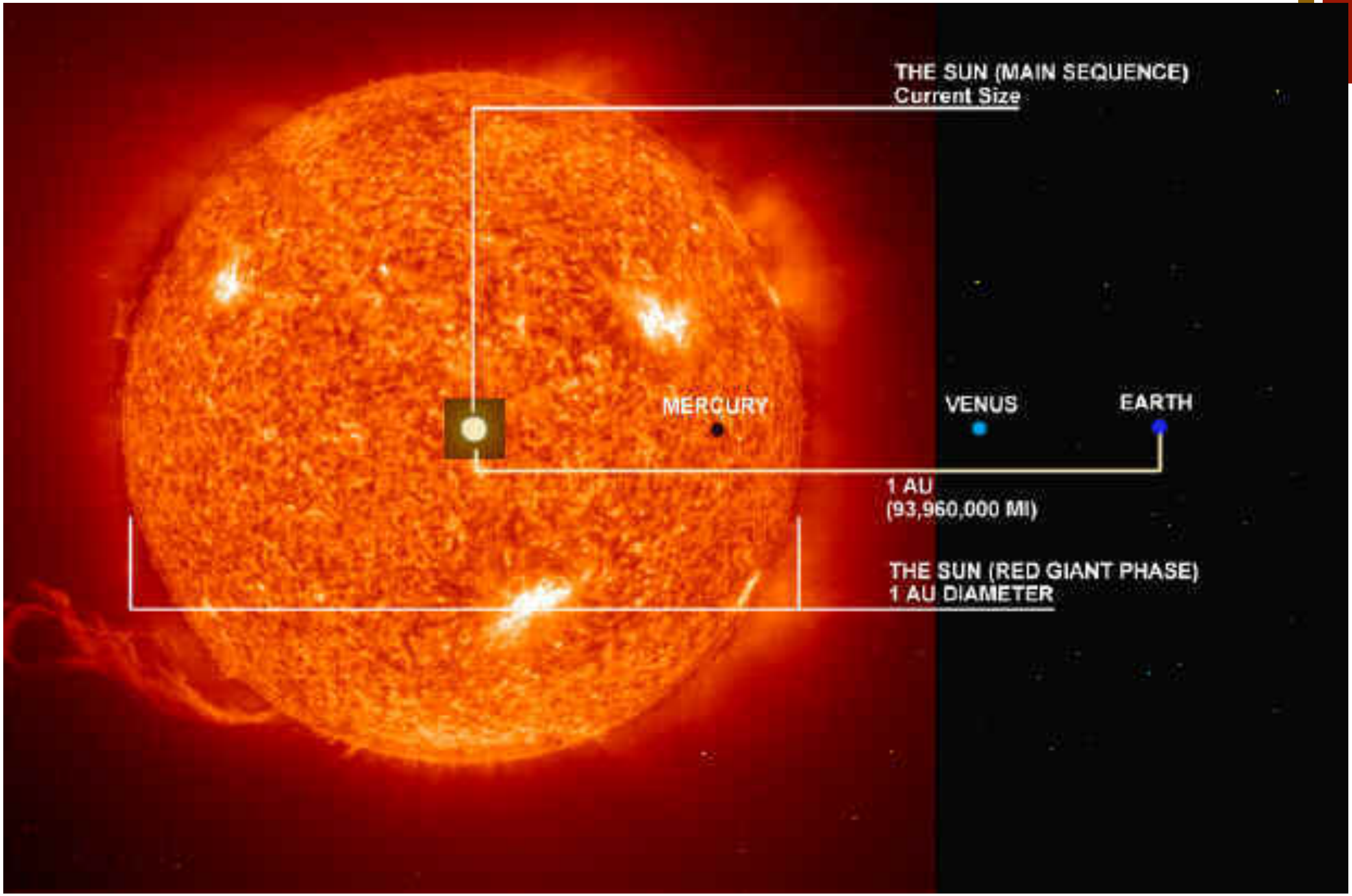
- The review of interferometric results is not complete, I apologize if I forgot your "preferred" paper
  - You are welcome to point it out to me after the presentation!

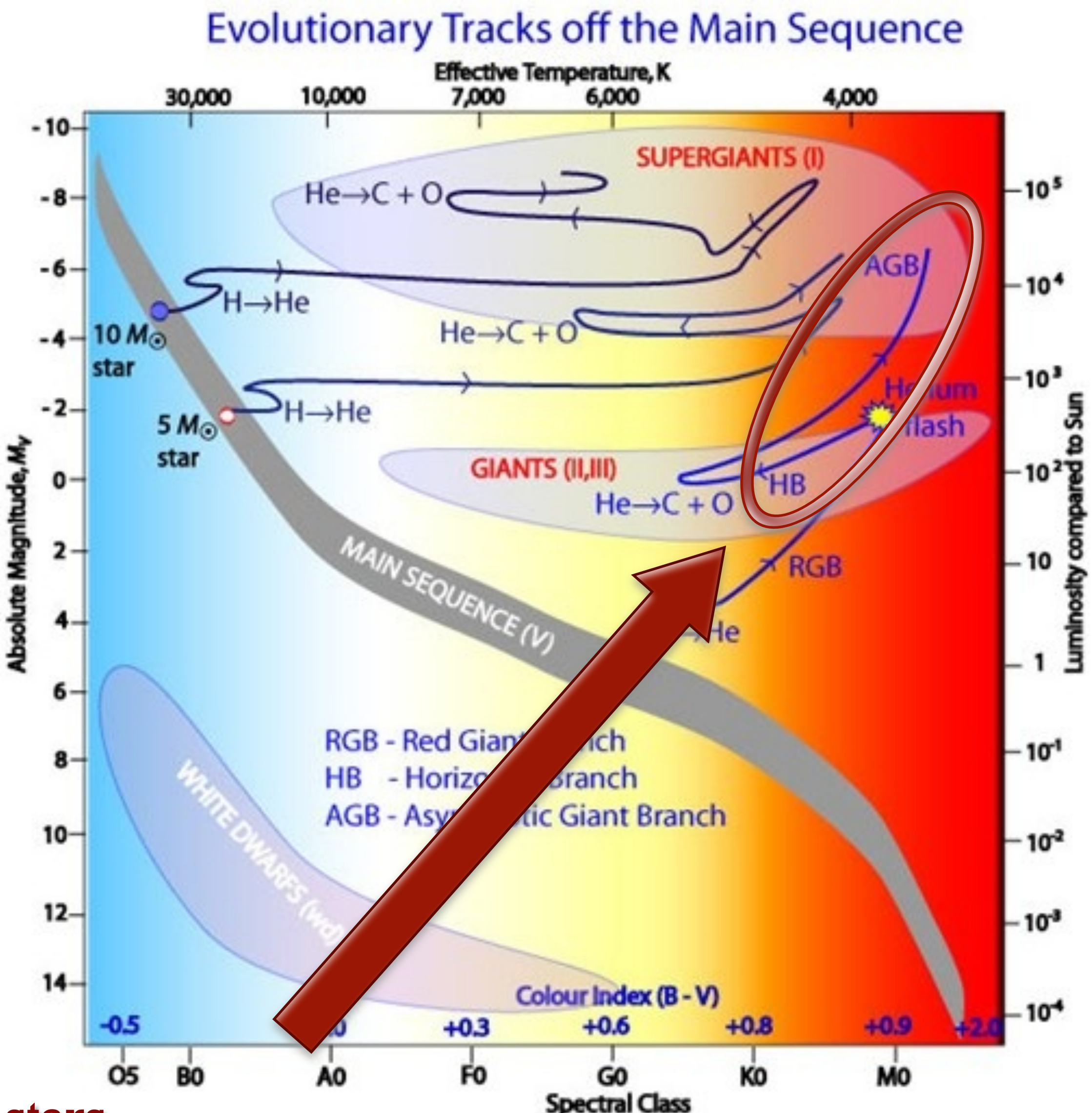
# Outline part I
(partially based on the lecture
"Final stages of stellar evolution", courtesy of J. Hron)

- What is an AGB star
- Why AGBs are important
- Atmospheric structure
- Molecules
  - Cooling & Back warming
  - Different chemistry
  - Effects on diameter definition
- Dust
  - Pulsation
  - Stellar wind C-rich stars
  - Stellar wind O-rich stars
  - Effects on interferometric observables

# What’s an AGB star?

# AGB stars = the future of our Sun





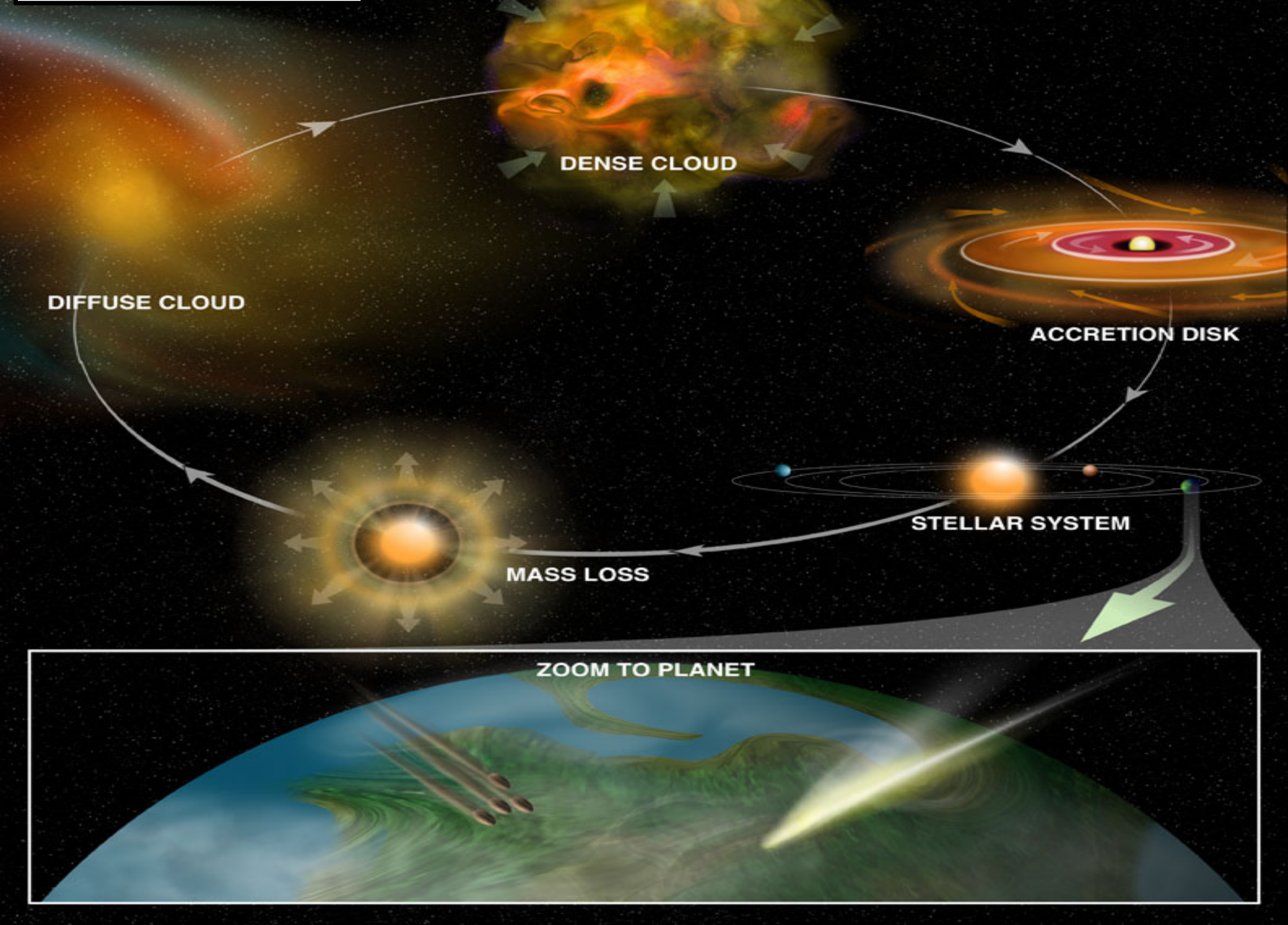

1-8 solar mass stars
Evolve on the
Asymptotic Giant Branch (AGB)

credit: http://outreach.atnf.csiro.au/

# AGB stars = the future of our Sun

# Why do we care about AGBs?

http://www.nrao.edu/pr/2006/gbtmolecules/



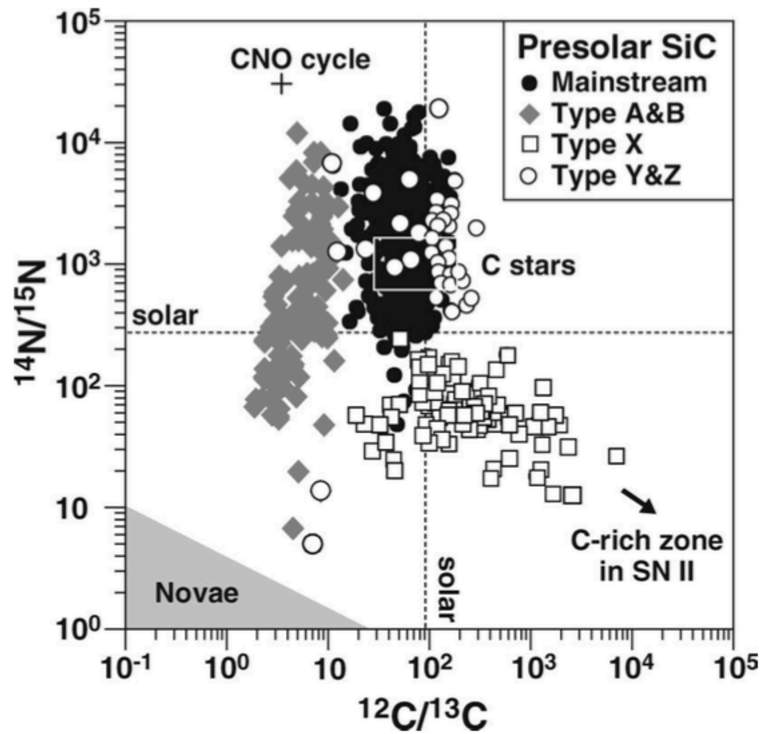
# Presolar dust grains (SiC)

Mainstream: 90% of all presola SiC grains origin in AGB stars

Type A&B origin unclear

Type X from SNe II

Type Y&Z from AGBs

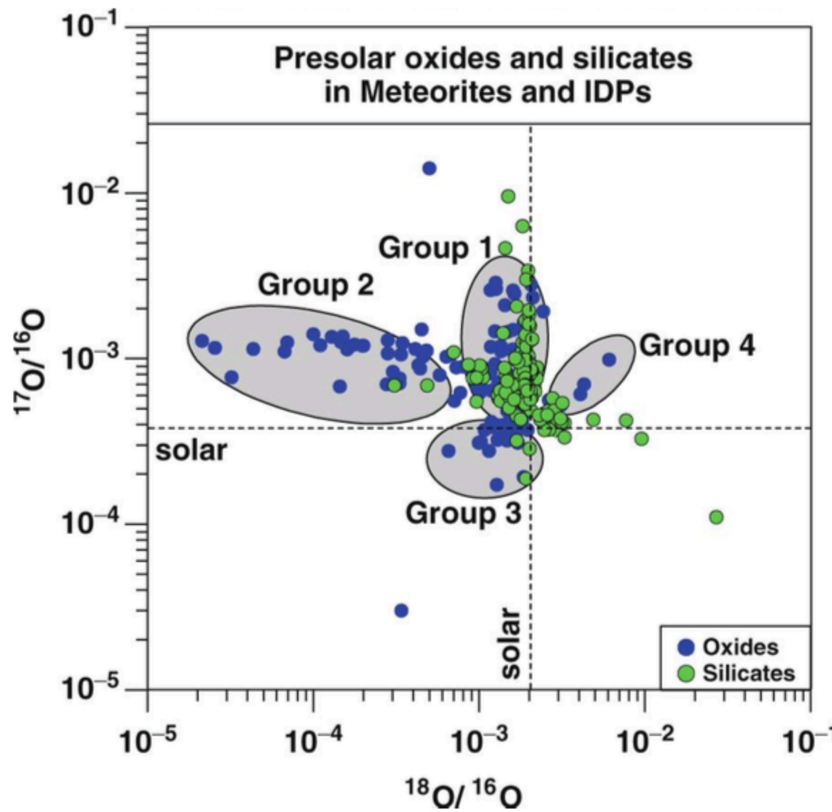



P. Hoppe, Nucl. Phys. A688, 94c (2001) 287-288

# Presolar Grains (O-rich)

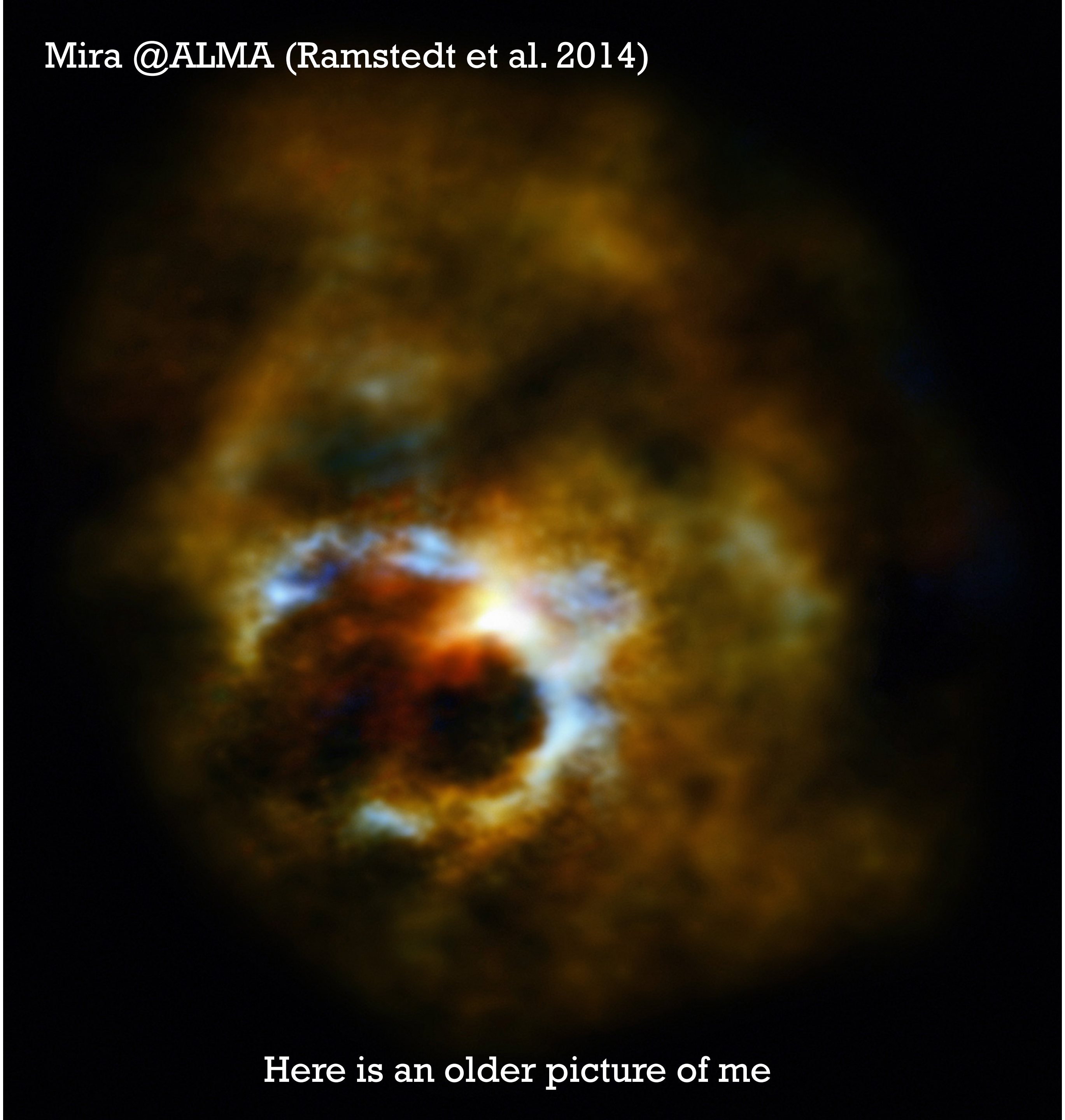
For oxides and silicates, $^{17}O/^{16}O$ and $^{18}O/^{16}O$ are the most relevant isotopic ratios.

- Group 1: ~70% of O-rich PSGs. Most probably from AGB stars with 1…2.5Msun
- Group 2: ~15%. From AGB's with cool bottom processing
- Group 3: rel. few grains. Origin: AGB's with lower masses and metallicities than parent stars of Group 1.
- Group 4: From Type II SNe




Astromineralogy, 2011, p. 292

# Mira @ALMA (Ramstedt et al. 2014)



Here is an older picture of me

# The Small Magellanic Cloud

- Most luminous red stars in any galaxy
- They are the brightest objects in the IR

⇒ Disadvantage: short live

Mass-loss one of the ingredients of stellar evolution codes

⇒ But we do not understand it!

Two Micron All Sky Survey
– Southern Facility –
2MASS Atlas Image Mosaic

Infrared Processing and Analysis Center/Caltech & University of Massachusetts

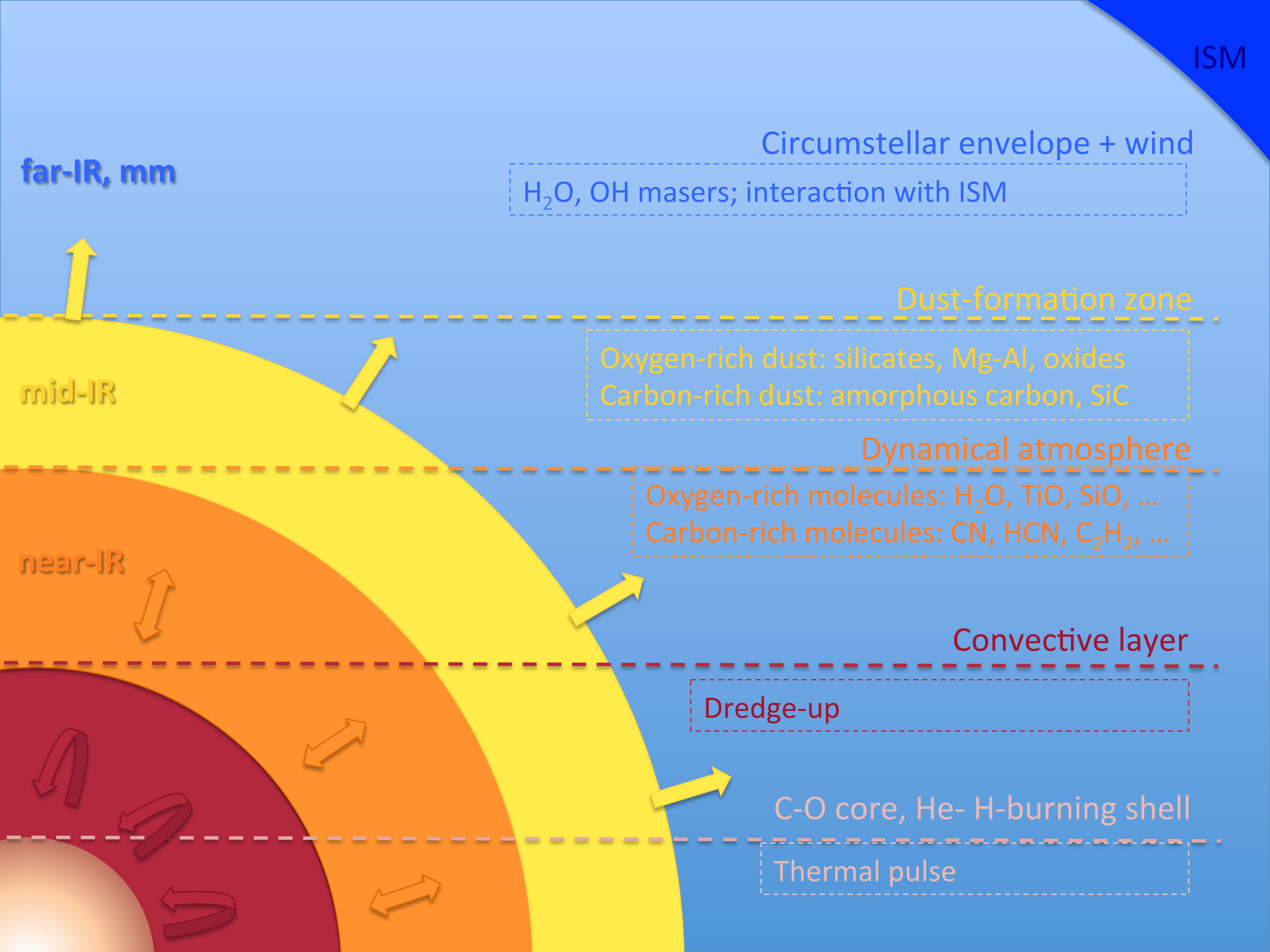
# The (complex) atmosphere

# Definition

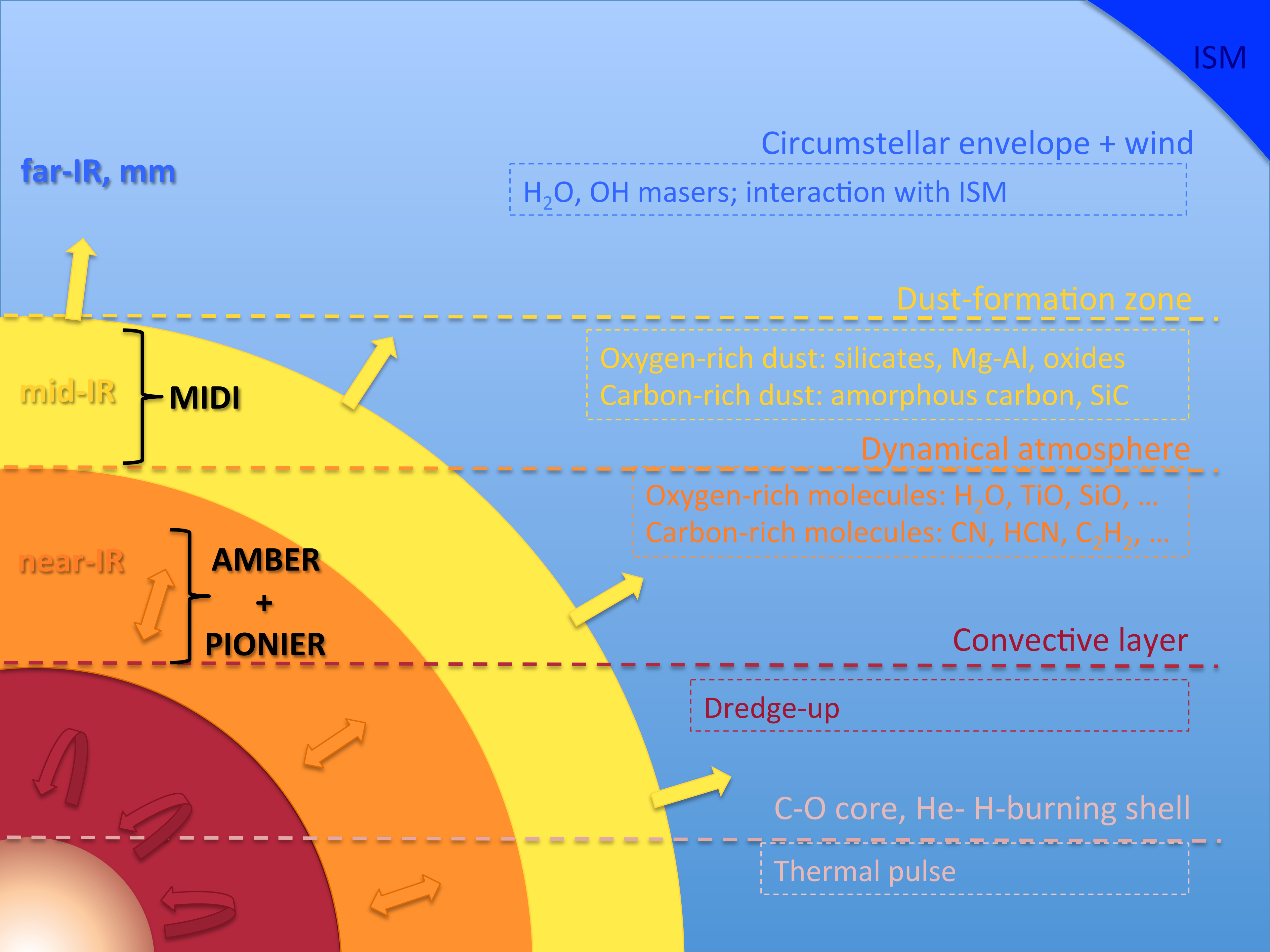
- atmosphere (greek [*atmos*] "vapor" + [*sphaira*] "sphere“)
  use of this term *atmosphere* for the outer layers of a star is not obvious (Gautschy-Loidl et al. 2004) lower boundary less easily defined, for AGB stars also the outer boundary

**Transition region from optically thick stellar interiors to optically thin outermost layers → photons can leave the star**

- radial coordinates → optical depth coordinates
- region of spectrum formation (“layers that are visible from outside”)
- since light is the only source of information from distant stars → understanding the physical processes in this region is essential for interpreting observations in terms of basic parameters



ISM
Circumstellar envelope + wind
far-IR, mm
$H_2O$, OH masers; interaction with ISM
Dust-formation zone
mid-IR
Oxygen-rich dust: silicates, Mg-Al, oxides
Carbon-rich dust: amorphous carbon, SiC
Dynamical atmosphere
Oxygen-rich molecules: $H_2O$, TiO, SiO, …
Carbon-rich molecules: CN, HCN, $C_2H_2$, …
near-IR
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse



ISM
Circumstellar envelope + wind
far-IR, mm
$H_2O$, OH masers; interaction with ISM
Dust-formation zone
mid-IR
MIDI
Oxygen-rich dust: silicates, Mg-Al, oxides
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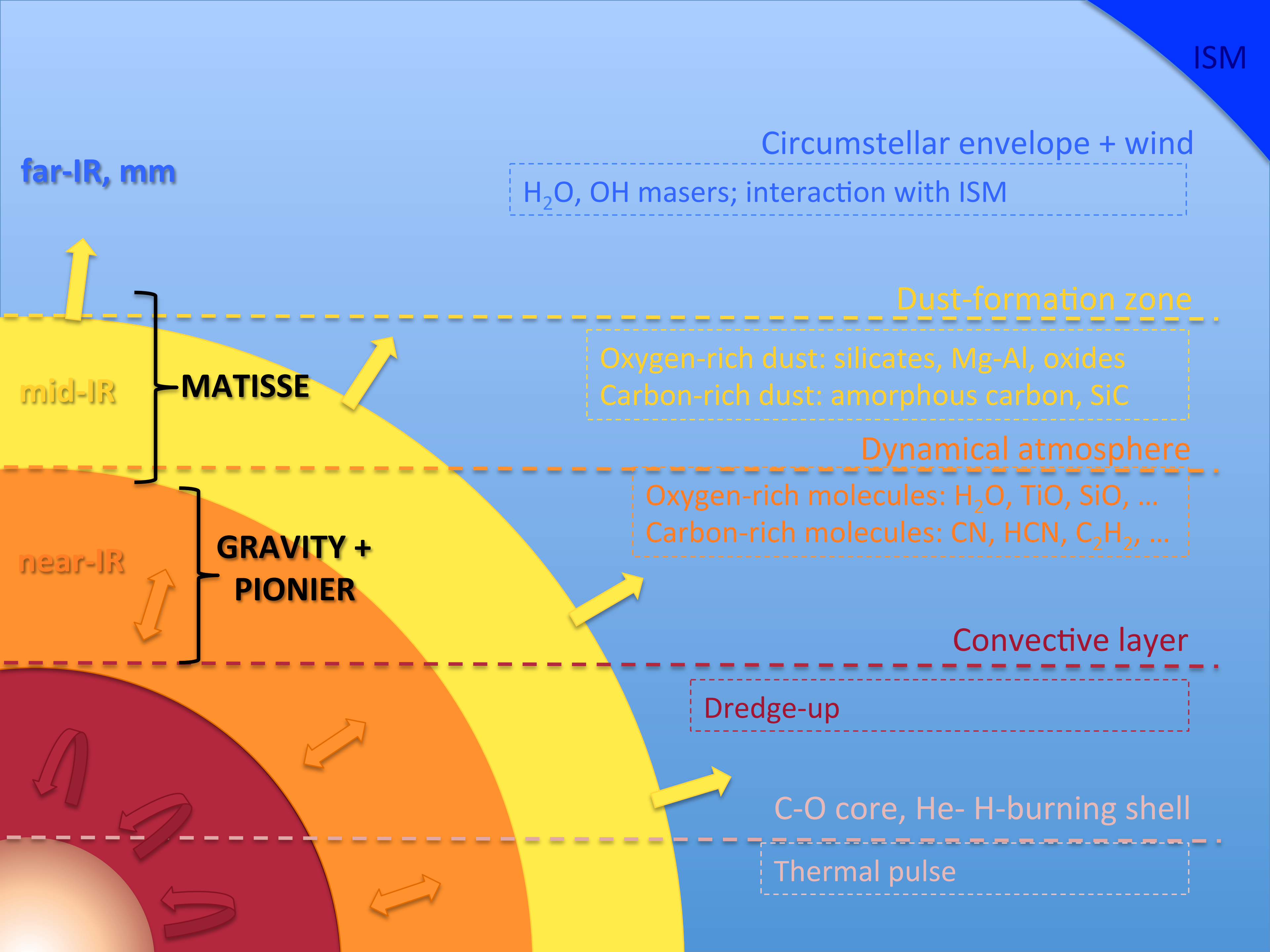
Oxygen-rich molecules: $H_2O$, TiO, SiO, …
Carbon-rich molecules: CN, HCN, $C_2H_2$, …
near-IR
AMBER
+
PIONIER
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse



ISM
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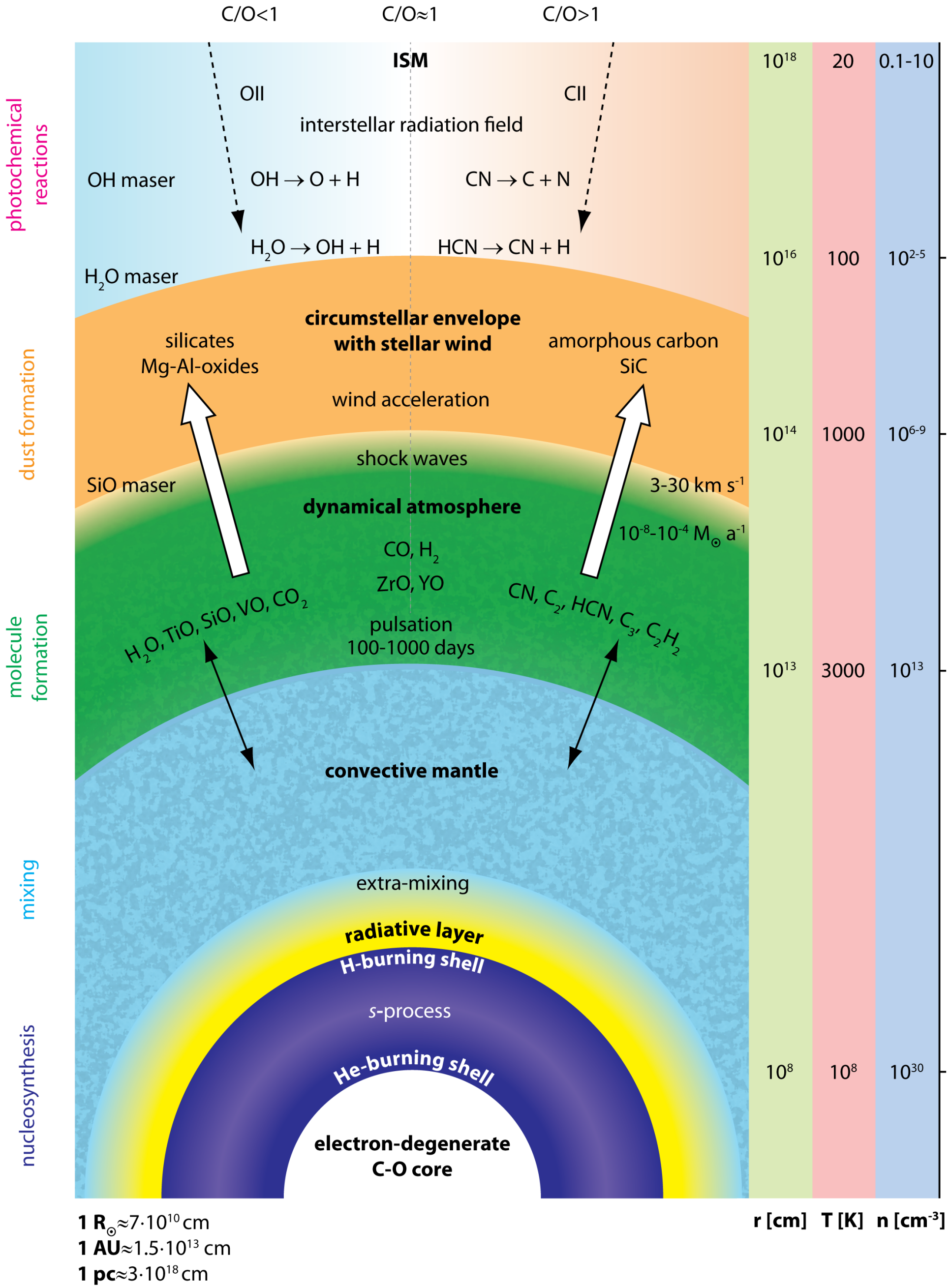
near-IR
GRAVITY +
PIONIER
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse

Schematic view of an AGB star




# AGB stars

- $1 < M < 8\ M_\odot$
- $R = 300\ R_\odot$
- $L = 5{,}000 – 10{,}000\ L_\odot$
- $T_{eff}$=2,600 – 3,500 K
- Infrared crucial
  - ~1 mag in near-IR
  - >40 Jy in the mid-IR

Ideal targets for interferometry!

# Stellar atmospheres and molecules

- cool + extended AGB atmospheres
  - → efficient formation of molecules
- molecules are most important constituent:
  - strong effects of molecular absorption → radiation fields within atmospheres are highly complex
  - significant opacity sources → important for the atmospheric structure (thermal balance)
  - determine the spectral appearance
- important for the process of **dust formation**
  - atoms → polyatomic molecules → small clusters = seed nuclei → dust grains


- People speak about „molecular layers“ but… Be careful!

# The role of CO

- $^{12}C$ most important element mixed up during 3rd dredge up

fundamental change of elemental abundances
in atmosphere M* → C*
(also relevant for dust chemistry)

credit: S. Hoefner

**CO**: highest dissociation energy (11.1eV)

acts as *switch* between atmospheric chemistries

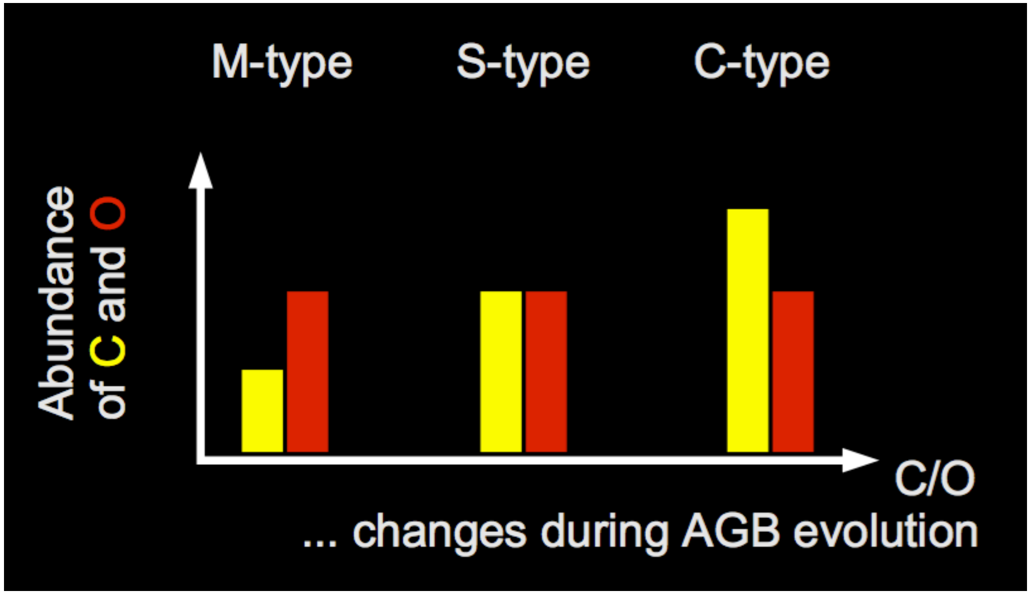


TABLE 1. The 40 diatomic, 8 polyatomic, and 3 ionic molecules observed in photospheres of M, S, and C stars and the Sun (photosphere + sunspots).

| Molecule | *observed in:* Sun | M | S | C | notes | Molecule | *observed in:* Sun | M | S | C | notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Diatomic molecules: | | | | | | SiN | | * | | | |
| AlH | * | * | * | * | | SiO | * | * | * | | K,S+ |
| AlO | | * | | | gi | SnH | | | | * | |
| BO | | * | | | | TiH | * | * | | | |
| CaH | * | * | | | CS, dw | TiO | * | * | * | | K |
| CaCl | | | | * | CS | TiS | | | * | | |
| CeO | | | * | | MS | VO | | * | * | | |
| CrO | | * | | | | YO | | * | * | | S+ |
| CrH | * | | | | | YS | | | * | | |
| $C_2$ | * | | | * | | ZnH | | | | * | |
| CH | * | * | * | * | G,K,Ap,d+ | ZrO | * | * | * | | SC,S+ |
| CN | * | * | * | * | G,K,RCrB, g+,S+ | ZrS | | | * | | |
| CO | * | * | * | * | K,SN,nova, g+,S+ | | | | | | |
| CS | | | | * | | Molecular ions: | | | | | |
| CuH | * | | | * | | | | | | | |
| FeH | * | * | * | | K,d+,S+ | $H^-$ | * | * | * | * | d+ |
| GeH | | | | * | | $SiH^+$ | * | | | | |
| $H_2$ | * | * | * | * | | $CH^+$ | * | | | | |
| HF | * | * | * | * | K | | | | | | |
| HCl | * | | * | | | Polyatomic molecules: | | | | | |
| LaO | | | * | | | | | | | | |
| MgH | * | * | * | | K, dw | $C_2H$ | | | | * | |
| MgO | | * | | | | $C_2H_2$ | | | | * | |
| NH | * | * | | * | | $C_3$ | | | | * | |
| NiH | * | | | | | CaOH | | * | | | K7,dw |
| OH | * | * | * | | K, d+ | HCN | | | | * | |
| ScO | * | * | * | | | $H_2O$ | * | * | | | d+ |
| SiF | | * | | | | $SiC_2$ | | | | * | SC |
| SiH | * | * | * | * | | $CH_4$ | | * | | | bdw |

Notes: gi, dw means that the molecule has been observed only in giants or dwarfs, respectively. g+ and d+ refers to the bands of the molecule being stronger in giants than in dwarfs (g+) or visa versa (d+). S+ refers to the bands being stronger in S stars than in M type giants. G, K, SC, CS, MS, Ap, RCrB, SN (super nova), and nova, respectively, refers to the molecule having been identified also in these types of stars. The note bdw for $CH_4$ reminds us that $CH_4$ has been observed not in "real M-type dwarfs" but in Brown Dwarfs only.

Jorgensen (1997)

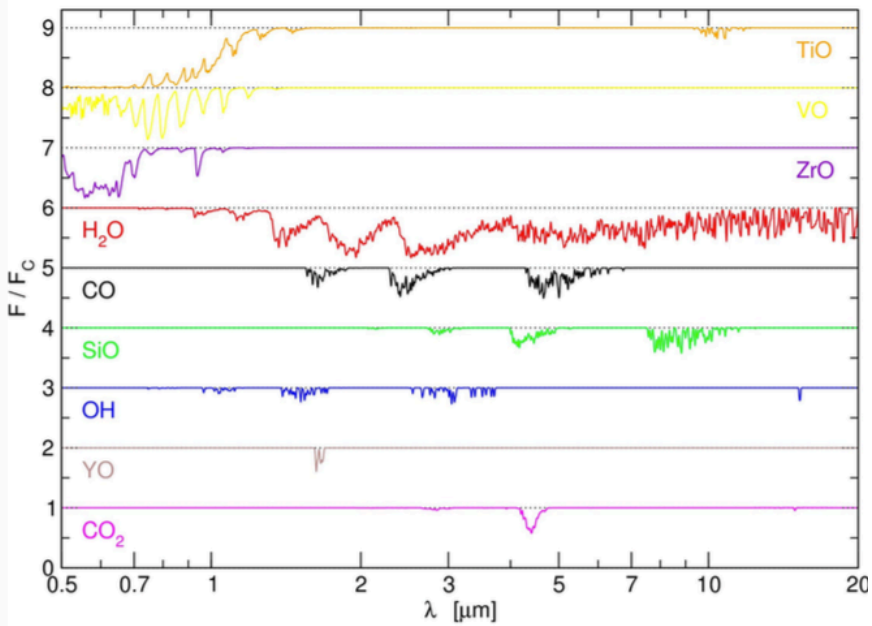
TABLE 1. Molecules detected at radio wavelengths in envelopes around AGB and post-AGB objects of different chemistries (O: $C/O<1$; S: $C/O\approx1$; C: $C/O>1$). The (rough) number of sources $\Sigma$ detected in each species is also given.

| Molecule | Chemistry O | S | C | $\Sigma$ | Molecule | Chemistry O | S | C | $\Sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| *2-atomic:* | | | | | | | | | |
| AlCl | | | * | 1 | NaCl | | | * | 1 |
| AlF | | | * | 1 | OH | * | | | 2000 |
| CO | * | * | * | 500 | SiC | | | * | 2 |
| CN | * | * | * | 50 | SiN | | | * | 1 |
| CP | | | * | 1 | SiO | * | * | * | 450 |
| CS | * | * | * | 40 | SiS | * | | * | 15 |
| KCl | | | * | 1 | SO | * | | | 25 |
| *3-atomic:* | | | | | | | | | |
| $C_2H$ | | | * | 10 | MgCN | | | * | 1 |
| $C_2S$ | | | * | 4 | MgNC | | | * | 1 |
| HCN | * | * | * | 130 | NaCN | | | * | 1 |
| $H_2O$ | * | | | 300 | OCS | * | | | 1 |
| $H_2S$ | * | | | 20 | $SiC_2$ | | | * | 5 |
| HNC | * | | * | 15 | $SO_2$ | * | | | 20 |
| *4-atomic:* | | | | | | | | | |
| $\ell$-$C_3H$ | | | * | 2 | $HC_2N$ | | | * | 1 |
| $C_3N$ | | | * | 5 | $H_2CO$ | * | | | 2 |
| $C_3S$ | | | * | 1 | $NH_3$ | * | | * | 6 |
| *5-atomic:* | | | | | | | | | |
| $C_4H$ | | | * | 6 | $HC_3N$ | | | * | 10 |
| $C_4Si$ | | | * | 1 | $HC_2NC$ | | | * | 1 |
| c-$C_3H_2$ | | | * | 7 | $H_2C_3$ | | | * | 1 |
| *6-atomic:* | | | | | | | | | |
| $C_5H$ | | | * | 1 | $H_2C_4$ | | | * | 1 |
| $CH_3CN$ | | | * | 6 | | | | | |
| *7-atomic:* | | | | | | | | | |
| $C_6H$ | | | * | 1 | $HC_5N$ | | | * | 6 |
| *9-atomic:* | | | | | | | | | |
| $C_8H$ | | | * | 1 | $HC_7N$ | | | * | 2 |
| *11-atomic:* | | | | | | | | | |
| $HC_9N$ | | | * | 3 | | | | | |
| *Mol. ions:* | | | | | | | | | |
| $CO^+$ | | | * | 1 | $HCO^+$ | | | * | 10 |
| $NH_2^+$ | | | * | 2 | | | | | |

Olofsson (1997)

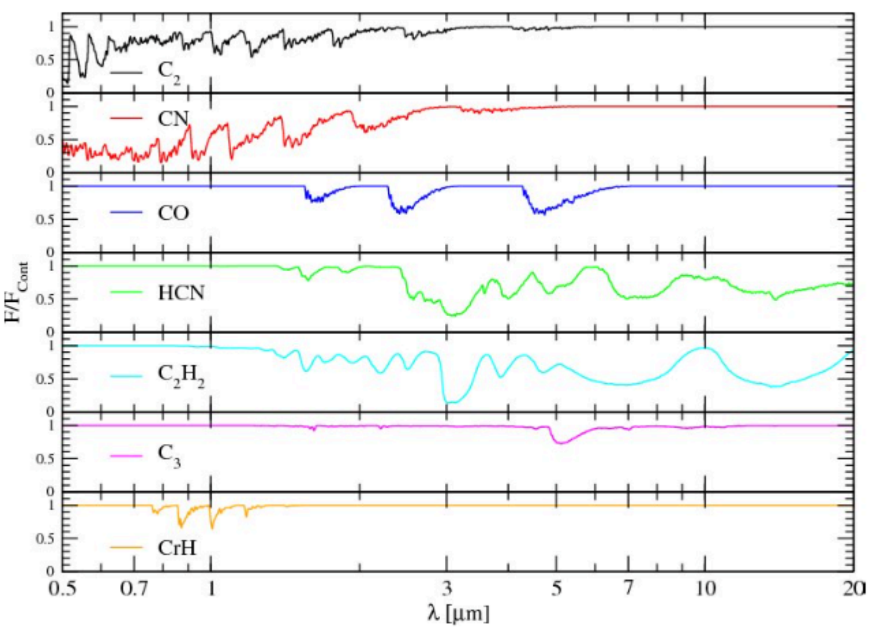
# Molecular features

M-type stars




*Nowotny (priv. comm.)*

C-type stars




*Aringer et al. (2009)*

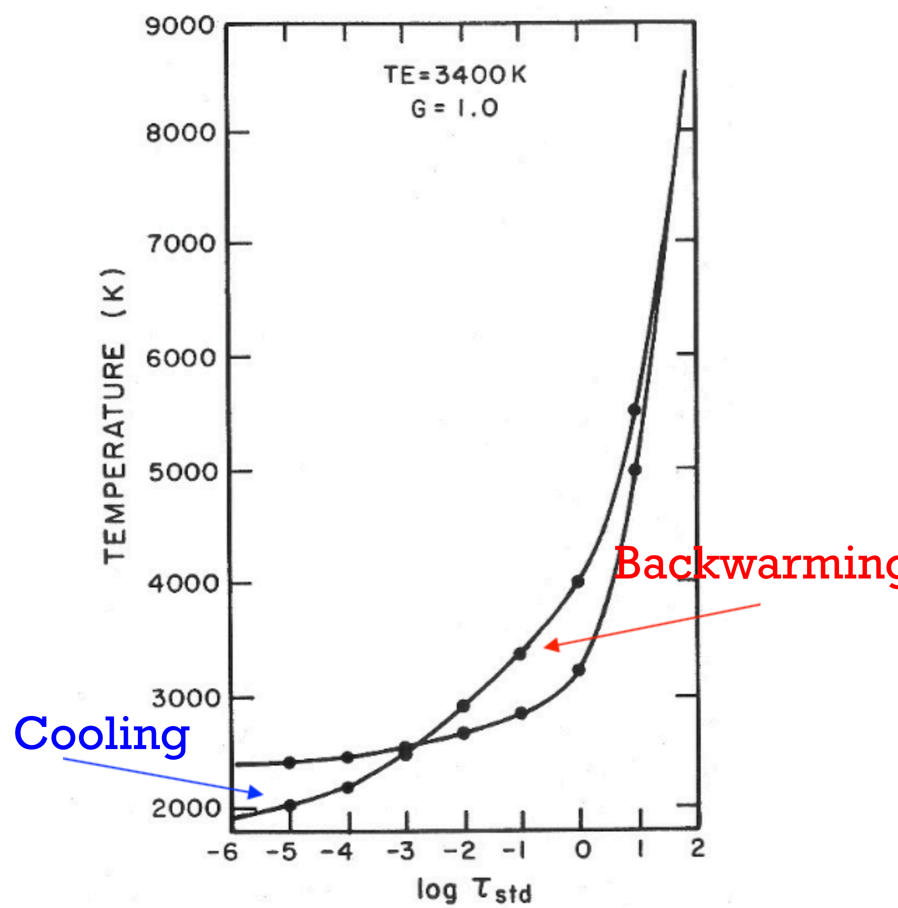
# Cooling & Back warming

- **Back warming of deep layers**: stellar radiation blocked by spectral lines ("line blanketing")
  Energy produced by thermo-nuclear processes in the interior → heating of deep (continuum flux-forming) layers + increased emission in between lines e.g.: 40% of flux blocked by lines → $\Delta T \approx 500K$

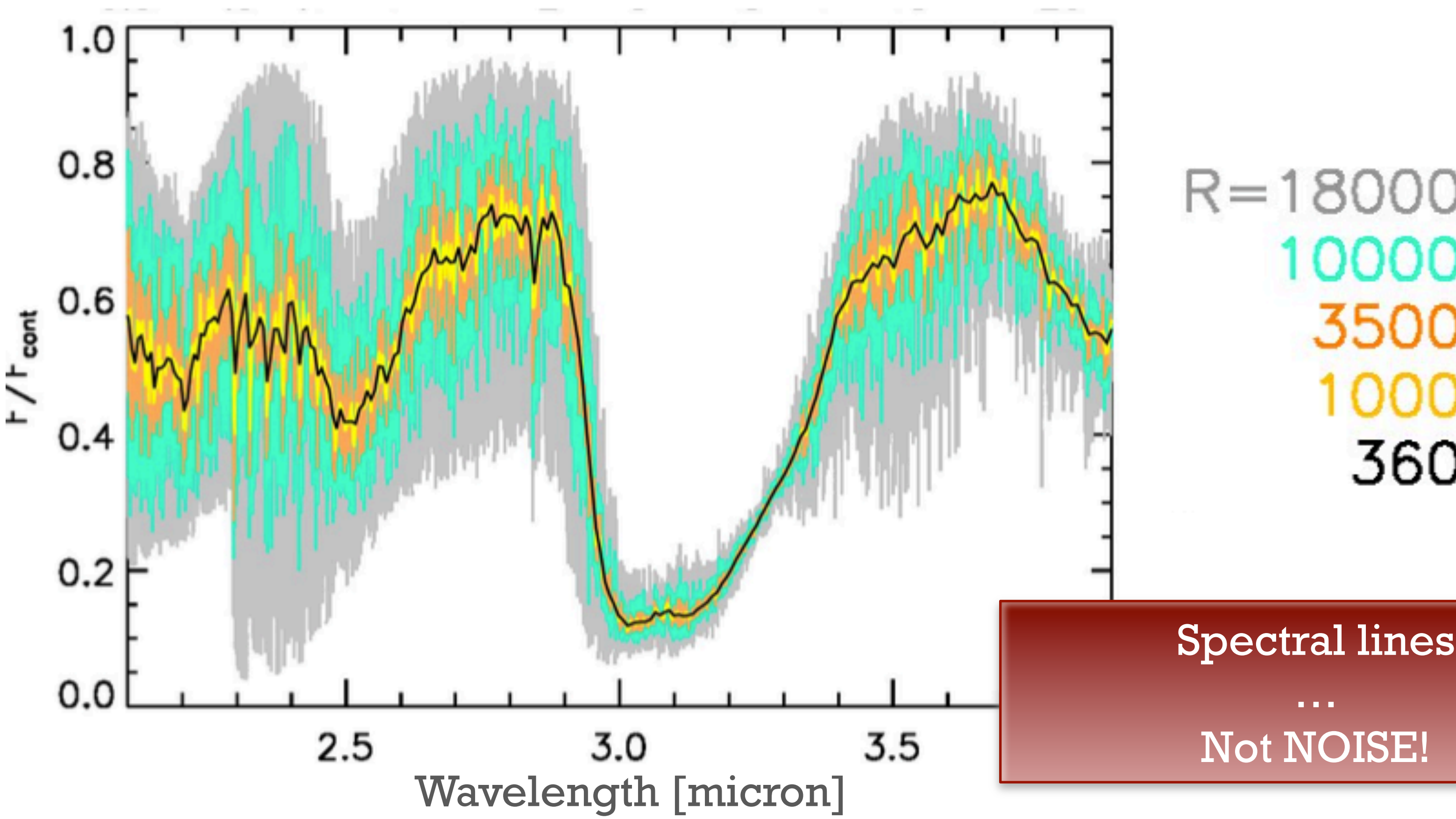
- **temperature change in outer atmospheric layers**: (cf. Sect. 4.6.2.2 in Gustafsson & Höfner 2004)

- Fragile molecule (e.g. $H_2O$, $C_2H_2$) in upper layers absorbs radiation from below via specific line if $\lambda$ line > $\lambda$ max[B($T_{local}$)] this results in **cooling of the layer (IR)** → contraction
  if $\lambda$ line < $\lambda$ max[B($T_{local}$)] this results in heating of the layer (blue-visual) → expansion

- effects of several 100K



# The effect of spectral resolution




Spectral lines
…
Not NOISE!

credit: W. Nowotny

# Molecular features and radii (I)

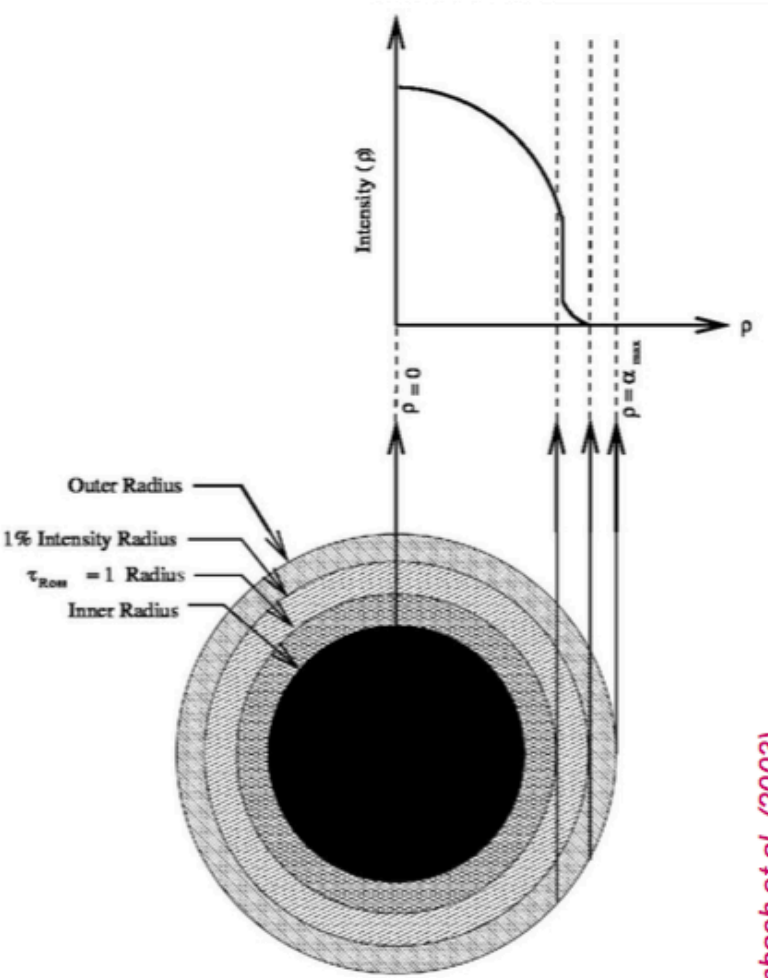
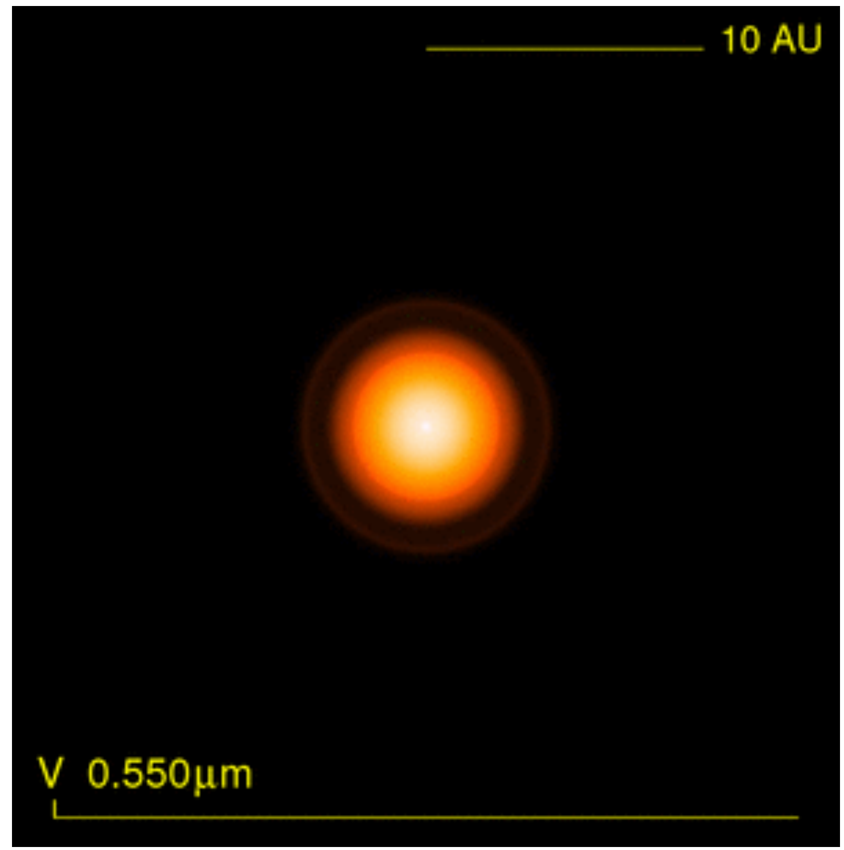



Figure 1. Schematic diagram showing the relationship between the angular intensity profile and the physical depth. The shape of the center-to-limb variation is typical for that predicted for a continuum band.

Quirrenbach et al. (2003)

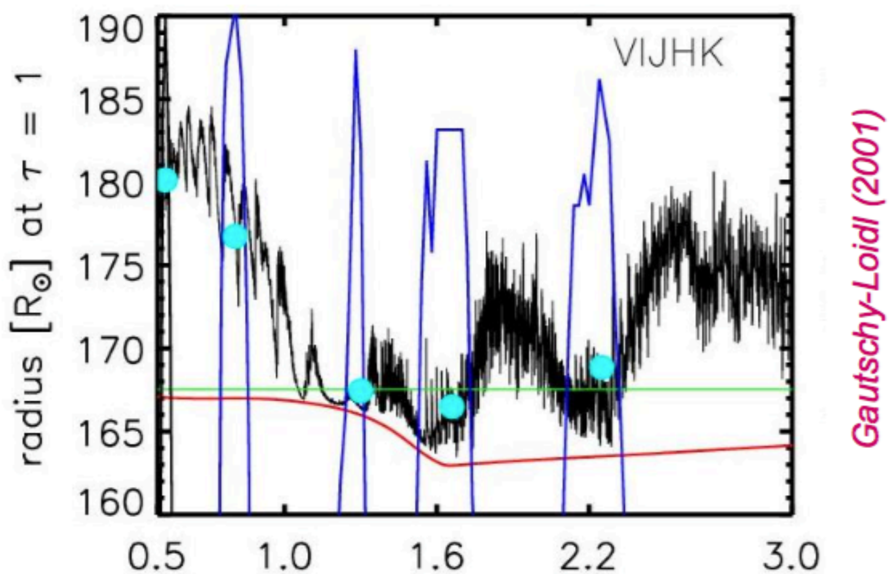


# Molecular features and radii (II)

Radius definition based on optical depth
$\tau = 1$

$$\tau_\nu = \int_0^L k_\nu \rho \, \mathrm{dx}$$

$\tau_{\text{Rosseland}} = 1$
$\tau_{\text{continuum}} = 1$




O-rich model $T_{eff}$=2800K radius measurement in standard broad-band filters

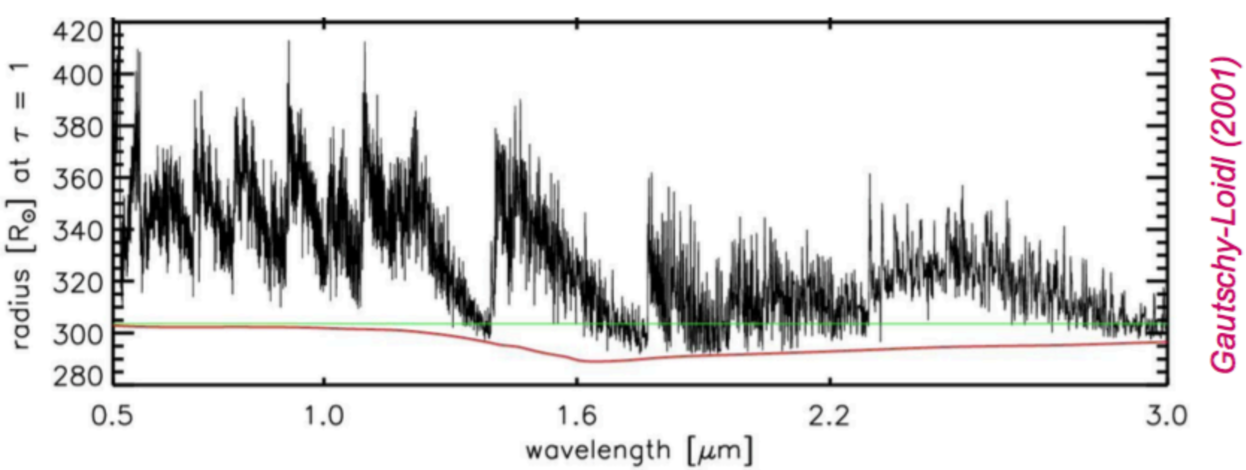
Diameter measurements in AGBs are tricky!

Be aware of molecular contaminations!

# Molecular features and radii (I)

Radius definition based on optical depth
$\tau = 1$

$$\tau_\nu = \int_0^L k_\nu \rho \, \mathrm{dx}$$




C-rich atmosphere
$T_{eff}$ =2950 K
$\tau_{\text{Rosseland}} = 1$
$\tau_{\text{continuum}} = 1$

Diameter measurements in AGBs are tricky!
Carbon stars situation even worst!

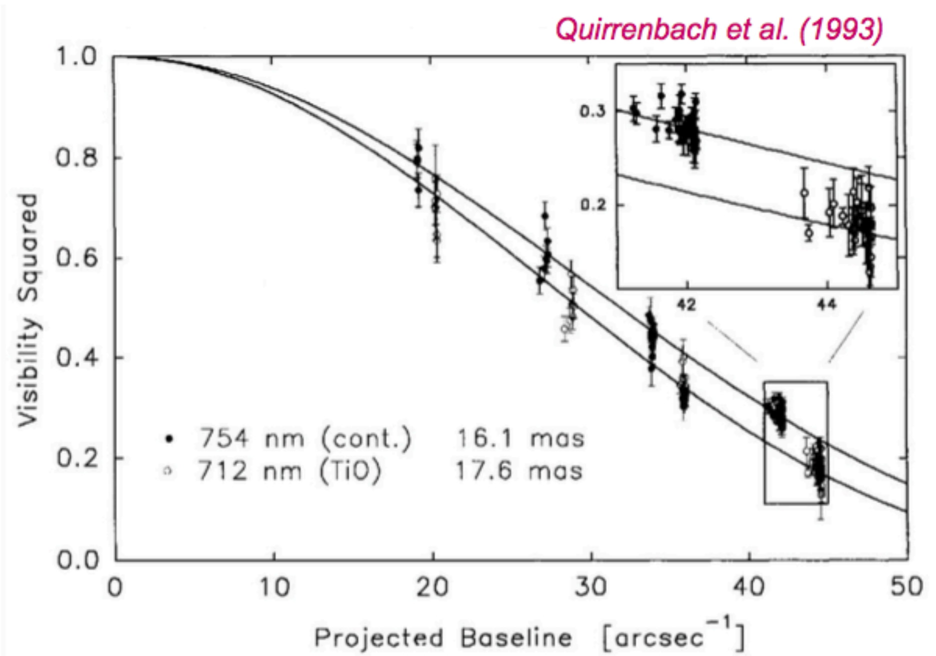
# Diameter measurement

- interferometric measurements (e.g. Quirrenbach 1993)interpreted by UD to derive radii
  - 754nm / cont → deep photosphere
  - 712nm / TiO → outer atmospheric layers

  → atmospheric extension can be estimated

Results:

- M-type giants 10% larger in TiO-band effect increasing with decreasing Teff
- (even larger effects for stars which are not hydrostatic anymore ...)

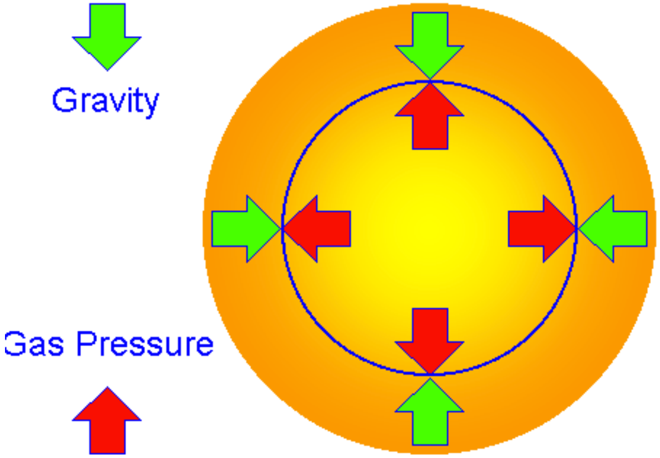


The dust

# Hydrostatic model atmospheres

MARCS, COMARCS, PHOENIX, ATLAS, KURUZ…

- 1-D models (spherically symmetric models);
- hydrostatic equilibrium, local thermal equilibrium & chemical equilibrium;
- treatment of molecular absorption with opacity sampling technique.




credit: R. Pogge

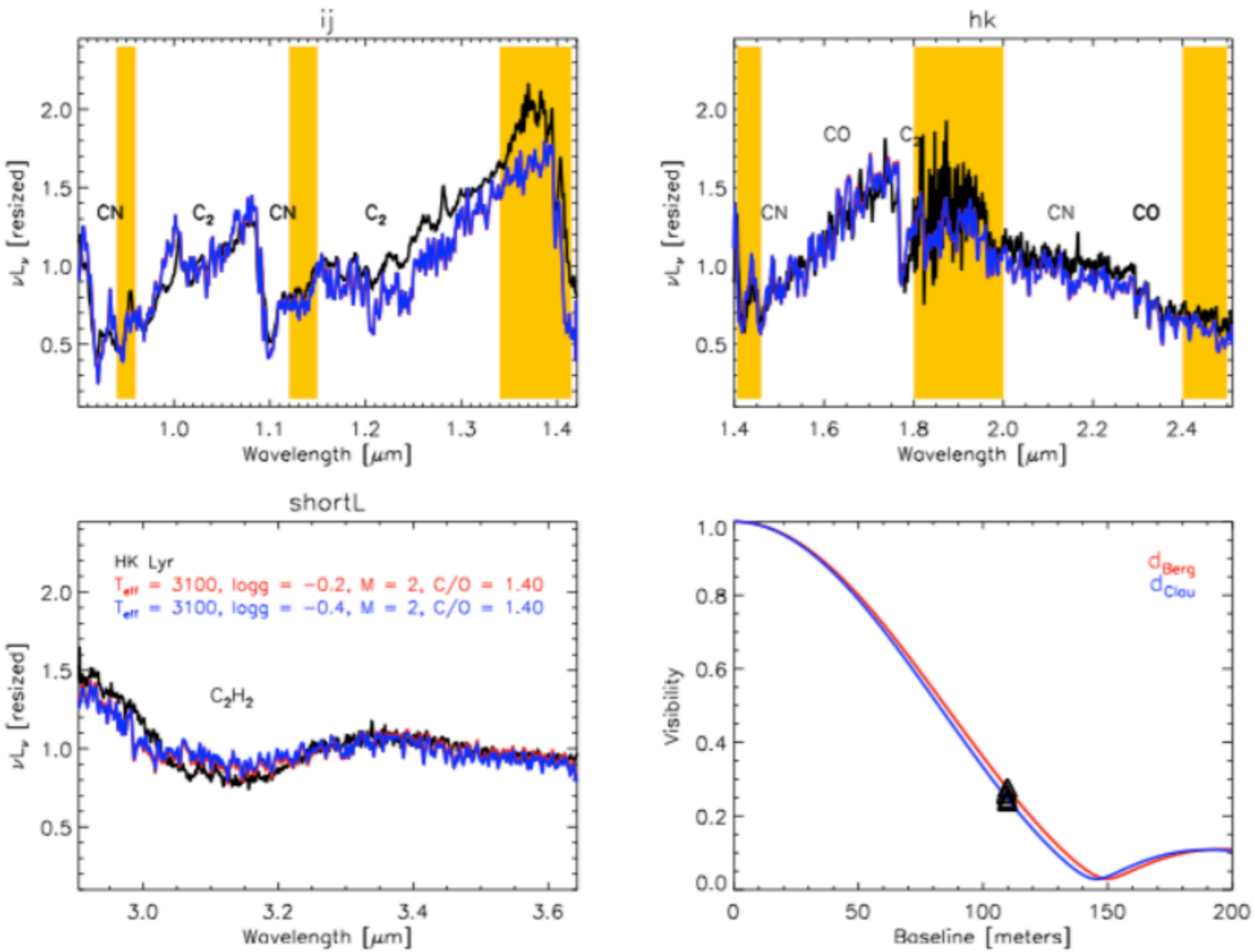
# Hydrostatic model atmospheres

Classical hydrostatic model atmospheres for red giants can reproduce observations of objects with

- $T_{eff}$ > 3300K (M-type stars) or 3000K (C-type stars)
- mild pulsations $\Delta m_{bol} \leq 0.1$
- small mass loss rates ($< 10^{-7} - 10^{-8}\ M_{\odot} yr^{-1}$)

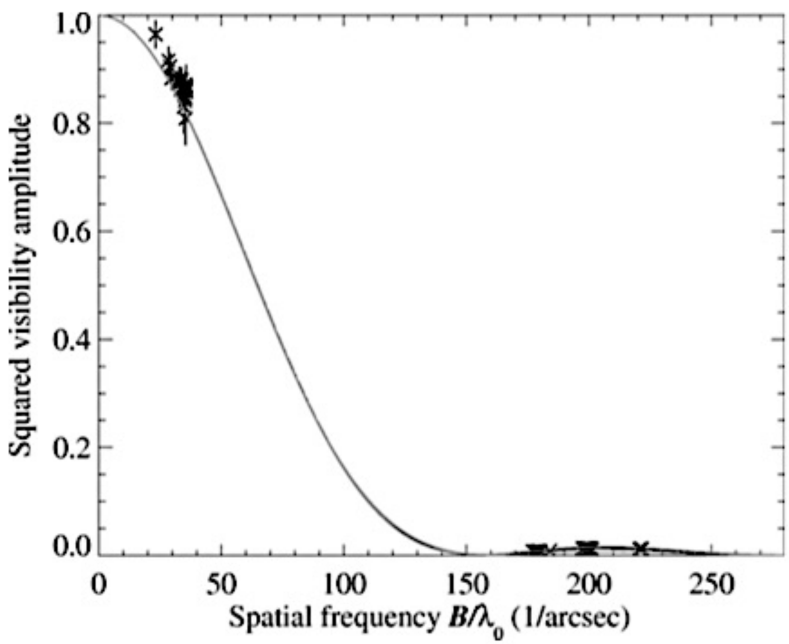
… but are of quite limited use to describe very evolved AGB stars dominated by dynamic effects

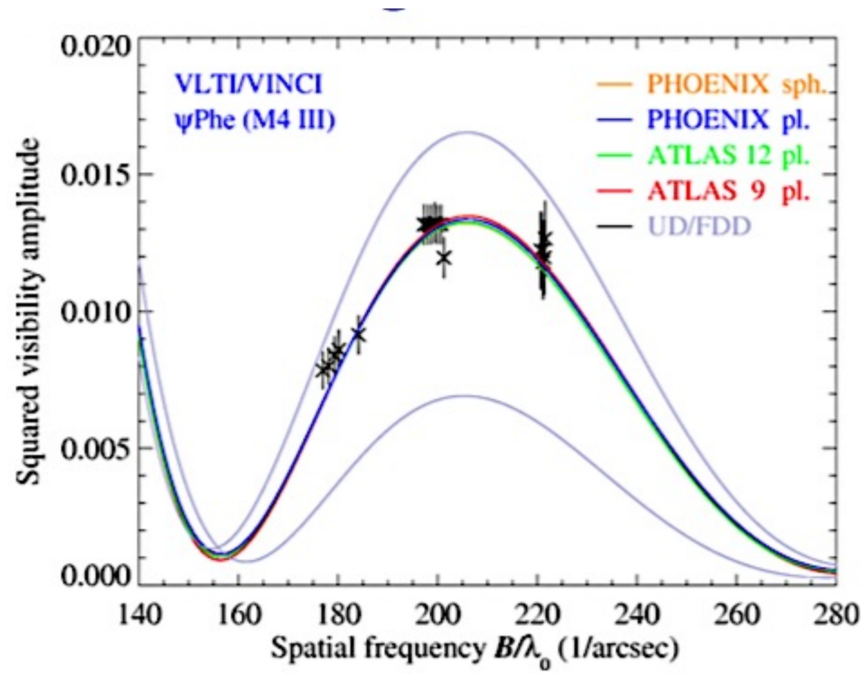
# Hydrostatic model atmospheres




*Paladini et al. 2011*

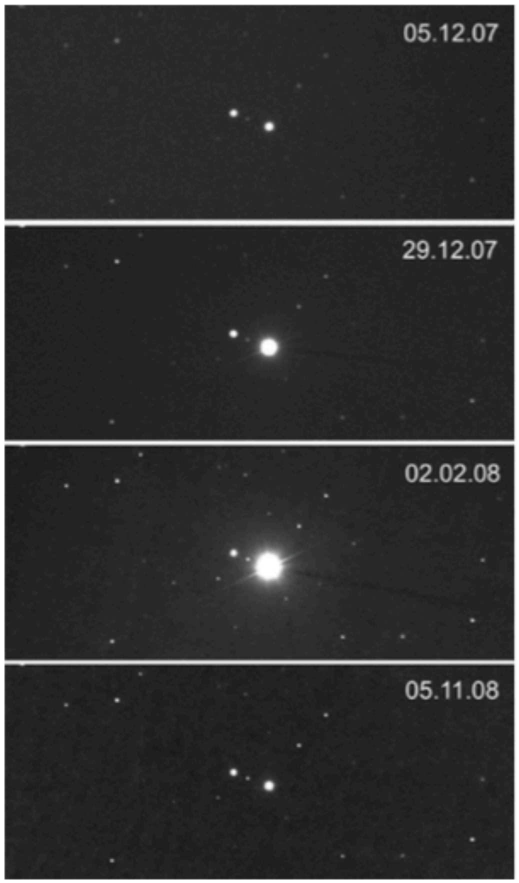
# Hydrostatic model atmospheres



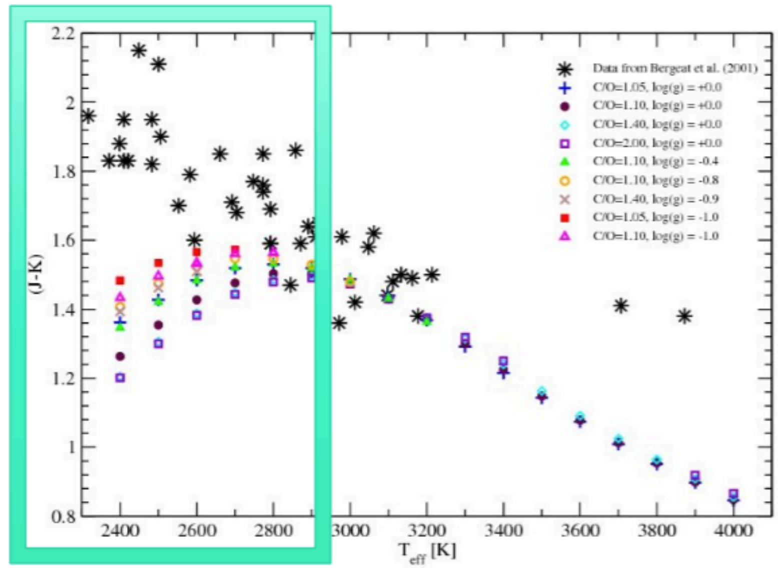

Wittkowski et al. 2004

# + Hydrostatic models cannot explain…




*M. Simon*

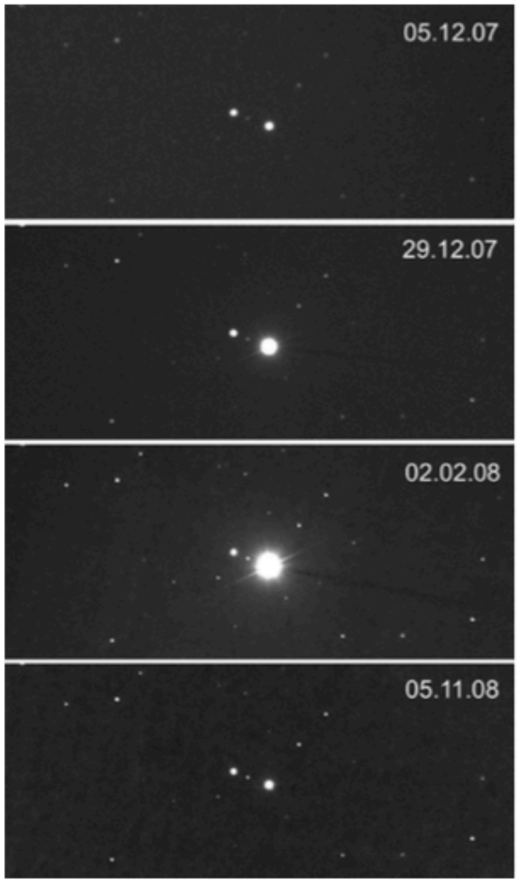
*o* Ceti (Mira)
periodic brightness variations




*Aringer et al. (2009)*

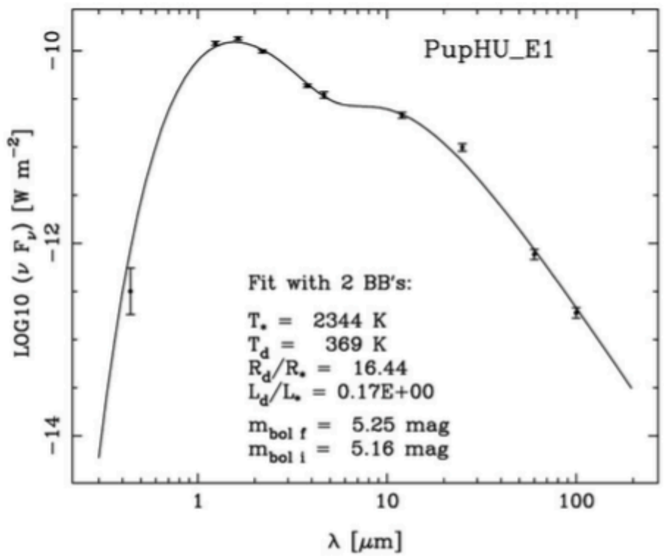
Color indices deviates!

# Hydrostatic models cannot explain…




M. Simon

*o* Ceti (Mira)
periodic brightness variations




Kerschbaum et al. (1996)

Cannot explain emission at long wavelengths!

# Beyond the hydrostatic description

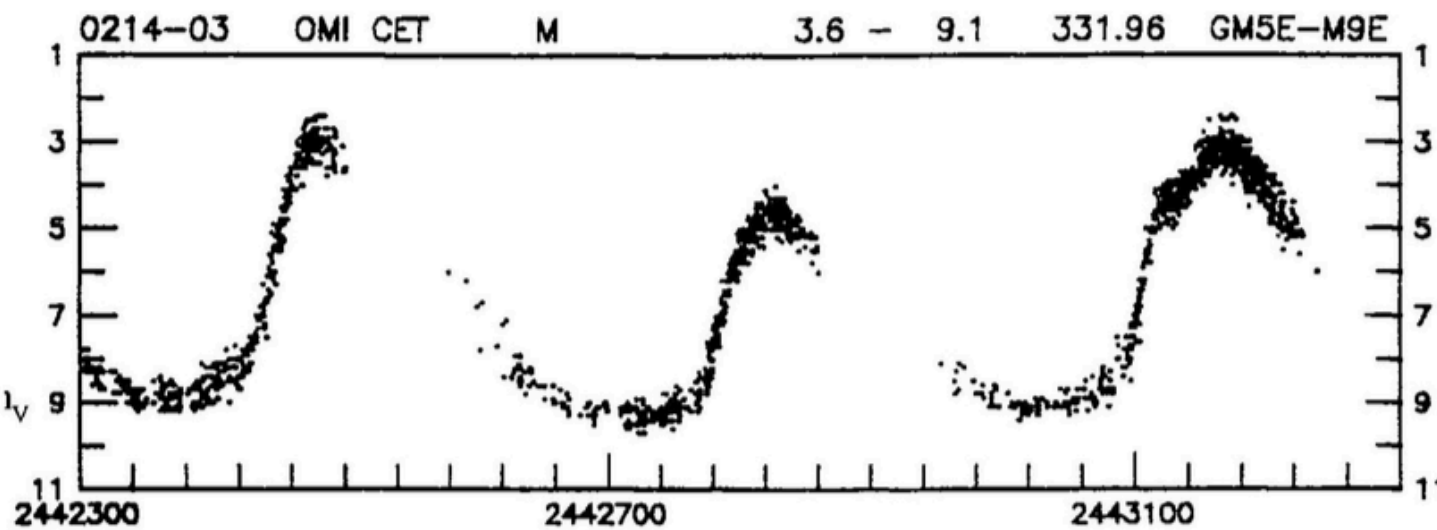
Effects becoming important towards the end of the AGB evolution:

- **Pulsations of stellar interiors**
  - unstable against radial pulsations driven by instabilities in H/He-ionisation zones
    $\kappa$ -mechanism acting in outer regions of convective envelope, still clearly below photosphere ($T_{gas} > 10^4$K)
  - Leading to pronounced photometric variability

# Beyond the hydrostatic description

Effects becoming important towards the end of the AGB evo

- P

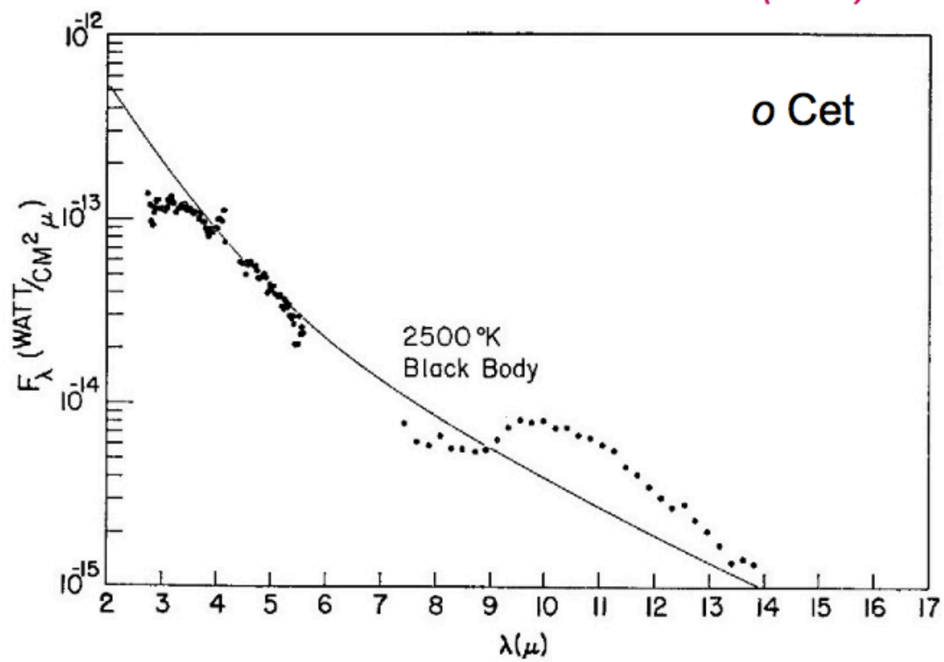



*Mattei (1997; AAVSO)*

# Evidence of mass loss

- Deutsch (1956) observed binary system $\alpha$ Her with common circumstellar envelope, → important evidence for mass loss through emissions+absorption lines, and gradient of radial velocity → estimated expansion velocity, MLR
- Reimers (1975) same for several systems (Reimers law for mass loss rate)
- 1960+: advent of IR spectroscopy
- Gillet et al. (1968), Woolf & Ney (1969): first observational evidence of silicates in spectra of M-type giants
- IR excess interpreted with emission of circumstellar silicate dust

Gillet et al. (1968)



# Other evidences of mass loss

… next evolutionary stage

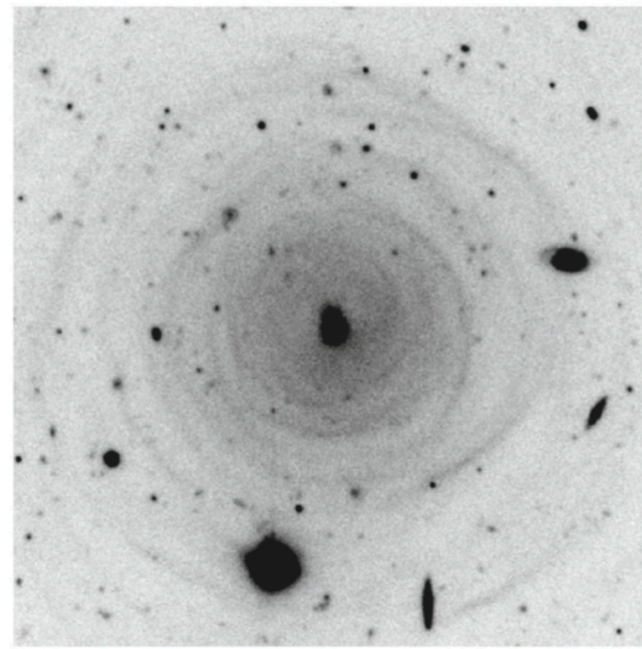
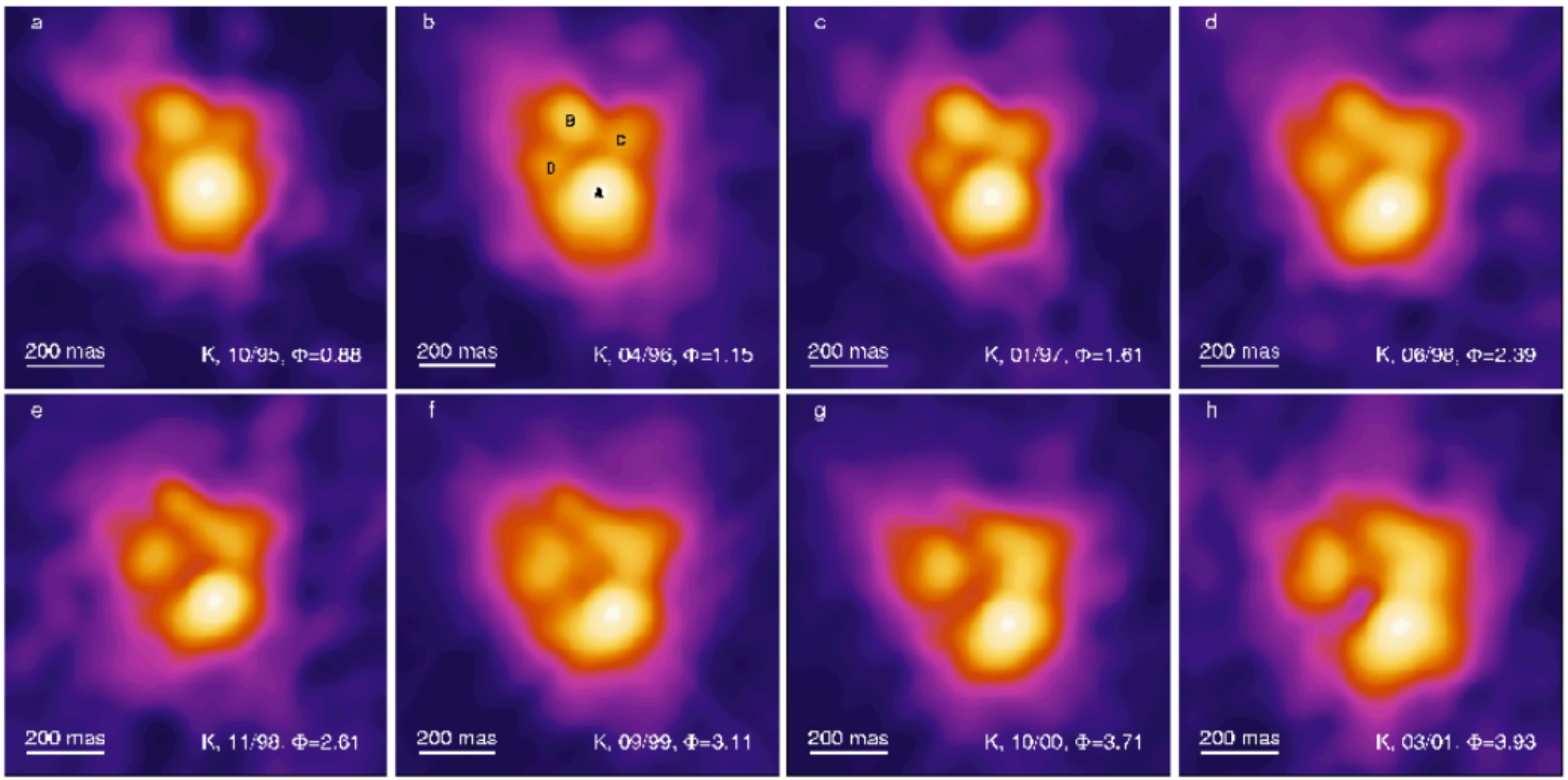


**Fig. 1.** *V*-band image of the circumstellar envelope of IRC+10216, made with the VLT. The field size is 90″ × 90″. The mass-losing carbon star is located at the center of the image, and Star 6 is the bright source near the bottom, 35″ from the center. North is to the top, East to the left.

*Mauron & Huggins (2010)*

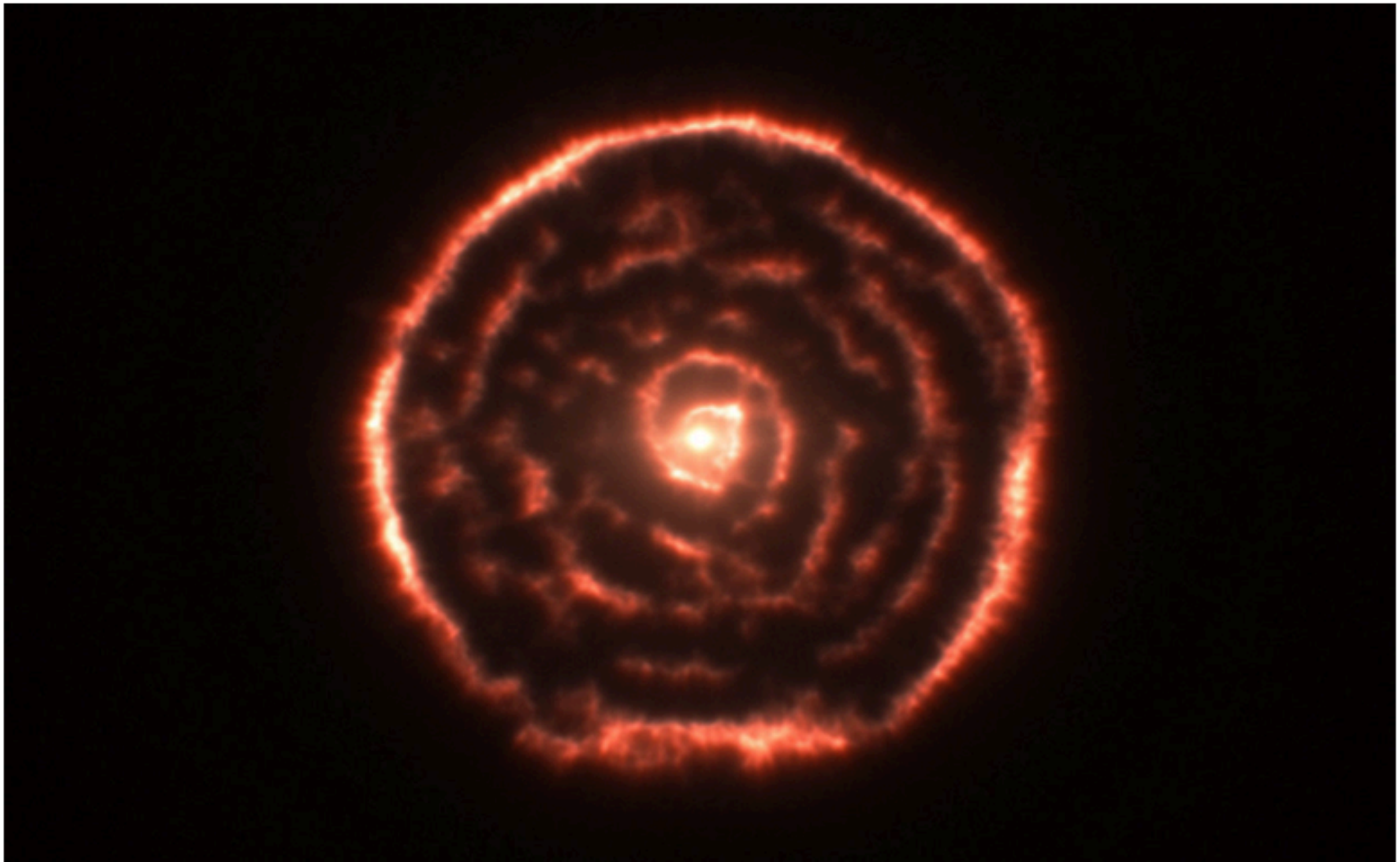
# Other evidences of mass loss




Weigelt 2002

# Other evidences of mass loss

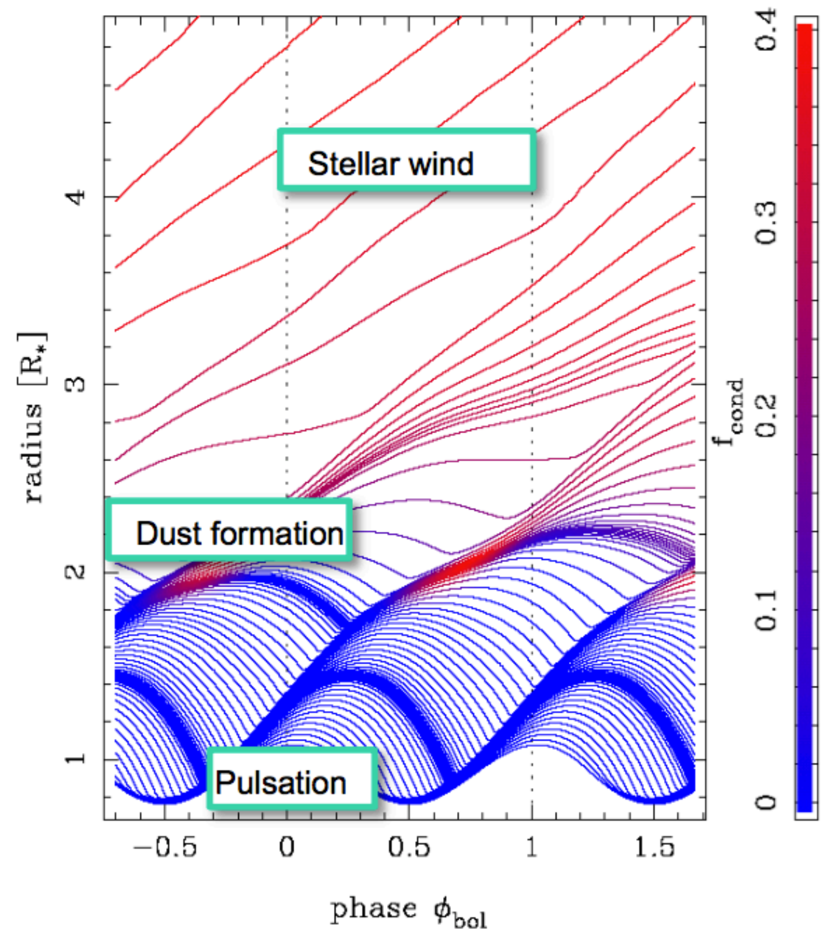
Maercker et al. 2012



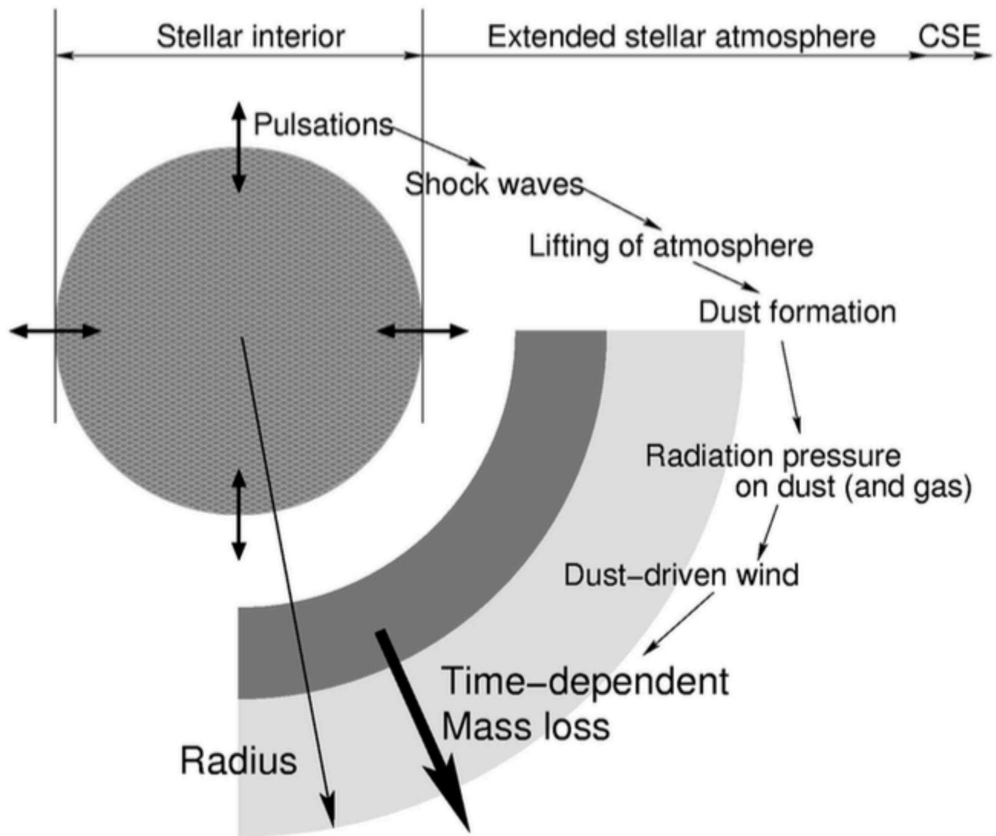
# Dust formation

Required for dust formation:

- Low temperature ($T_c$<1400K) … condensate stable against evaporation … efficiency of grain growth
- High density



# Mass loss in C-stars




Sandin (priv. comm.)

pulsation + dust formation in outer atmosphere → mass loss

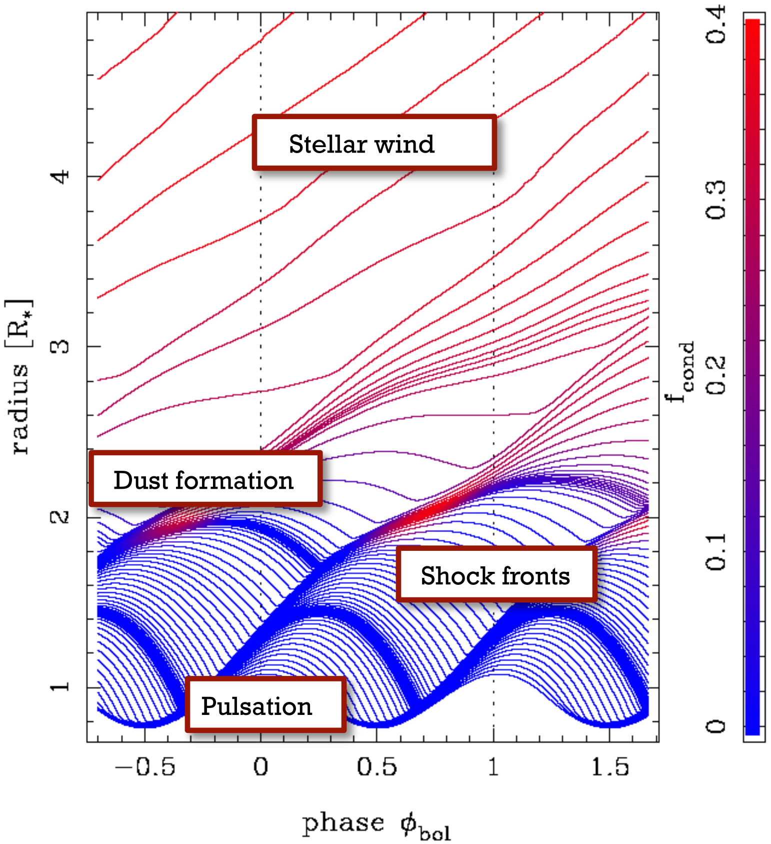
# Dynamic model atmospheres (DMA)

Models from Höfner et al. (2003), Mattsson et al. (2010)

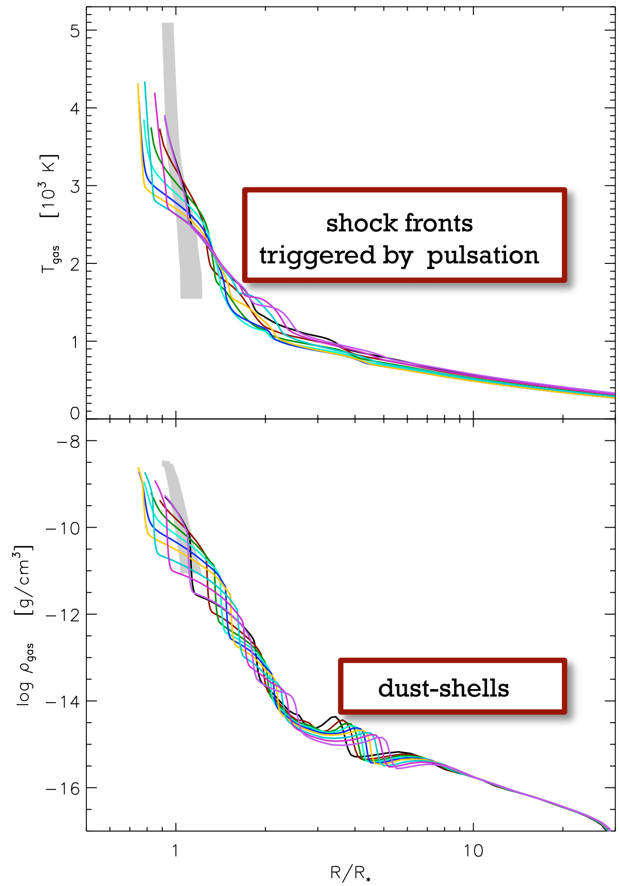
- 1-D models, spherically symmetric;
- Solving the coupled system of equations for:
  - hydrodynamics
  - frequency-dependent radiative transfer
  - time-dependent treatment dust formation (Gail & Sedlmayr 1988; Gauger et al., 1990)
- assume local thermal equilibrium for gas and dust
- Pulsation simulated by piston boundary condition

(Other models: CODEX…)

# DMA Radial Structure



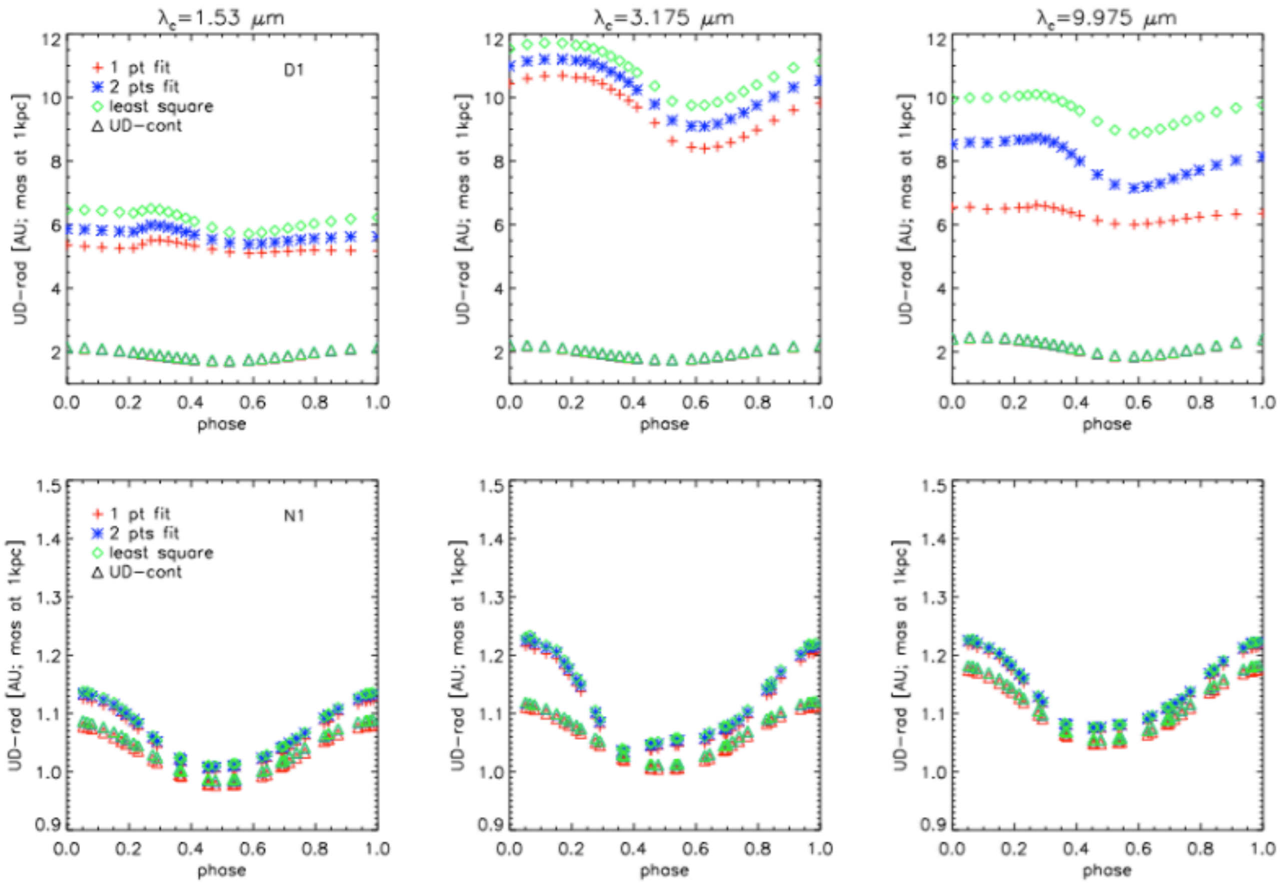

Hoefner et al. 2003




Paladini et al. 2009

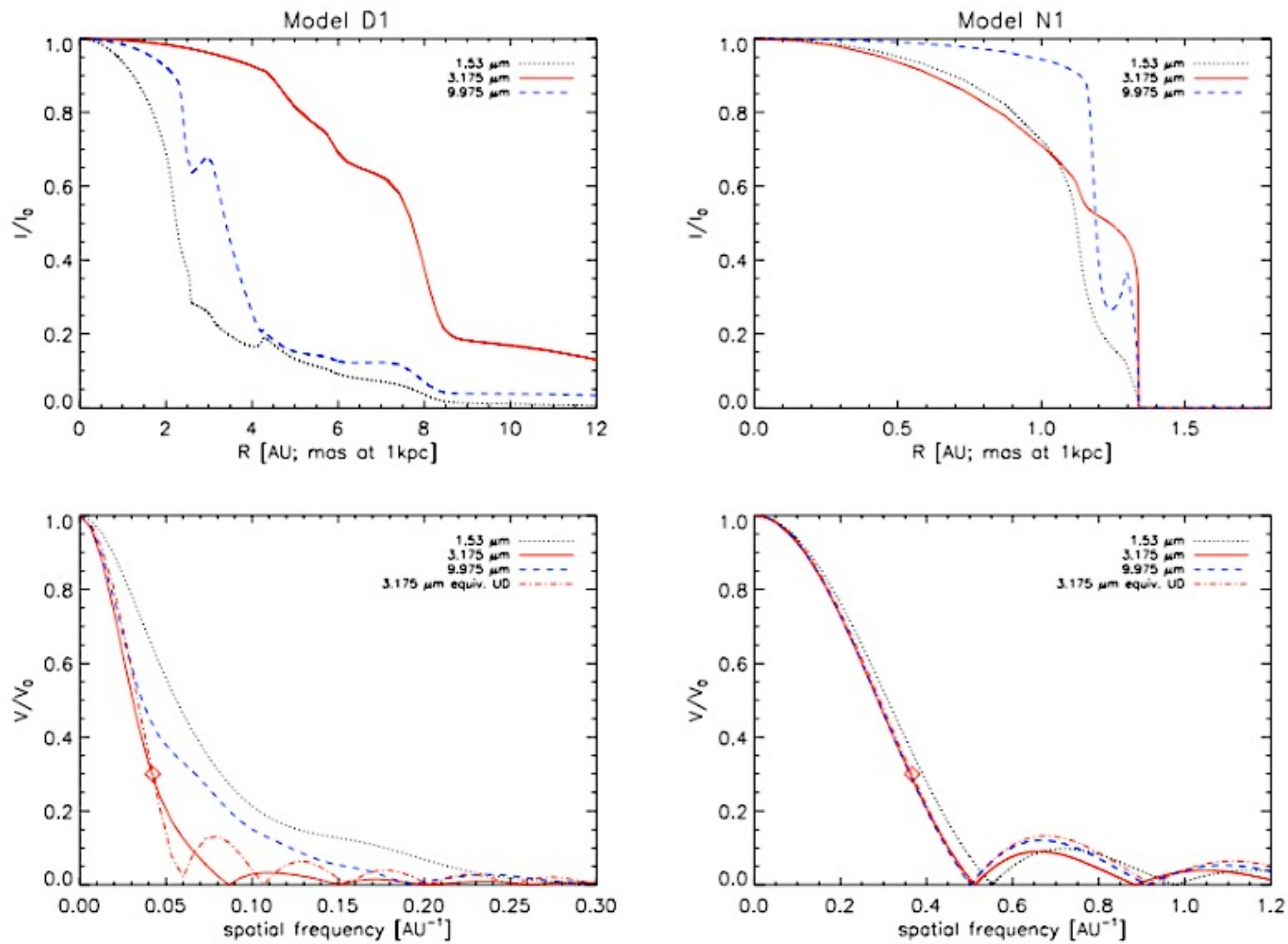
Grey shade = windless model
Colored lines = different phases for a DMA
with mass-loss

# Influence of pulsation on interferometric observables

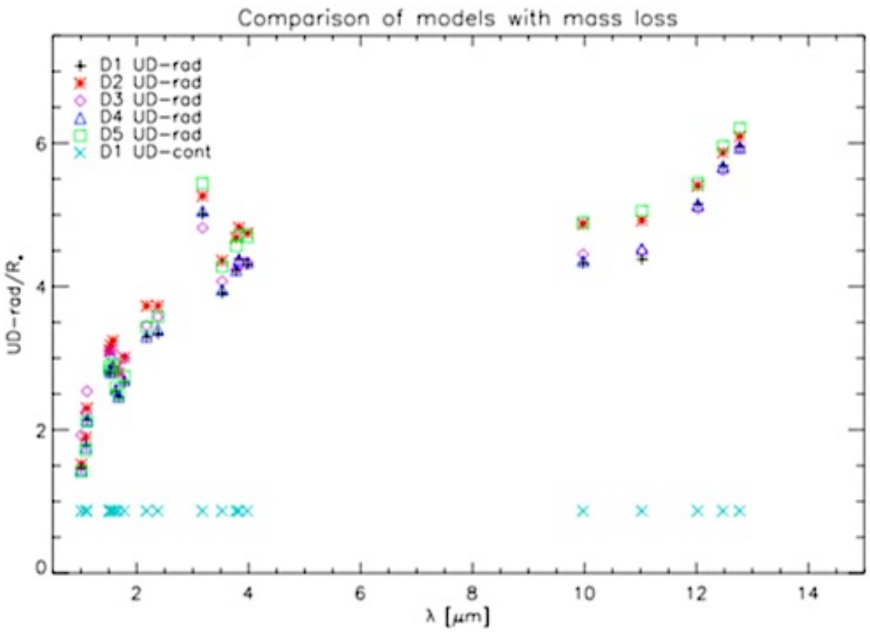


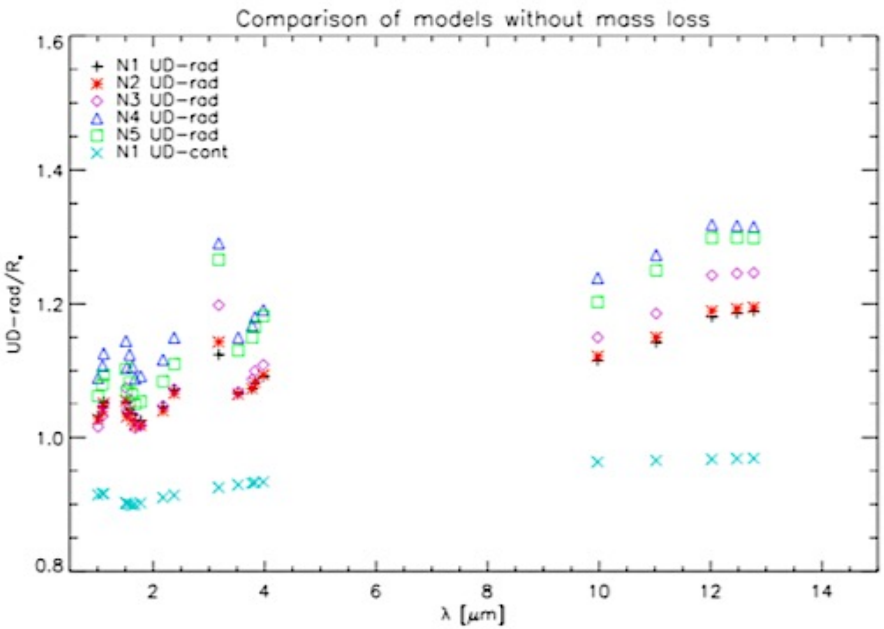

Paladini et al. 2009

# Intensity and Visibilities



# Diameter variation



# Mass loss in O-rich AGBs

**Höfner et al. (2008,09,11):**

Outflow driven via micron-size Fe-free silicate grains (i.e. Forsterite $Mg_2SiO_4$) and their substantial radiative scattering cross section

Scenario confirmed with
VLT SAM/NACO observations
By Norris et al. (2012)

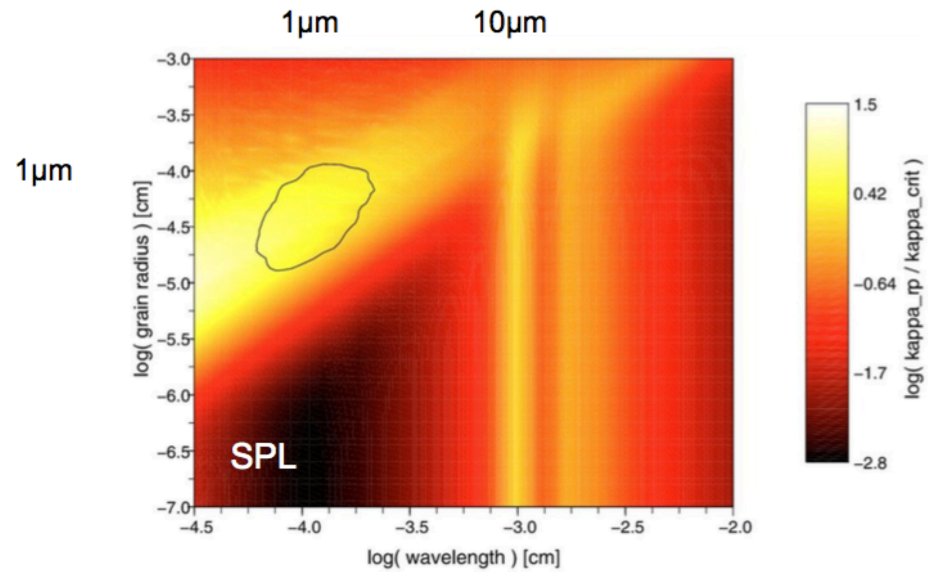
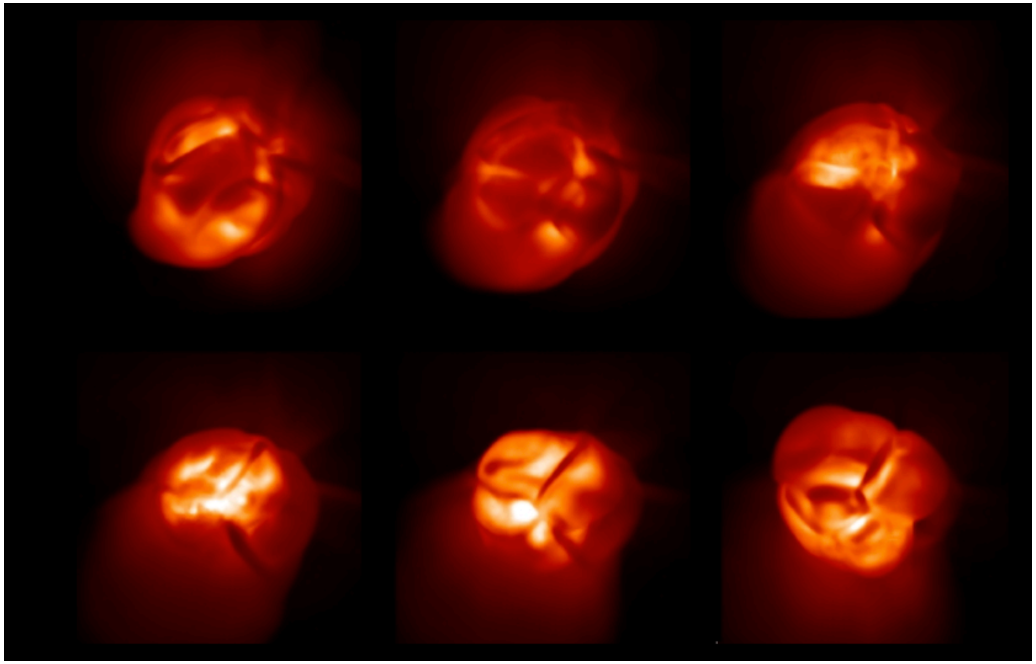



**Fig. 1.** Opacity $\kappa_{rp}$ of forsterite grains in units of the critical opacity $\kappa_{crit}$ ($M_\star = 1\ M_\odot$, $L_\star = 7000\ L_\odot$), assuming that 30 percent of Si is condensed into grains; The black contour shows the region where the flux-weighted opacity exceeds the critical opacity, assuming a Planckian flux distribution with $T_\star = 2700$ K.

# 3D models do exist but…

- Only very few
- O-rich dust
- Not fully consistent

More needed!
Need to be tested!



Freytag & Hoefner 2008

+

# Wake up!
# Summary part I

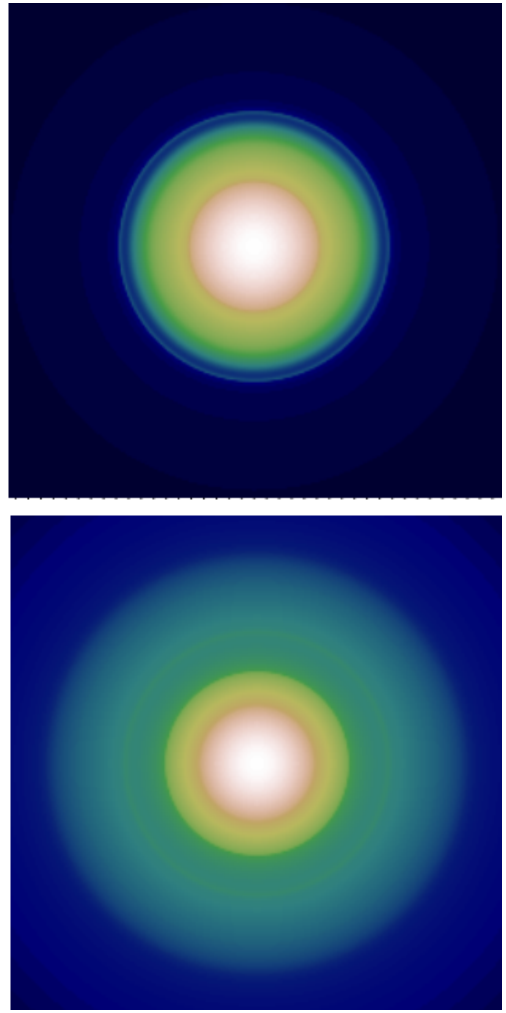
- What is an AGB star
- Why AGBs are important
- Atmospheric structure
- Molecules
  - Cooling & Back warming
  - Different chemistry
  - Effects on diameter definition
- Dust
  - Pulsation
  - Stellar wind C-rich stars
  - Stellar wind O-rich stars
  - Effects on interferometric observables

# Atmospheric structure at high angular resolution

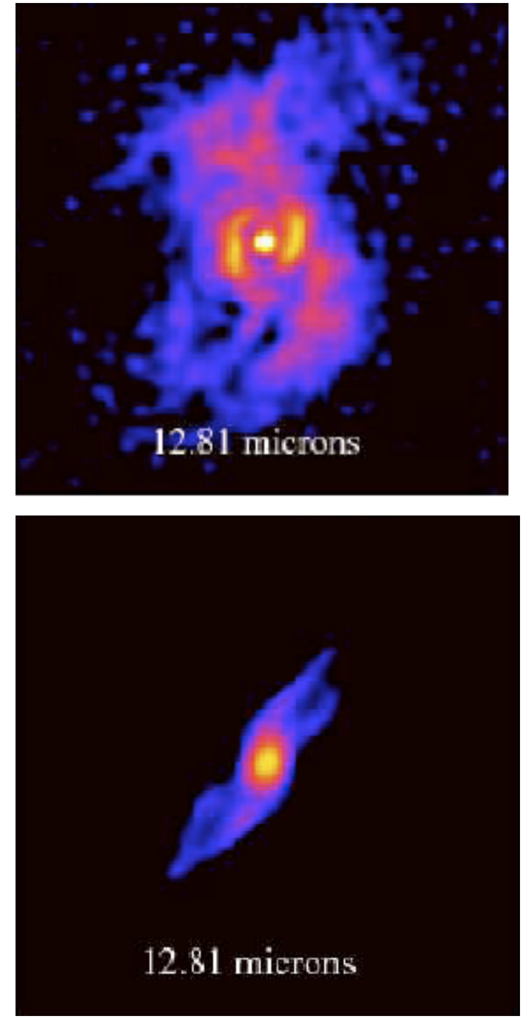
# Old concept

AGB are round

Post-AGB, planetary nebulae are not



1D models Höfner 2003




Lagadec et al., 2011

# Where are the asymmetries?

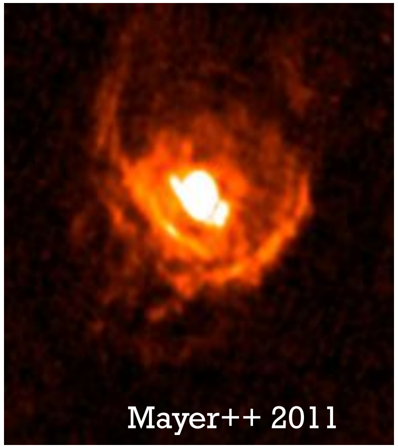
Asymmetries are there but in the past:

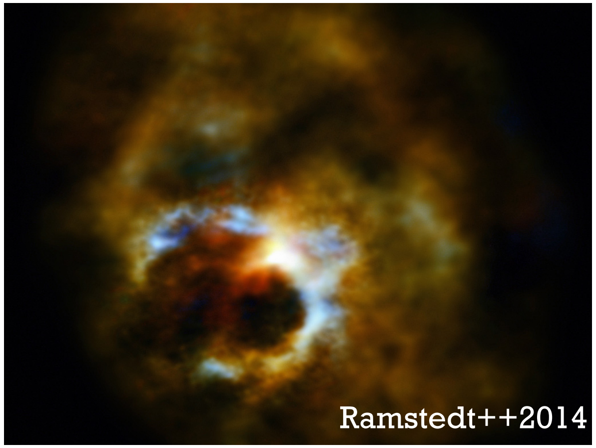
- Poor instrument sensitivity
- No coordinated (multi-wavelength) programs
- Not enough angular resolution
- (partially consequence) no suitable models

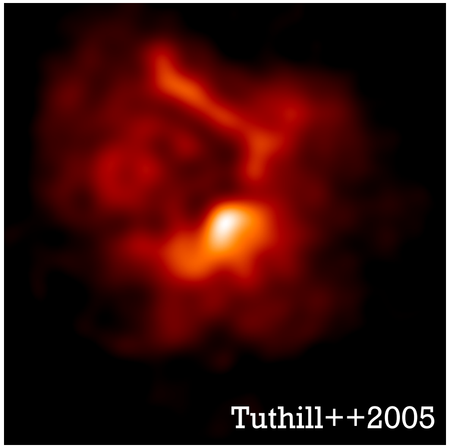
Picture still puzzling, no answer for basics questions like:

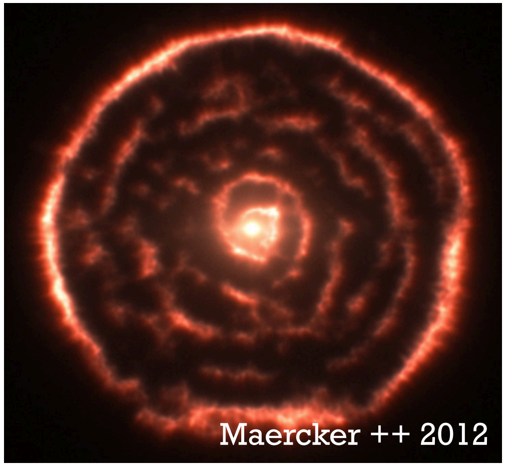
- Is the dusty mass-loss process episodic?
- At which height in the atmosphere can asymmetries develop?
- How does this change with the evolutionary phase of the star?

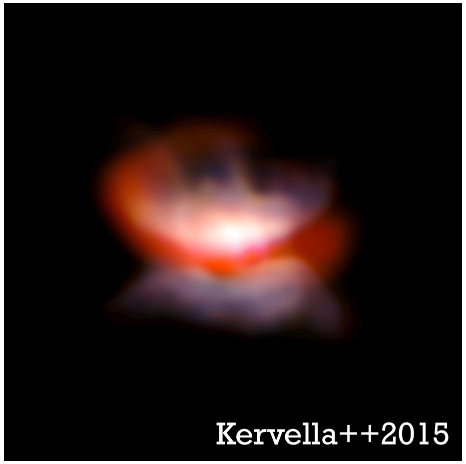
# + New observations

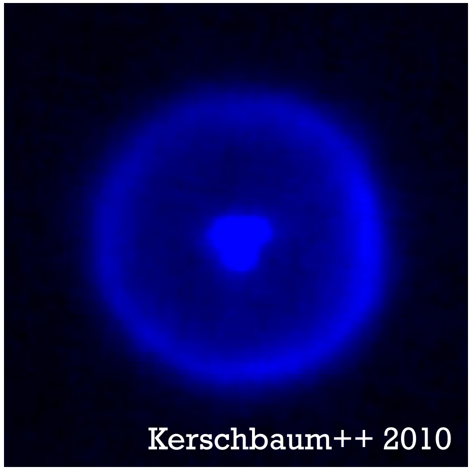

Mayer++ 2011


Ramstedt++2014


Tuthill++2005

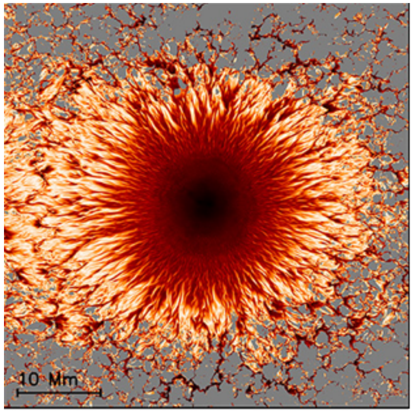

Maercker ++ 2012


Kervella++2015

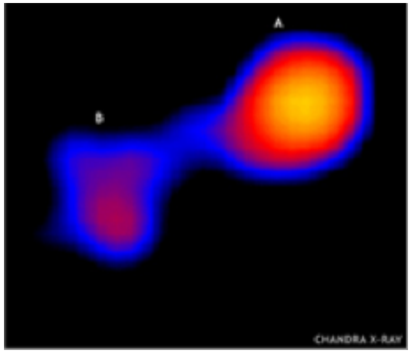

Kerschbaum++ 2010

# What does it shape the stellar envelope?

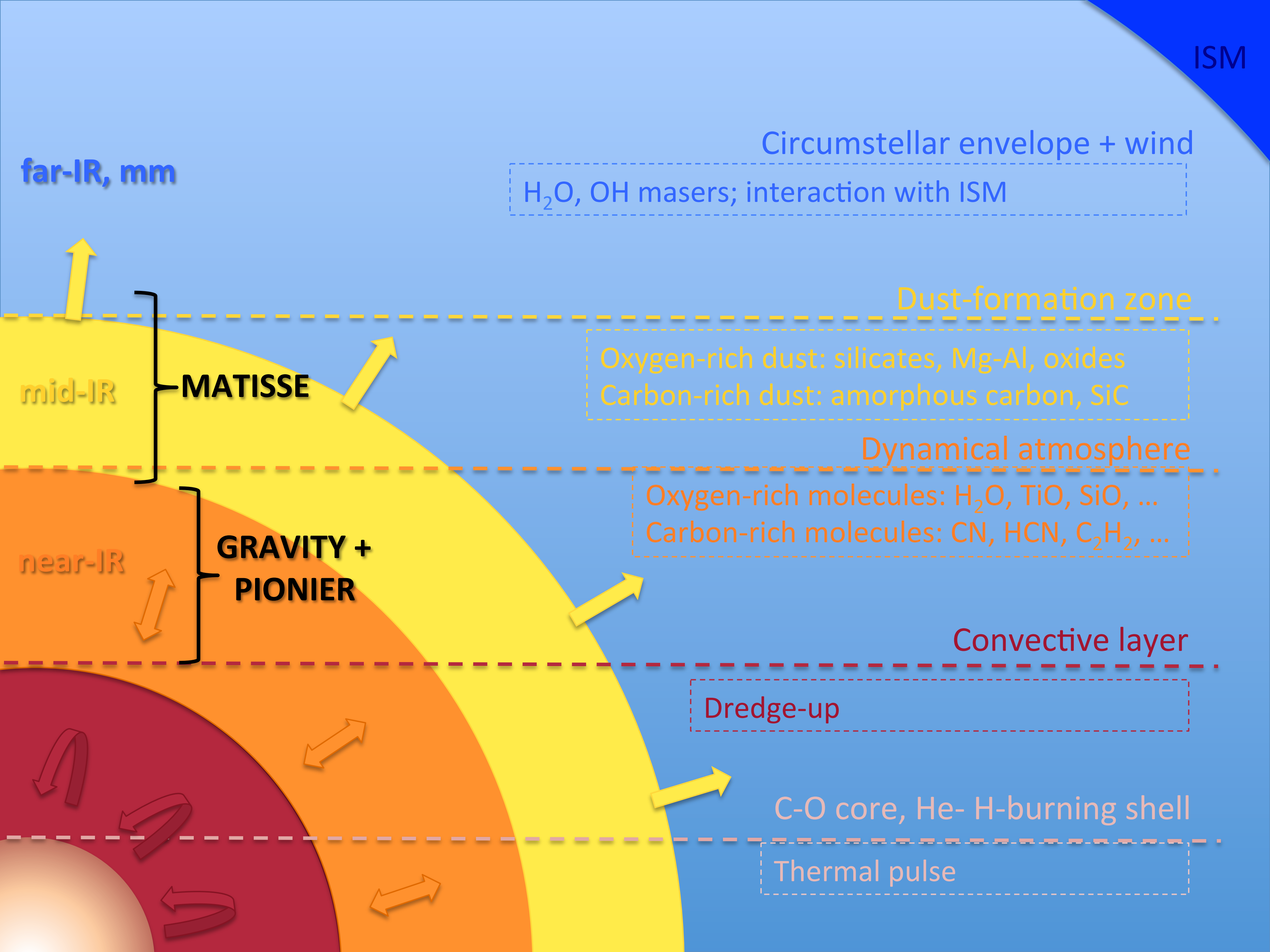
- Convection
- Magnetic activity
- Rotation
  - Increase density scale height in the equatorial plane
- Binarity = companion transfers angular momentum
  - Influence of rotation on dust distribution
  - System may capture lost mass in circum-binary disc






chandra.harvard.edu



ISM
Circumstellar envelope + wind
far-IR, mm
$H_2O$, OH masers; interaction with ISM
Dust-formation zone
Oxygen-rich dust: silicates, Mg-Al, oxides
Carbon-rich dust: amorphous carbon, SiC
mid-IR
MATISSE
Dynamical atmosphere
Oxygen-rich molecules: $H_2O$, TiO, SiO, …
Carbon-rich molecules: CN, HCN, $C_2H_2$, …
near-IR
GRAVITY +
PIONIER
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse

# Literature

Lunar Occultation (Richichi et al. 1995; Meyer et al. 1995), aperture masking, speckle, optical interferometry

- Departure from spherical symmetry detected at 1-5 stellar radii
- Ragland 2006:"only" 29% AGB stars asymmetric (C-stars more asymmetric)

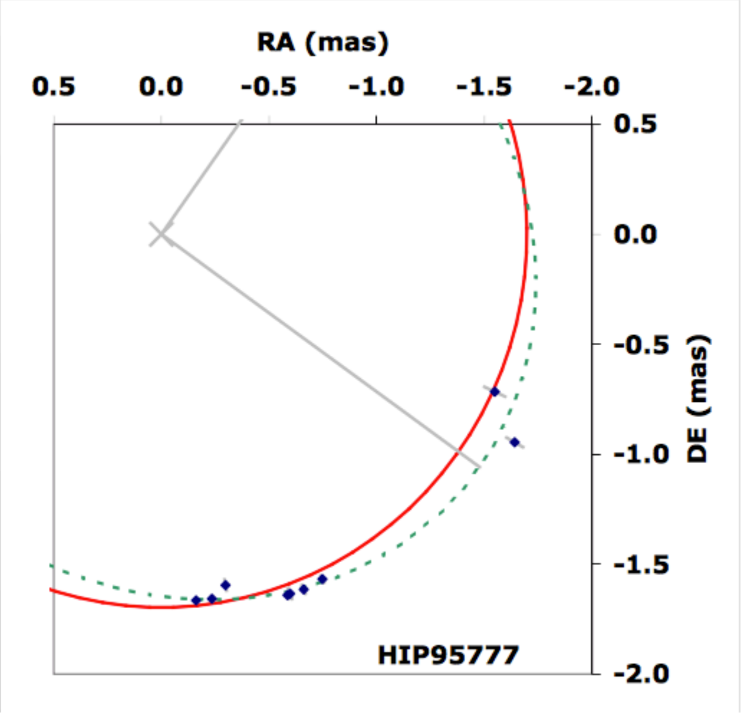
Many works are in *broad band or with low resolution*.
**Still no clear answer on what process is causing those asymmetries!**

# Rotation?

van Belle et al. (2013) studied a sample of C-stars by means of model atmospheres and geometric models

evidence of asymmetries for many C-stars

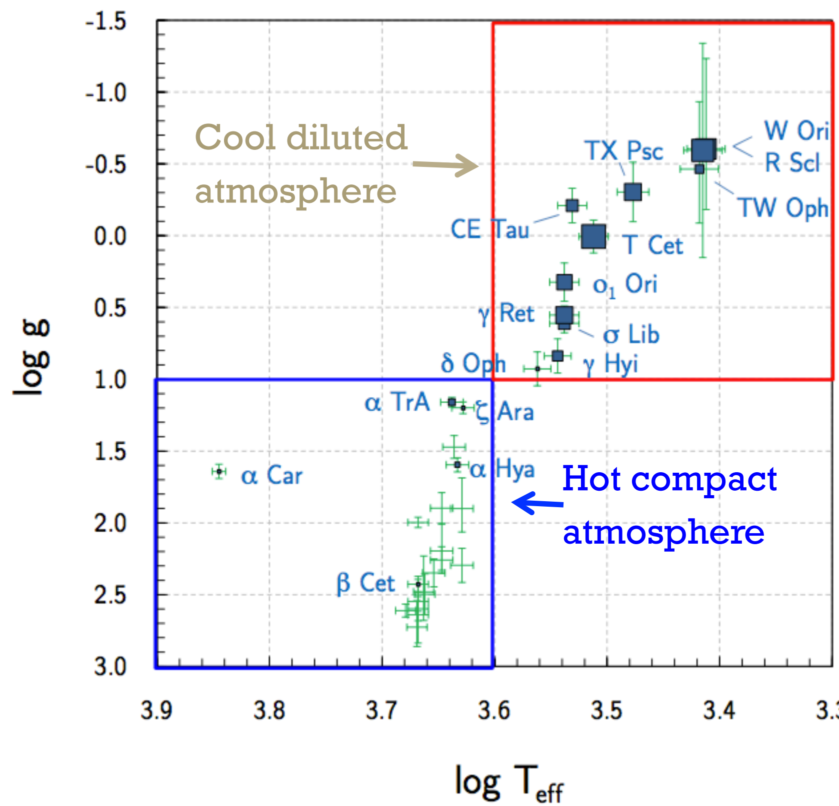
- surface inhomogeneities or effect of stellar rotation?



# Convection (I)

Cruzalebes et al. (2014) found closure phase signatures with VLTI/AMBER for many AGB

- Asymmetry increase following the sequence
- K giants -> RSG -> AGB

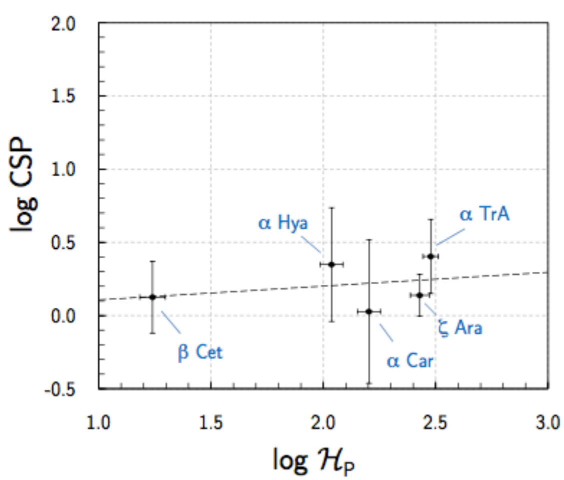


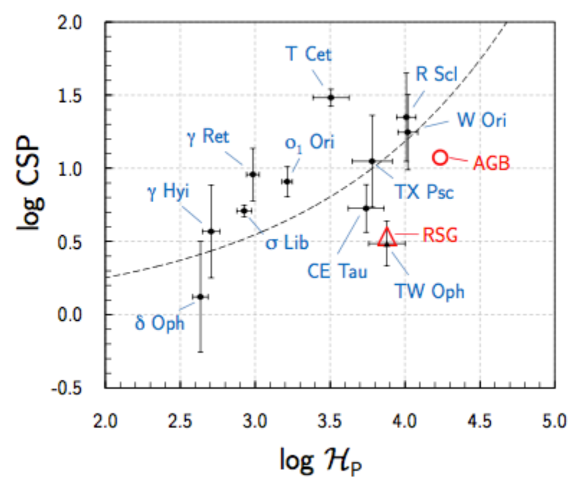
# Convection (II)

Cruzalebes et al. (2014)
Asymmetries increase with pressure-scale-height $H_p$ parameter

Agreement with photocentric motion relation predicted by 3D-RHD simulations (Chiavassa et al. 2011)

$$H_p \sim \frac{T_{\mathrm{eff}}}{g}$$



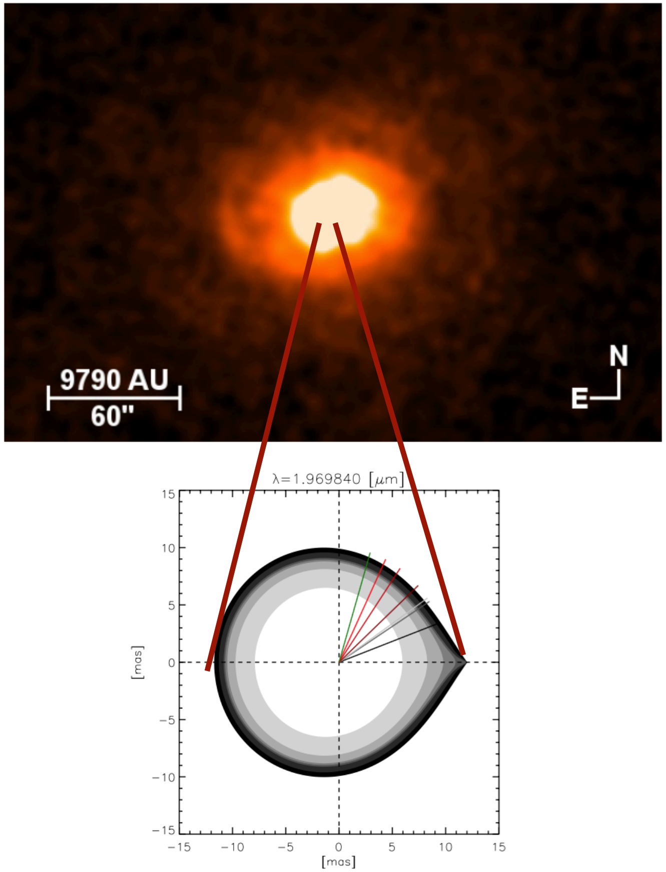



# The effect of binarity

Mayer et al. (2014)

Herschel/PACS + Hipparcos + VLTI/AMBER data S-type AGB

- Literature +Hipparcos +AMBER suggest presence of close binary



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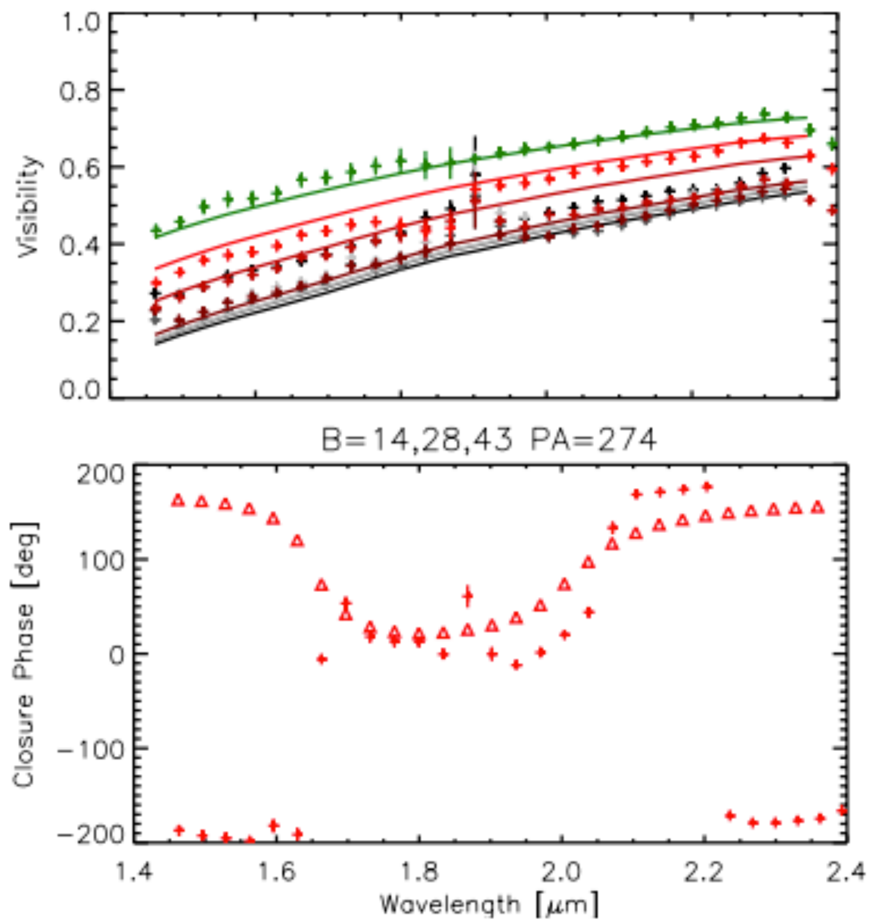
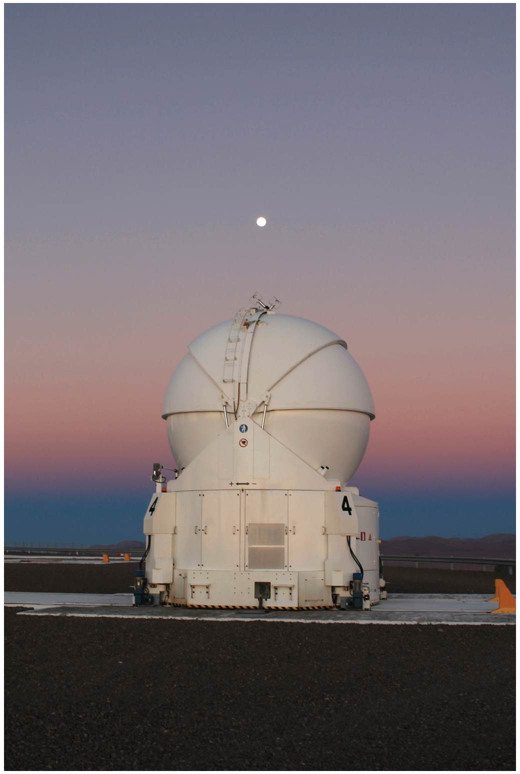


# Imaging of Giants things to be aware of

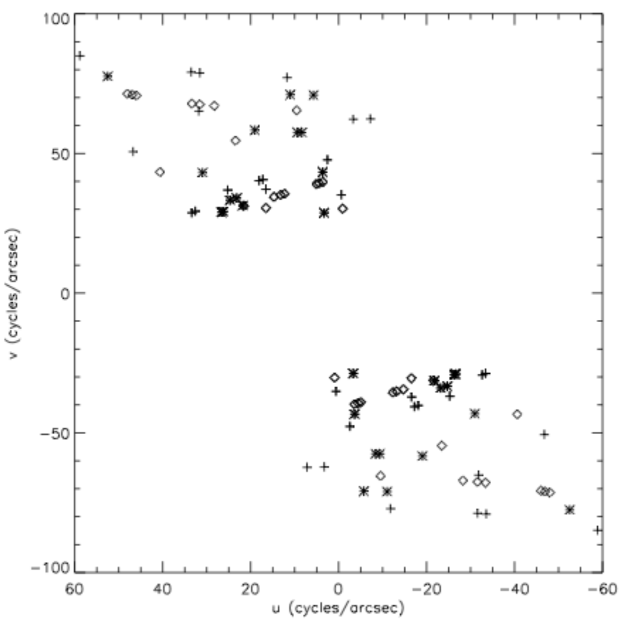
Not an easy task. Why?

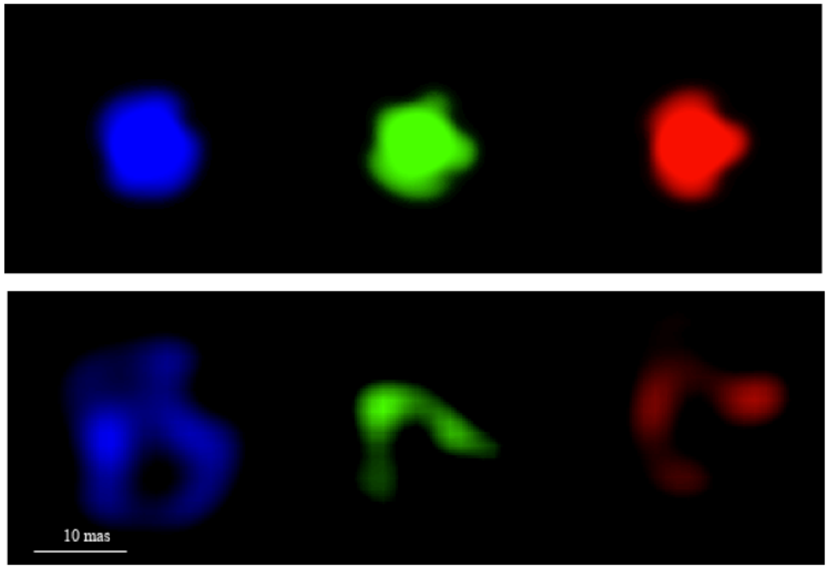
- Very extended objects bright sources means very low visibilities
- Good uv-coverage needed
- Different wavelength cannot be combined
- Image reconstruction algorithms & multi-wavelength
- Stars are variable: need to have all configurations in a short time



# Asymmetric shells

R Aqr reconstructed in 3 channels 1.51, 1.64 and 1.78 micron with IOTA (Ragland 2008)

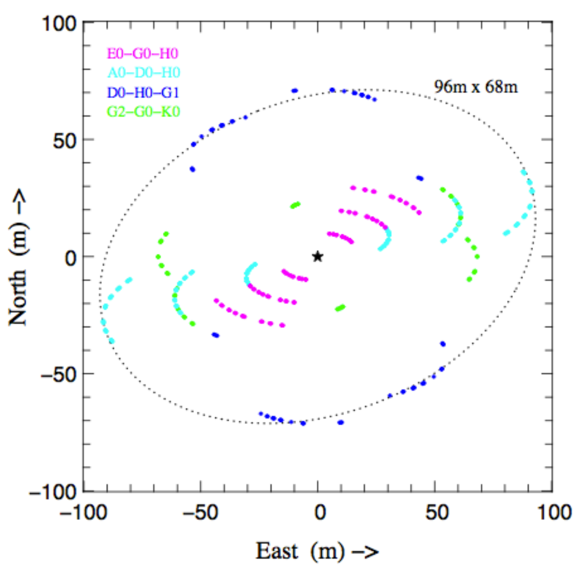


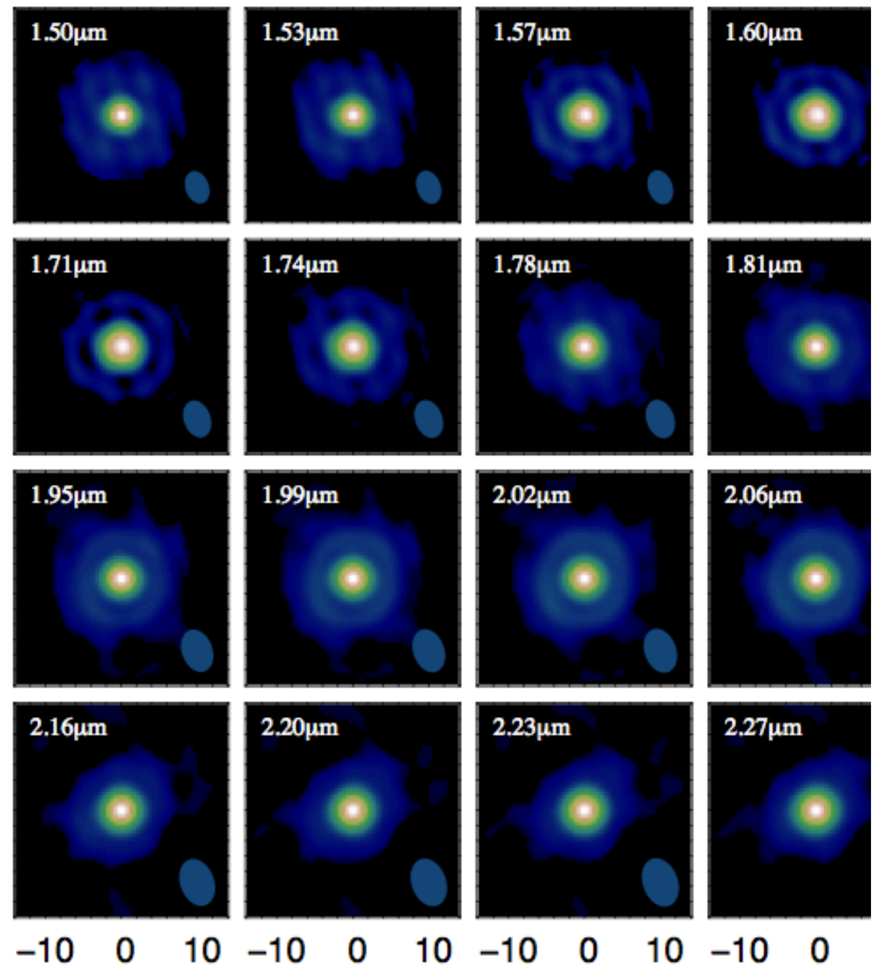

Strong asymmetric structures in the $H_2O$ molecular layer

# Molecular shells

T Lep imaged with VLTI/ AMBER (Le Bouquin et al. 2009)

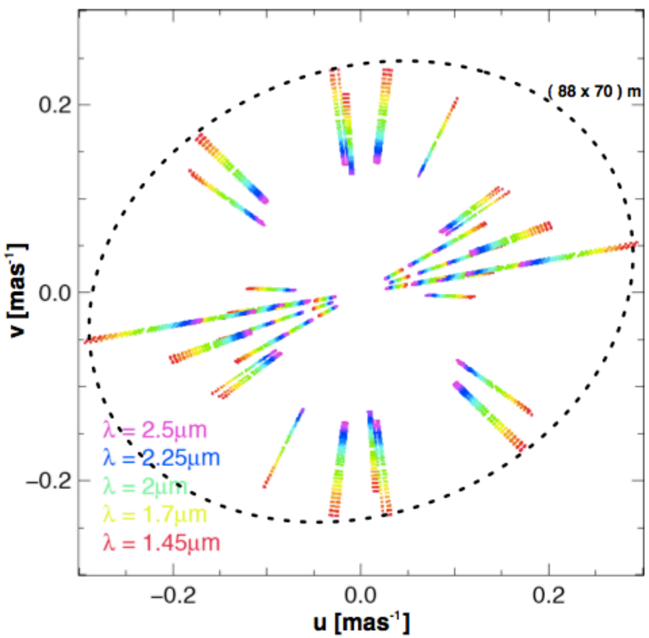


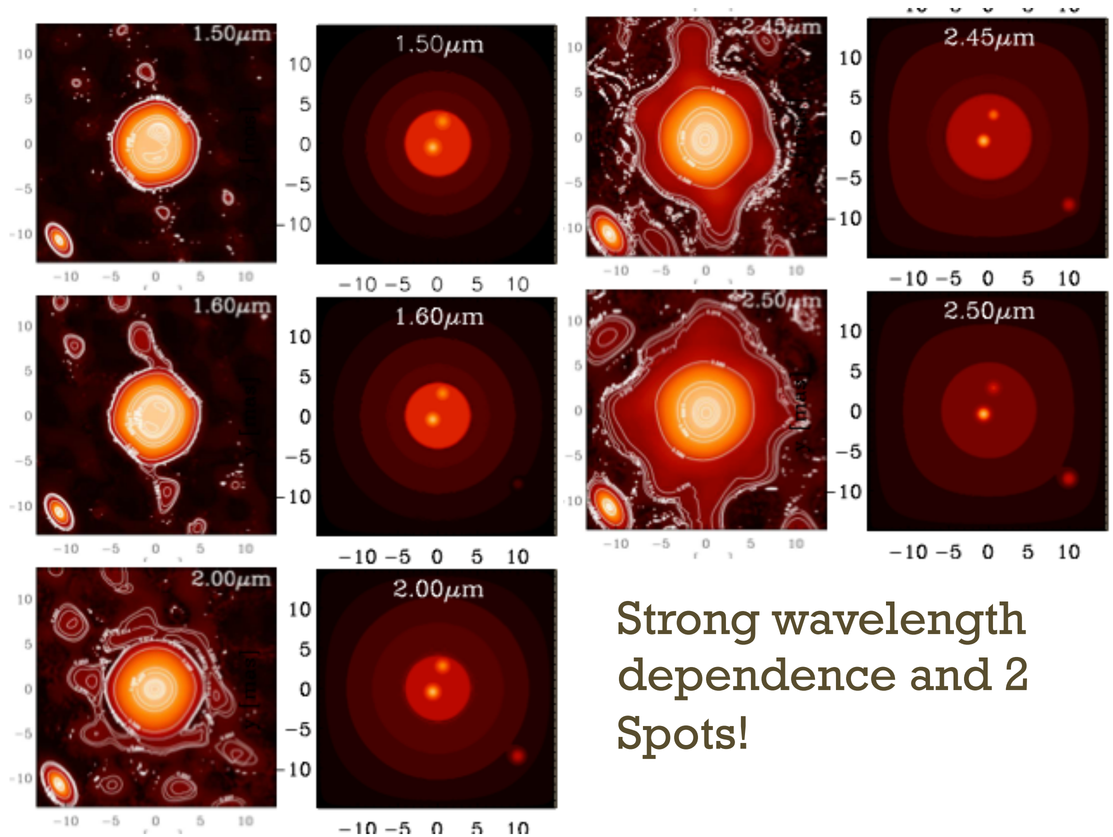

Unveil a "onion-like" shape (molecular shells)



# Spots!

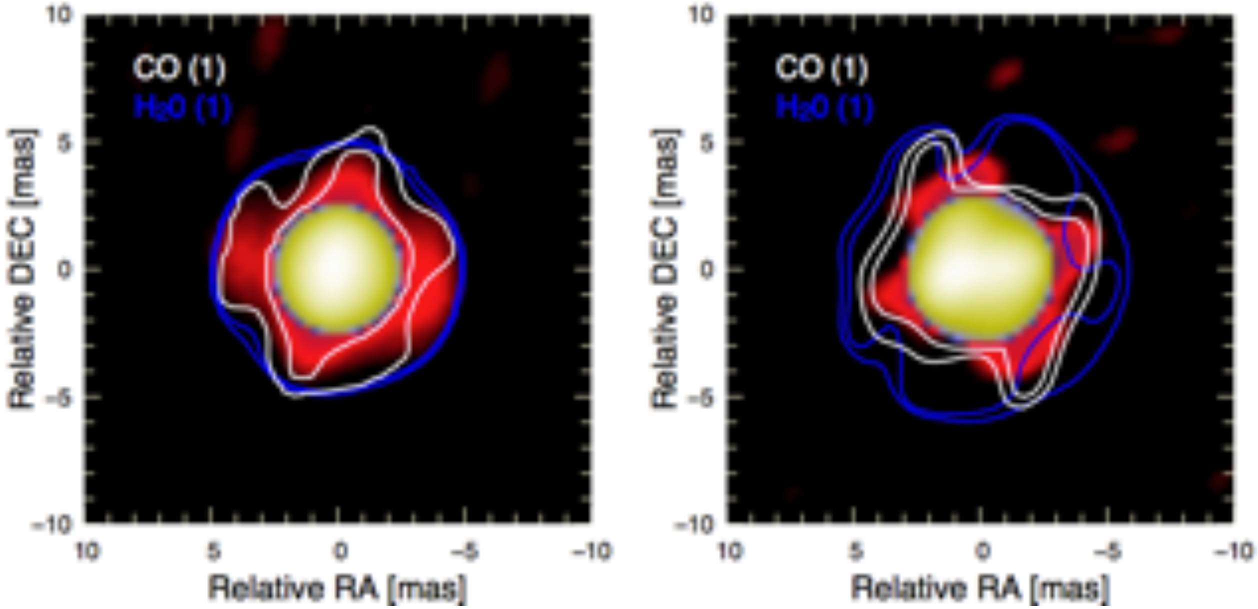
VX Sgr imaged with AMBER
(Chiavassa et al. 2009)



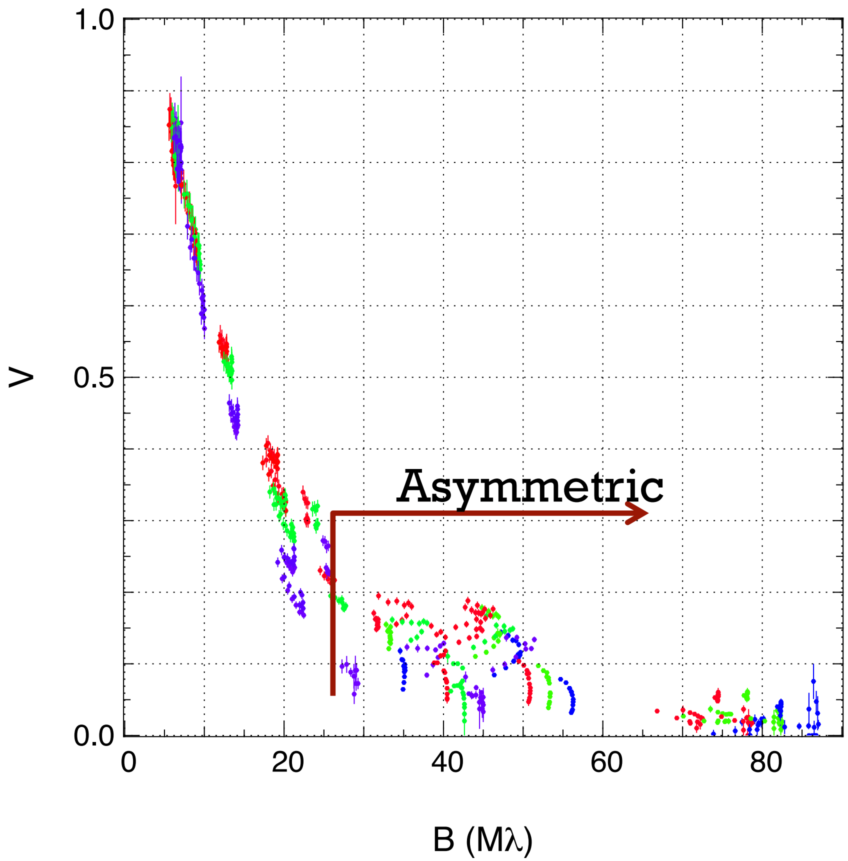

Strong wavelength dependence and 2 Spots!

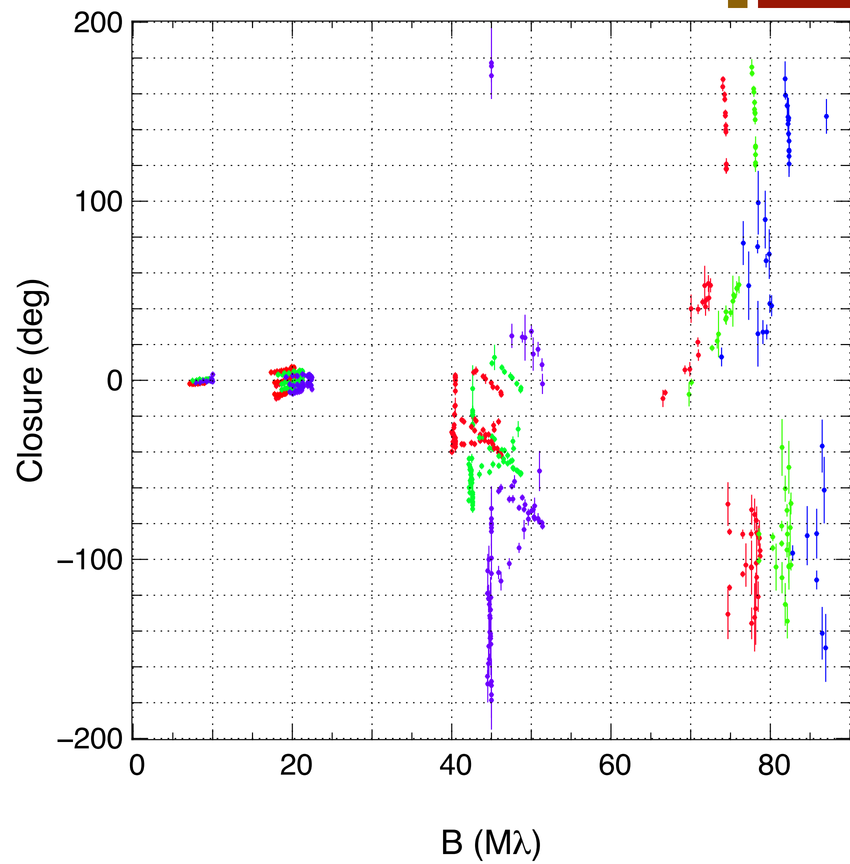
# Variability




Haubois et al. (2015)
VLTI/AMBER, low resolution data (R~30)
Variability of the shell of a Mira over pulsation period

# VLTI PIONIER data of C-rich Mira

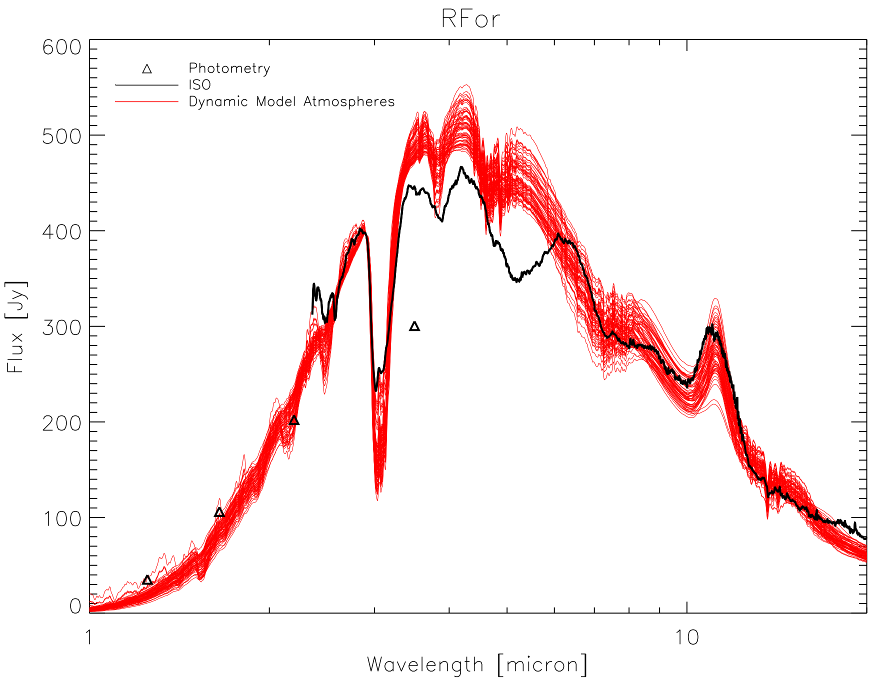


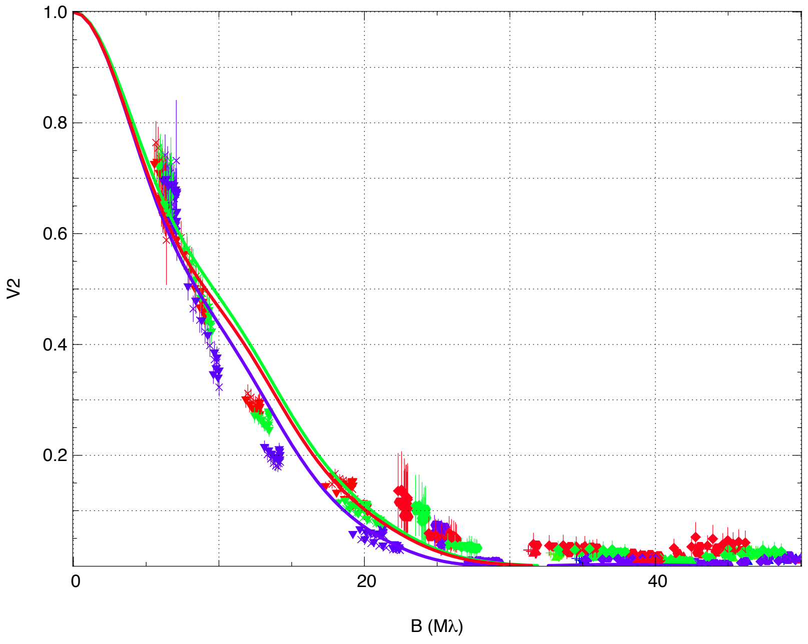




3-half nights within 2 weeks with 3 quadruplets!

Paladini et al., prep.

# Modelling the data



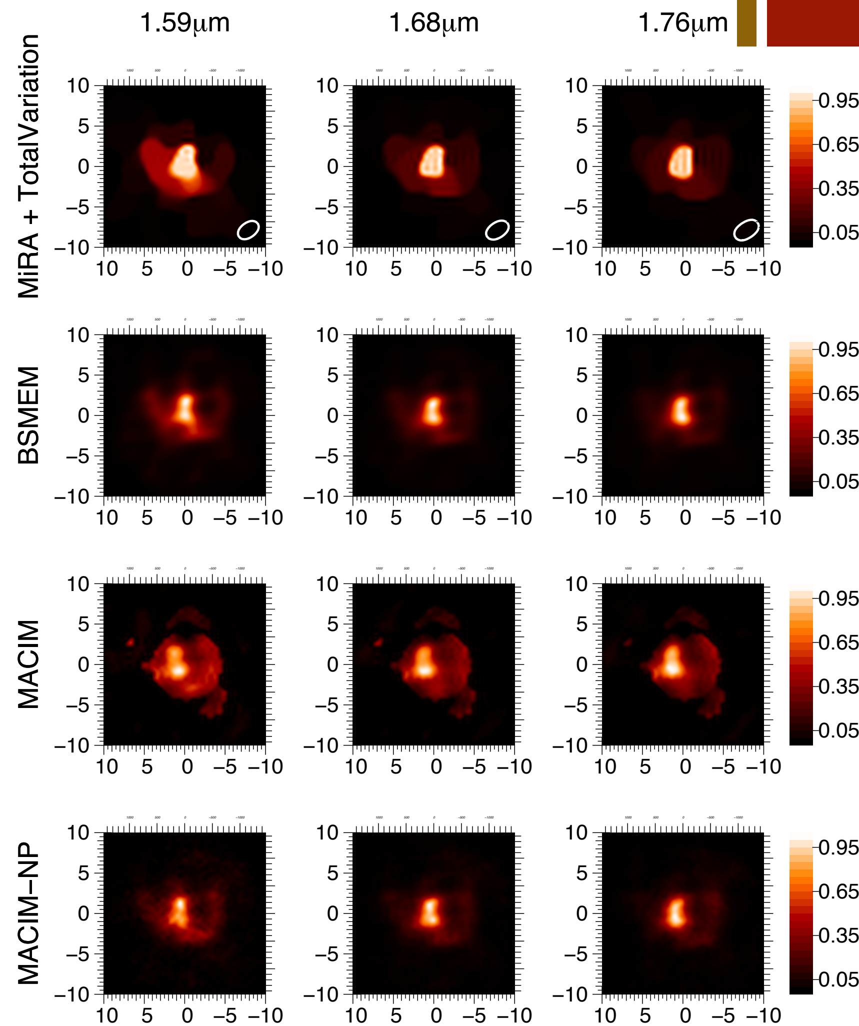

1D dynamic model atmospheres (Höfner et al. 2003, Mattsson et al. 2010)

# Image reconstruction (our internal beauty contest)

Blind reconstruction with different tools.

What we trust:

- Elongated structure + diffuse environment
- FWHM of the elongated structure ~2-4 mas
- Extended bright "arc" in the first channel



# Preliminary interpretation

Image compatible with models from Freytag & Höfner 2008

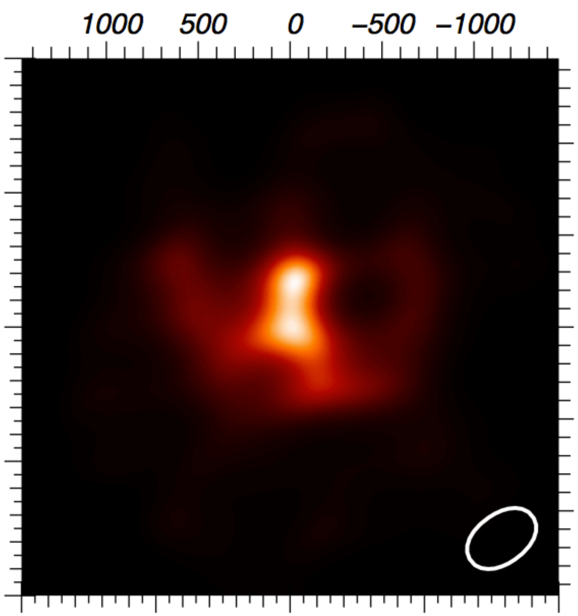
- Where is the star?

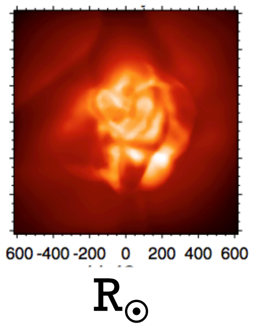
(Vassiliadis & Wood 1993)

$$\log P = -2.07 + 1.94 \log R - 0.9 \log M$$

- Radius~700$R_\odot$ => 3 $M_\odot$
- Radius~360$R_\odot$ => 0.4 $M_\odot$

Be aware of uncertainties..




Is there a disc in front of the object?

=> Other spatial scales + time series

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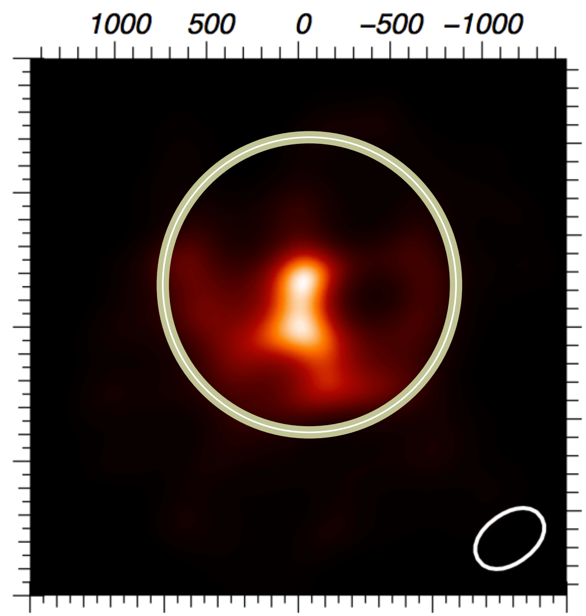
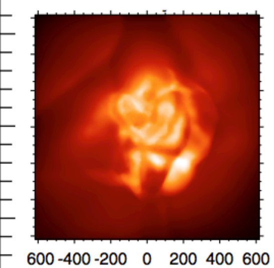
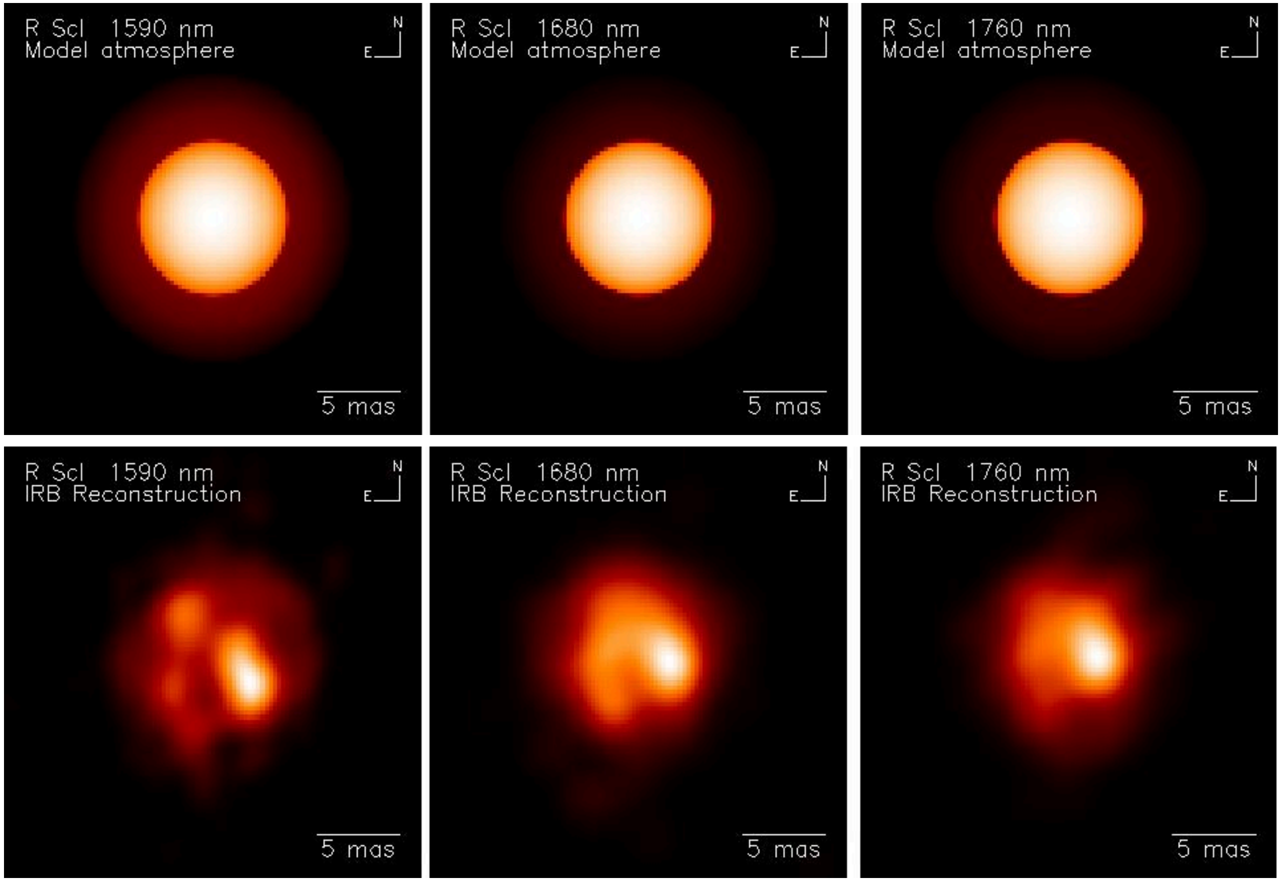


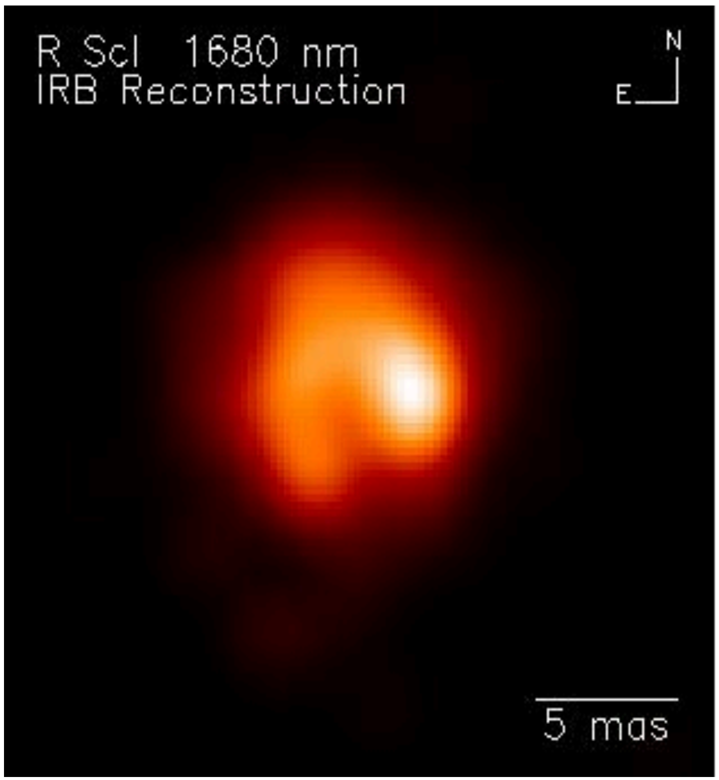

$R_\odot$

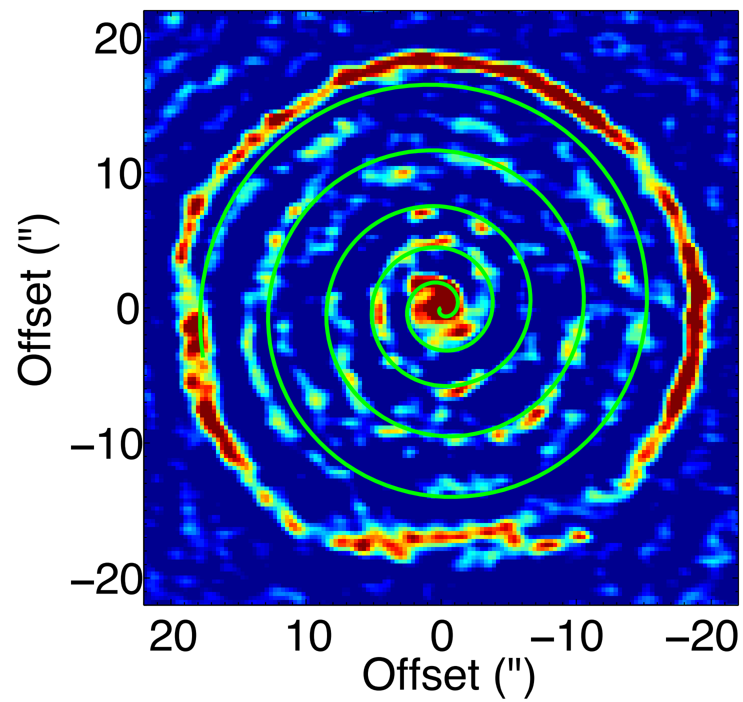
# VLTI/PIONIER image of R Scl




Wittkowski et al., in prep

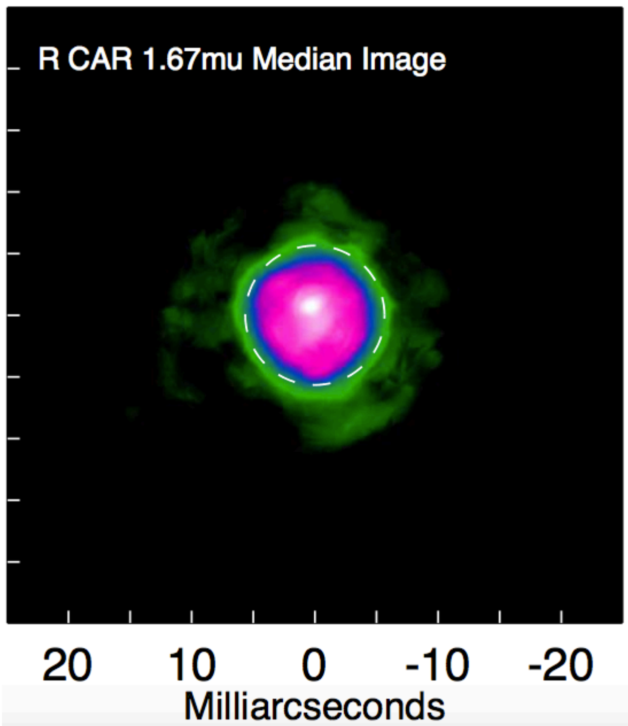
# VLTI/PIONIER image of R Scl



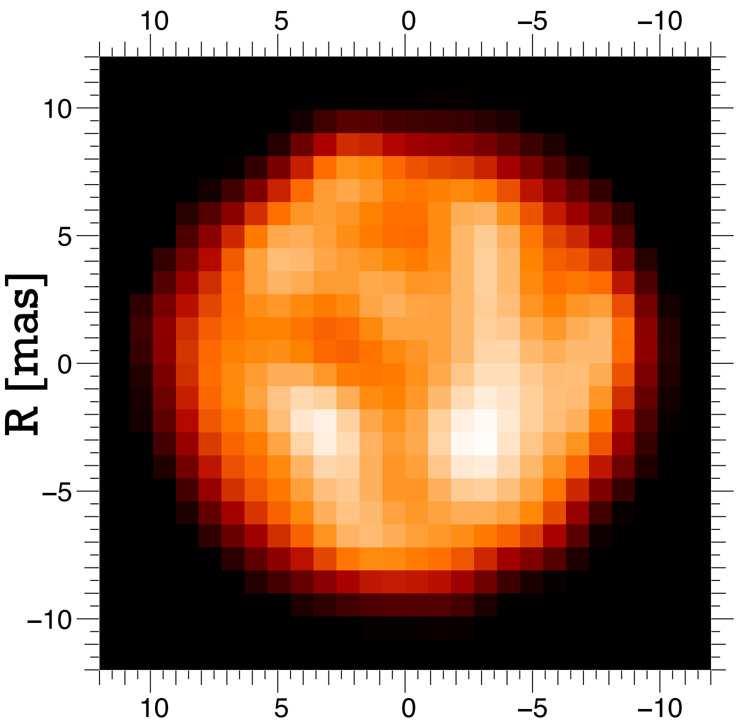




- Dominant (mass-loosing?) spot on the surface of R Scl.
- Spiral structure consistent with large spiral, or simply a random convective morphology?

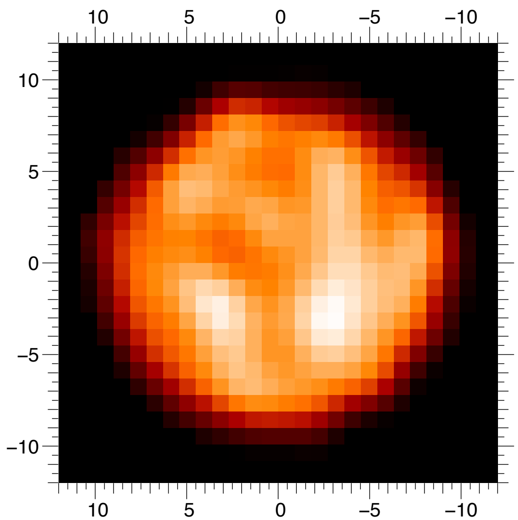
# Even more surface structures

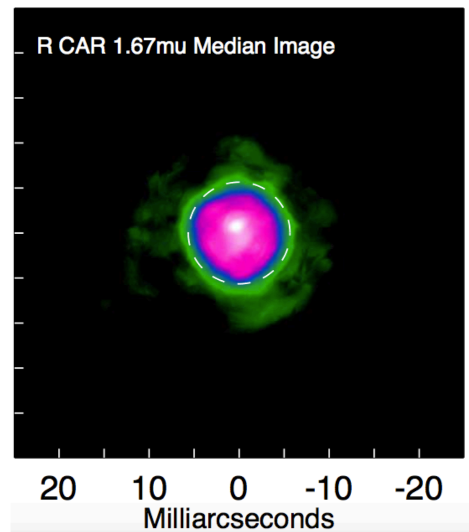


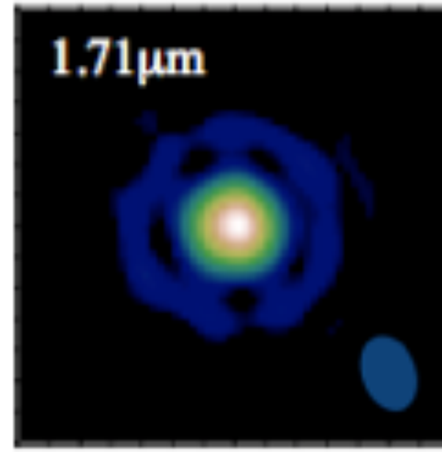

Monnier et al. 2014

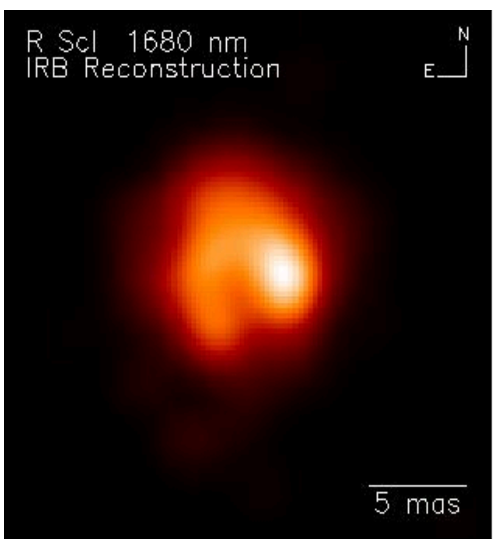


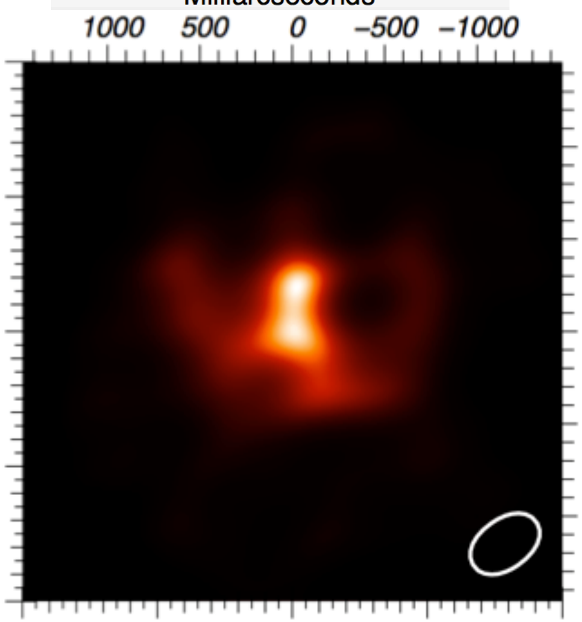

Paladini, Mayer et al. prep.

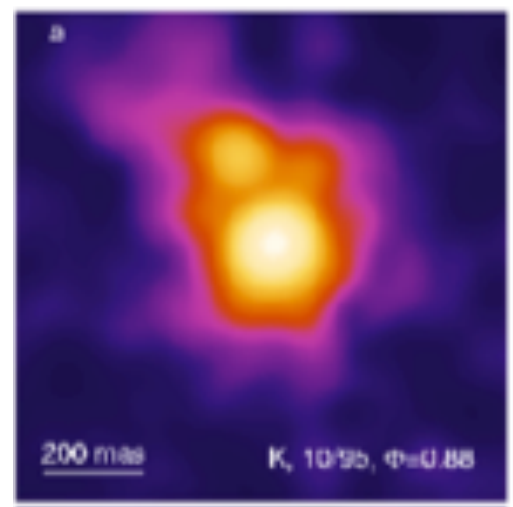

10 5 0 −5 −10
10 5 0 −5 −10
10 5 0 −5 −10


R CAR 1.67mu Median Image
20 10 0 -10 -20
Milliarcseconds

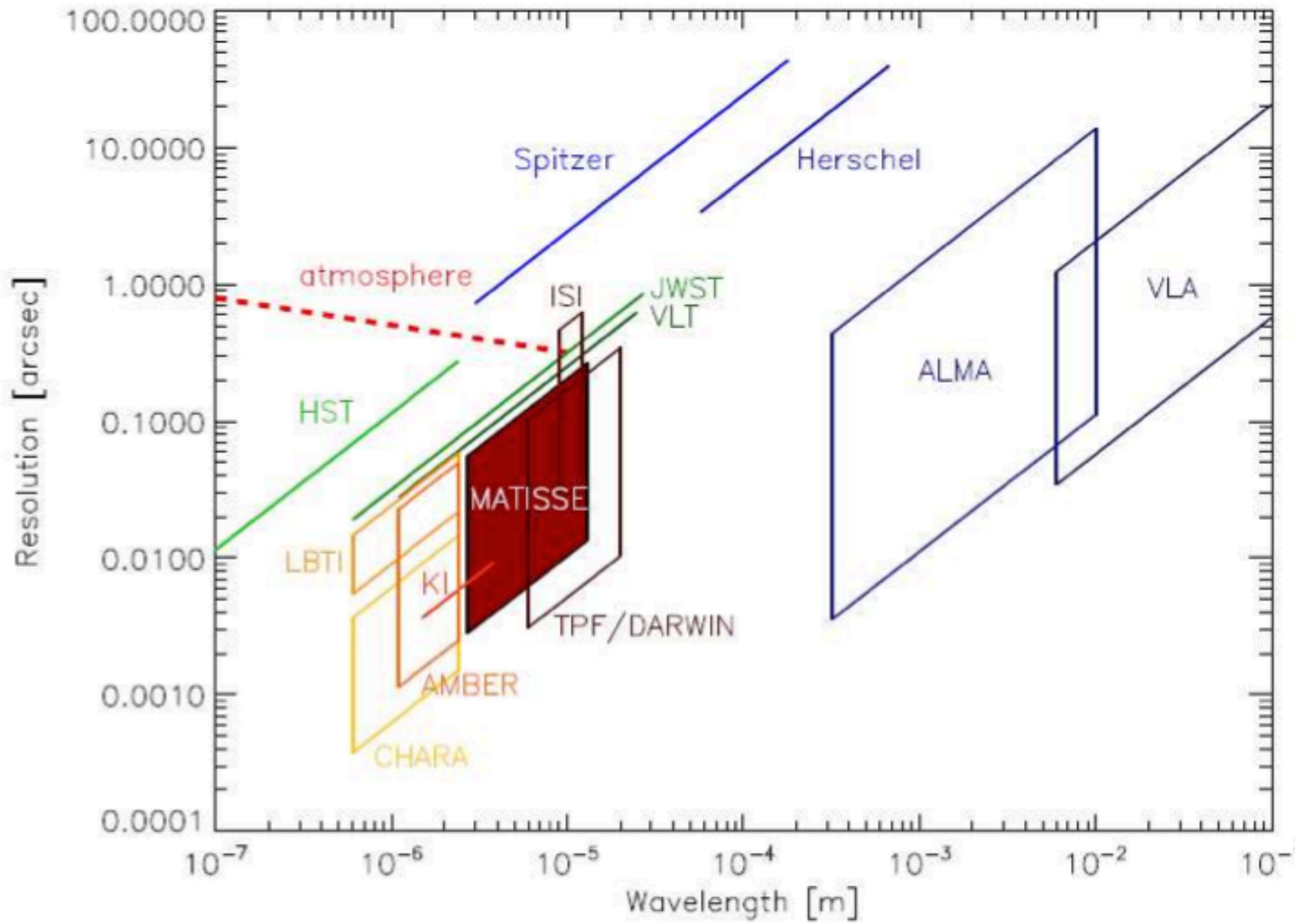

1.71μm


R Scl 1680 nm
IRB Reconstruction
N
E
5 mas


1000 500 0 −500 −1000


200 mas
K, 10/95, Φ=0.88

# Current wavelength GAP




Lopez et al. 2008

AMBER stops at 2.4 microns and MIDI starts at 8 microns… waiting for MATISSE

# Asymmetries in the mid infrared

Outside the photosphere, in the molecular and dust formation zone. Until '90 mass-loss considered constant outflow. Using interferometry:

- Danchi (1994) reported episodic dust formation @ 3-5 stellar radii
- Tabete (2006): asymmetries in 6 AGB stars. R Aqr asymmetry due to presence of binary

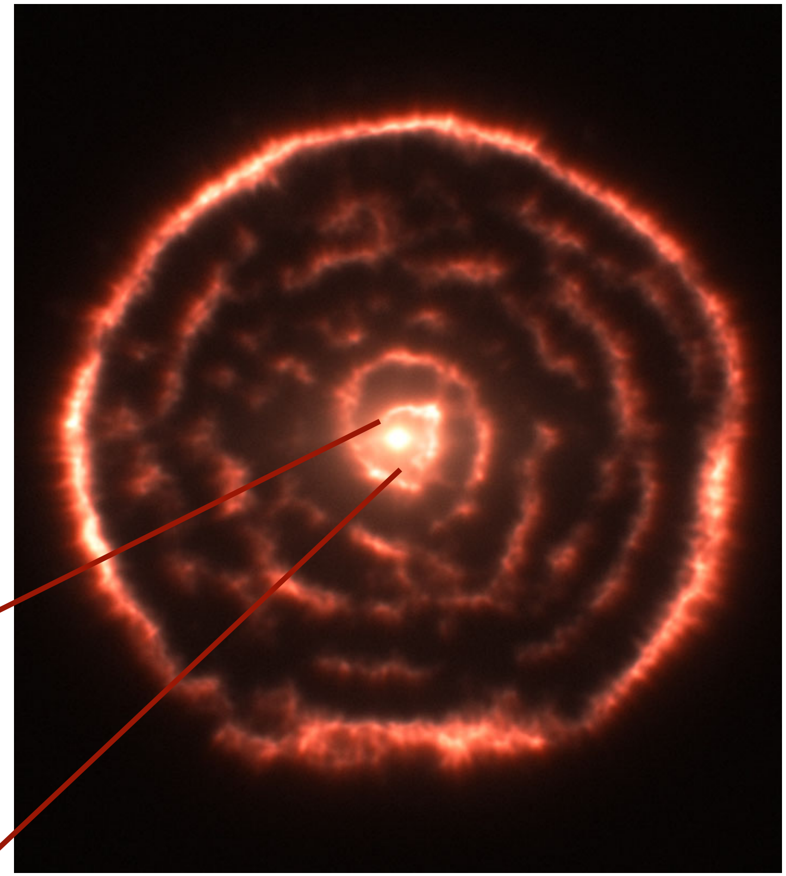
…

# Spirals? Discs?

Many studies on IRC+10216 (Weigelt et al. 1998; Tuthill et al. 2000; Leão et al. 2006; Chandler et al. 2007) report asymmetries due to dust clumps

Do the clumps follow a random distribution? or a preferential one (disc, spiral)?

Still an open question for imaging campaign



Maercker et al., 2012

# Asymmetries with MIDI

EWS extracts differential phase from MIDI data.

Non zero differential phase means asymmetric object

BUT

only very few detections.

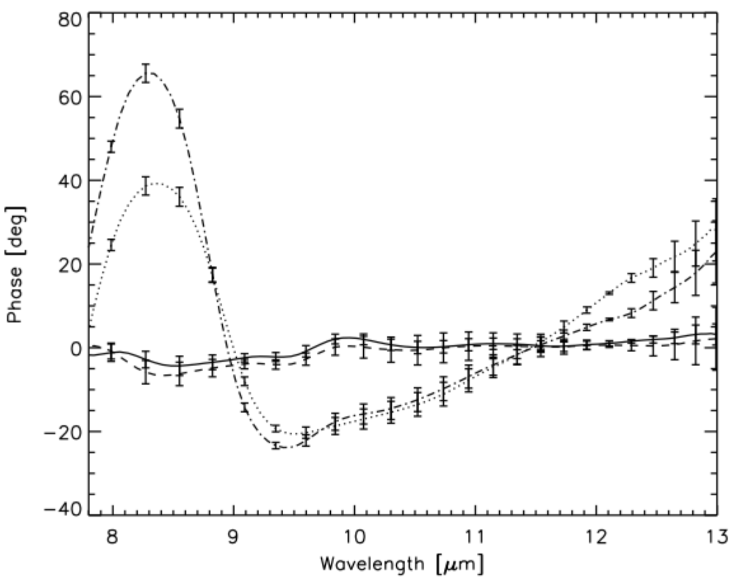
credit: F. Millour, VLTI school 2013

# Differential Phase (I)

Deroo et al. (2007) observed differential phase for a J-type carbon AGB star.

J-type stars believed to be result of a merge.

Asymmetry interpreted as presence of circumbinary disc.



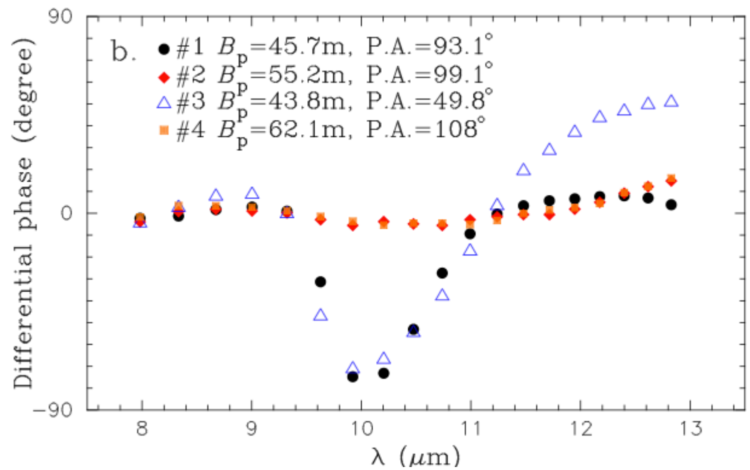
# Differential Phase (II)

Ohnaka et al. (2008): another J-type AGB star showing non zero differential phase.

Asymmetry interpreted as presence of circum-companion disc.

Questions

- Are this differential phases common only among J-type AGB stars?
- Are they the signature of a binary?




Note: the differential phase jump is Different from previous star.
Dust chemistry!

# Differential Phase (III)

Paladini et al. (2012): differential phase detected for a carbon Mira. "Normal" object, well studied, no signatures of binaries so far…

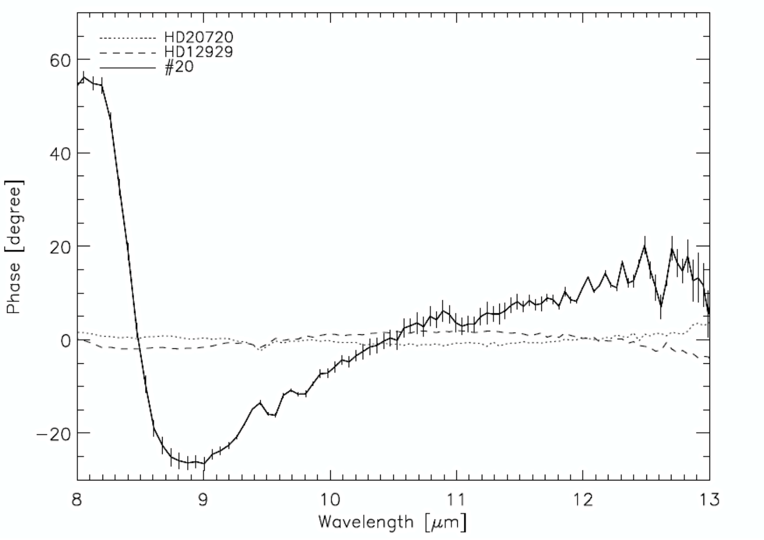
The signature is very similar to the one of Deroo's star

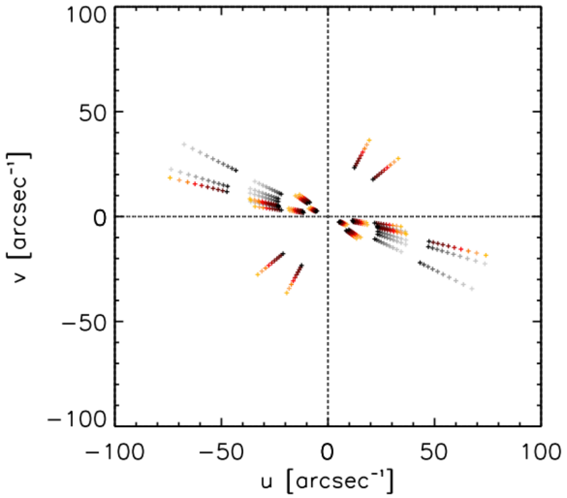
Interpretations:

- Signature of a dust clump
- Dust clump enshrouding a sub-stellar companion

How do we distinguish?

Be careful! Non unique interpretation because of limited uv-coverage.



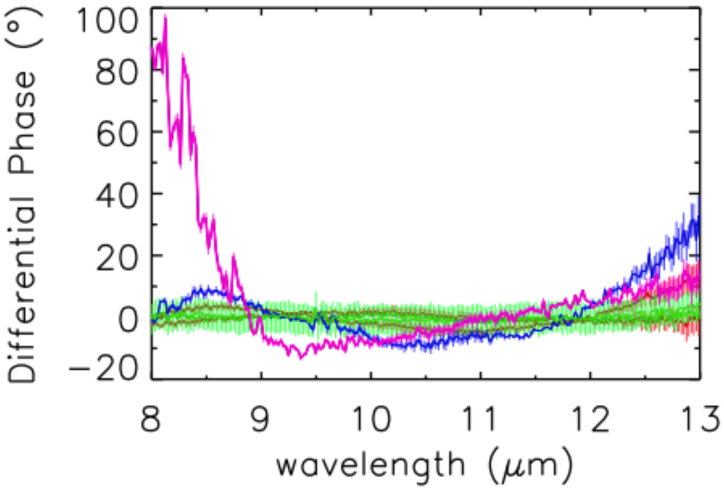



# Differential Phase (IV)

Sacuto et al. (2013): another differential phase for a "normal" AGB star.

Same interpretation as previous cases.

Are all the AGB binaries? Or we are looking at something else?

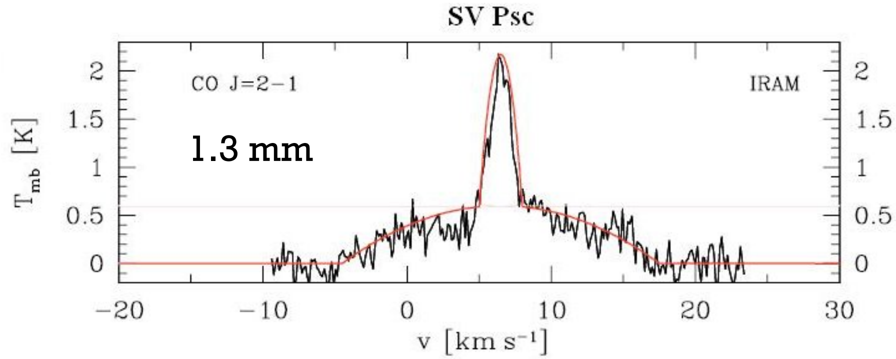


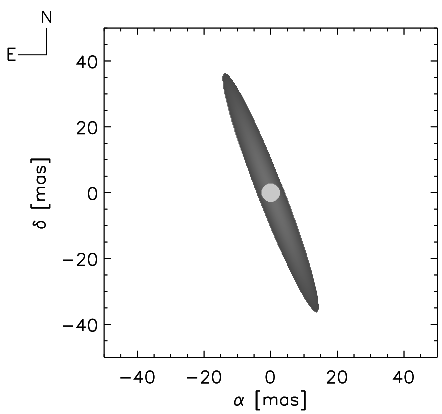
# Discs and binaries

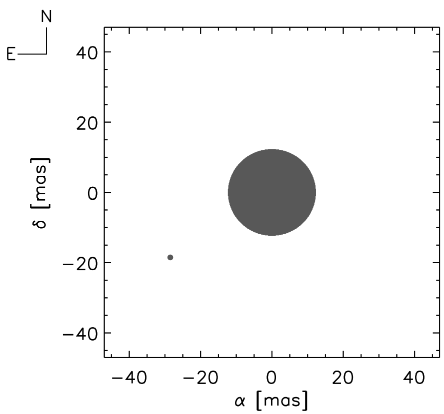
Klotz et al. (2012)

- Double-velocity component (Kerschbaum & Olofsson 1999)
- narrow feature (1.5 $kms^{-1}$) centered on broader (9.5 $kms^{-1}$)
- only visible in small number of stars (< 10)
- 4 scenarios
- MIDI excludes 2 scenarios: binary & disc are the scenarios left

Winters et al. 2003



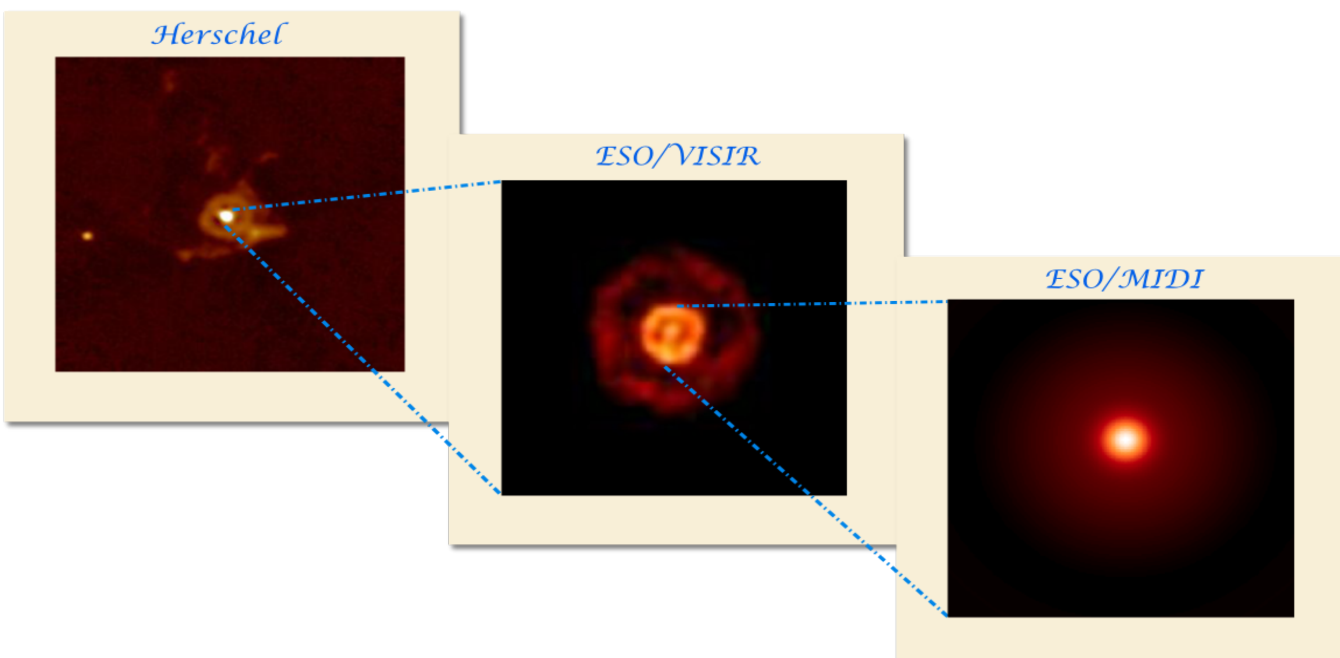
# Where are the other asymmetries?

- Very few works report asymmetries, although they are expected. Where are the dust clumps?
- Ohnaka et al. 2005; Wittkowski et al. 2007; Sacuto et al. 2011; Zhao-Geisler et al. 2011, 2012; Karovicova et al. 2011 did not observe any asymmetric structure
- MIDI observes between 5-100 stellar radii, the range is the right one but…
  - Minimum angular resolution is 20 mas. Is it possible that clumps are smaller?
  - uv-coverage is limited by 2 telescope configuration, difficult to disentangle between various geometries
  - More probable to find asymmetries at high spatial frequencies (i.e. long baselines configurations)

# Coordinated works on a statistical sample

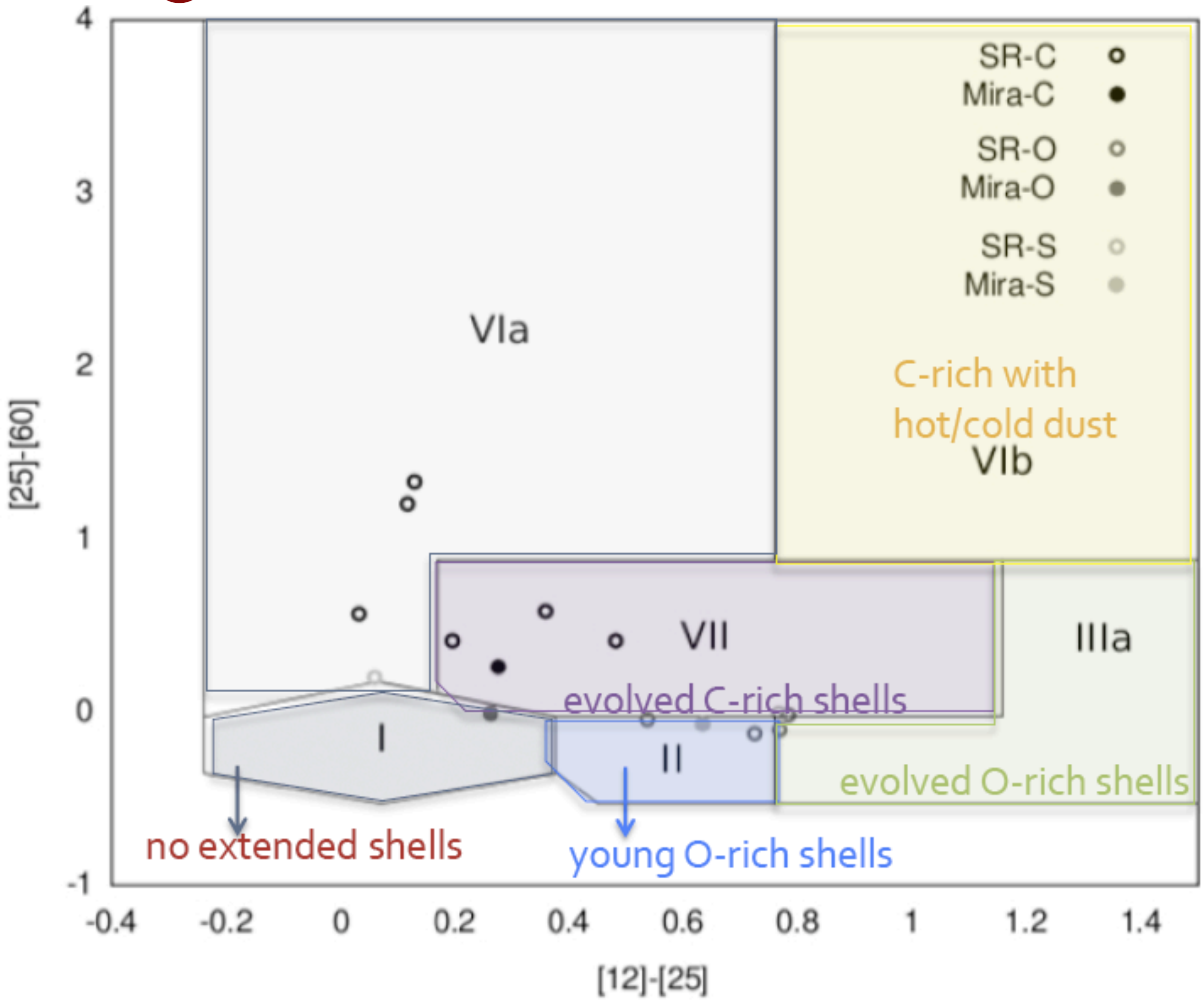
To understand properly the physics of the environment of AGB stars, coordinated works on large samples of stars are needed.

Multi-wavelength + multi-techniques




Paladini et al. subm.

# The AGB sample in the IRAS color-color diagram

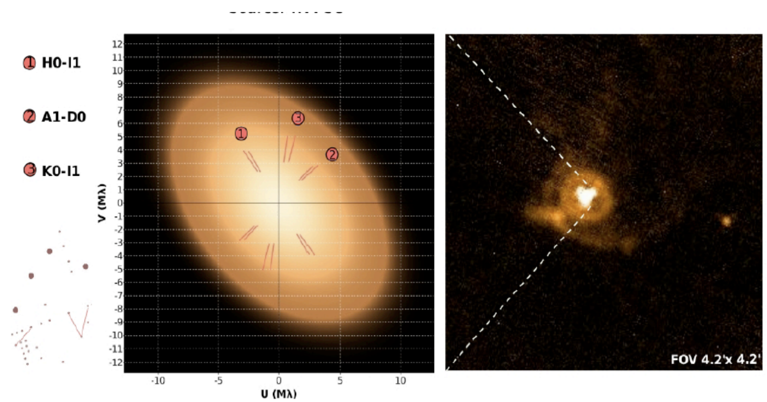


# The MIDI large program on AGBs

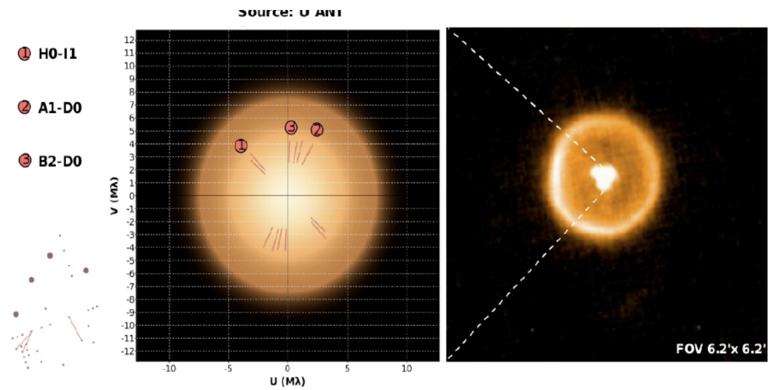
- 2 new differential phases all O-rich stars
- 3 cases of elliptical best fitting models (O-rich)

=> Are O-rich stars more asymmetric in their dust distribution? Why?

- No interferometric variability (maybe 1 case, C-star)
- Spectroscopic variability
- Detached shell of (Sic) dust



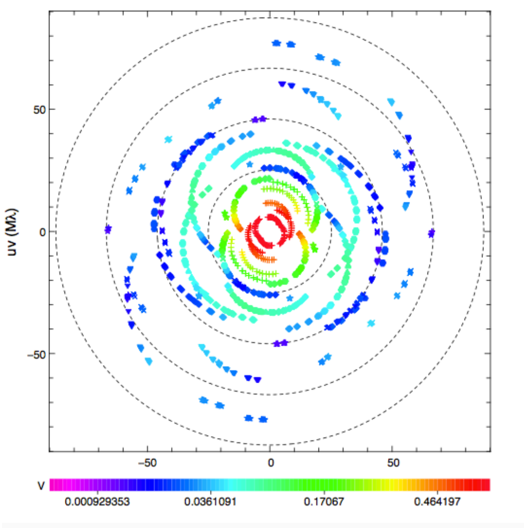

Jorissen et al., 2011



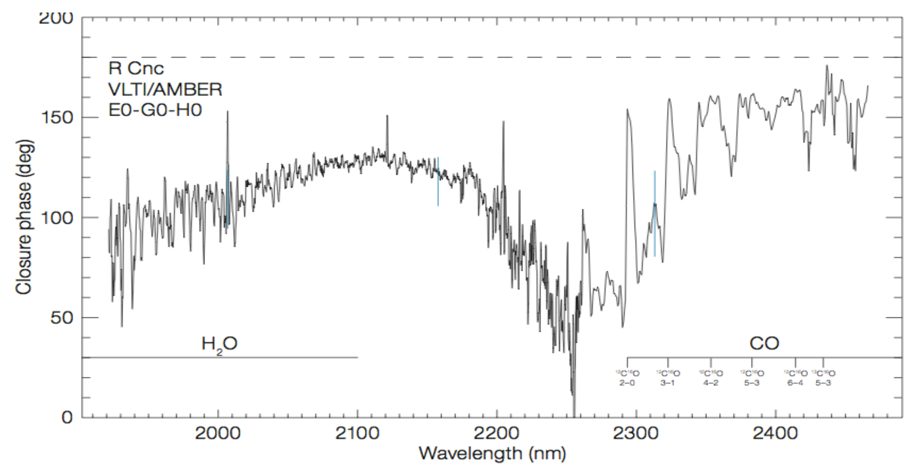

Kerschbaum et al., 2010

# Second generation instruments

Imagine…




Wittkowski et al. 2011




What will you do with GRAVITY? (K-band)
What will you do with MATISSE? (L-M-N band)

# Lessons to learn

- AGB stars are perfect targets for interferometry, but very challenging for imaging programs
  - uv-coverage
  - Multi-wavelength image reconstruction
  - observations to be taken in a short time (variability!)
- Plenty of physics to investigate!
  - mass-loss
  - variability
  - dust formation
  - geometry of the environment at different scales
- Not primary targets for second generation instruments, but a lot can be done.

Start thinking!

Thank you!