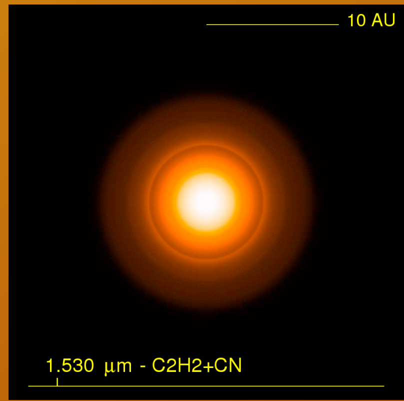

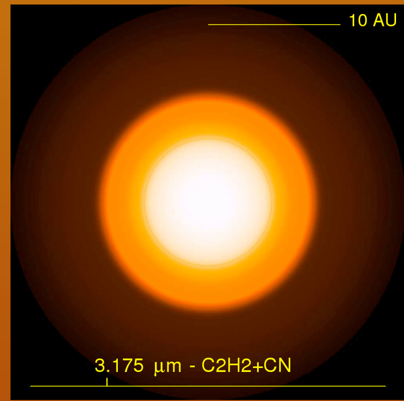

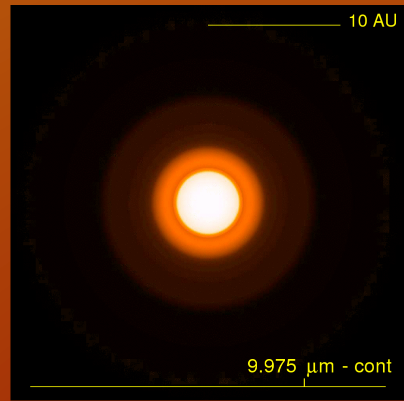

Infrared interferometry of C-stars : a tool to study the stellar atmosphere and to constrain evolutionary models

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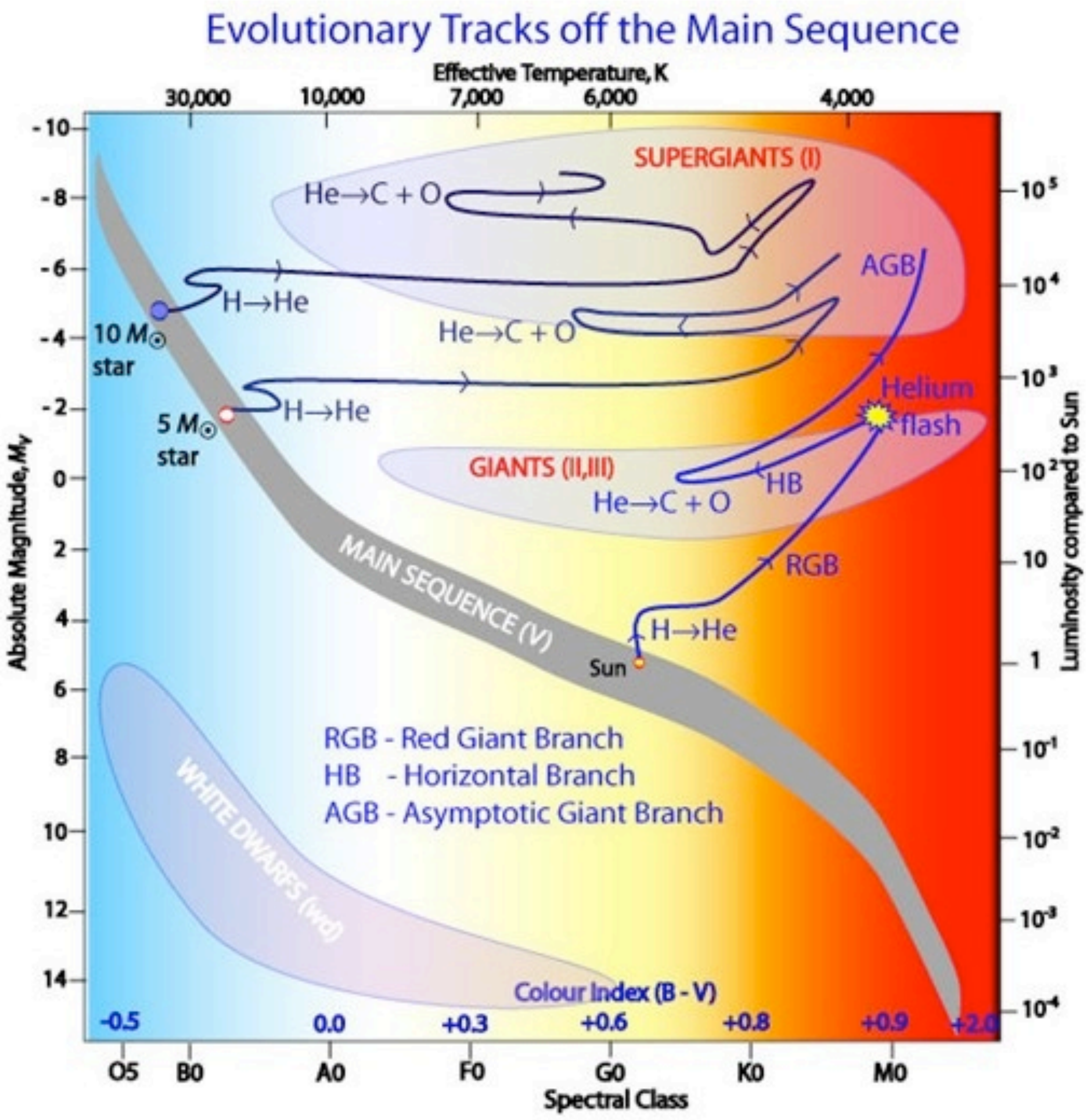
Layout of this presentation

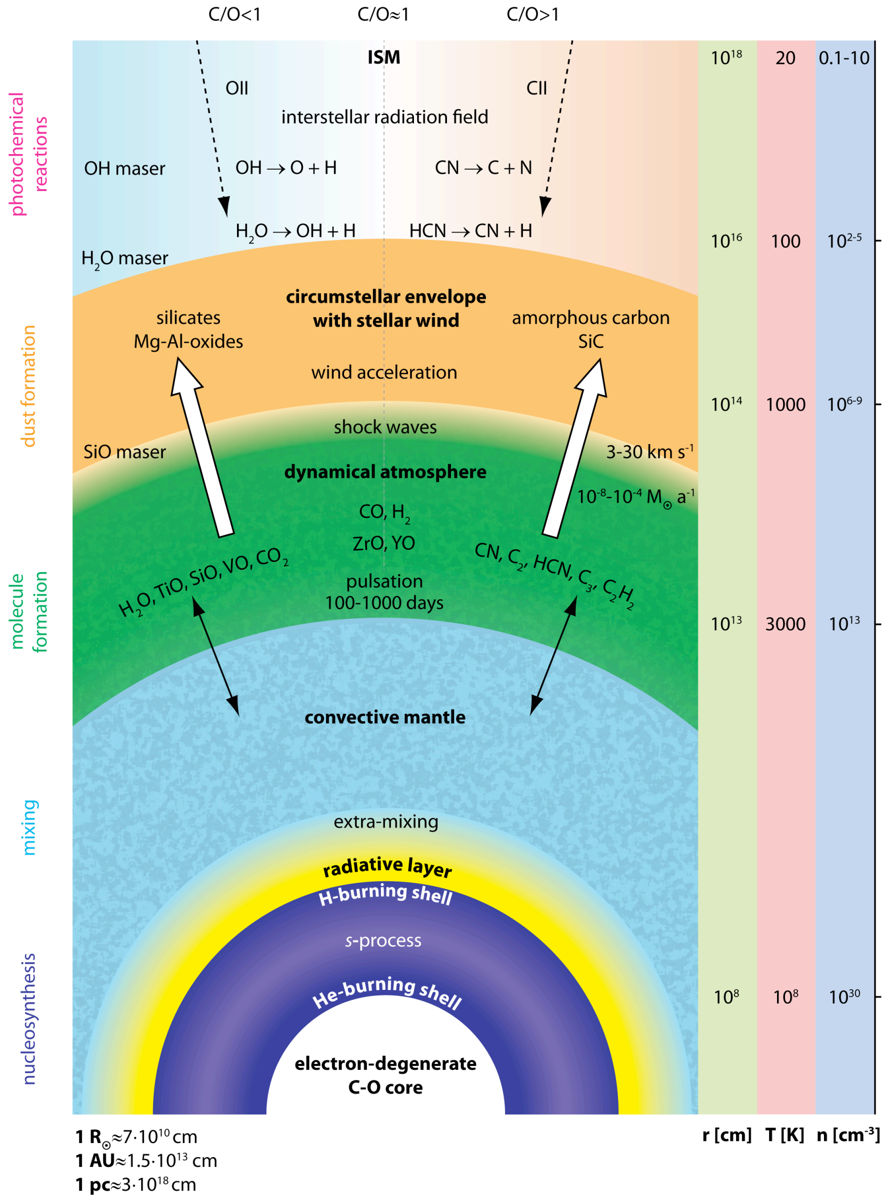
- AGB stars
- Why AGB stars? Why interferometry?
- Stellar parameter determination
  - mildly C-star variable with UKIRT & PTI
  - dynamic objects with AMBER
- Study of the geometry of the mass-loss process
  - HERSCHEL+MIDI+VISIR
  - AMBER+NACO follow-up
- Conclusion & future perspectives



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

AGB carbon stars

- $1 < M < 4\ M_{\odot}$
- C-O core and He/H burning shell, a convective envelope
- [C/O] > 1
- Presence of CO, C_2, C_2H_2, C_3, CN, HCN
- SiC dust, amorphous carbon



Schematic view of an AGB star (adapted by J. Hron & M. Lederer) after an idea from T. Le Bertre.

Why studying C-stars?

Important for galactic evolution:

- 70% material returned to ISM comes from AGB-stars
- C-stars are the main source of carbonaceous material

… as well as for stellar evolution:

- understand the complicate interaction of pulsation and the stellar atmosphere
- gain inside dynamical processes of dust formation and mass-loss

Why using interferometry?

Very bright in the infrared, close by, extended atmosphere to look through

- High angular resolution allows resolving the close circumstellar structure
  - understanding mass loss processes
  - studying the stratification and different opacity sources
- Complementary with other techniques (photometry and spectroscopy) to give observational constraints for model atmospheres and evolutionary models

Stellar parameter determination

- Basic properties & evolutionary status of a star can be determined knowing mass, luminosity, radius, chemical composition.
  - Thanks to interferometry, it is possible to give mass estimates not only for binaries
- Wittkowski et al. (2001, 2004); Neilson & Lester (2008) determined stellar parameters for a sample of AGB stars
  - constraints for model atmosphere
  - constraints for evolutionary models

  BUT: parallax indetermination a major problem…

Determination of stellar parameter for mildly variable C-stars*

5 mildly variable stars selected

- bright objects ($K < 3$)
- low variability amplitude (semiregular, irregular variables)
- (very) low mass-loss values from literature

HK Lyr, DR Ser, Z Psc, RV Mon, CR Gem

UKIRT/UIST spectra (*IJHKL* bands) R = 400-2400

PTI & IOTA (for Z Psc) *K* broad-band visibility

****Paladini C.**, van Belle T.G., Aringer B., Hron J., Reegen P., Lebzelter T., Davis C.J., A&A referee process*

Hydrostatic model atmospheres

Recent new grid of ~ 730 COMARCS models (Aringer et al. 2009) based on *MARCS code* (Gustaffson et al., 1975; 2008) used in Jørgensen et al. (1992), Aringer et al. (1997)

- 1-D models (spherically symmetric models)
- hydrostatic equilibrium, LTE & chemical equilibrium
- treatment of molecular absorption with opacity sampling technique
- spherical radiative transfer code: spectrum+spatial intensity

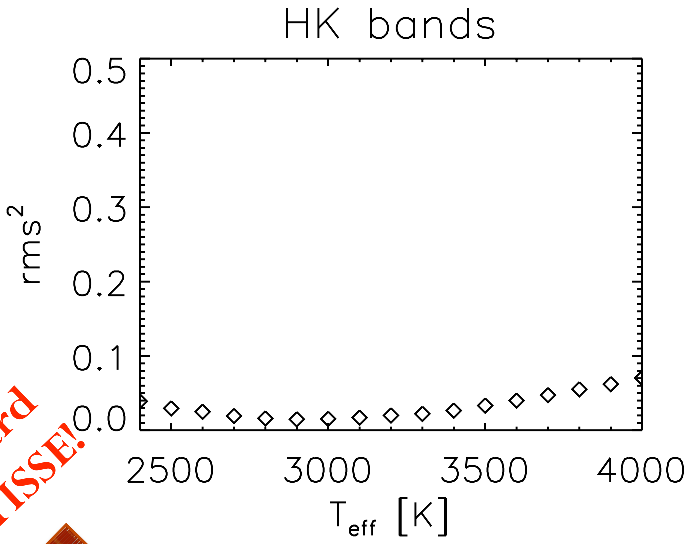
Parameters: temperature, mass, C/O, log g, metallicity (solar)

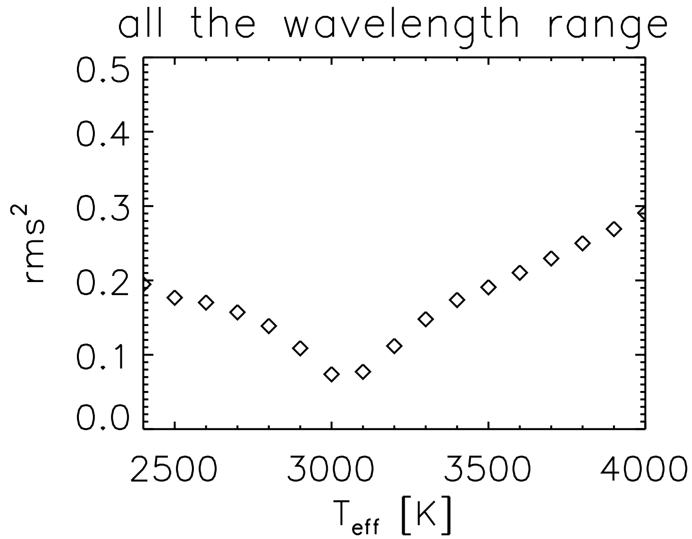
Spectroscopic analysis

- Temperature (main parameter)
  χ^2 fit comparing the full UKIRT spectra and the grid of models (quite precise, especially using the 3.1 μm feature C_2H_2+HCN)

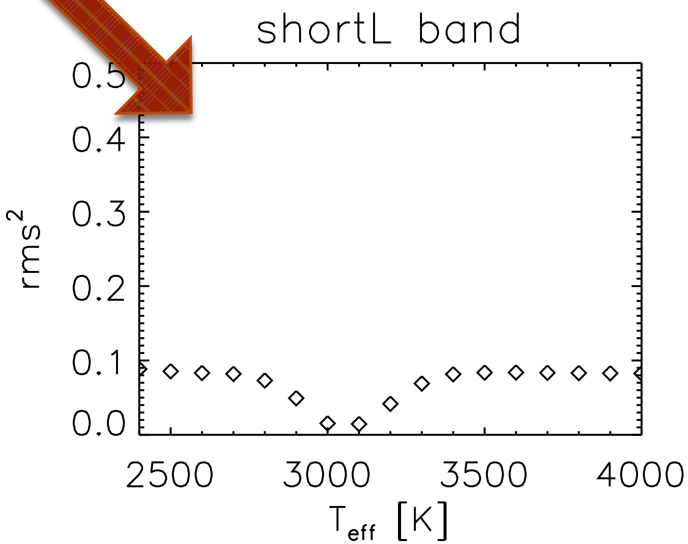
- C/O ratio
  χ^2 fit for single spectral features :
  C_2 (1.02, 1.20 μm); CO(2.29 μm);
  C_2H_2+HCN (3.1 μm)
  Low spectral resolution ➡ not very sensitive…
  but values obtained are in agreement with literature ☺

Determination of temperature



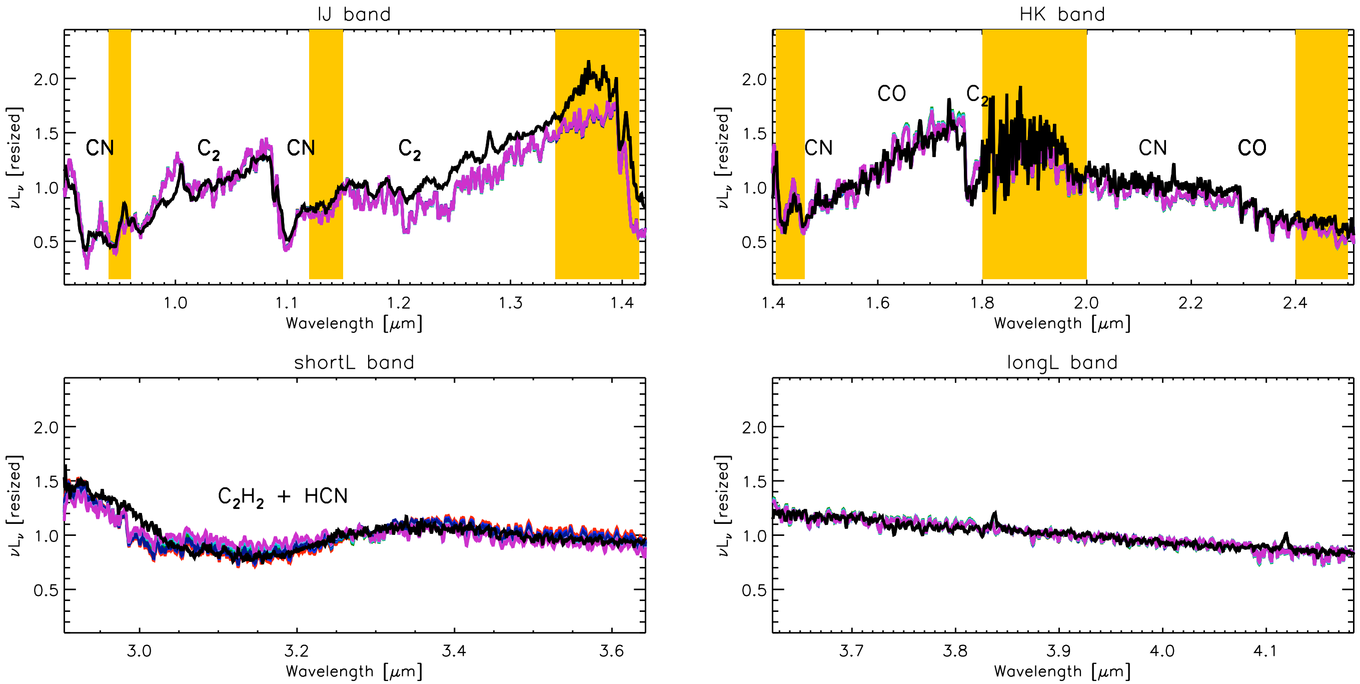


Looking forward to have MATISSE!



ID	Temperature [K]
HK Lyr	3090 ± 50
CR Gem	3070 ± 50
Z Psc	3130 ± 60
RV Mon	3170 ± 50
DR Ser	3070 ± 40

Models vs observations
(after spectroscopic fit)



black line = HK Lyr spectrum
colored lines = models
T_{eff} = 3100 K; $Z = Z_\odot$; C/O = 1.4 M = 1, 2 $M_\odot$; log g = 0., -0.2, -0.4, -0.5

Log *g* and mass are not constrained!!!!

Determination of mass, log g

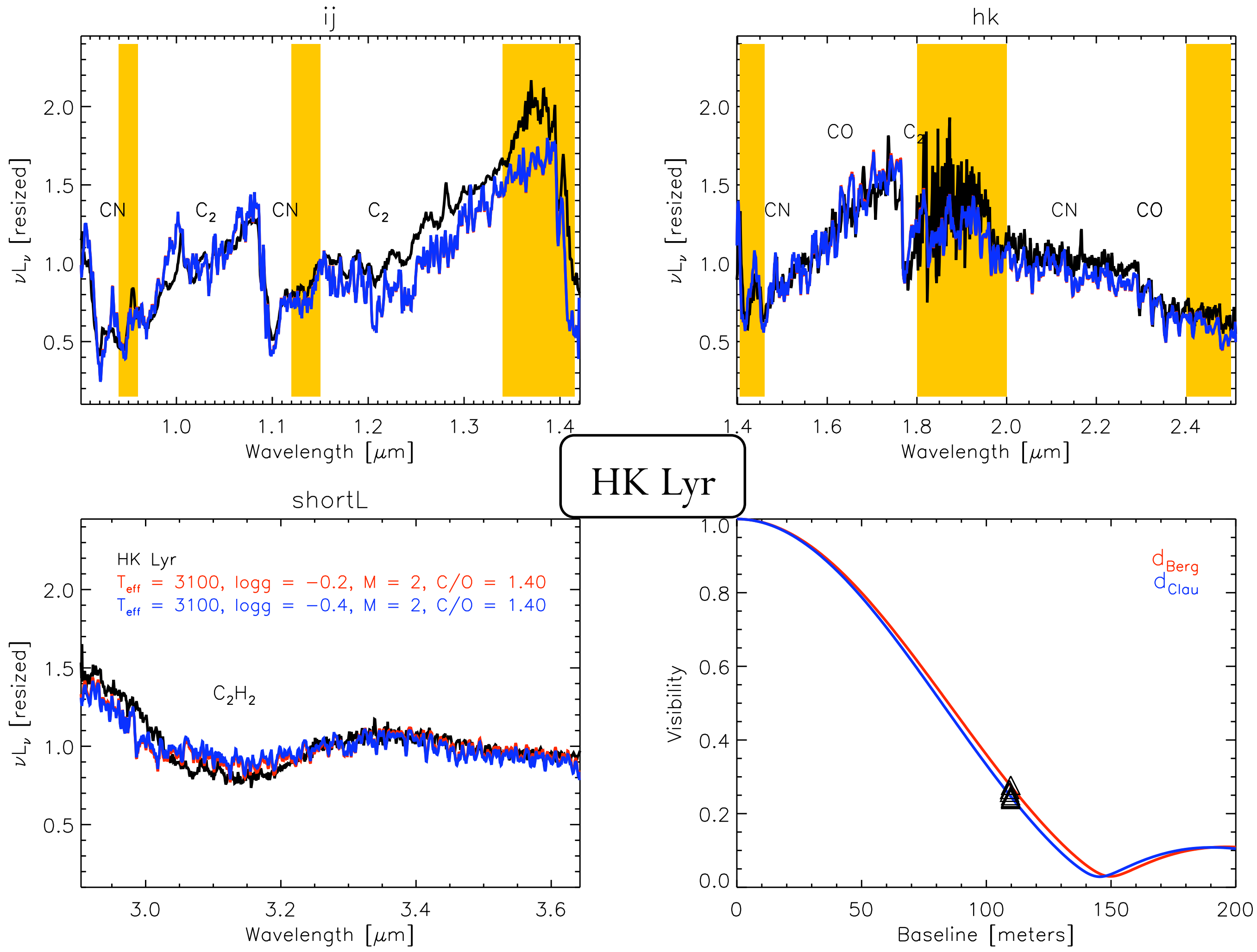
Distance, luminosity, mass & radius…

→ degenerate problem! ☹

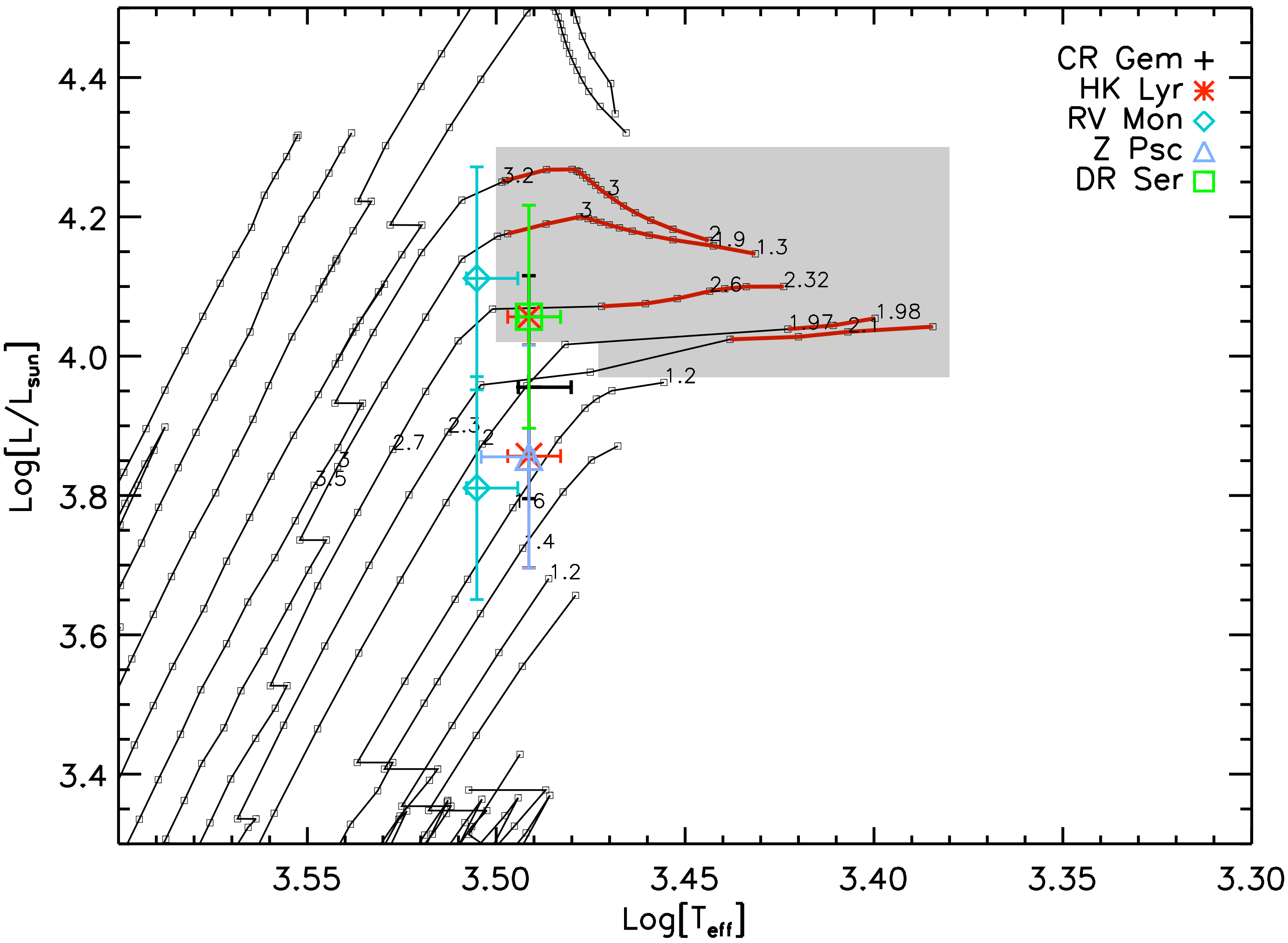
Interferometry

1. check of variability or eventual asymmetries via uniform disc fitting;
2. adopt 3 different distance estimates
   (Hipparcos; Bergeat et al., 2004; Claussen et al. ,1986)
3. χ^2 to fit PTI interferometry data;
4. best fitting model constraints log g and mass for a given distance;
5. discussion on best fitting parameters using stellar evolution models.

Fit of spectro-interferometric observations



Comparison with evolutionary models



Isochrones from **Marigo et al., 2008**

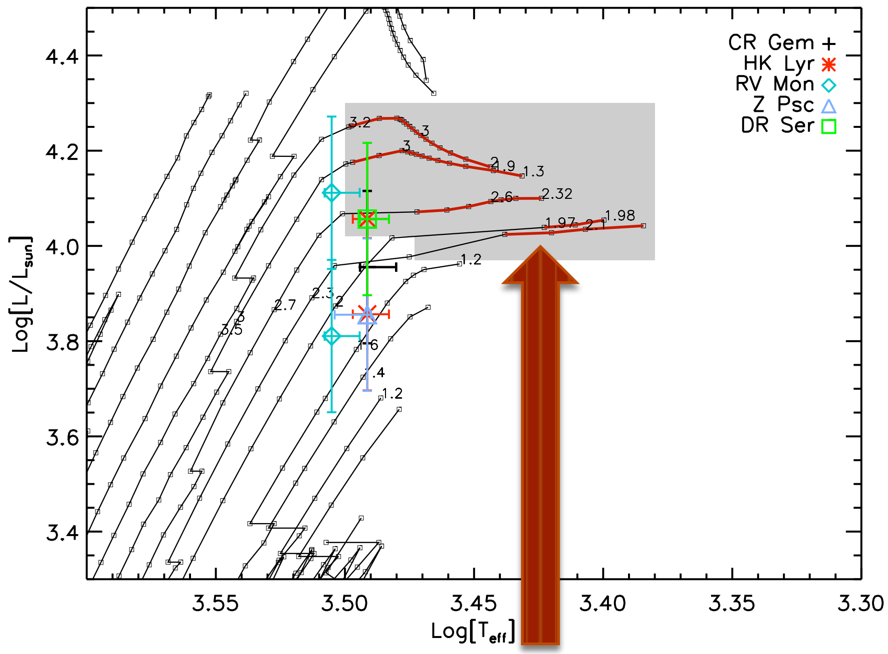
Next step: stellar parameters for a set of dynamic C-stars

Selection of 3 objects dust-enshrouded to be observed with AMBER in MR-H & MR-K. Spectroscopy already available.

I want also AMBER spectrum!

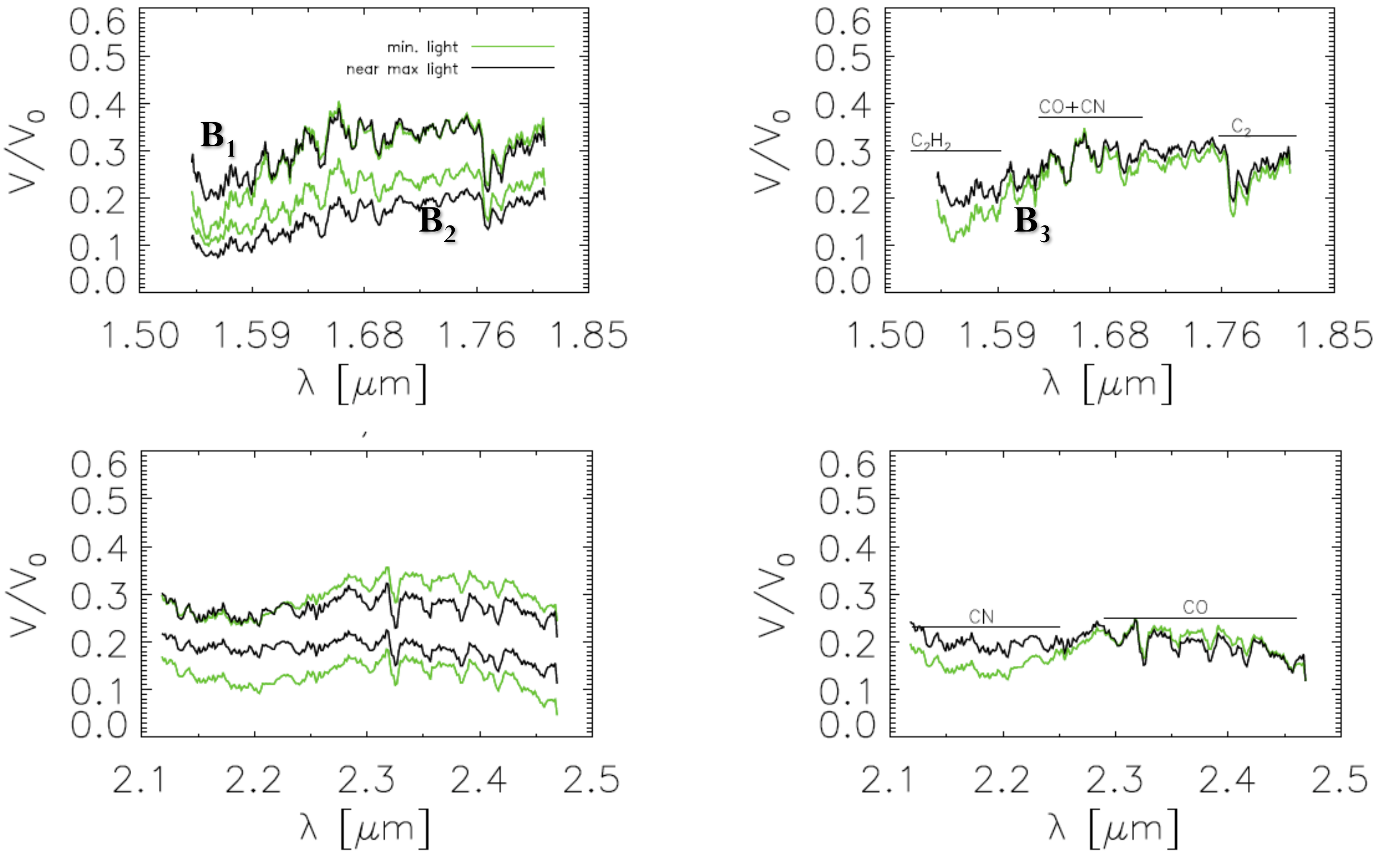
Observations will be compared with dynamic model atmospheres from Höfner et al. (2003); Mattsson et al.(2010).

Models include dust driven wind.



region of the HR-diagram we expect to sample

Model predictions for AMBER observations



10% precision needed for the visibility!

Summary

- Models vs Observations:
  - ➢ Determined stellar parameters for a set of 5 mildly variable objects.
  - ➢ All the targets have at least one combination of parameters in the predicted C-stars region.
  - ➢ Using a multi-technique approach (spectroscopy, interferometry) we can well constrain the stellar parameters for carbon stars. *But the distance is an important assumption!*
  - ➢ Spectroscopic and interferometric observations of C-stars can be fitted at the same time in consistent way by hydrostatic models!
  - ➢ *L*-band spectroscopy is a powerful tool for estimating the temperature of the mildly variable carbon stars

- This kind of work, extended to different stellar types, can furnish constraints for evolutionary models

ESO/VLT(I) Large Program:

A joint venture in the red: Herschel+MIDI+VISIR view on mass-loss from evolved stars

Paladini C., Sacuto S., Lagadec E., Verhoelst T., **Klotz D.**, Hron J., Groenewegen M.T., Kerschbaum F., Richichi A., Wittkowski M., Olofsson H., Jorissen A.

Goal

Study the geometry of the mass-loss process for evolved red giants on the AGB at different scales of their atmosphere.

The data will complement **Herschel** observations for a subsample of AGB stars selected from the **MESS program** (Groenewegen et al., 2011).

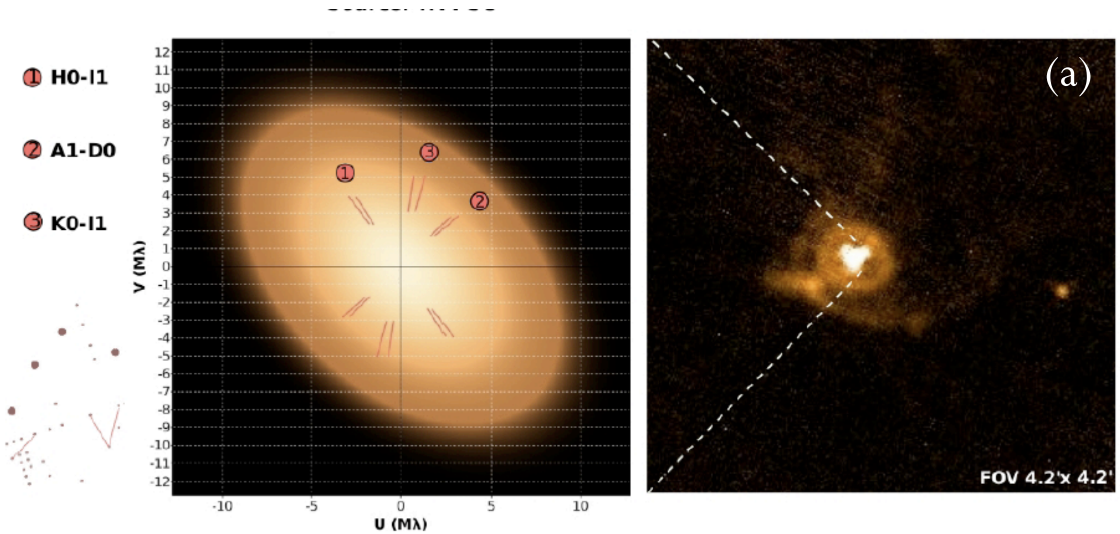
Herschel maps the outer envelope unveiling the interface between stellar wind and ISM.

The inner CSE will be mapped with MIDI (2-25 $R_{\star}$) and VISIR (25-2500 $R_{\star}$).

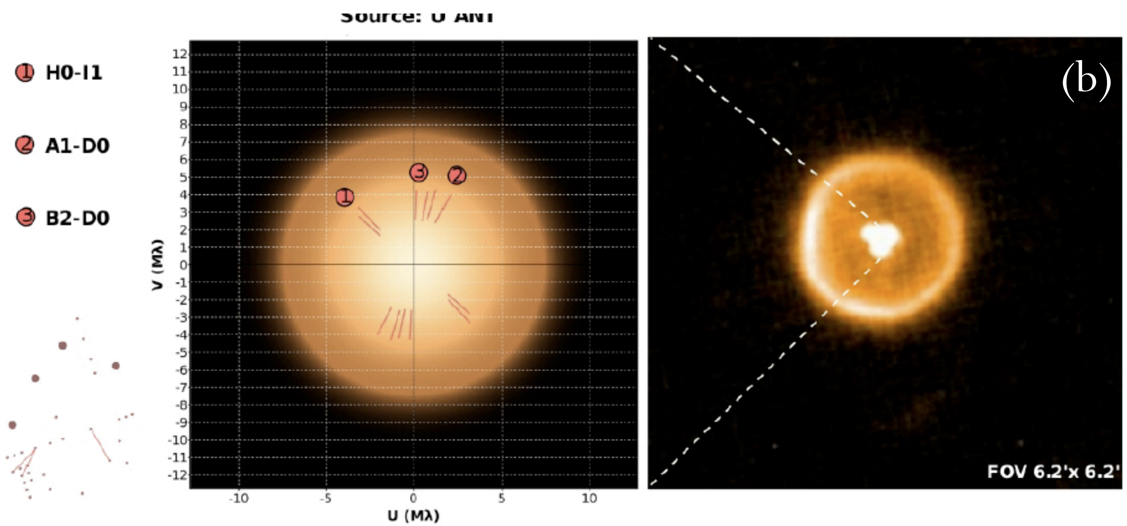
- 15 targets (M-, S-, C-type AGB stars; different variability class)
- ~ 140 hours of MIDI + VISIR time over 2 periods
- 2 observations x 3 configurations with MIDI (N-band 8-13 microns)
- N+Q band observations with VISIR

Herschel observations & MIDI (preliminary) modeling

(a) target with asymmetry: Herschel observations and MIDI preliminary modeling (ASPRO2) of TX Psc.



(b) symmetric target: Herschel observations of U Ant and MIDI modeling (ASPRO2).

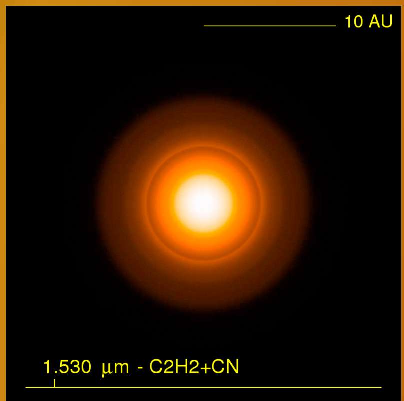


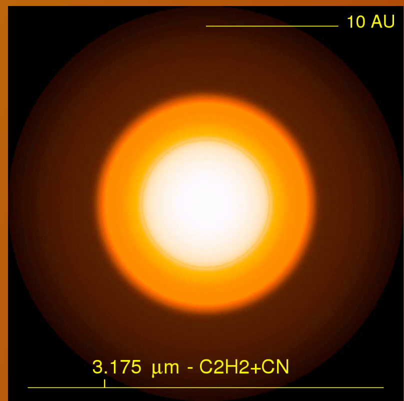
What's next?

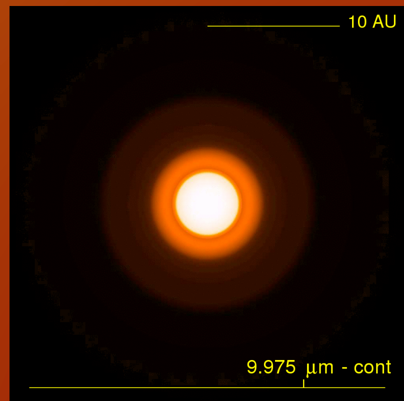
Next step is to extend the wavelength covarage to nearIR (*JHK* bands) to study the geometry in the region where pulsation starts and molecules dominate:

- AMBER will complement the MIDI observations probing the inner region close to the photosphere.
- NACO will complement the VISIR observations.

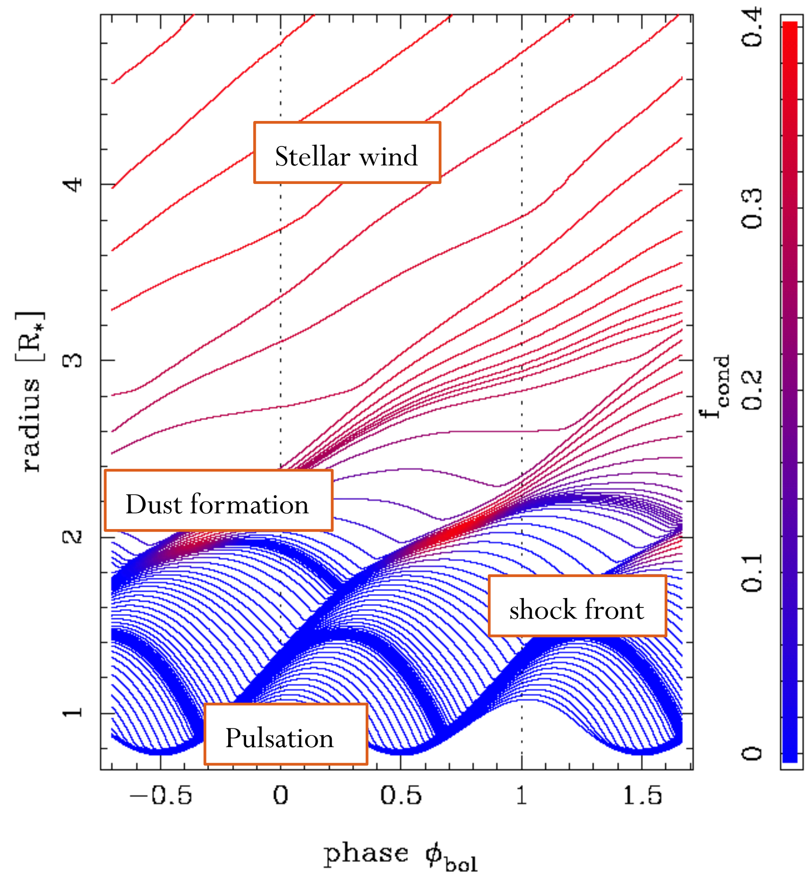
Merci à tous



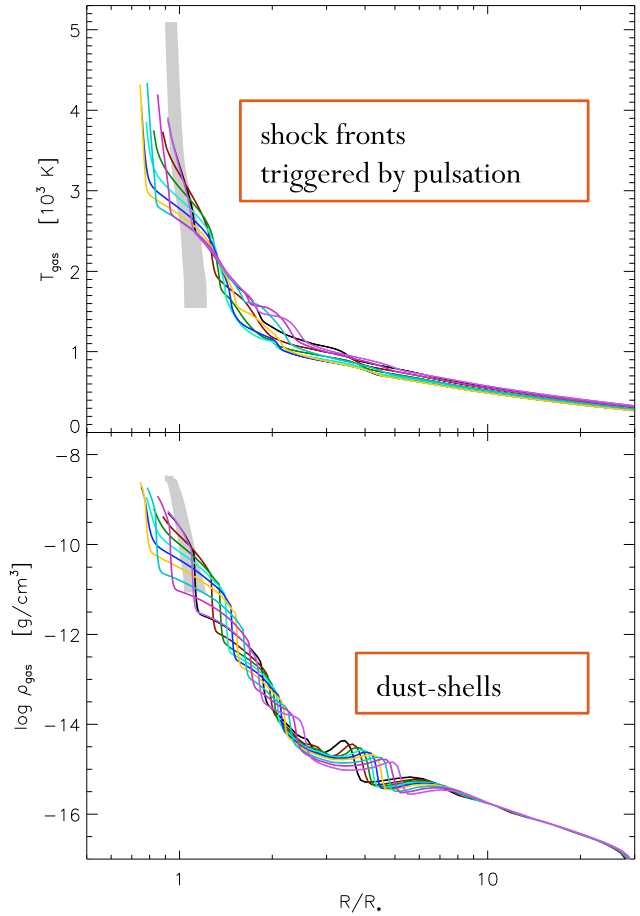




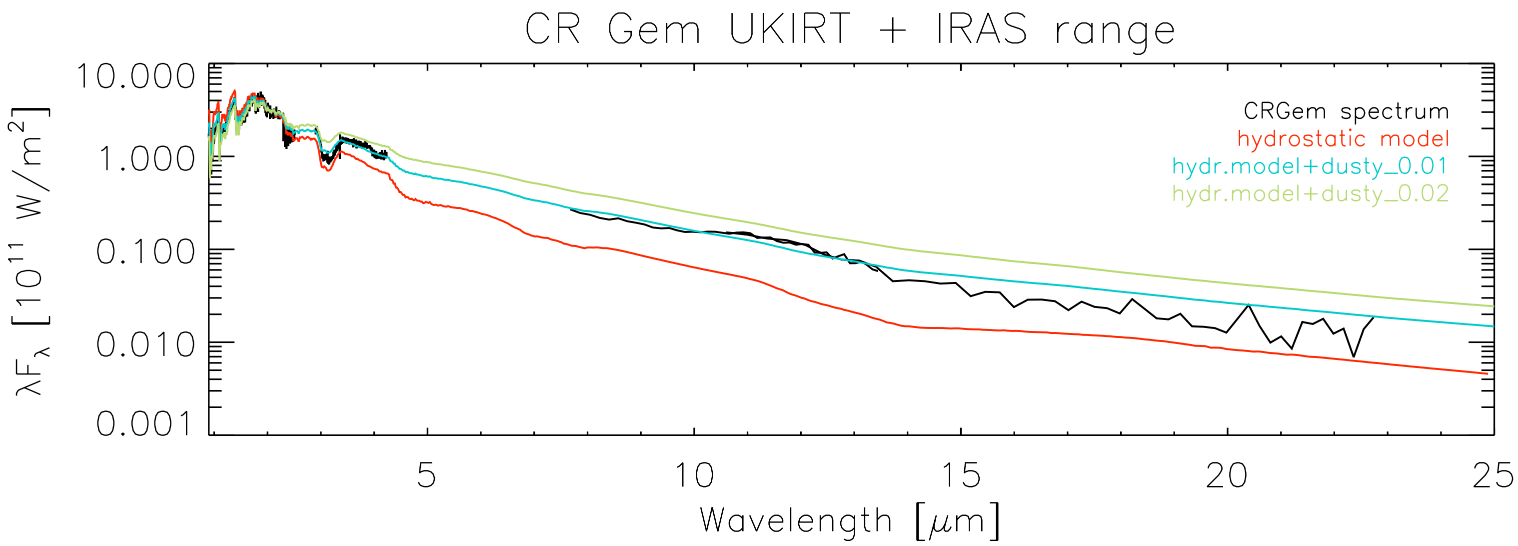
DMA Radial Structure

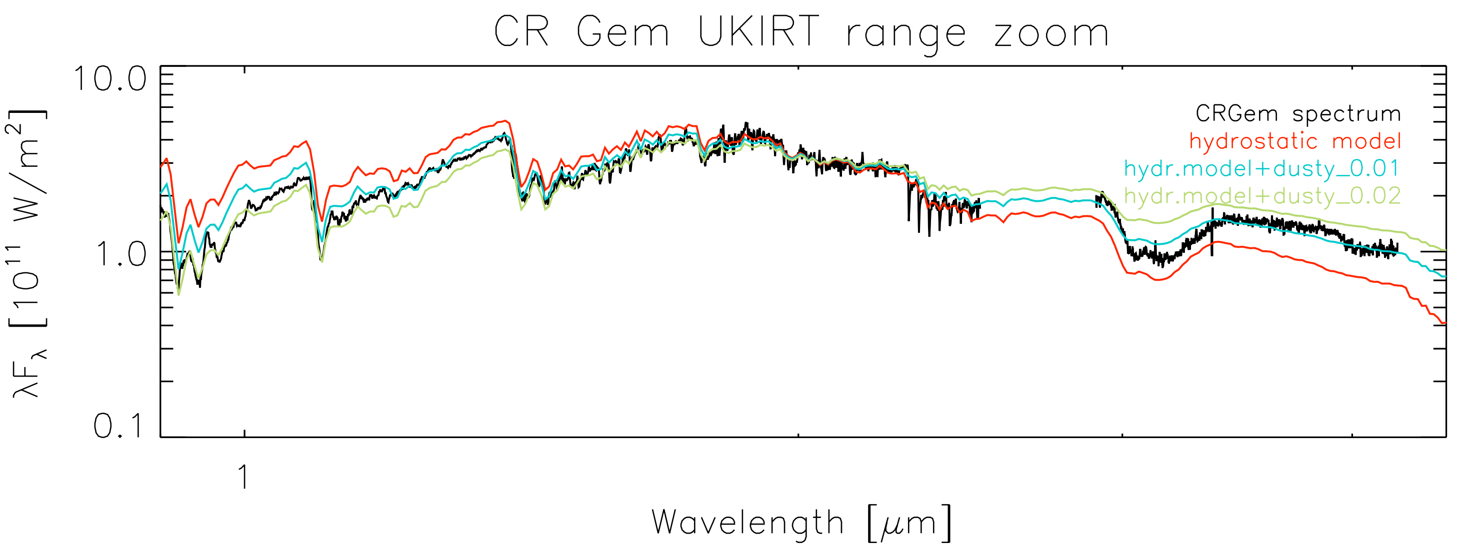


e.g. Nowotny et al. (2005)



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


CR Gem UKIRT + IRAS range
10.000
1.000
0.100
0.010
0.001
λF$_λ$ [10^{11} W/m^2]
5
10
15
20
25
Wavelength [μm]
CRGem spectrum
hydrostatic model
hydr.model+dusty_0.01
hydr.model+dusty_0.02


CR Gem UKIRT range zoom
10.0
1.0
0.1
λF$_λ$ [10^{11} W/m^2]
1
Wavelength [μm]
CRGem spectrum
hydrostatic model
hydr.model+dusty_0.01
hydr.model+dusty_0.02