Variability of the photosphere and molecular layers of evolved stars R Car and VX Sgr using VLTI-GRAVITY

XIV Torino Workshop on AGB stars

Daniel Jadlovský (ESO & MUNI, CZ)

Markus Wittkowski (ESO), Jiří Krtička (MUNI), Andrea Chiavassa (OCA), Kateryna Kravchenko (MPE), …

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Content

Unveiling the stellar atmospheres and mass-loss process using VLTI

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I. Mass-loss process of cool evolved stars

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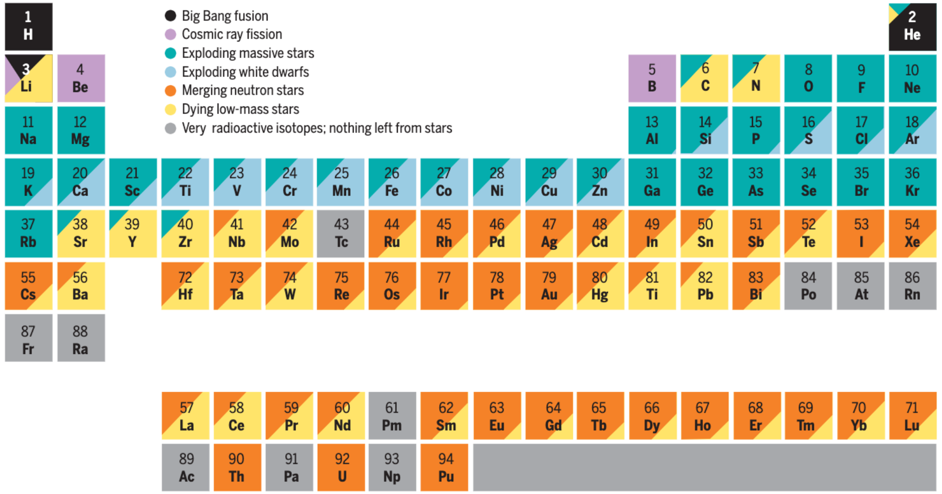
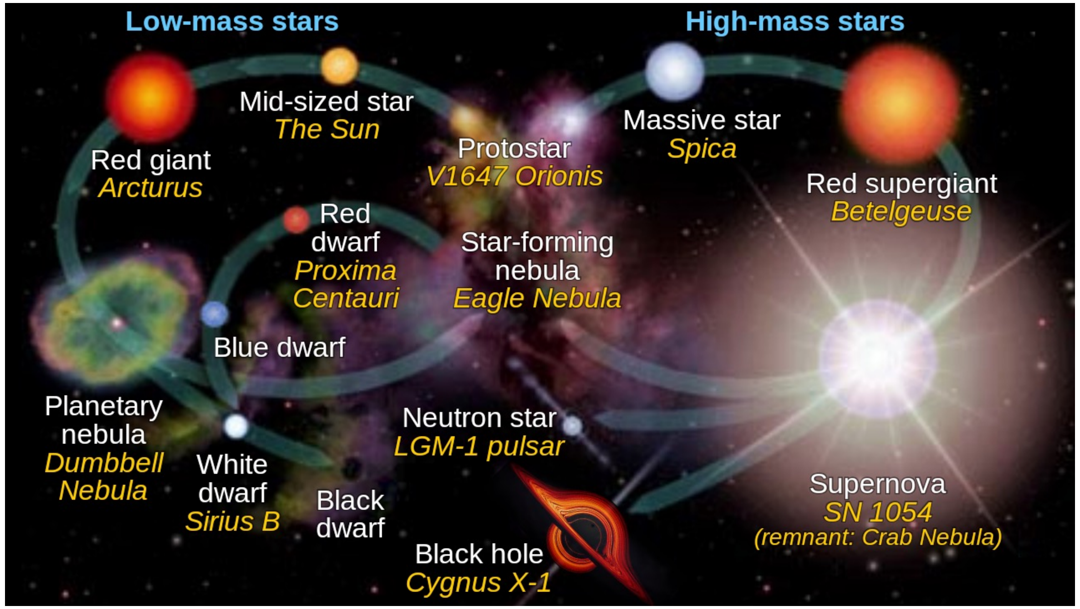
Red giants and supergiants

Why should we care?

- **red supergiants:** massive stars ($> 8\ M_0$) → nuclear burning up to iron → supernova explosion (blue/red evolution) → NS, BH
- **AGB stars:** → degenerate CO core → planetary nebula + white dwarf
- high mass-loss rates, up to $10^{-6} – 10^{-4}\ M_0 yr^{-1}$
- **Importance:**
  - The crucial extreme of stellar evolution
  - The mass-loss process is essential for stellar evolution, interstellar medium, and study of supernovae
  - Major dust contributors to the interstellar medium
  - Chemical enrichment of the universe, building material for new stars and planets!





Sources: Johnson 2019, Wittkowski et al. 2020

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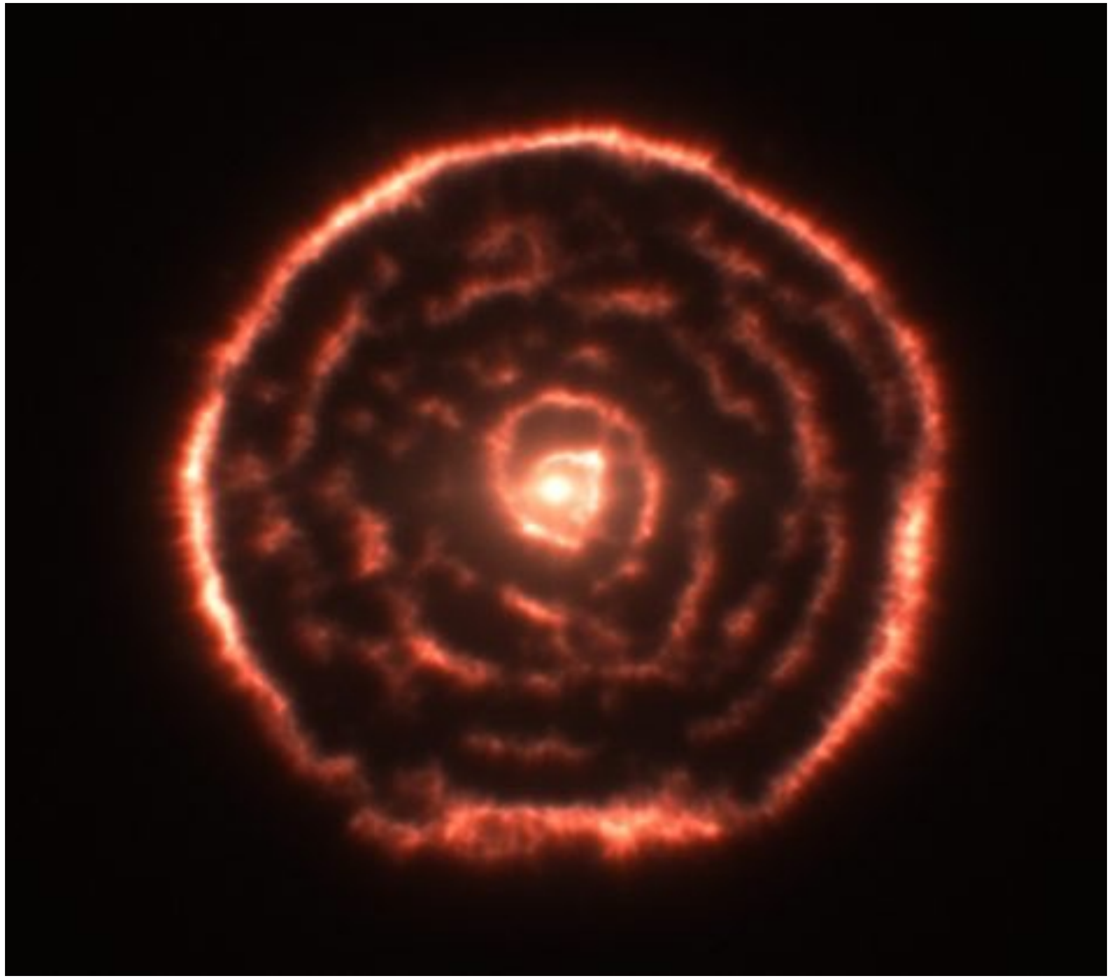
Mass-loss process

So far, no model is able to fully explain the observed mass-loss rates for red supergiants

- **AGB stars:**
  - models: dust-driven wind + levitation of material by pulsations is likely sufficient to explain the observed mass-loss rates for red giants on the asymptotic giant branch (e.g., Freytag & Höfner 2023)
- **red supergiants:**
  - levitation of material by pulsations is less effective → another mechanism needed
  - episodic mass-loss events? (e.g., Dupree et al. 2022)
  - „coronal“ mass ejections due to magnetic fields? (e.g., Humphreys et al. 2022)
  - radiative pressure on molecules? (Josselin et al. 2007)
  - the activity of giant convection cells, the interplay between pulsations and convection, …?



Binary interaction also plays a significant role, R Scl, Source: ALMA, Maercker et al. 2012

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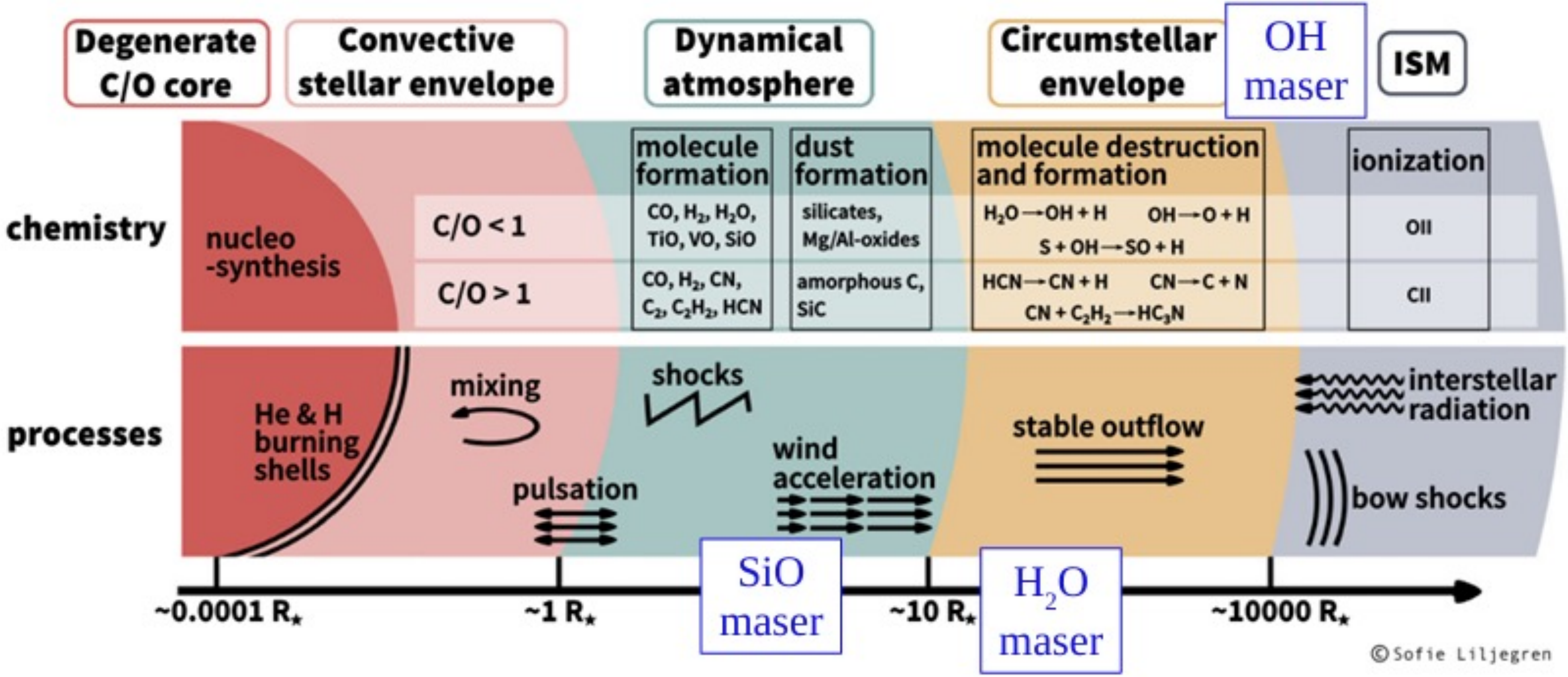
AGB stars



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II. Optical interferometry with Very Large Telescope

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Very Large Telescope Interferometer (VLTI)

VLTI is one of the most advanced ground-based optical instruments in the world

- Optical interferometer, operates in near- and mid-infrared bands
- Four 8.2-m Unit Telescoples (UTs)
- Four 1.8-m Auxiliary Telescopes (ATs) – can be relocated
- Instruments combine 4 beams (from ATs or UTs)
- For imaging, max baseline is from about 130m (UTs) to 200m (ATs) → max resolution from 0.8 mas (1.5 um) to 10 mas (13 um)
- Instruments: PIONIER (*H*), GRAVITY (*K*), MATISSE (*LMN*)

Paranal Observatory, 2635 m altitude

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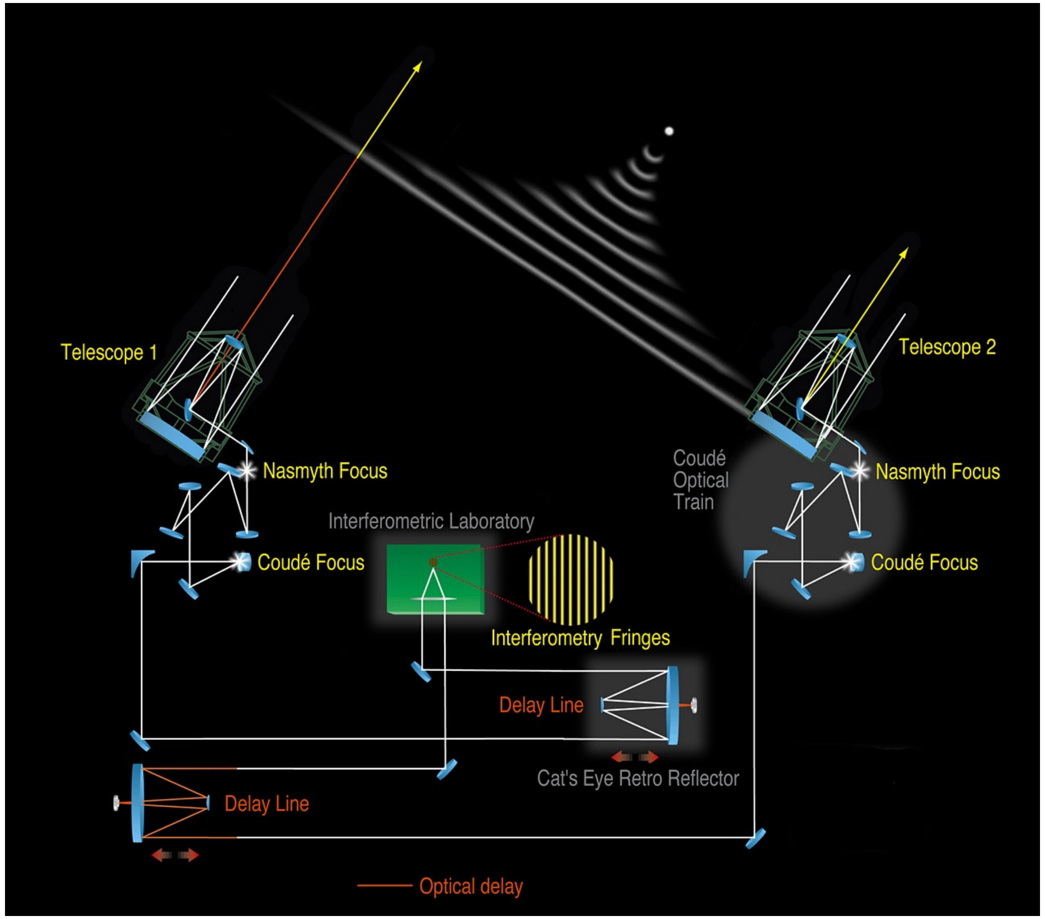
Optical interferometry

Instead of one giant telescope, it is more feasible to have several smaller telescopes

- Infrared signals (VLTI) are physically combined, unlike at the longer wavelengths (ALMA), where the radio waves are amplified digitally combined
- The light waves from a distant object arrive at each telescope at different time → adjustable delay lines are introduced, to ensure that the light interferes constructively
- combined light waves – interferometric fringes



Schematics of the VLTI,, Source: ESO

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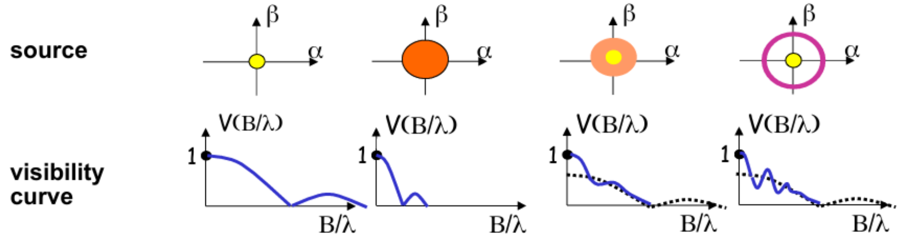
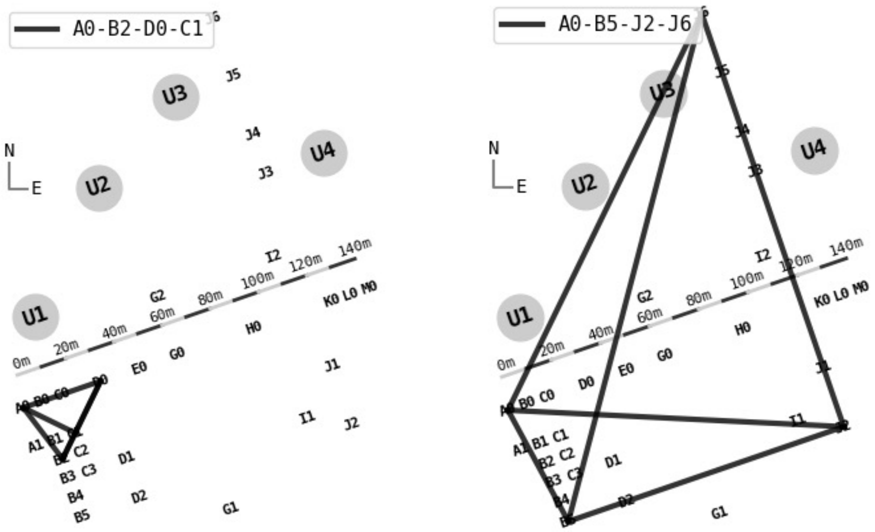
Optical interferometry

The positions and distances of telescopes are crucial

- From the contrast of the fringe pattern, we measure the interferometric visibility
- For proper reconstruction of images, we need high u-v coverage → more baselines, and **time**





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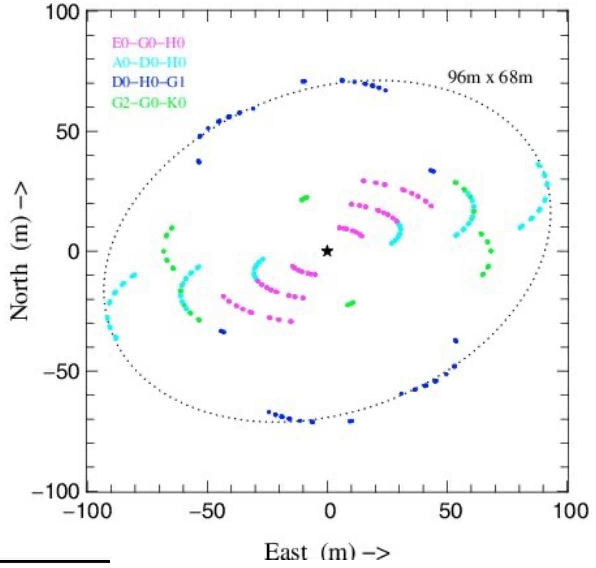

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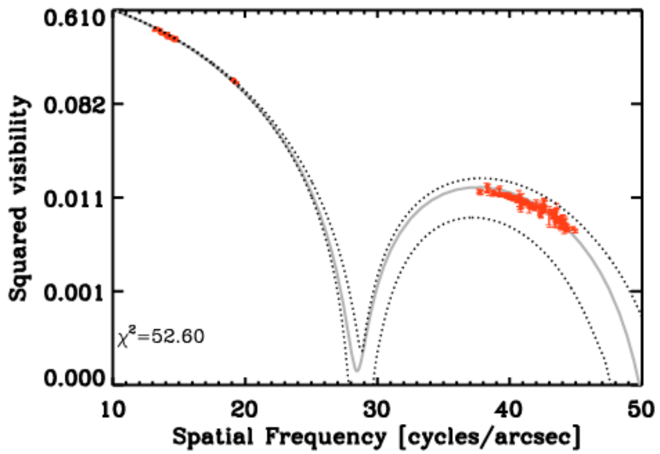

Sources: ESO, Chiavassa et al., 2010

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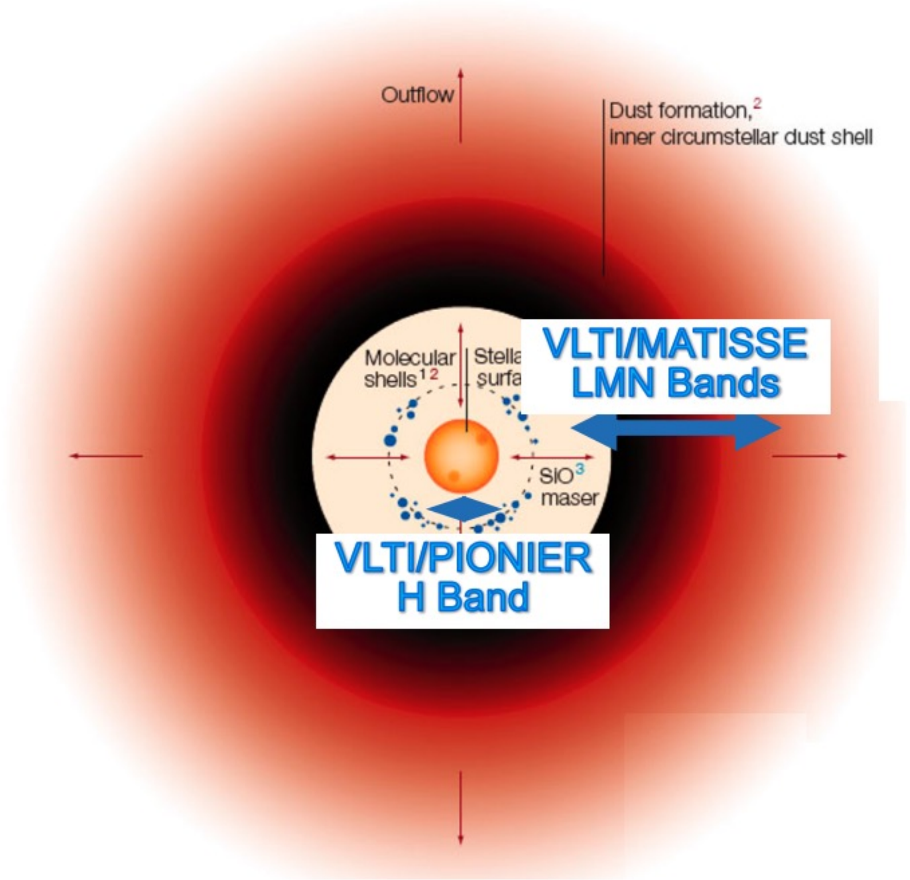
Using ESO instruments to unveil the mass-loss process

Different bands/instruments allow us to study different parts of atmosphere

- **photosphere:**
  - VLTI – PIONIER (*H*-band)
- **molecular layers and dust formation zone:**
  - VLTI – GRAVITY (*K*-band), MATISSE (*L*, *M*, *N*-bands)
- **extended circumstellar environment and masers:**
  - ALMA (sub-mm and mm)



Wittkowski et al. 2020, VX Sgr - Chiavassa et al. 2022, ATOMIUM - Decin et al. 2020

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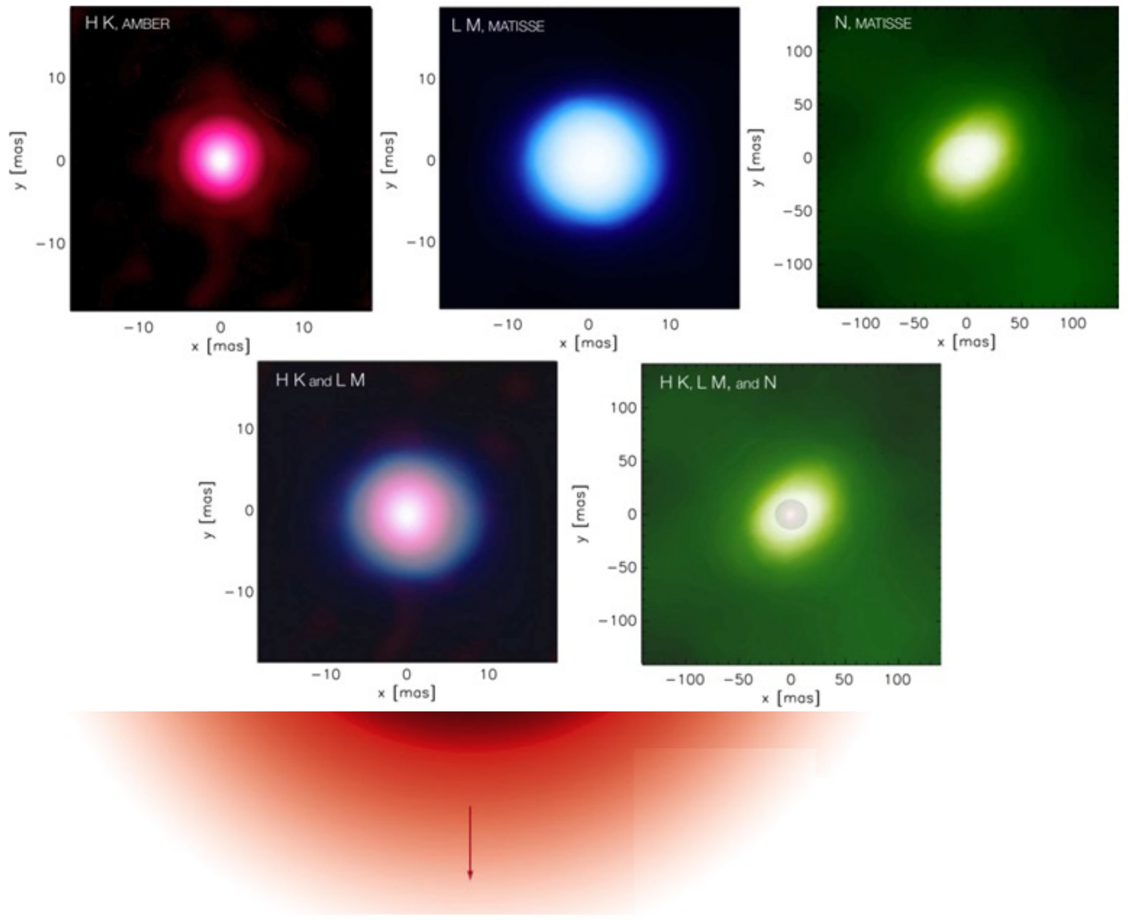

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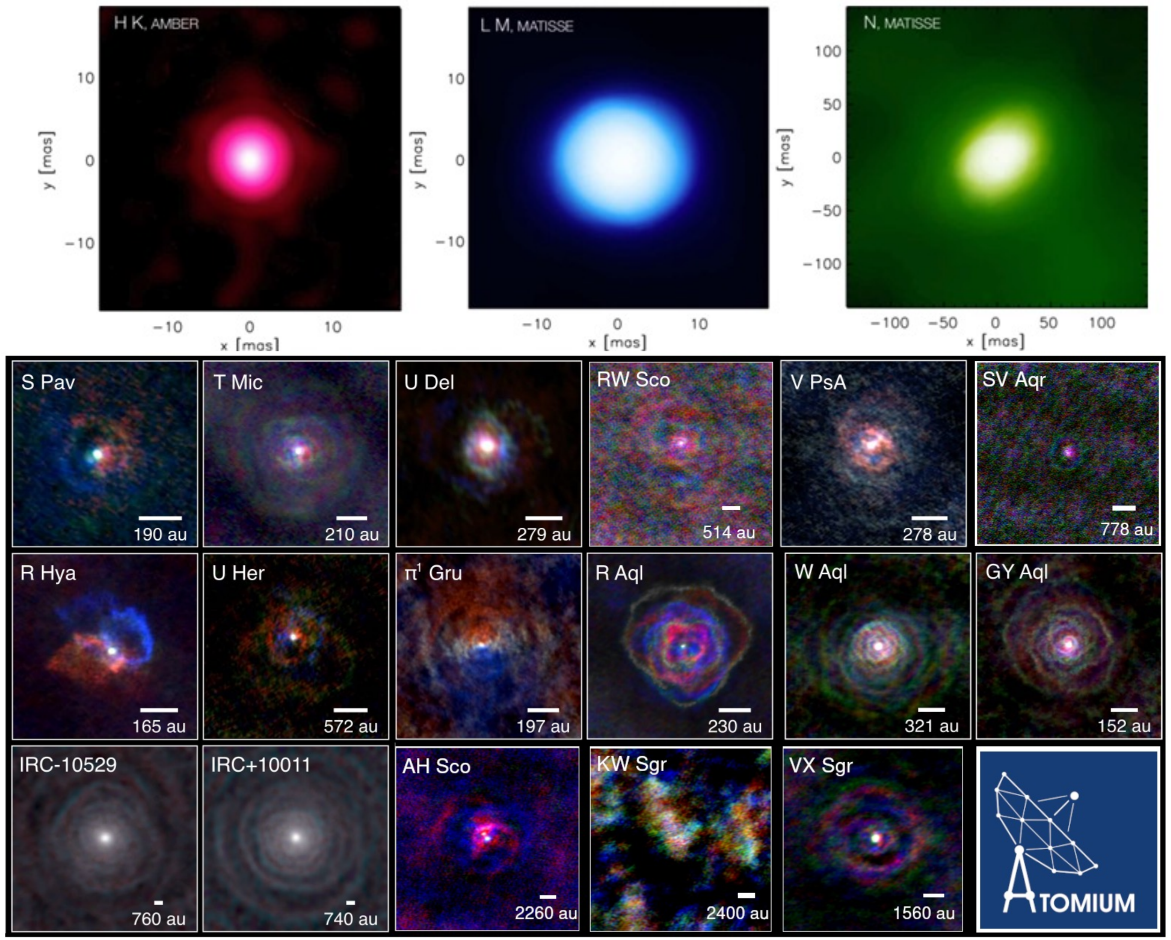

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III. Our (preliminary) results

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Variability and mass-loss process of evolved stars with VLTI-GRAVITY

Supervisors: Markus Wittkowski (ESO), Jiří Krtička (MUNI)
Collaborators: Andrea Chiavassa (OCA), Kateryna Kravchenko (MPE), Susane Hofner (UU), Bernd Freytag (UU), Gemma Gonzalez-Tora (UHD), et al.

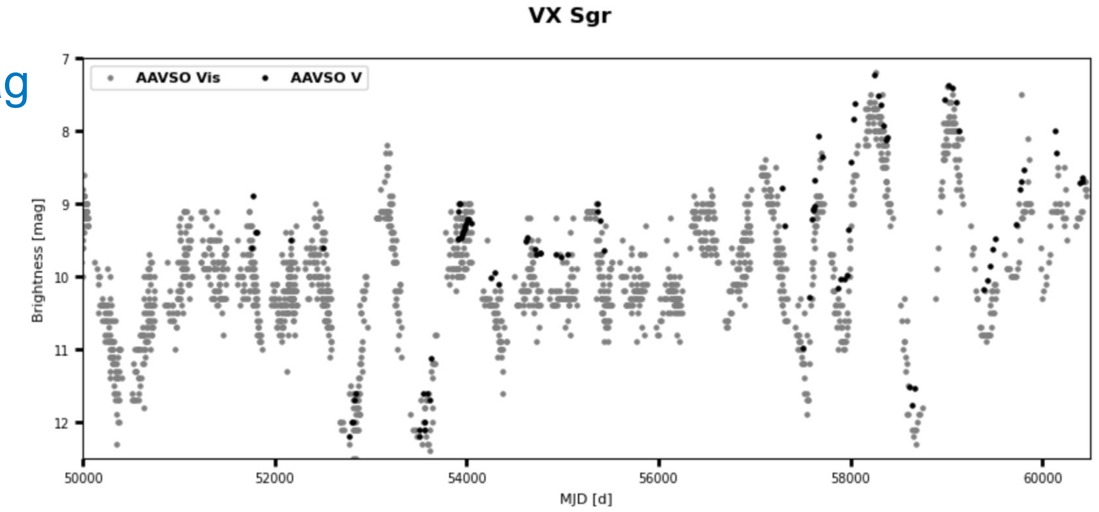
- Many epochs of VLTI-GRAVITY observations for an AGB star R Car and a red supergiant VX Sgr → spectro-interferometry time series

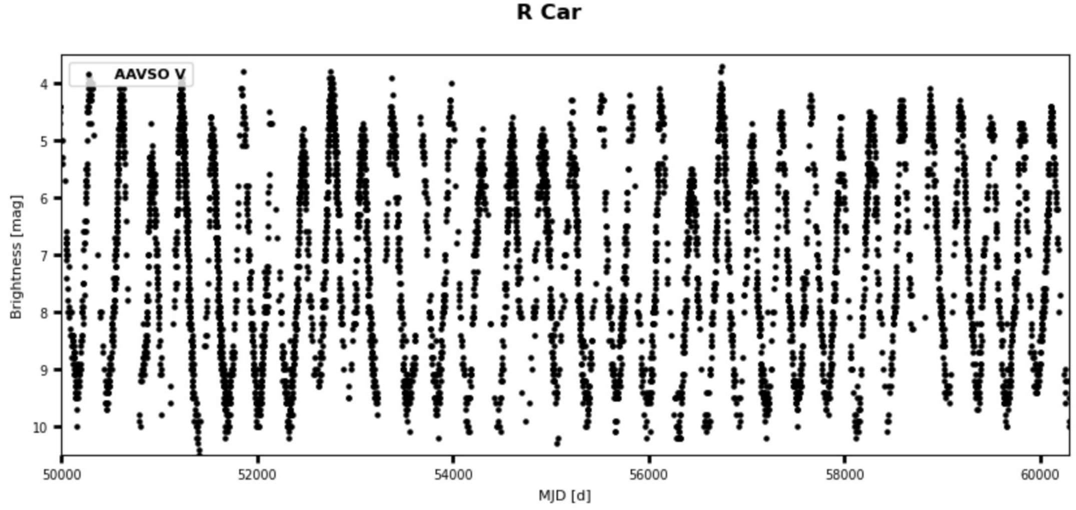
- Determination of **angular diameter** → variability of the photosphere and molecular layers

- Comparison between oxygen-rich AGB and RSG stars

- **R Car**: M5-8 (Mira), $M \sim 0.85\ \mathrm{M}_0$, $P \sim 310$ d

- **VX Sgr:** M8.5Ia (RSG), $M \sim 12\ \mathrm{M}_0$, $P \sim 730$ d





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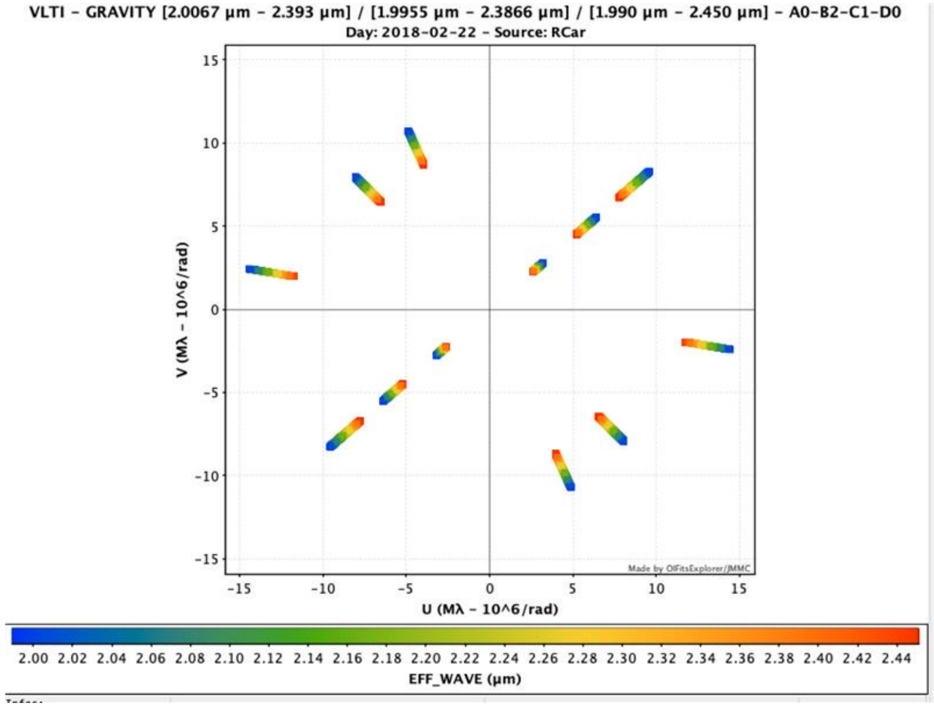
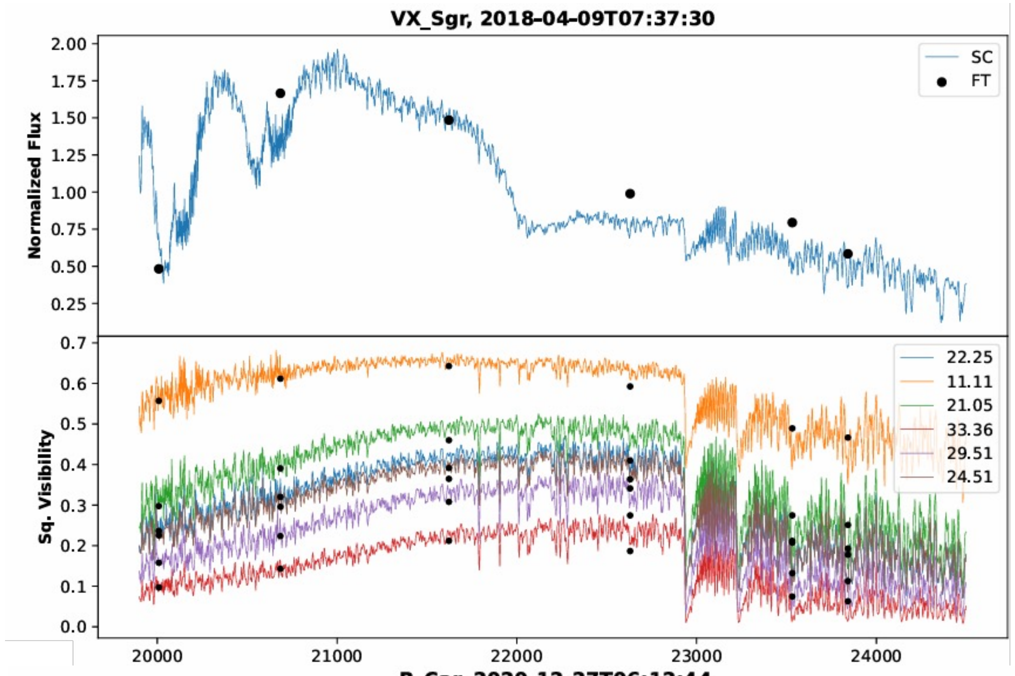
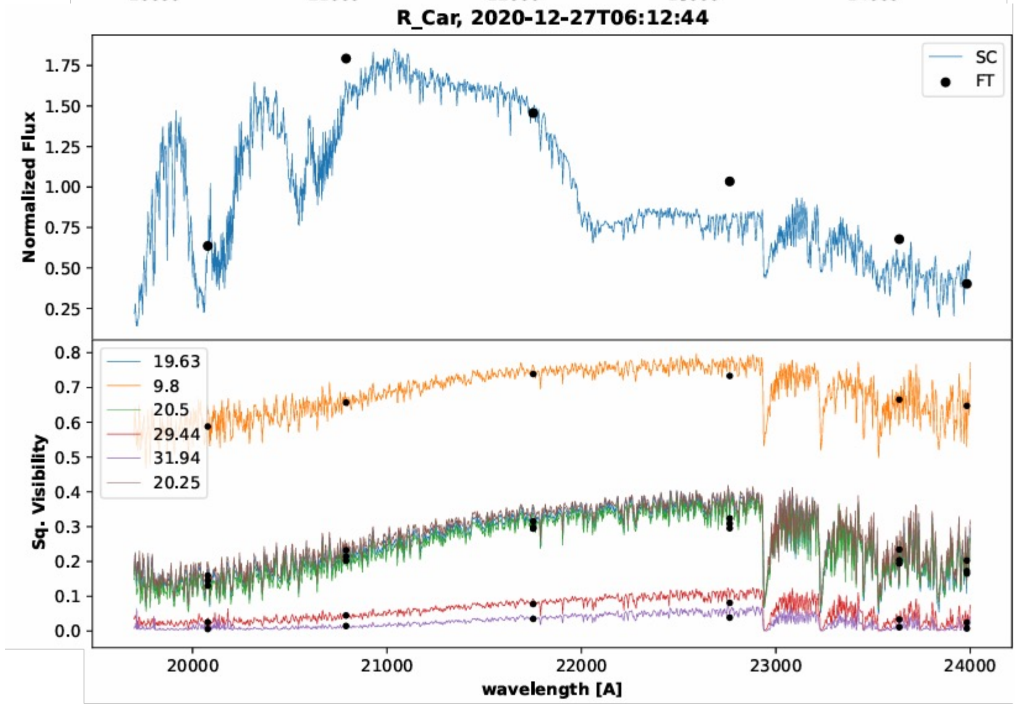
Data sample

The goal is to analyze only the first lobe, no imaging → short baseline, snapshots, small uv coverage

- About 35 nights for VX Sgr and 20 nights for R Car (between 2018-2023) → extensive dataset







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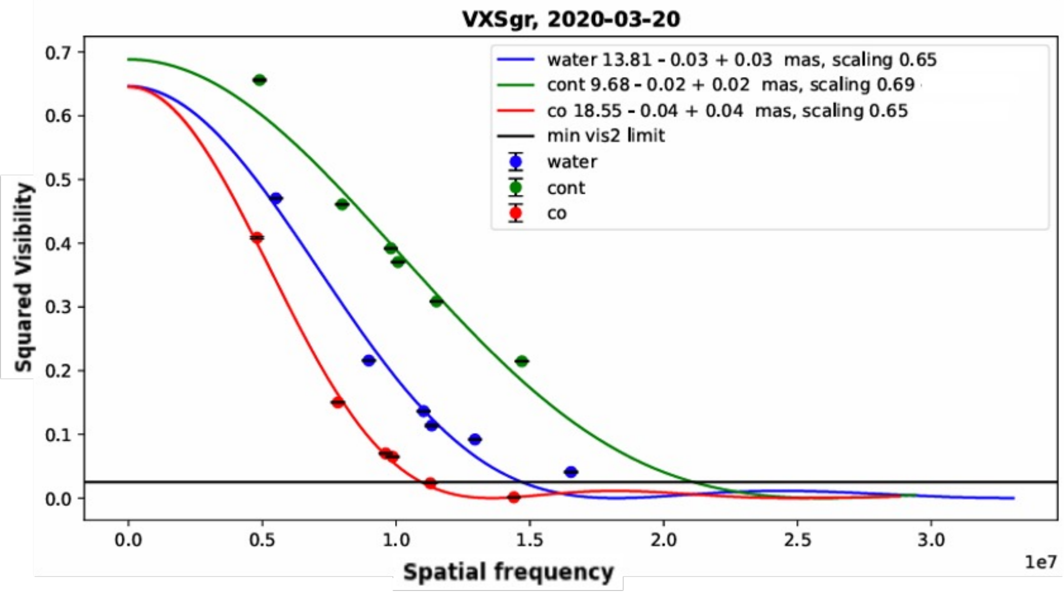
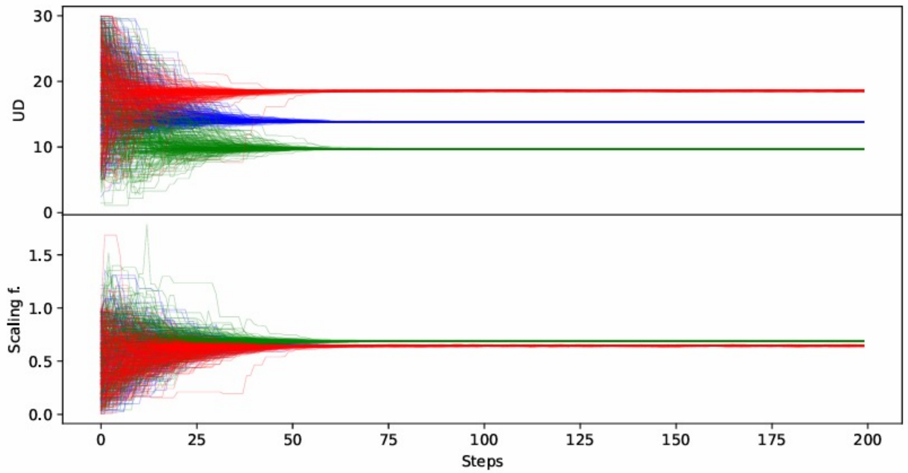
Determining the angular diameters

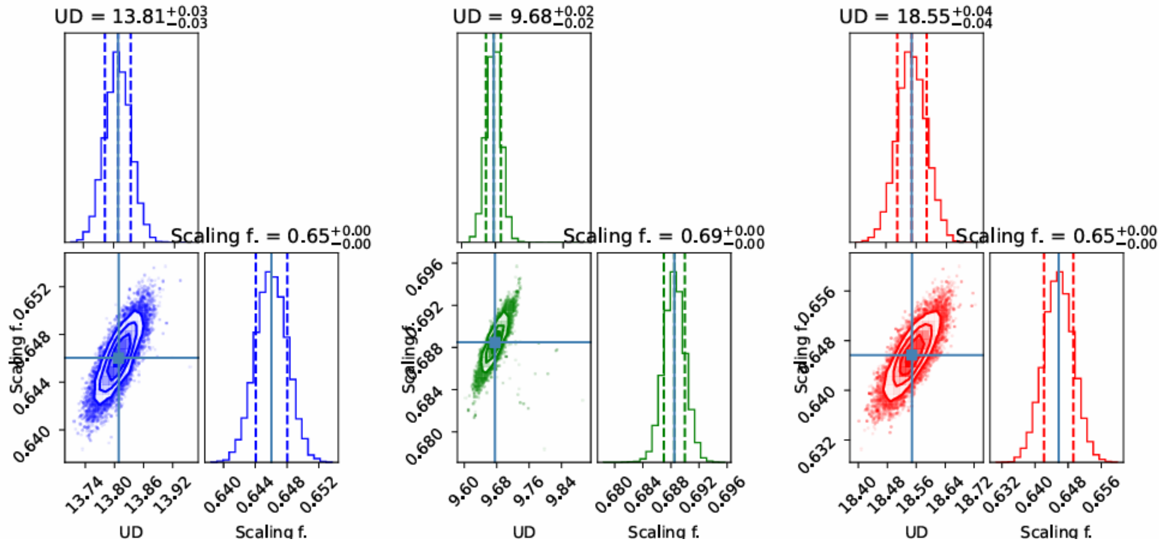
Uniform disk fitting example

- First lobe of the visibility function can be fitted with the uniform disk model (Bessel function). For the best fitting results, we use Markov-Chain Monte Carlo (MCMC)

- We study 3 main spectral regions: continuum and H2O/CO molecular bands → atmospheric extension.







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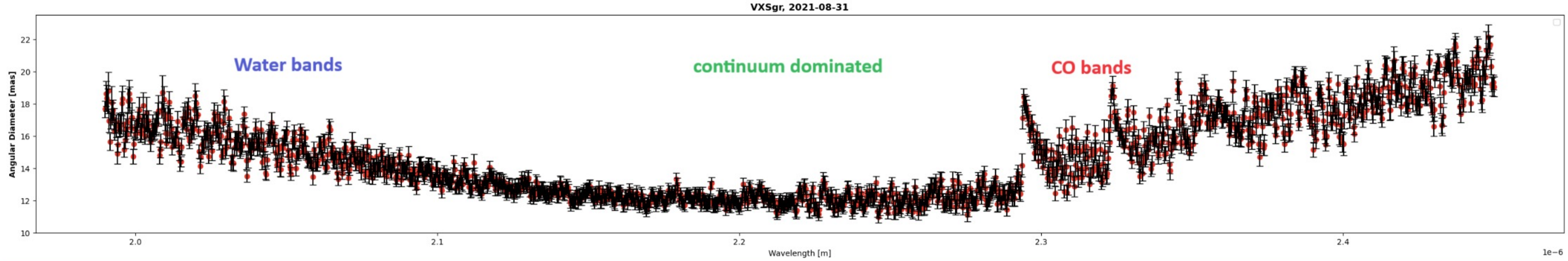
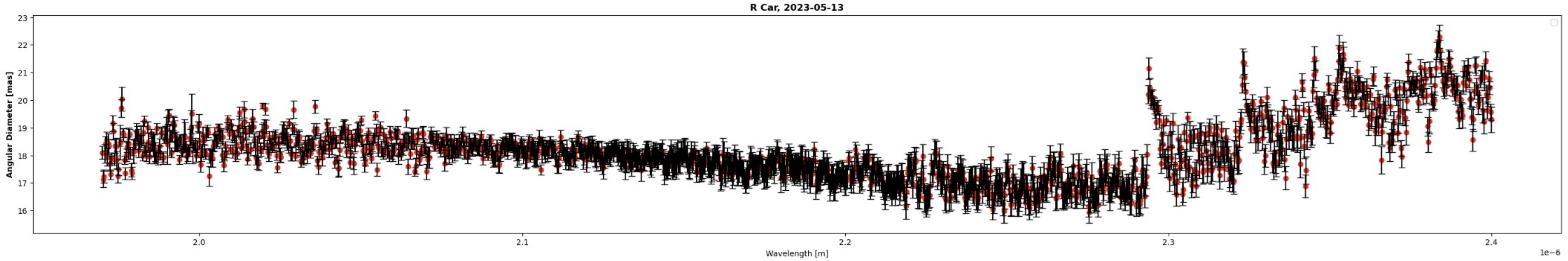
Determining the angular diameters

Diameters across the full spectrum





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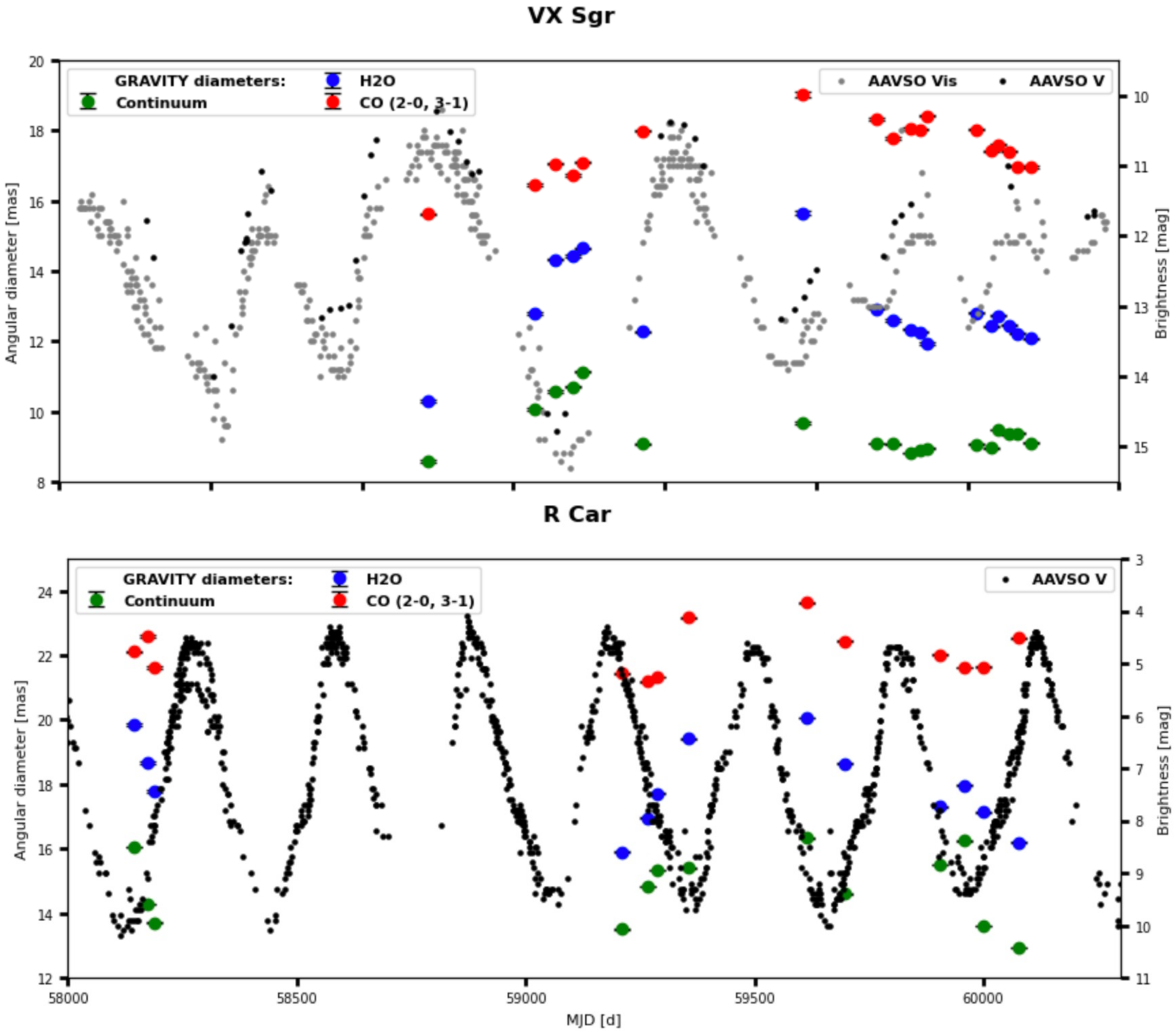
All epochs

Continuum and molecular layers are related to brigtness variability with a phase shift. First reported for R Peg by Wittkowki et al. 2017

- **Our results:** the continuum and molecular layers are indeed variable and related to the brightness variability.
- **R Car:** the continuum and molecular layers are regularly phase shifted to the brightness variability → phase diagram
- **VX Sgr**: very irregular variability, difficult overall phase analysis. However, a similar behavior can be observed during cycles.



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Phase shifts

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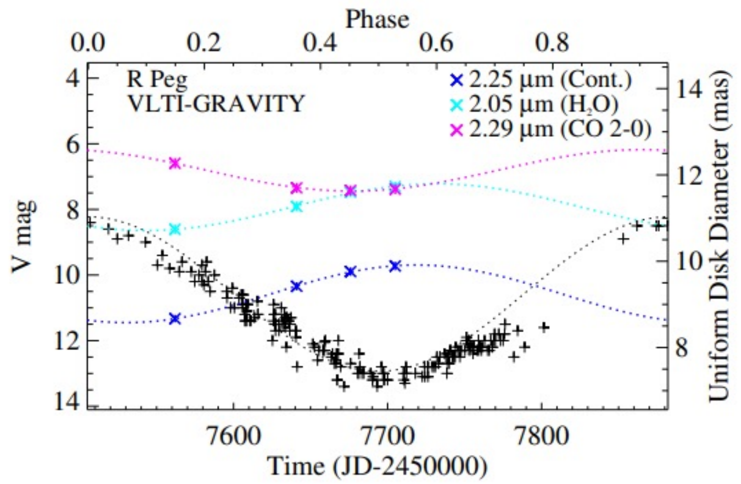

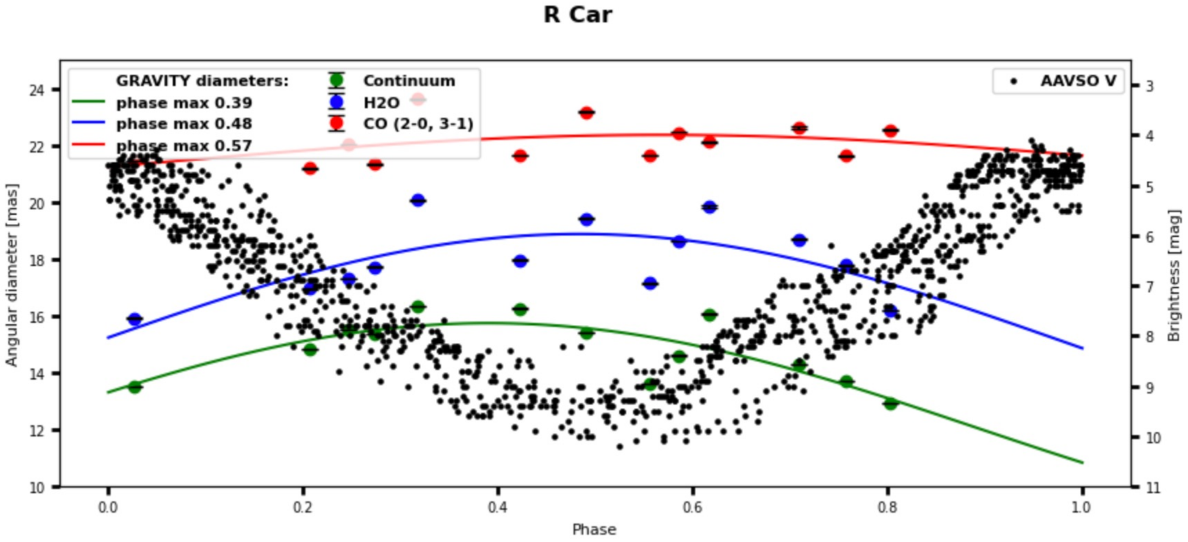

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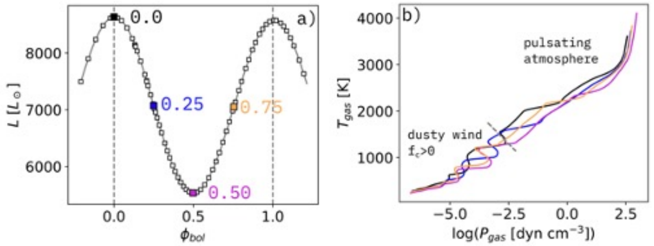


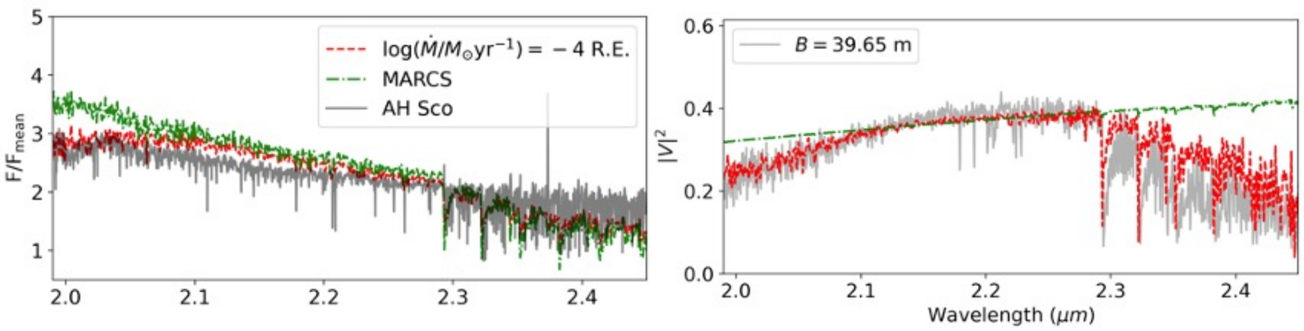
Comparison with 1D models

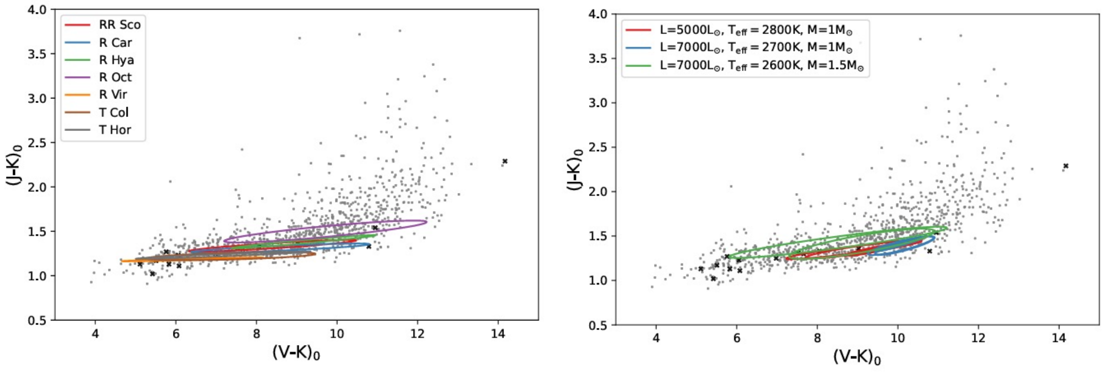
MARCS model atmospheres (Gustafsson 2008) with added wind (Gonzalez-Tora et al. 2023)

- Recently, Davies et al. 2021 and Gonzalez-Tora et al. 2023 were able to add the effects of the wind into the MARCS models.
- The new 1D models finally agree with the observations, for the first time for RSGs

DARWIN dynamical model atmospheres (Bladh et al. 2019, Höfner et al. 2022)

- Dynamical models, include self-consistent dust formation
- Model properties compatible with observations, extensive grid for AGBs
- Model series A: close parameters to R Car





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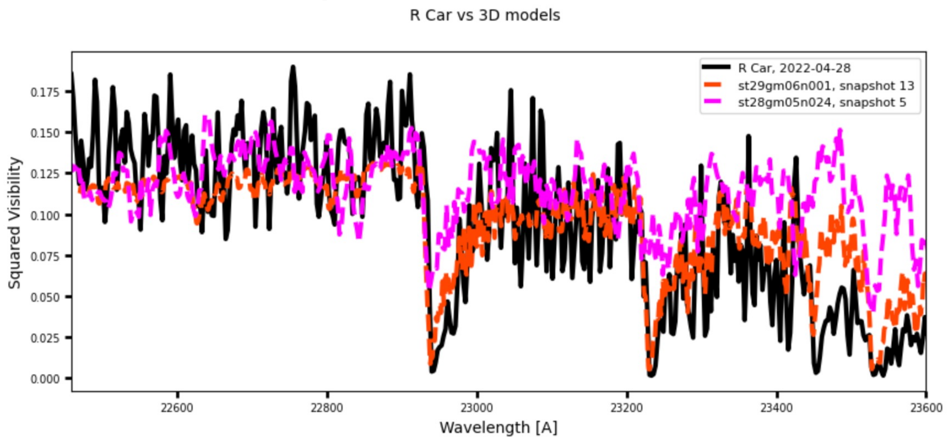
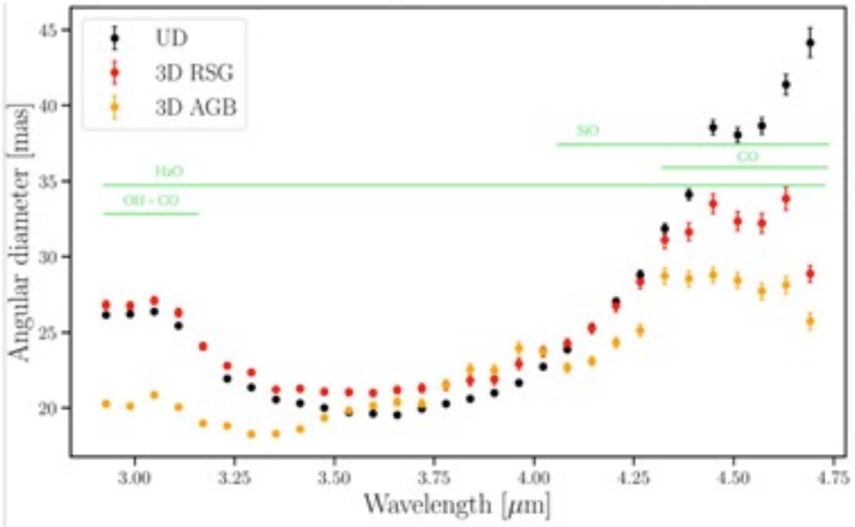
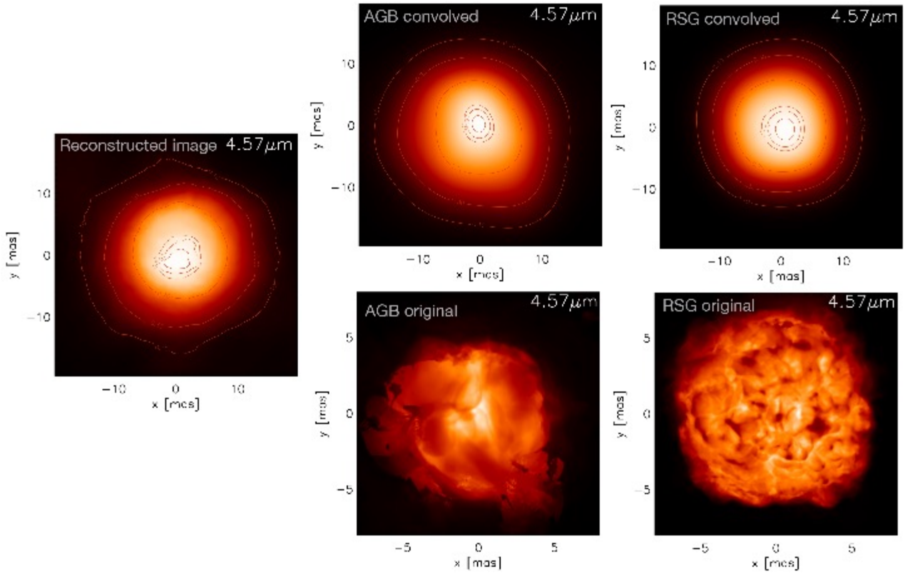
Comparison with 3D models

CO5BOLD 3D RHD simulations (Freytag et al. 2008, 2023), Optim3D (Chiavassa et al. 2009, 2024)

- „star-in-a-box" models, allows to model the surface features and atmospheric extension for AGBs.
- However, so far problems with reproducing observed features for red supergiants
- R Car: several suitable models, but some have a weak atmospheric extension







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Summary

Work in progress…

- AGB and RSGs have similar observed atmospheric extensions.
- Variability of near-IR continuum and H_2O/CO molecular layers is phase shifted to the brightness.
- Phase shift increases from the innermost layers (continuum) to the outermost layers (CO), by ~ 1 month → likely propagation of large-scale shock fronts (triggered by surface pulsation and convection)
- For most AGB stars, models including pulsation and convection can reproduce the observed properties. For more massive RSGs, the situation is less clear.
- New and better models are now available → more observations will help to further test and constrain the models
- Submitted proposal for new VLTI and ALMA observations

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Thank you!

Daniel Jadlovsky
daniel.jadlovsky@eso.org

@ESOAstronomy
@esoastronomy
@ESO
european-southern-observatory
@ESOobservatory

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