ALMA+VLTI imaging of cool evolved stars at high angular and spectral resolution

AGB stars and stellar pulsation workshop, Konkoly, 5th October 2026

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Main collaborators: *László Molnár, Andrea Chiavassa, Kateryna Kravchenko, Sussane Höfner, Bernd Freytag, Gemma González i Torà, Thomas Granzer, et al.*



Content

Unveiling the stellar atmospheres and mass-loss process using ALMA and VLTI

I. Mass-loss process of cool evolved stars

- Importance and physical properties

II. Optical and radio interferometry

- ALMA and VLTI

III. Pulsations and mass loss near the stellar surface

- Observations of AGB stars, signatures of mass loss

IV. Red supergiants

- Our VLTI-GRAVITY survey of red supergiants, *P-L, P-R*, and mass-loss relations

V. Multiplicity (if there is time left)

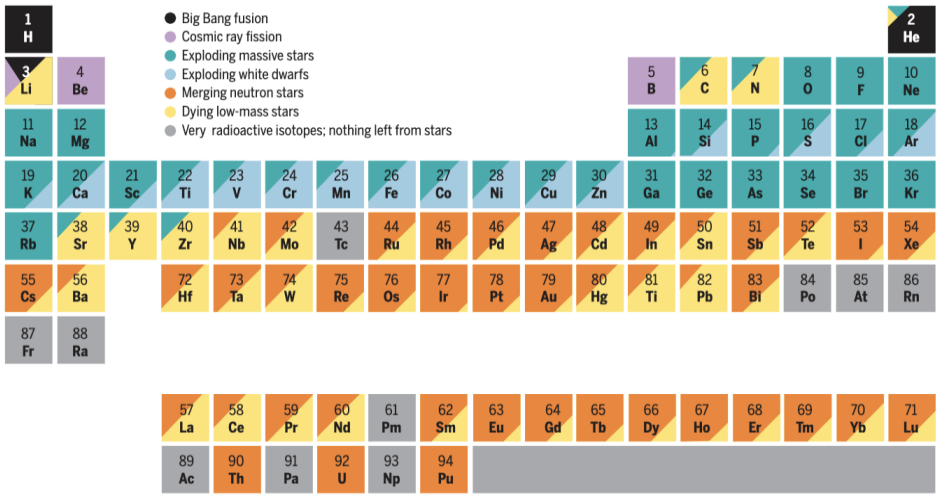
- Hidden companions of cool evolved stars

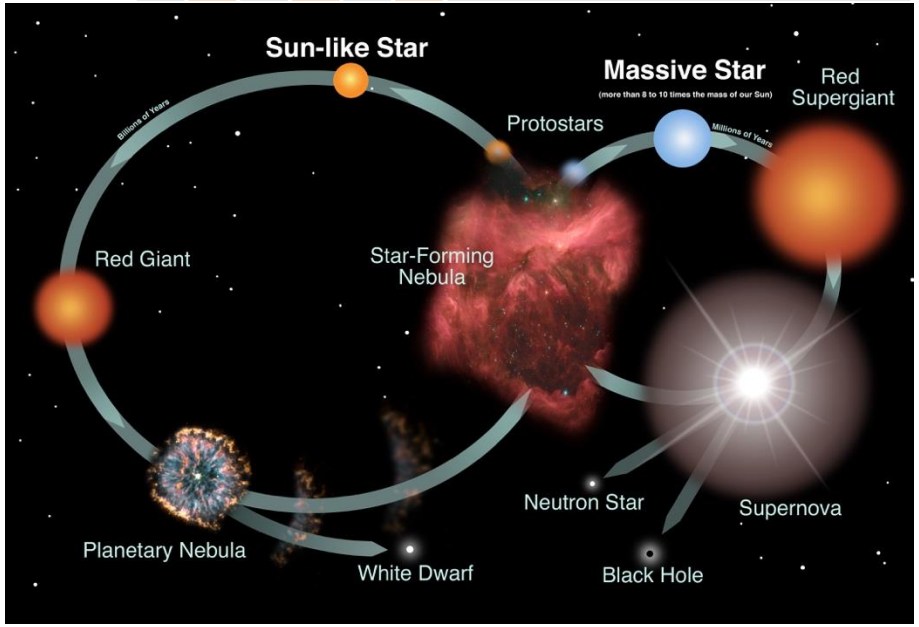
Mass-loss process

Red giants and supergiants

Why should we care?

- **red supergiants (RSGs):** massive stars ($> 8\,M_\odot$) → nuclear burning up to iron (blueward evolution for higher mass loss) → supernova (SN) → neutron star/black hole
- **asymptotic giant branch stars** (**AGB,** $< 8\,M_\odot$): → degenerate CO core → planetary nebula + white dwarf
- high mass-loss rates, up to 10^{-6}–$10^{-4}\,M_\odot yr^{-1}$
- **Importance:**
  - the crucial extreme of stellar evolution, major sources of chemical enrichment and dust production in galaxies
  - mass loss shapes the circumstellar medium (CSM) and the properties of subsequent SNe
  - due to their high *L*, they are also important for the distance ladder (new distance determinations using TRGB, JAGB stars, RSGs as SN progenitors, e.g., Csörnyei+2023, Lee+2024)



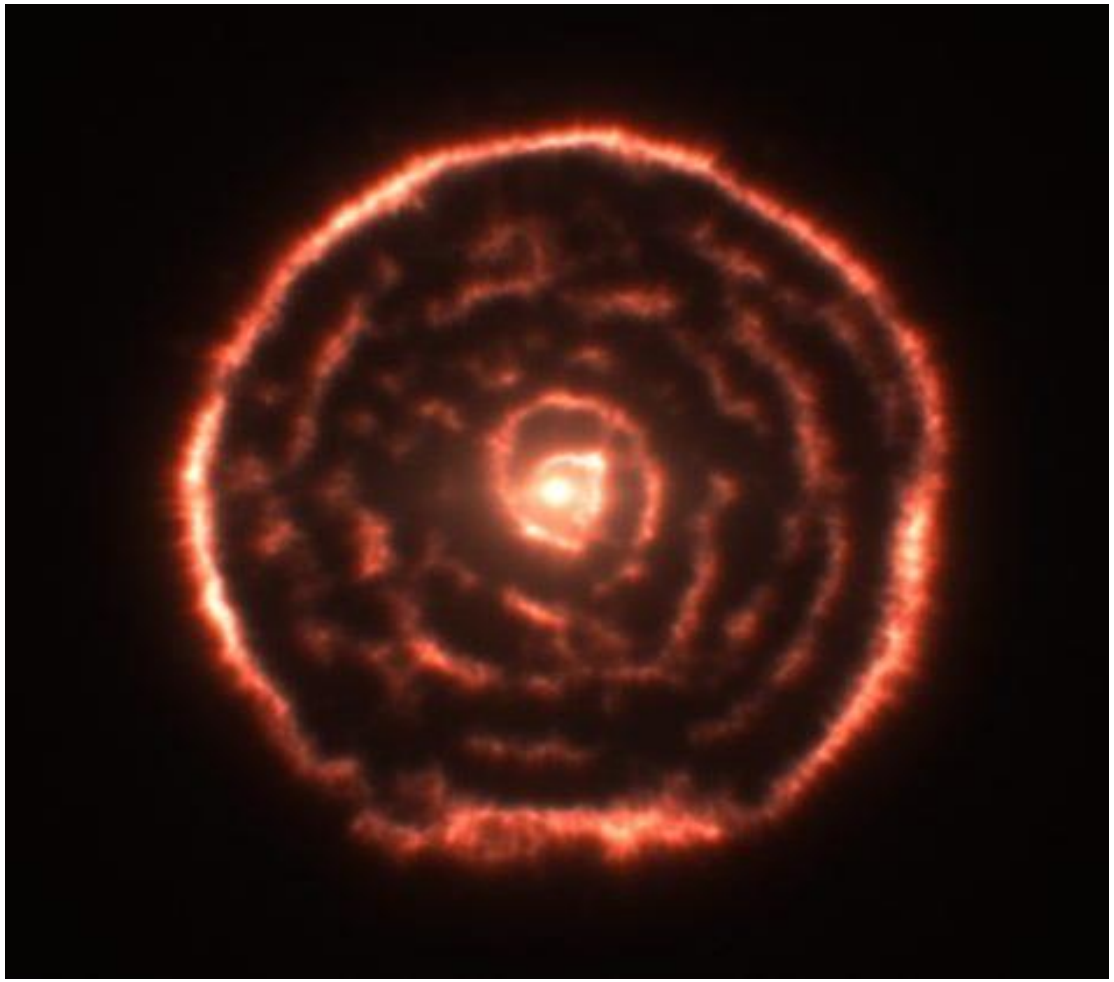


Sources: Johnson2019, de Jaeger+2020, Freedman+2021

Mass-loss process

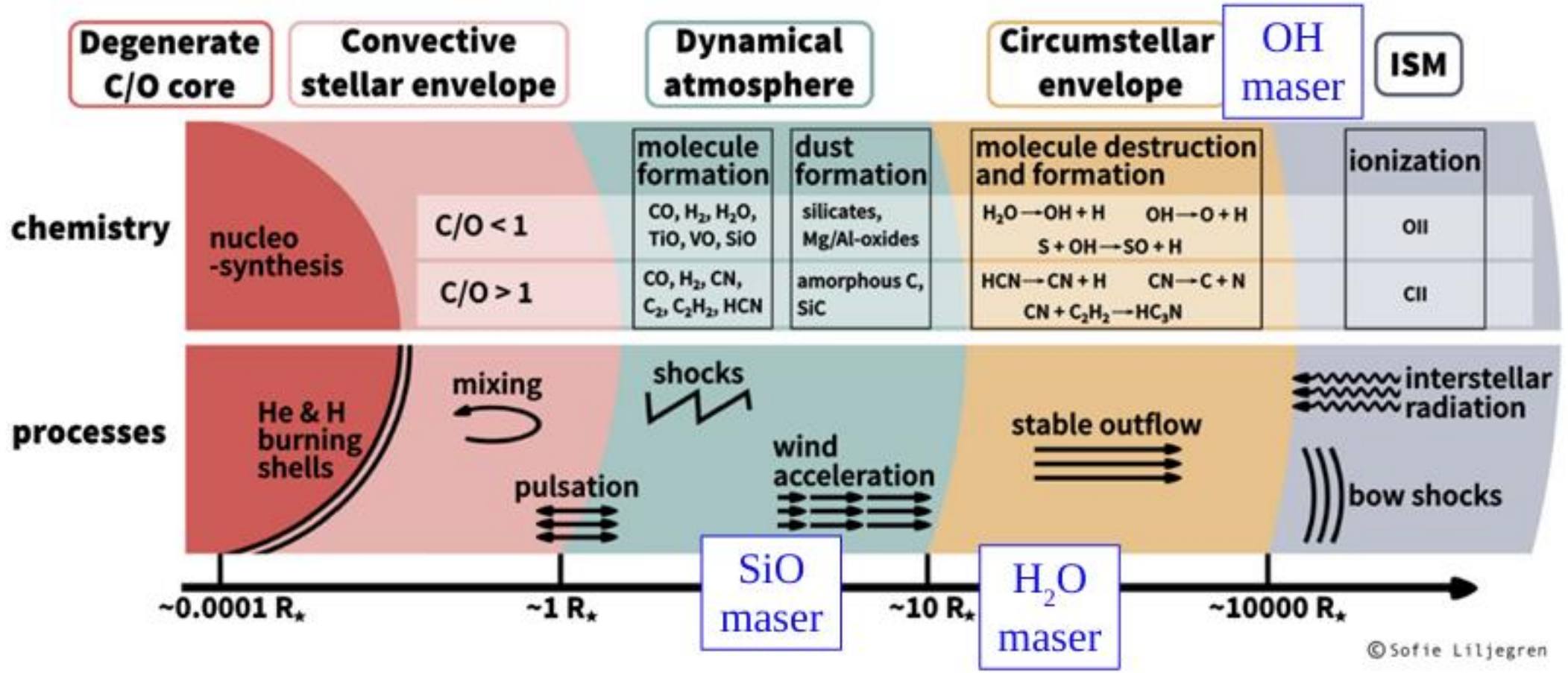
So far, no model is able to fully explain the observed mass-loss rates for all AGB and RSG stars

- **AGB stars:**
  - models: dust-driven wind + levitation of material by pulsations is likely sufficient to explain the observed mass-loss rates for the Mira-type AGB stars (e.g., Freytag & Höfner 2023)
- **red supergiants:**
  - levitation of material by pulsations is less effective → another mechanism needed?
  - episodic mass-loss events? (e.g., Betelgeuse, Dupree+2022, Jadlovský+2024)
  - „coronal“ mass ejections due to magnetic fields? (e.g., Humphreys+2022, Vlemmings+2026)
  - radiative pressure on molecules? (Josselin+2007)
  - red supergiants not pulsating? (Pilates+2024)



Binary interaction may also play a significant role, R Scl, Source: ALMA, Maercker+2012

AGB stars


Degenerate C/O core
Convective stellar envelope
Dynamical atmosphere
Circumstellar envelope
OH maser
ISM
chemistry
nucleo -synthesis
C/O < 1
C/O > 1
molecule formation
CO, H2, H2O, TiO, VO, SiO
CO, H2, CN, C2, C2H2, HCN
dust formation
silicates, Mg/Al-oxides
amorphous C, SiC
molecule destruction and formation
H2O → OH + H
OH → O + H
S + OH → SO + H
HCN → CN + H
CN → C + N
CN + C2H2 → HC3N
ionization
OII
CII
processes
He & H burning shells
mixing
pulsation
shocks
wind acceleration
stable outflow
interstellar radiation
bow shocks
SiO maser
H2O maser
~0.0001 R★
~1 R★
~10 R★
~10000 R★
©Sofie Liljegren

Optical and radio interferometry

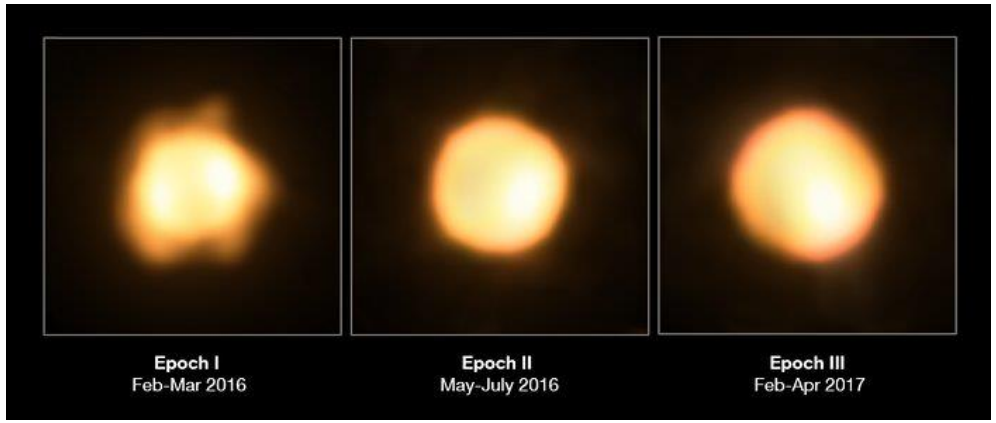
Motivation for observations at high angular resolution

Despite its importance, mass-loss process for cool evolved stars remains poorly understood.

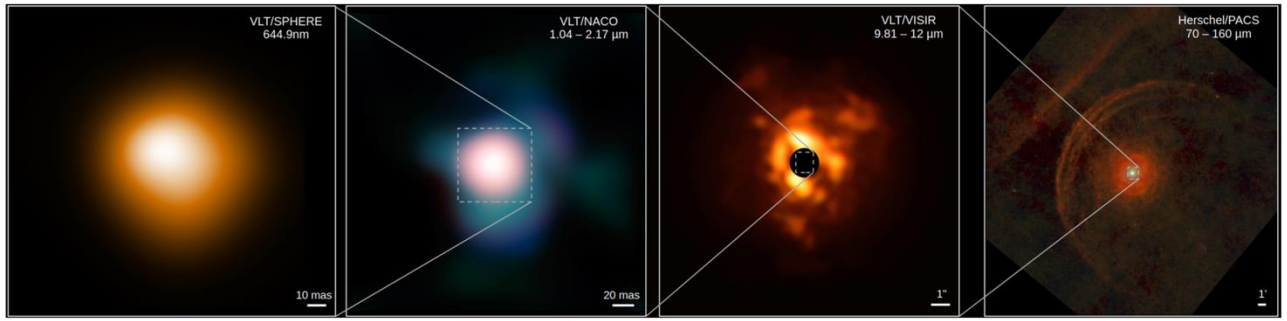
*Using the unprecedented angular resolution of VLTI (up to ~1 mas), we can **spatially resolve the atmospheres** of evolved giant and supergiant stars!*

→ *unveiling the complex surface variability (pulsation, convection) and its connection to the **wind launching mechanism***

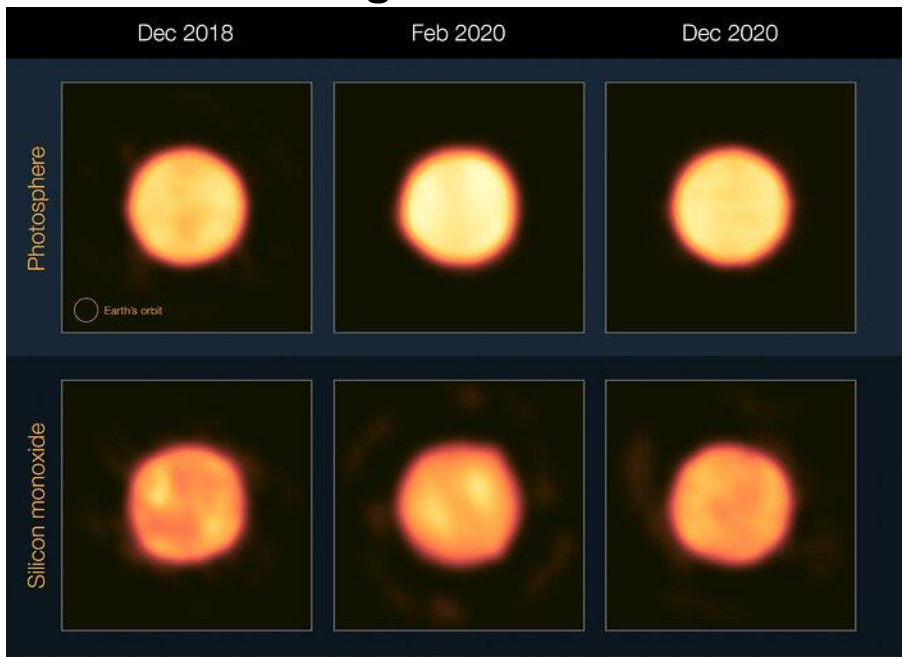
Other stars (e.g., V766 Cen)



Betelgeuse



→ Betelgeuse with VLTI



Sources: ESO, Betelgeuse: Drevon+2024, Dupree+2025, V766 Cen: Wittkowski+2017

Very Large Telescope Interferometer (VLTI)

The most advanced ground-based optical interferometer in the world

- optical interferometer, operates in near- and mid-infrared bands (~1.5 - 13 μm)
- four 8.2-m Unit Telescopes (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 angular resolution from 1 mas (1.6 μm) to 10 mas (13 μm)
- astrometric precision up to ~10-50 μas!
- instruments: PIONIER (*H*), GRAVITY (*K*), MATISSE (*LMN*) + visitor ins. ASGARD (*YJH*)
- other current facilities: CHARA (USA)



Paranal Observatory, 2635 m altitude, Chile

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Laser trial run kickstarts new era of interferometry

10 November 2025

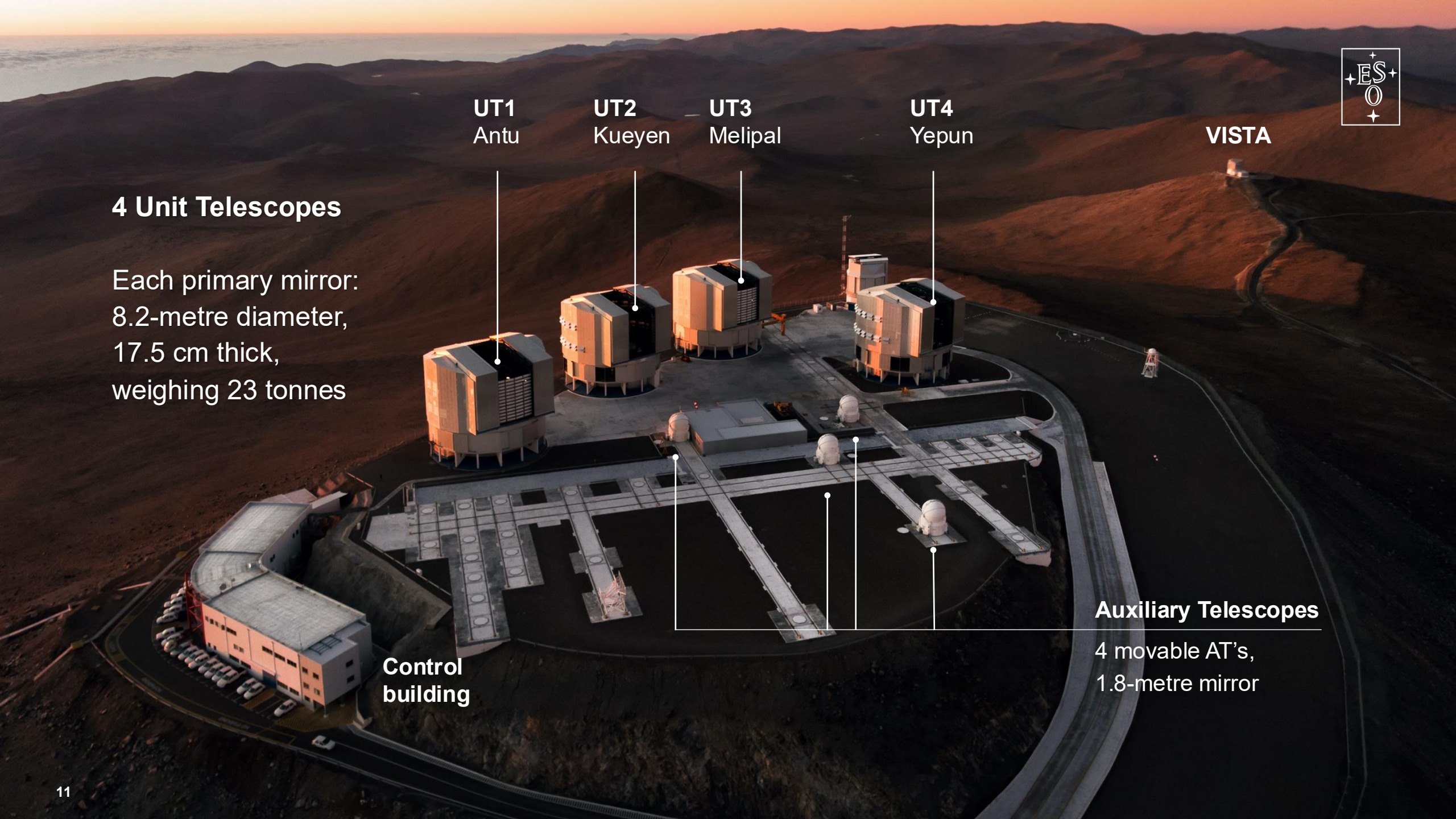


Four lasers for the VLTI (Credit: A. Berdeu/ESO)

Last week, four lasers were projected into the skies above the European Southern Observatory's (ESO's) Paranal site in Chile. The lasers are each used to create an artificial star, which astronomers use to measure and then correct the blur caused by Earth's atmosphere. The striking launch of these lasers, one from each of the eight-metre telescopes at Paranal, is a significant milestone of the GRAVITY+ project — a large and complex upgrade to ESO's Very Large Telescope Interferometer (VLTI). GRAVITY+ unlocks a greater observing power and a much wider sky coverage for the VLTI than previously possible.

"*This is a very important milestone for a facility that is completely unique in the world*," says Antoine Mérand, an ESO astronomer and VLTI Programme Scientist.

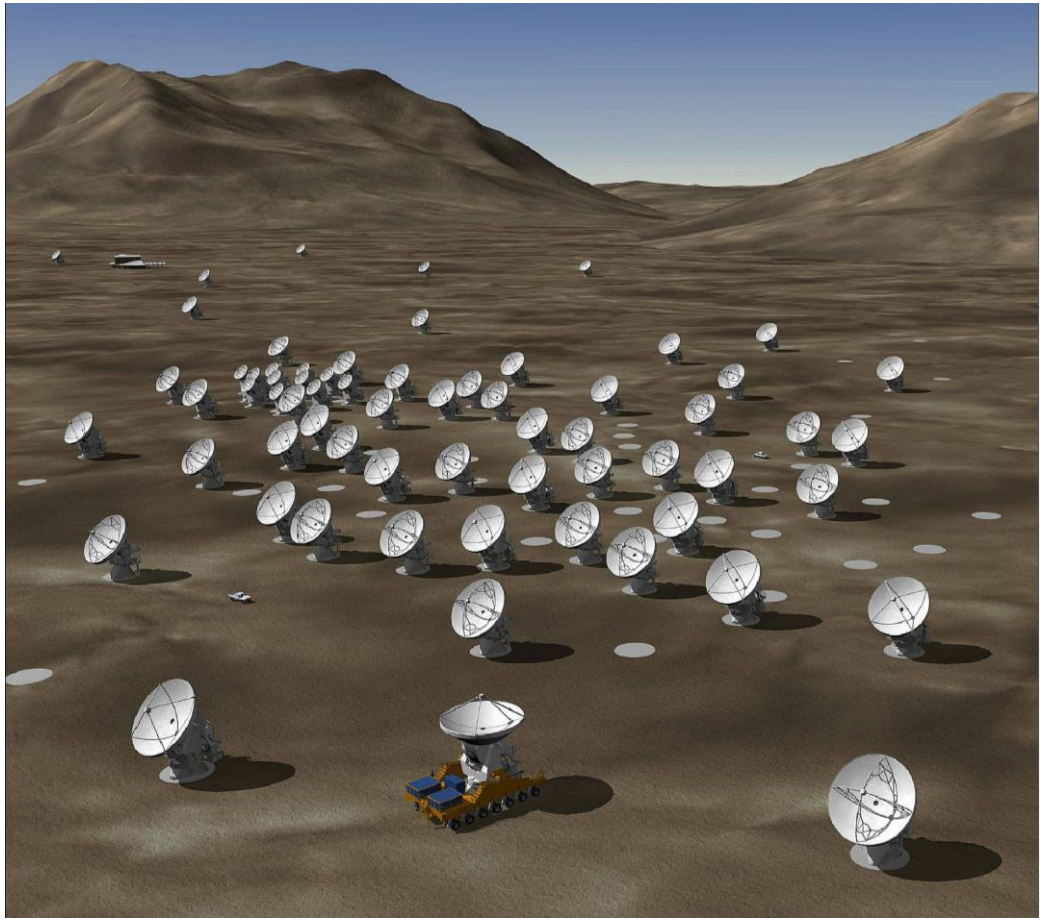
Paranal Observatory, 2635 m altitude, Chile


UT1
Antu
UT2
Kueyen
UT3
Melipal
UT4
Yepun
VISTA
4 Unit Telescopes
Each primary mirror:
8.2-metre diameter,
17.5 cm thick,
weighing 23 tonnes
Auxiliary Telescopes
4 movable AT's,
1.8-metre mirror
Control
building

Atacama Large (sub)mm Array (ALMA)

Unprecedented spatial and spectral resolution for millimeter-wave astronomy

- interferometry (sub)mm wavelengths (from 30 GHz up to 1 THz), the largest (sub)mm telescope in the world
- fifty 12-m antennas and an additional array of four 12m and twelve 7-m antennas
- 12m telescopes can be relocated for the max baseline of 16km, max resolution from ~100 mas (Band 1) to ~5 mas at the highest frequency (Band 10)
- upcoming ALMA sensitivity upgrade
- part of Event Horizon Telescope (EHT), an Earth-sized virtual telescope, achieving resolution up to to ~20 μas!



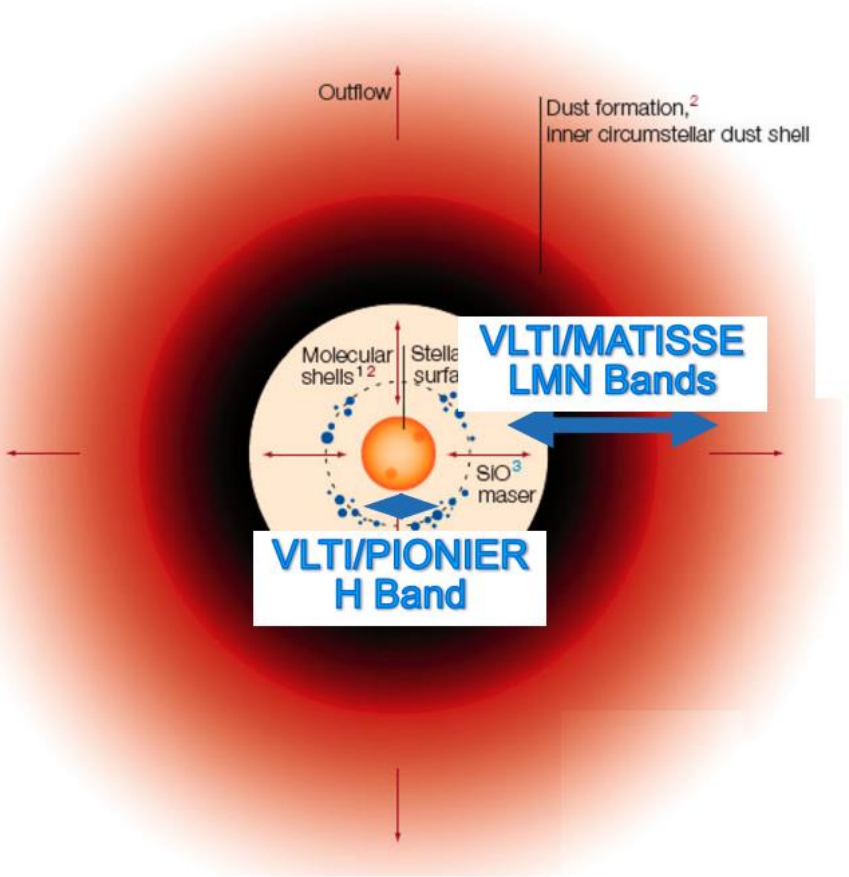
Chajnantor plateau, 5000 m altitude, Chile

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)
- **more extended circumstellar environment:**
  - ALMA (sub-mm and mm)

    + the inner regions of the atmosphere → SiO masers and the continuum



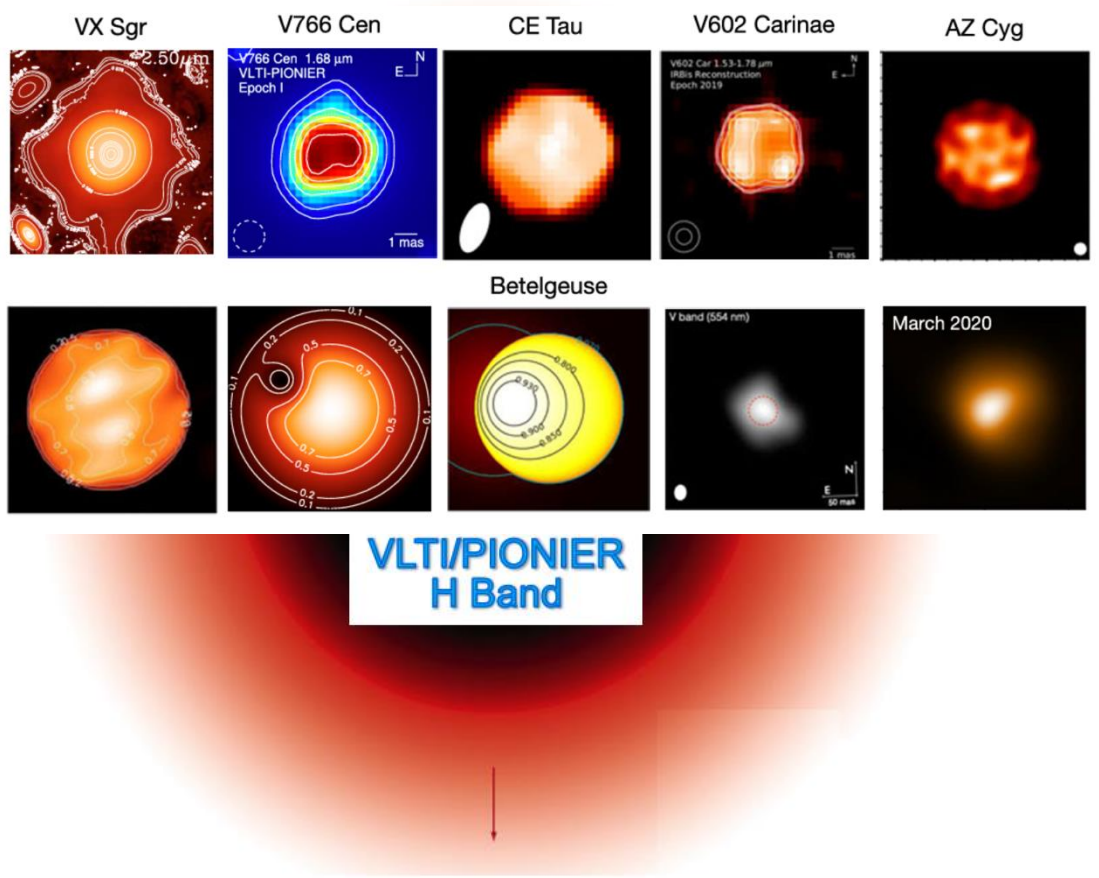
Wittkowski+2020, VX Sgr – Chiavassa+2022, ATOMIUM – Decin+2020

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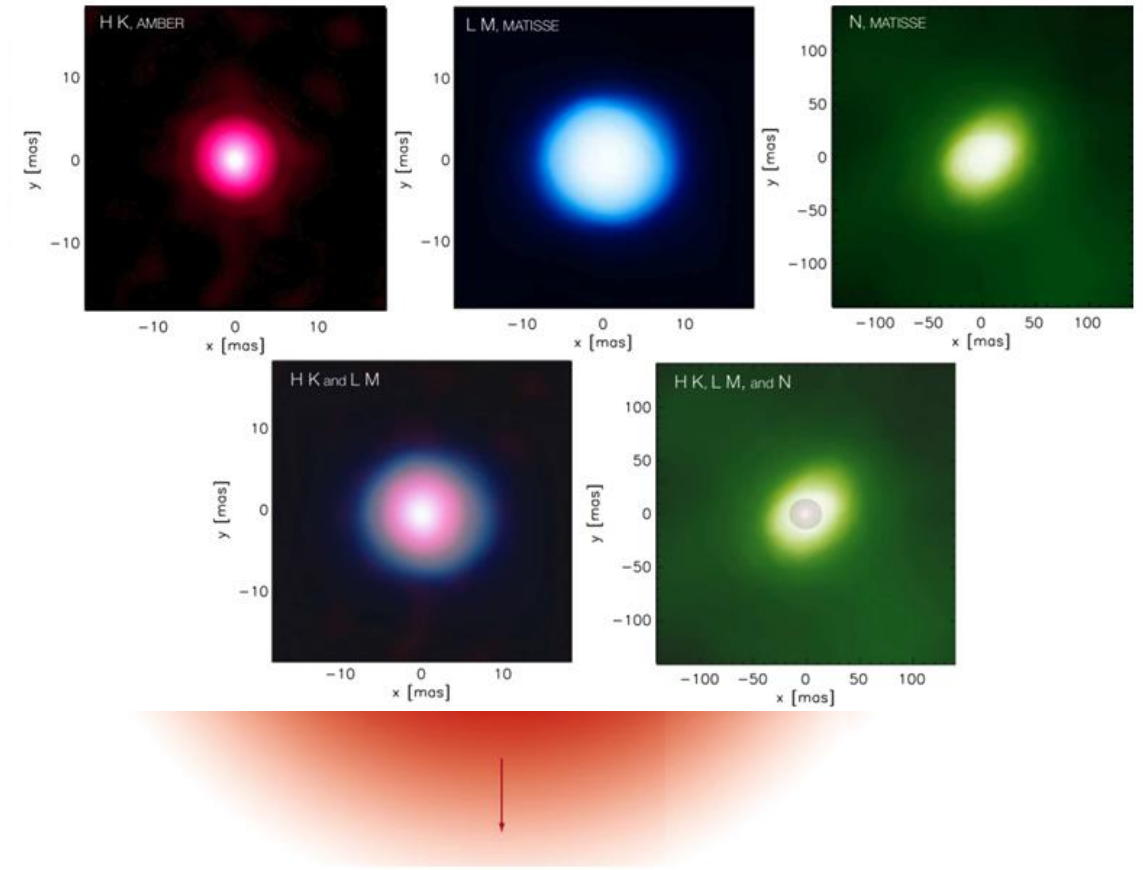
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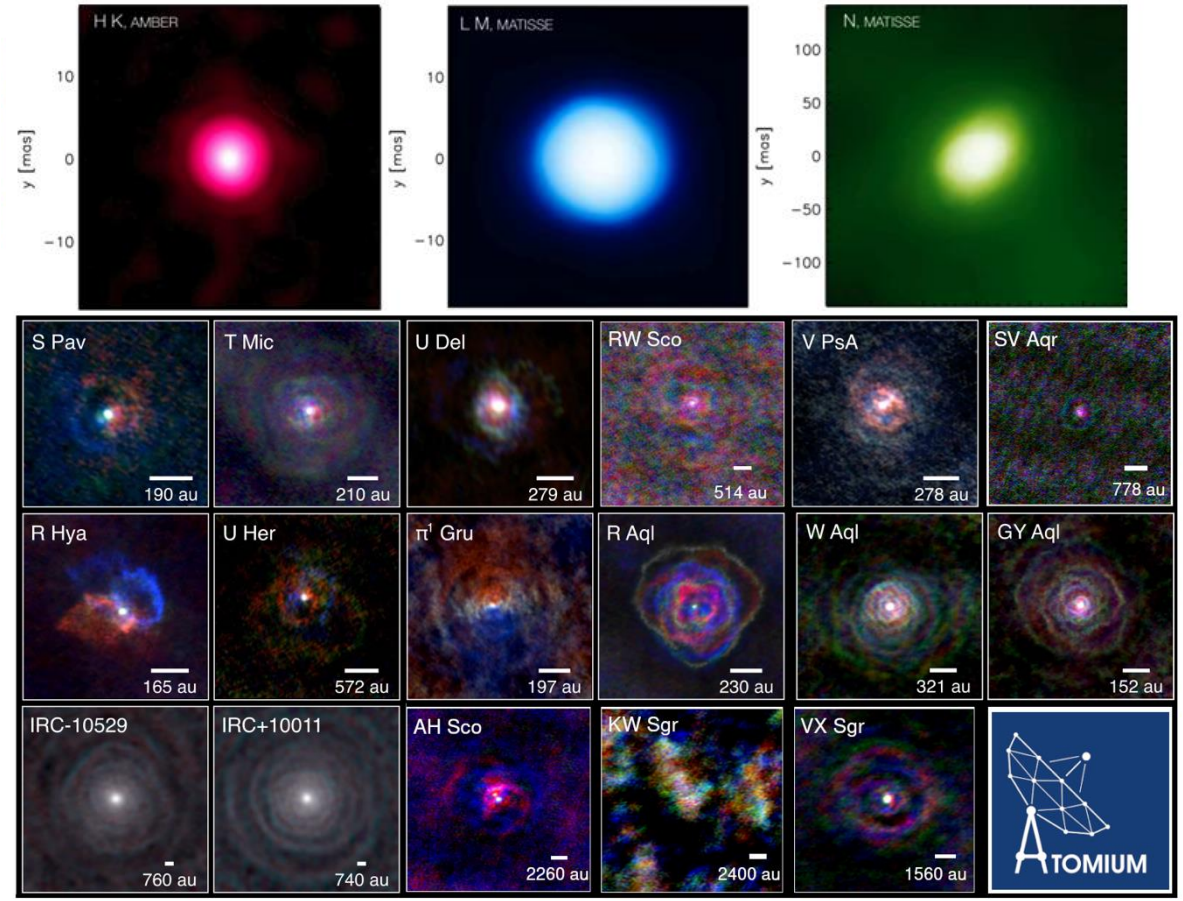
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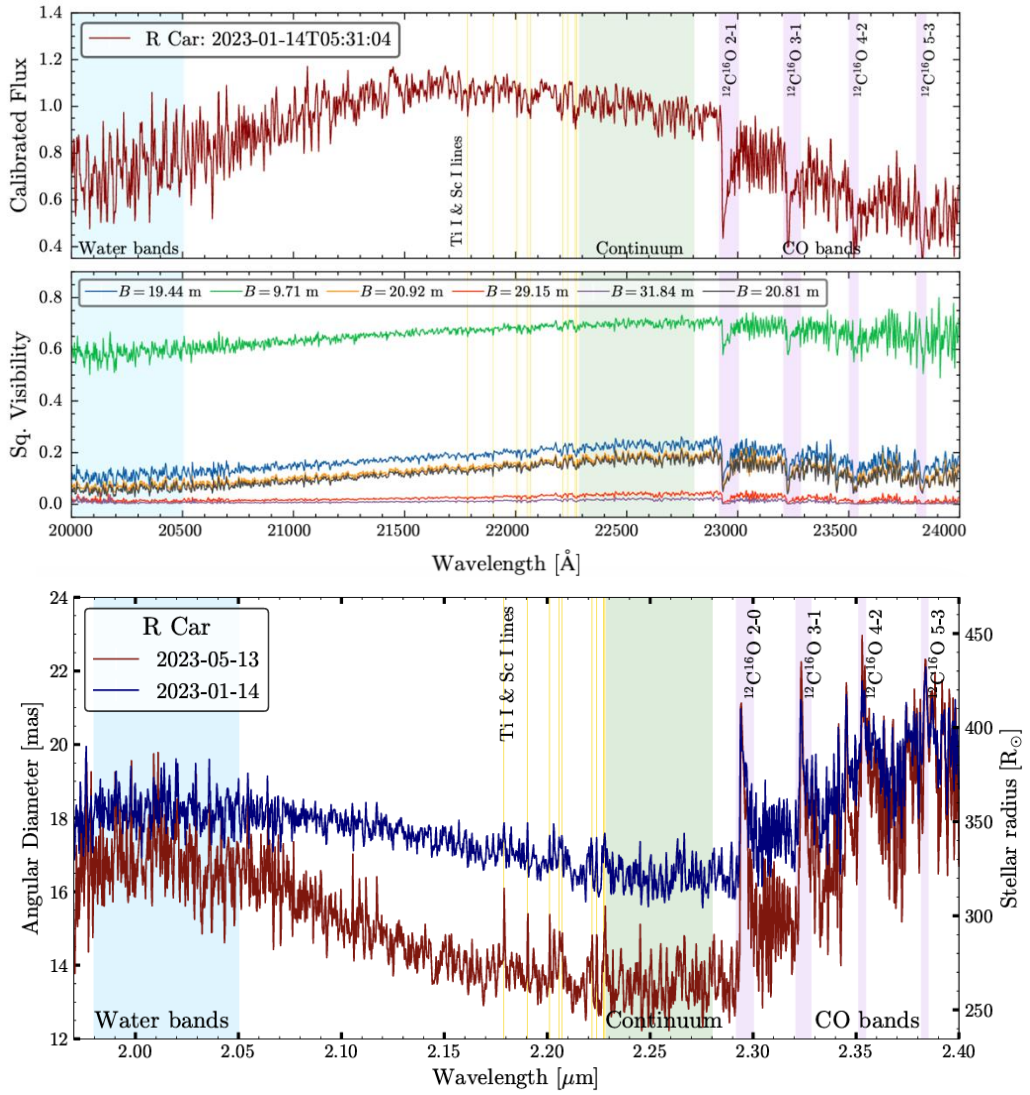
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Observational signatures of pulsations and mass loss (near the stellar surface)

Light curve and radius variations

Interferometry allows us to spatially resolve AGB stars

- Mira-type AGB stars show regular brightness variations, with amplitudes up to a few ~ mag (visual photometry available for nearby targets)
- due to their large angular diameters, optical interferometry allows us to resolve their surface and **measure diameter variations**
- observations show the anticorrelation of the photospheric radius (near-IR continuum) and *V*-band light curve (**max *R* near maximum brightness** for O-rich Miras) → brightness variations primarily caused by $T_{\rm eff}$ variations (and related formation/destruction of molecules)
- other related results: VLTI – Wittkowski+2017, PTI - Thomson+2002, Baylis-Aguirre+2024, also see H. Prager's talk!

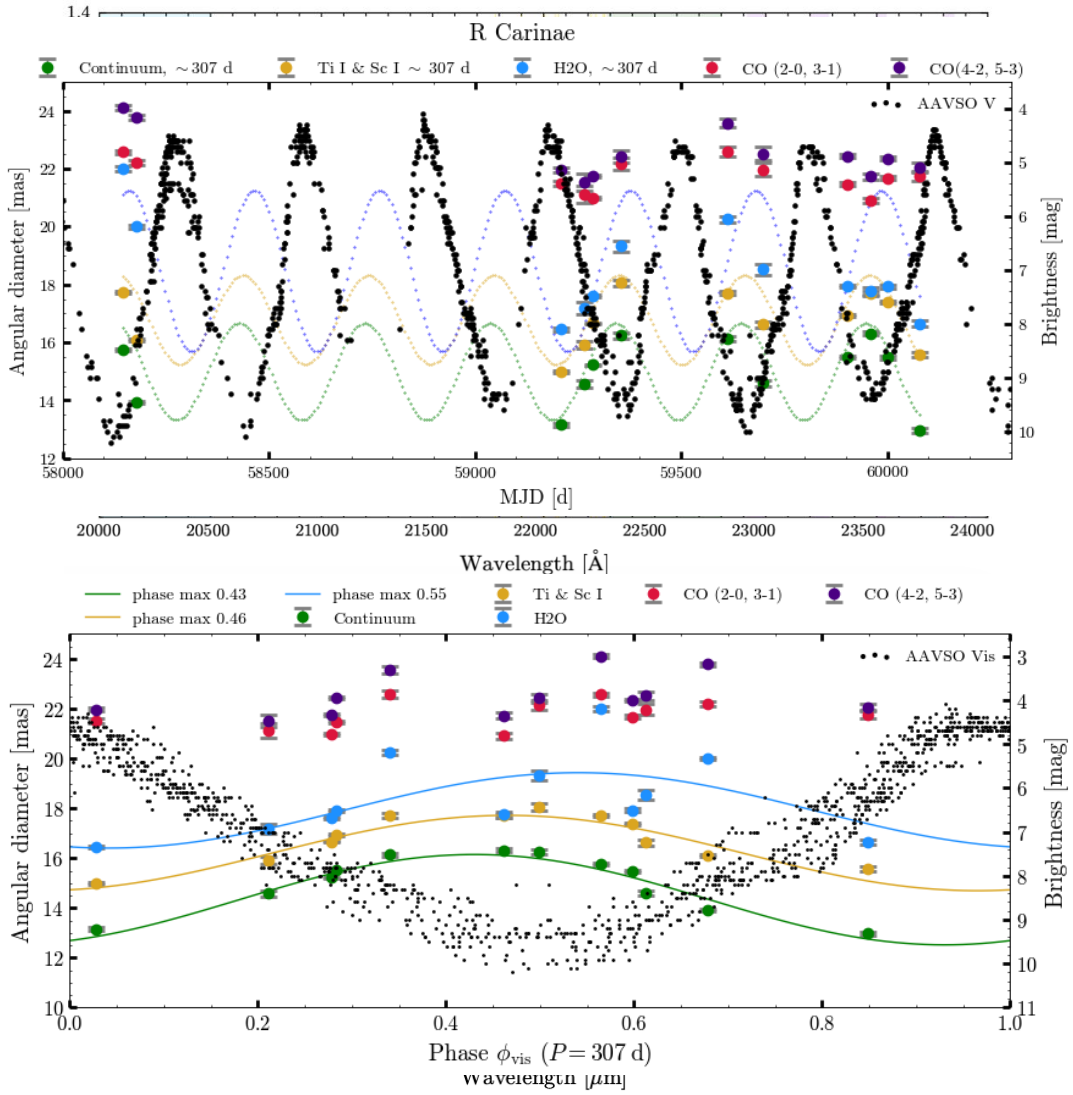


R Car: Jadlovský+2026a. First: flux and visibility (VLTI), angular diameter (min/max). Second: diameter variations vs time and phased.

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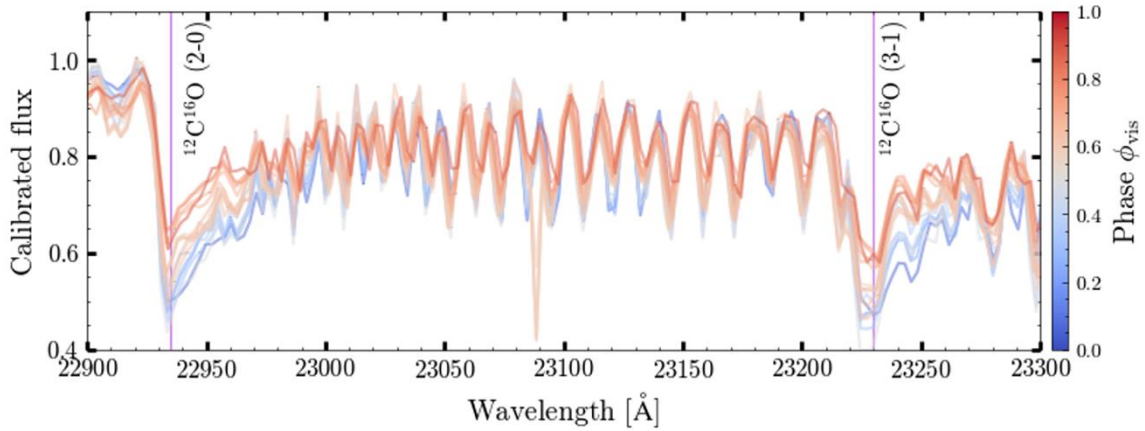


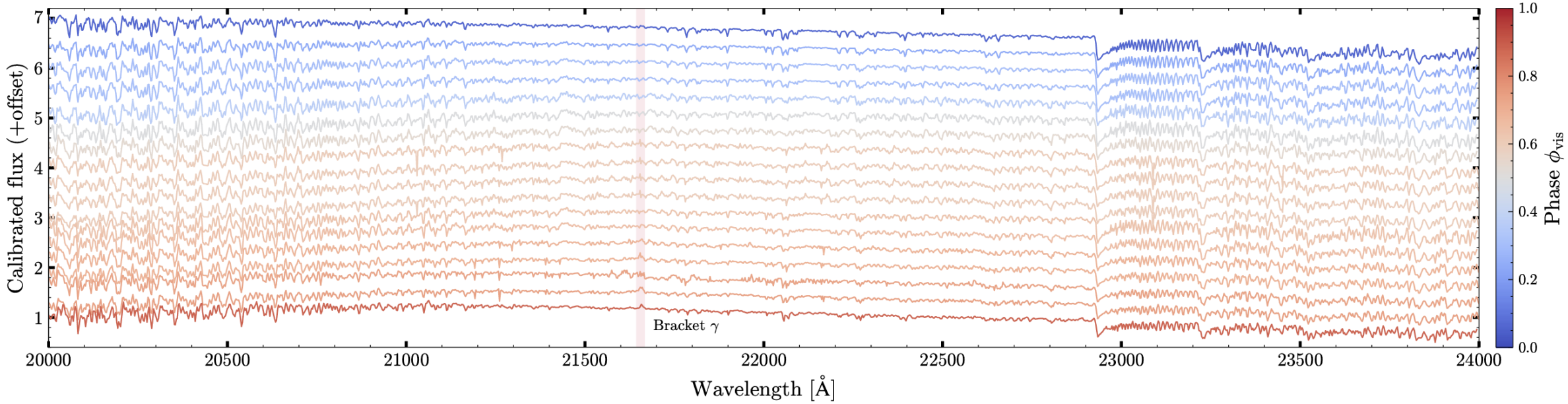
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Spectroscopic variability

Molecular opacity depends on the pulsation phase

- stellar pulsations cause $T_{\rm eff}$ variability
- the CO absorption is strongest during/after the brightness maximum ($\phi_{\rm vis}$~0), while it is weakest for H2O → opposite situation for the brightness minimum ($\phi_{\rm vis}$~0.5)





R Car, first: flux variability (Jadlovský+2026a)

Comparison to red supergiants

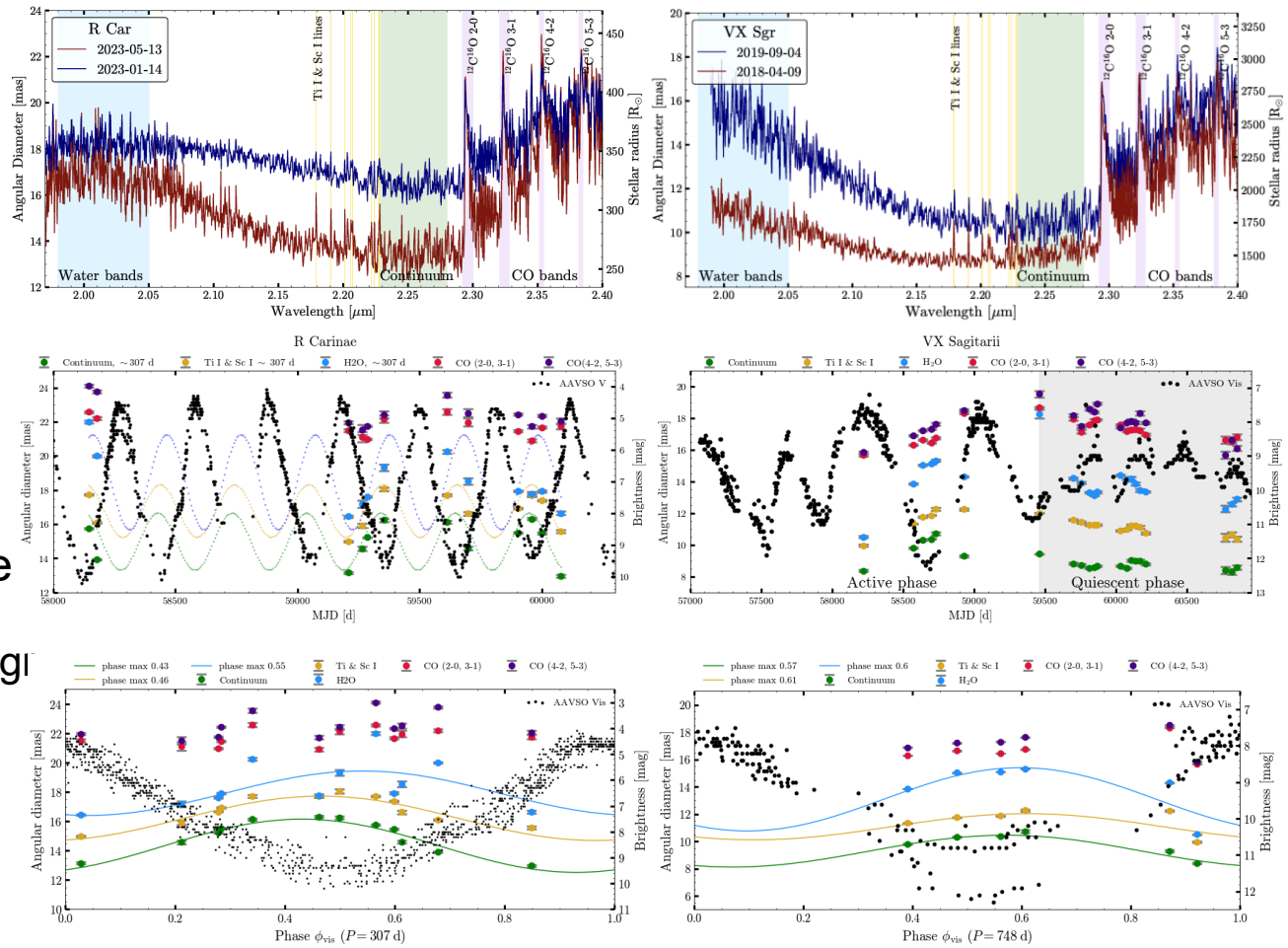
Jadlovský, D., et al., 2026, A&A, 711, A259

- comparison of pulsation properties of a Mira and a RSG star
- anticorrelation of the photospheric radius and *V*-band light curve (max *R* at Φ_{Vis}~0.5)
- **R Car** (Mira): regular fundamental mode (FM) pulsations (~ 13% of *R*) → stable mass loss
- **VX Sgr** (RSG): FM pulsations in the active cycle, first overtone (1O) in the quiescent cycle
  - an extreme **mass-loss event around 2020:** VX Sgr may have temporarily become **the largest star in our Galaxy** (1798 ± 127 $R_\odot$), followed by expansion of molecular layers (2021)
- Do RSGs drive mass loss only episodically?

VLTI-GRAVITY measurements of cool evolved stars

II. Pulsation properties and mass-loss process of the Mira star R Car and the red supergiant VX Sgr

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Upper: angular diameter vs wavelength (min/max), middle: diameter variations vs time, lower: phased diagram, last: a schematic pulsation diagram

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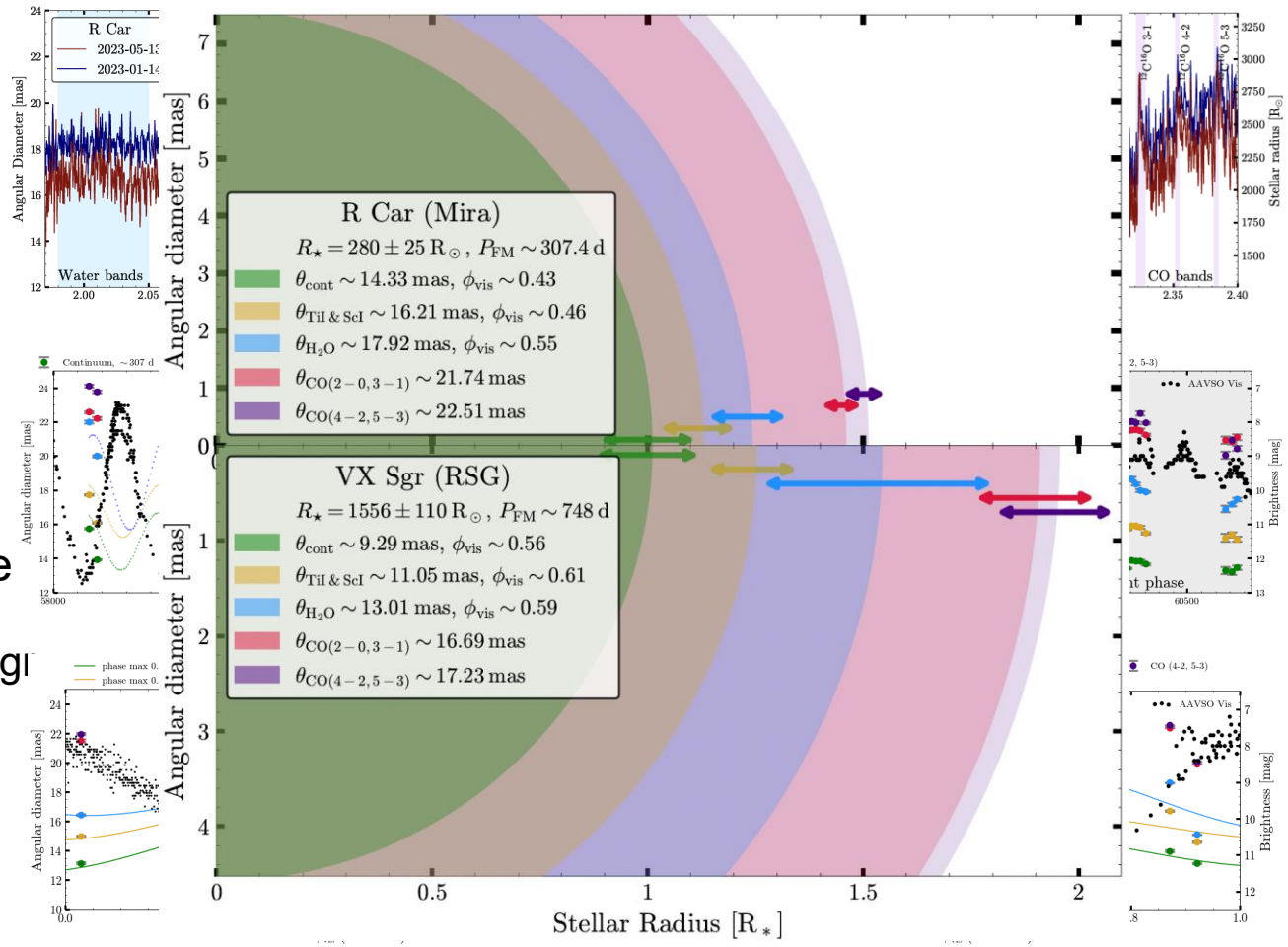
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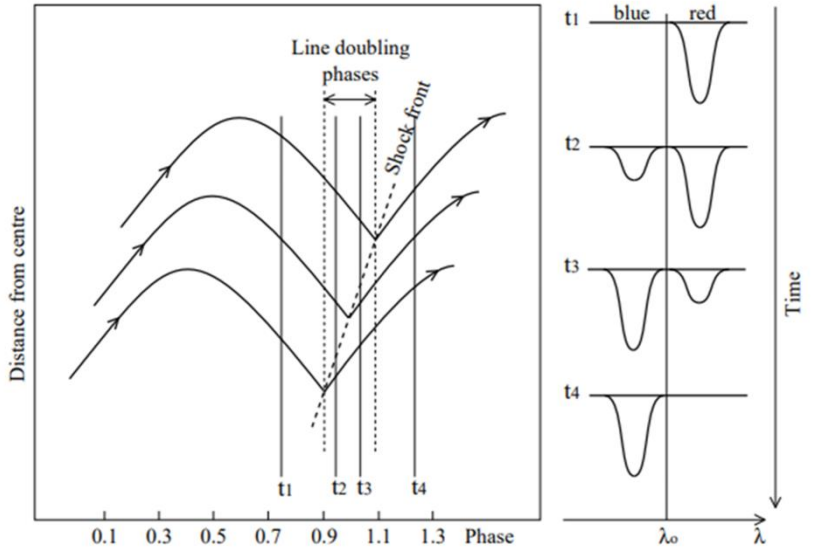


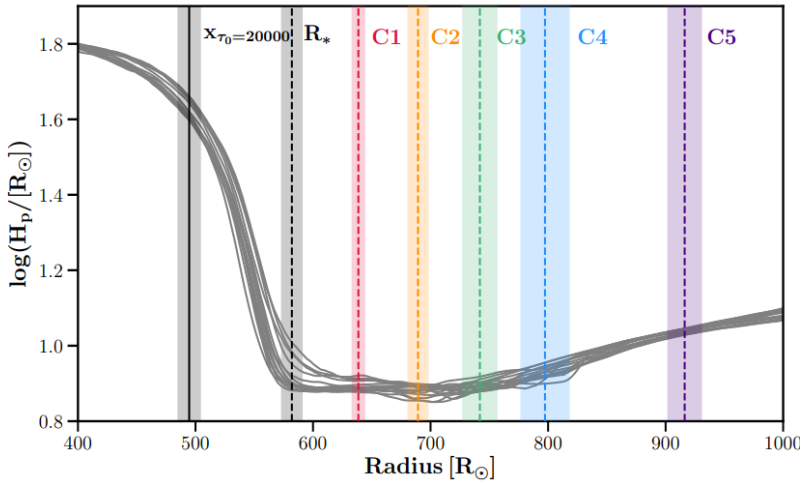
Upper: angular diameter vs wavelength (min/max), middle: diameter variations vs time, lower: phased diagram, last: a schematic pulsation diagram

Line-doubling due to shocks

High-resolution spectra reveal line profile variations

- spectra of some Miras show line-doubling near brightness maxima, with a **blue-shifted velocity** component appearing (towards us)
- **Tomography** (e.g., Alvarez+2000, Kravchenko+2018): spectral lines forming at different optical depths → propagation of shocks through different layers of the atmosphere, blue-shifted component propagates from the innermost layer
- evidence of new **rising material** appearing each pulsation cycle → allows us to study atmospheric dynamics, interplay between pulsation and convection, and mass loss
- also applied to Betelgeuse (Kravchenko+2021, Jadlovský+2024)



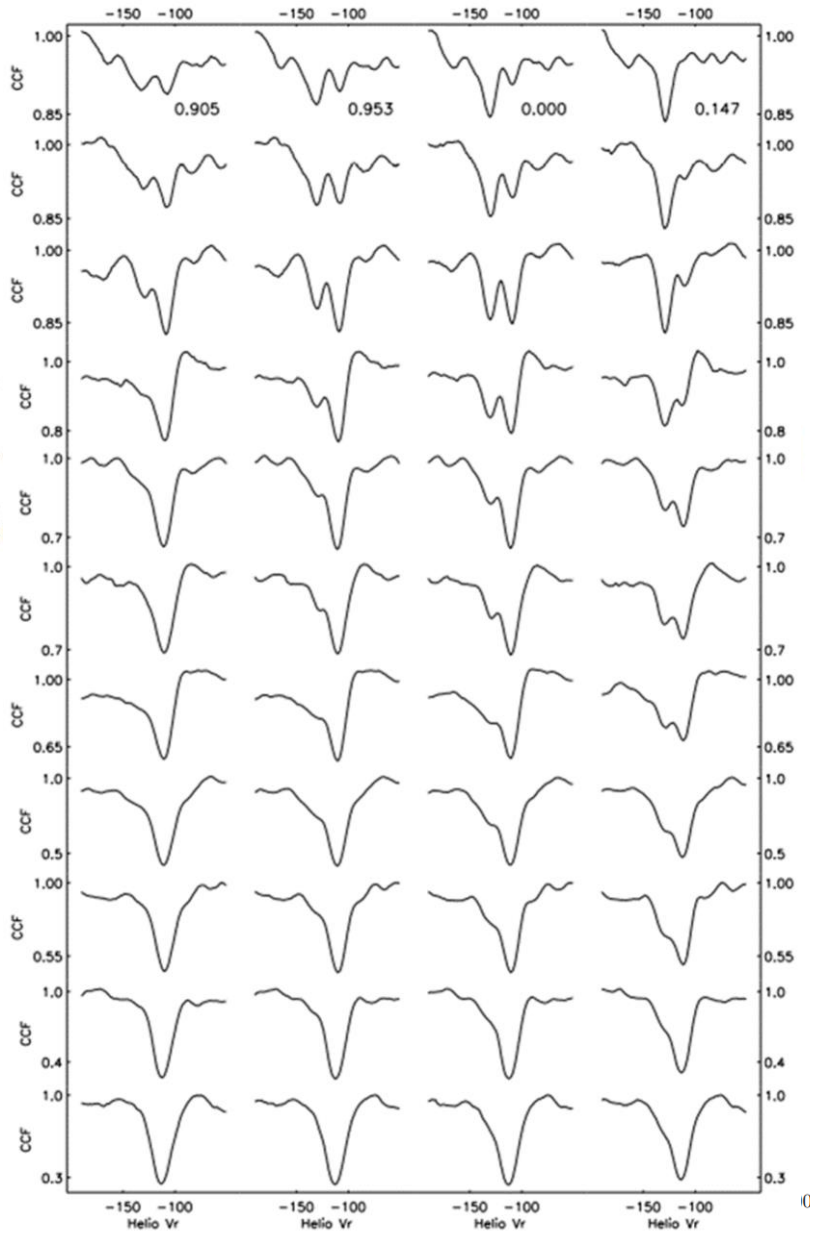


The method first introduced in a series of papers by Alvarez et al. (2000, 2001a,b), validated by Kravchenko et al. (2018, 2019, 2020). Last image: RT Cyg.

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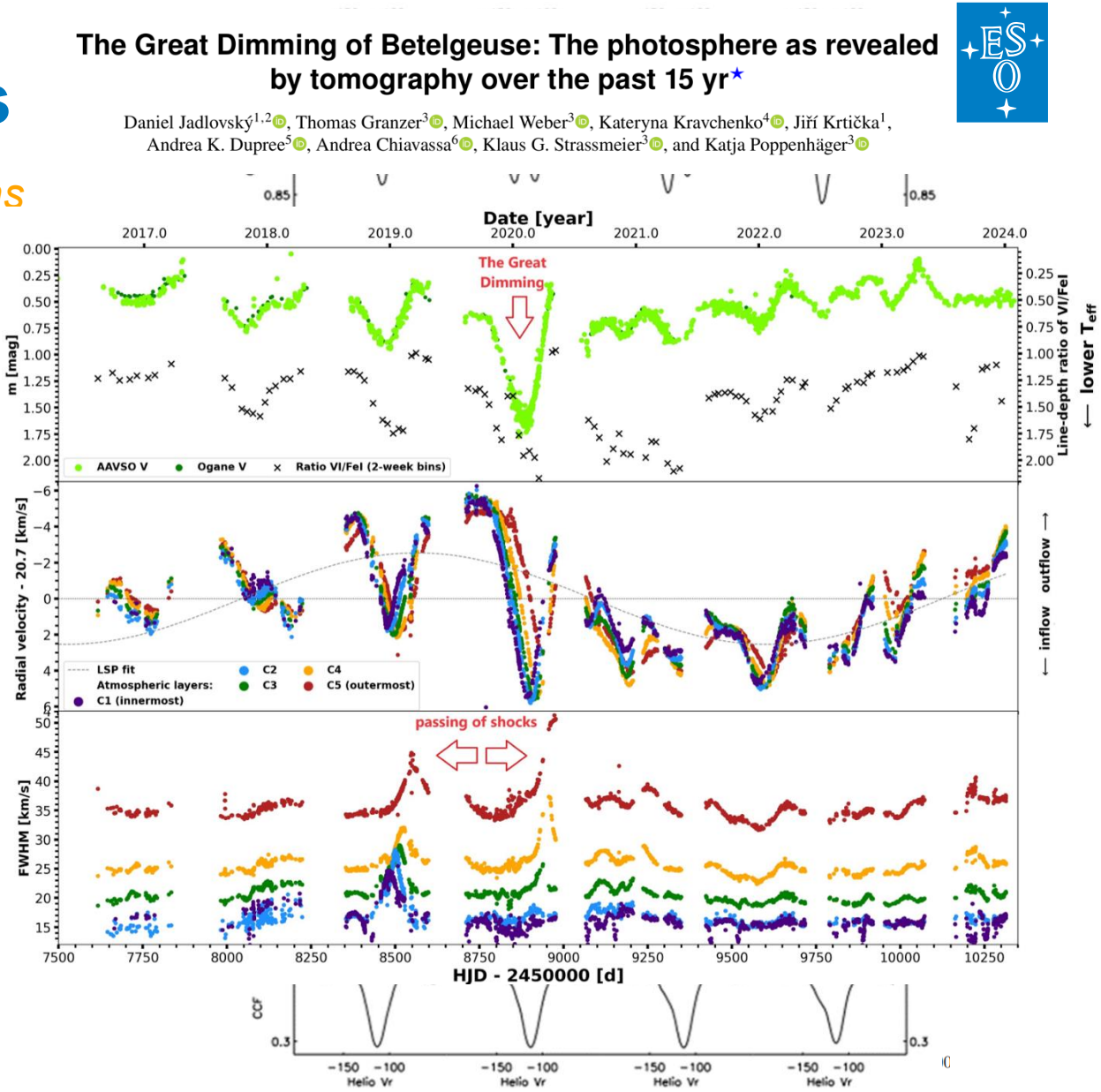


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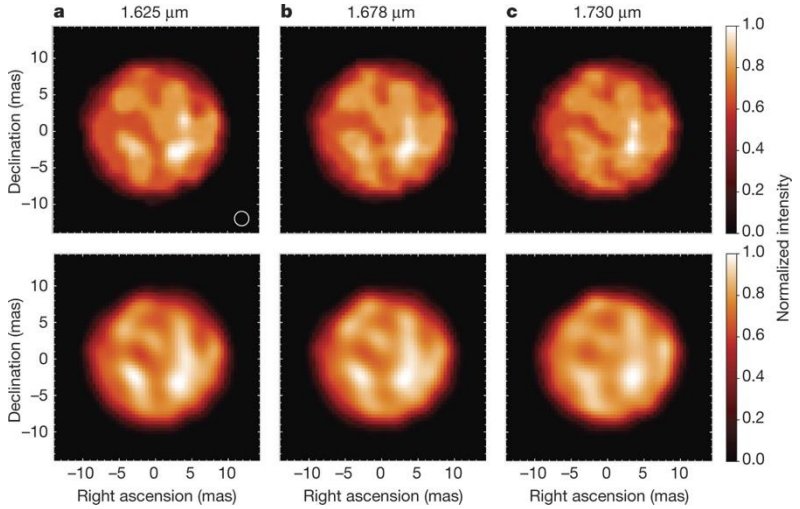
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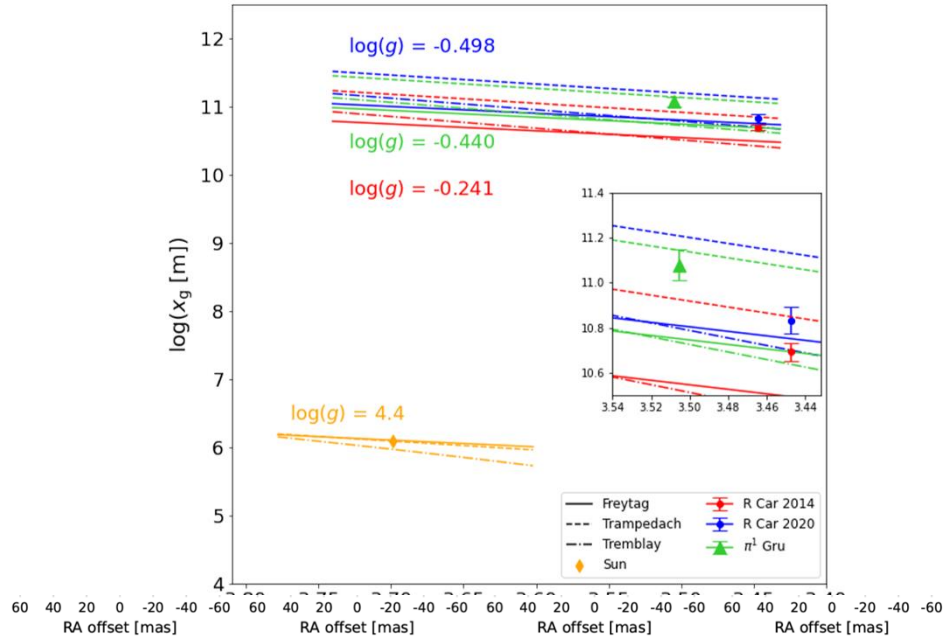
Surface features

Resolved surface images are feasible for nearby AGB and RSG stars (VLTI, ALMA, CHARA, …)

- reconstructed images show bright/dark surface structures, usually associated with turnover of material in the convective cells (e.g., Paladini+2018)
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π^1 Gruis images (single epoch, VLTI)





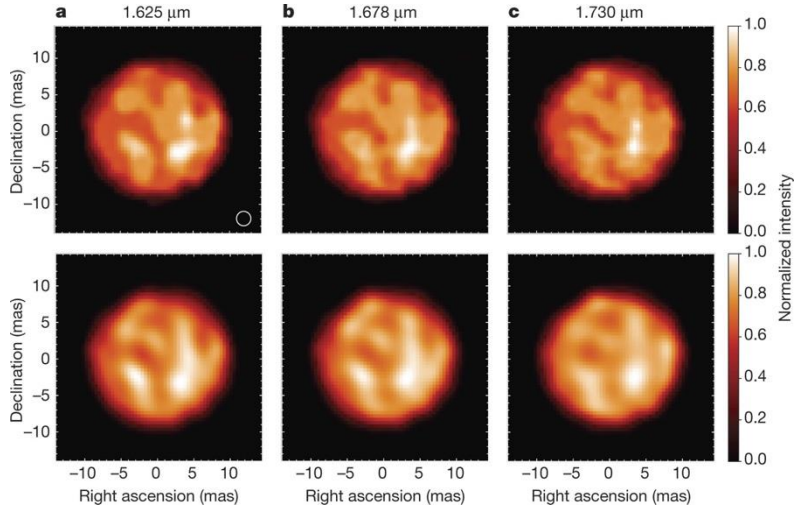
π^1 Gruis (Paladini+2017), Mira A (ALMA): Andriantsaralaza+2026

Surface features

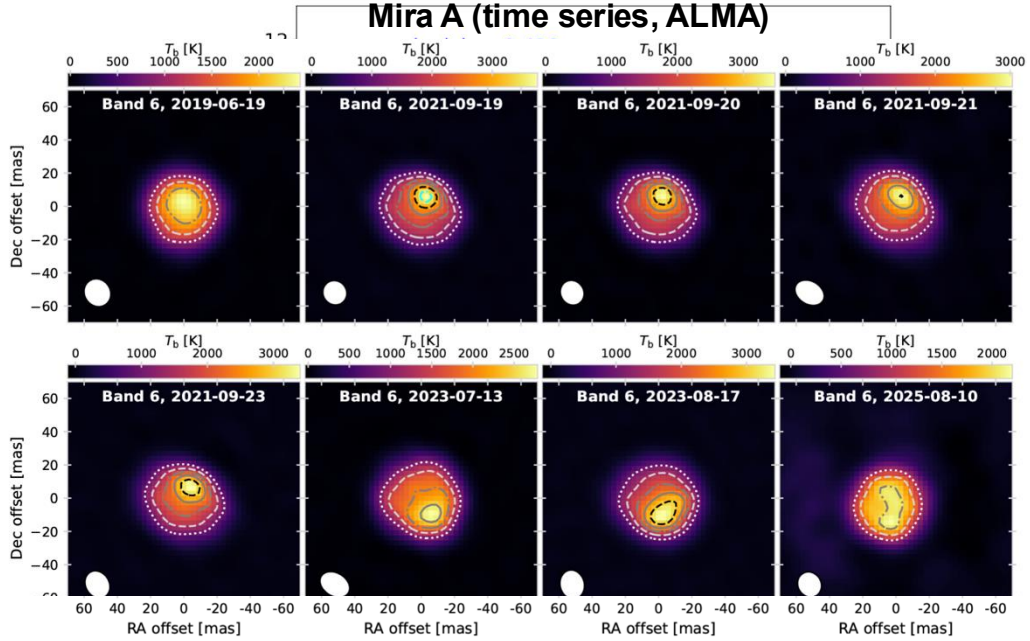
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Mira A (time series, ALMA)

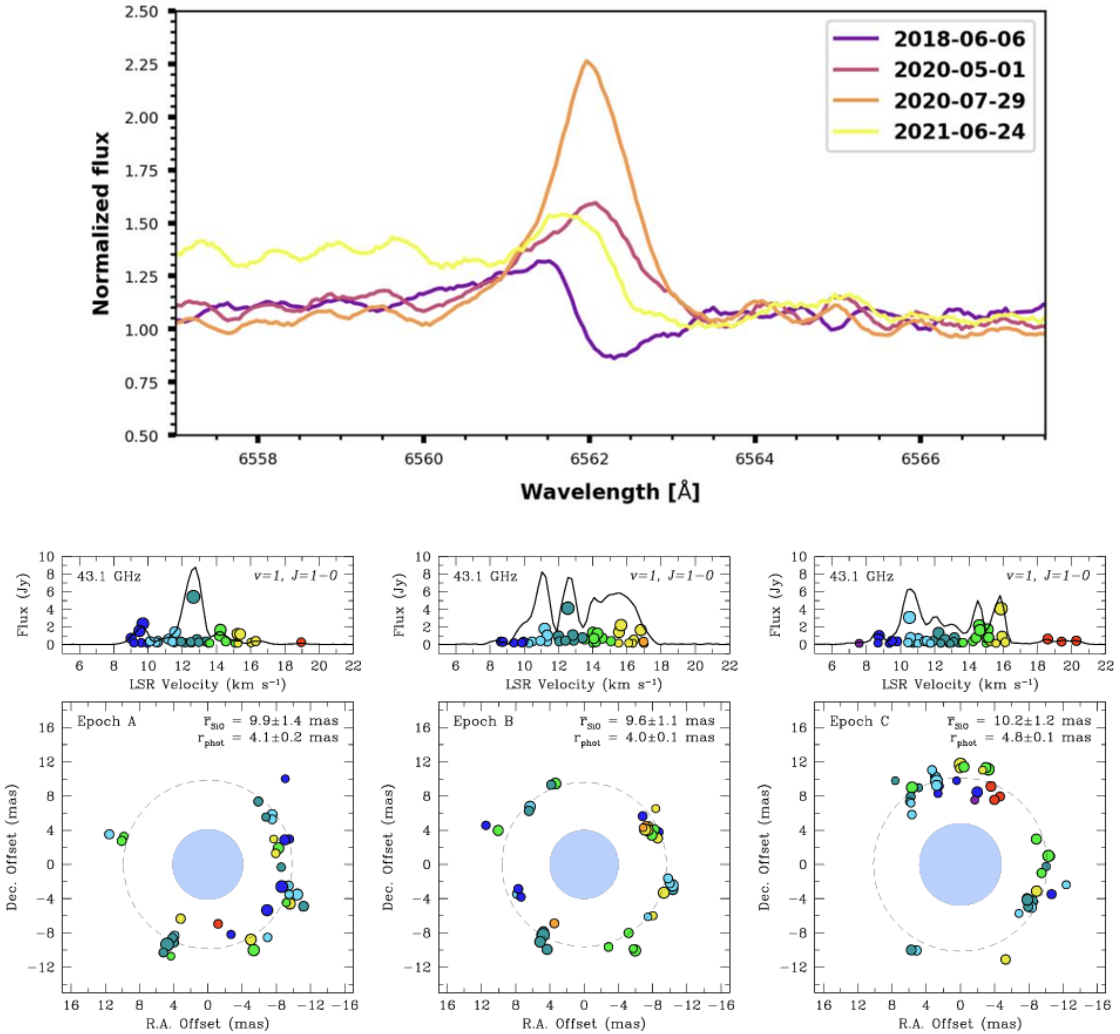


π^1 Gruis (Paladini+2017), Mira A (ALMA): Andriantsaralaza+2026

Other tracers of the shocks and mass loss

Emission lines and SiO masers

- Luminous Miras and RSGs typically also show **hydrogen emission**, with the strongest emission near brightness maxima
- the emission observed in the Balmer, Paschen series (e.g., Fabas+2011), and the Brackett series (Jadlovský+2026a), chromospheric UV emission for some stars (e.g., Saberi+2026) → unclear origin: due to material heated by shocks or re-accretion of infalling material?
- **SiO maser emission**: maser transitions pumped by mid-IR SiO molecular transitions → also strongest near or after brightness maxima, excited by shocks? (e.g., Gray+2009)
- SiO maser radius correlated with the SiO layers in the mid-IR atmosphere (Wittkowski+2007)



Upper: Balmer emission in VX Sgr (Jadlovský+2026a). Lower: SiO masers for S Ori with VLBA, overplotted with mid-IR atmosphere size (Wittkowski+07)

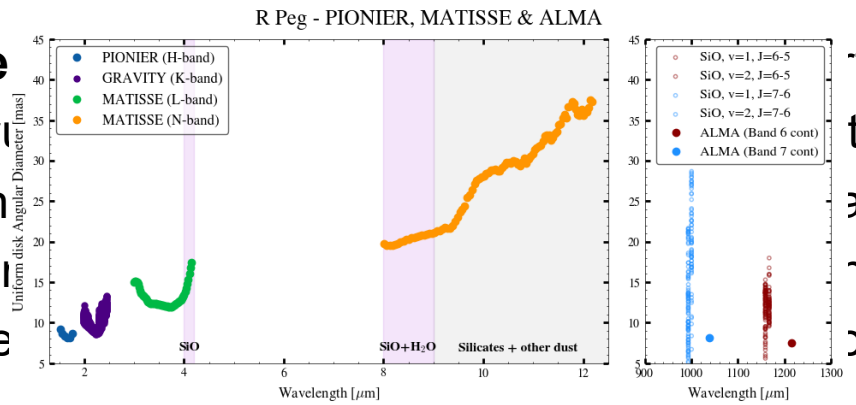
Our joint ALMA+VLTI observations of R Peg

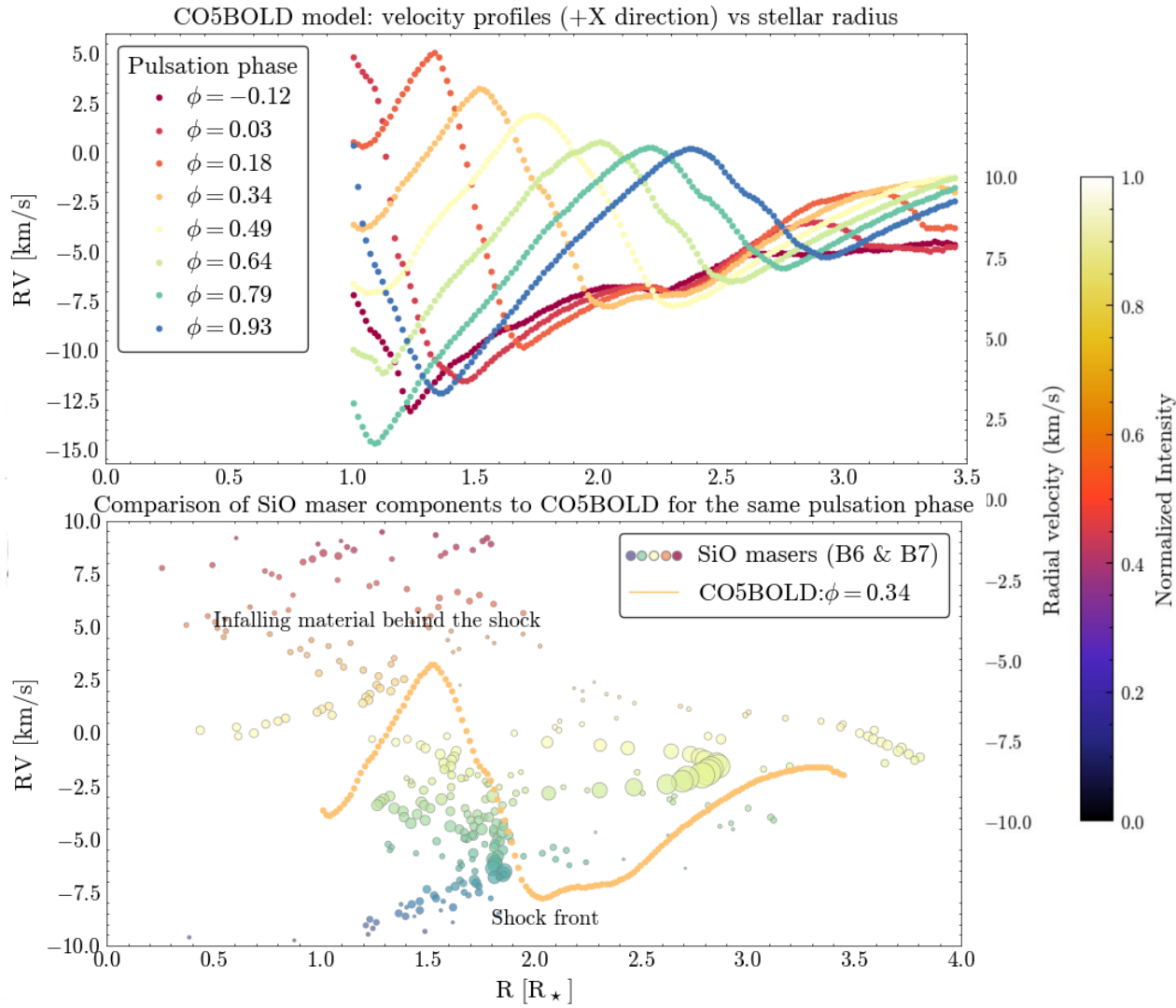
Observations from summer 2021, PI: Wittkowski

- **ALMA**: high-frequency SiO masers (300 GHz) at high angular and spectral resolution (0.2 km/s), **VLTI**: PIONIER & MATISSE (*H, L, N*-bands) imaging

- **Goal**: SiO masers form within ~ 2-3 stellar radii, pumped by SiO molecular bands (4.1/8.1 μm) → trace pulsations and shocks from the stellar surface out into the extended atmosphere

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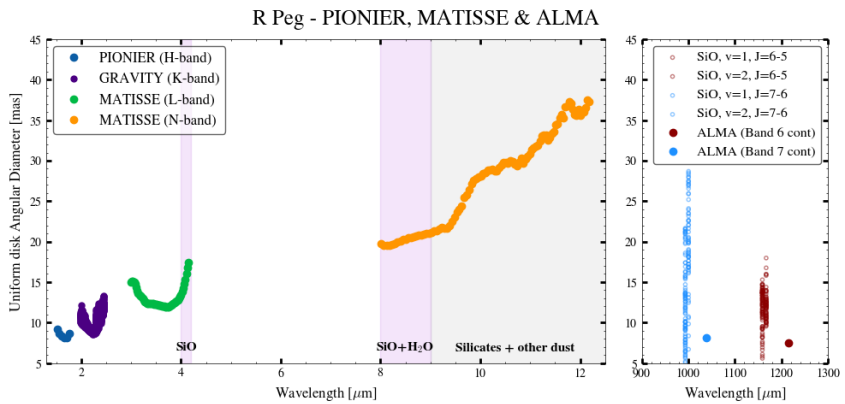


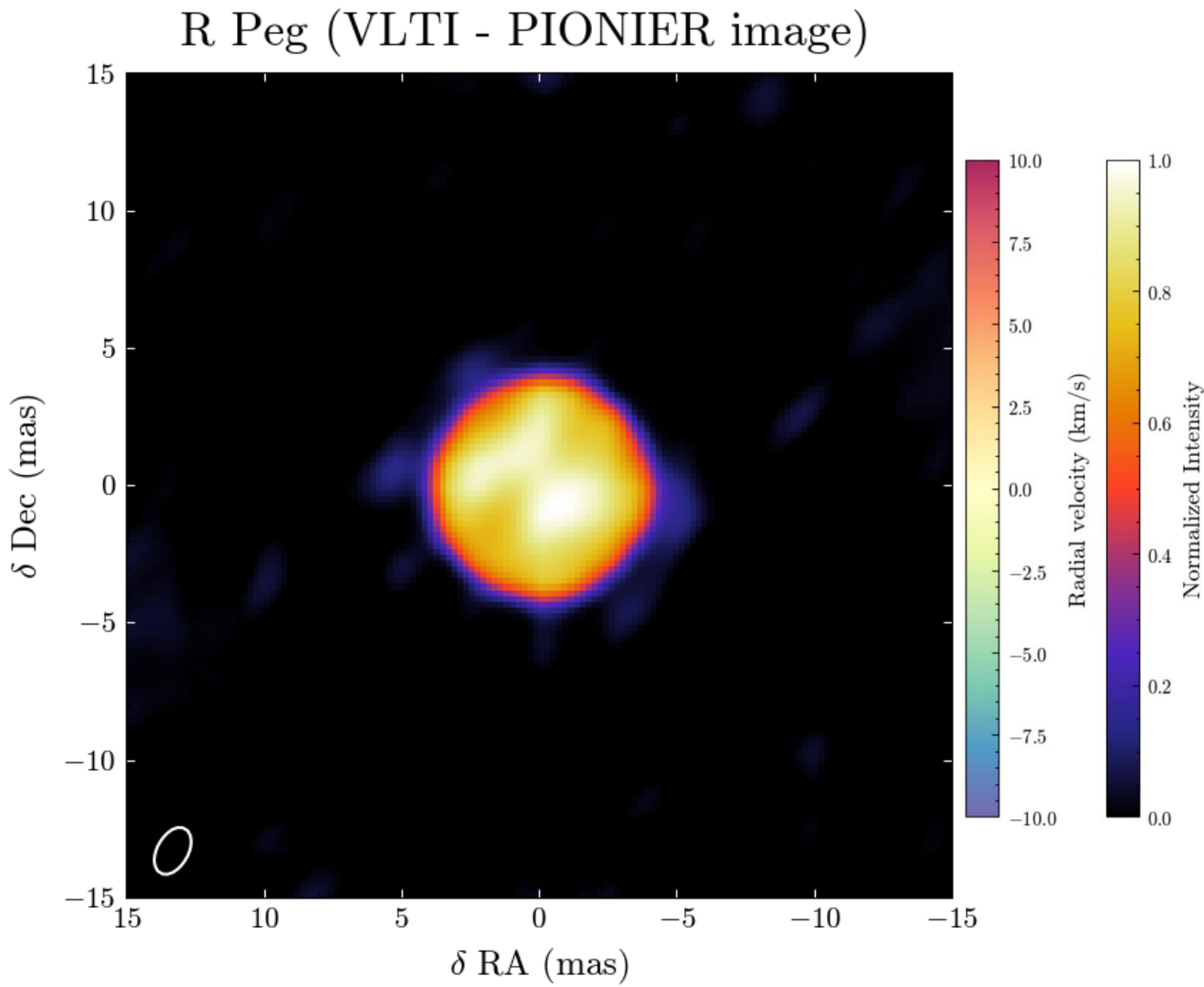
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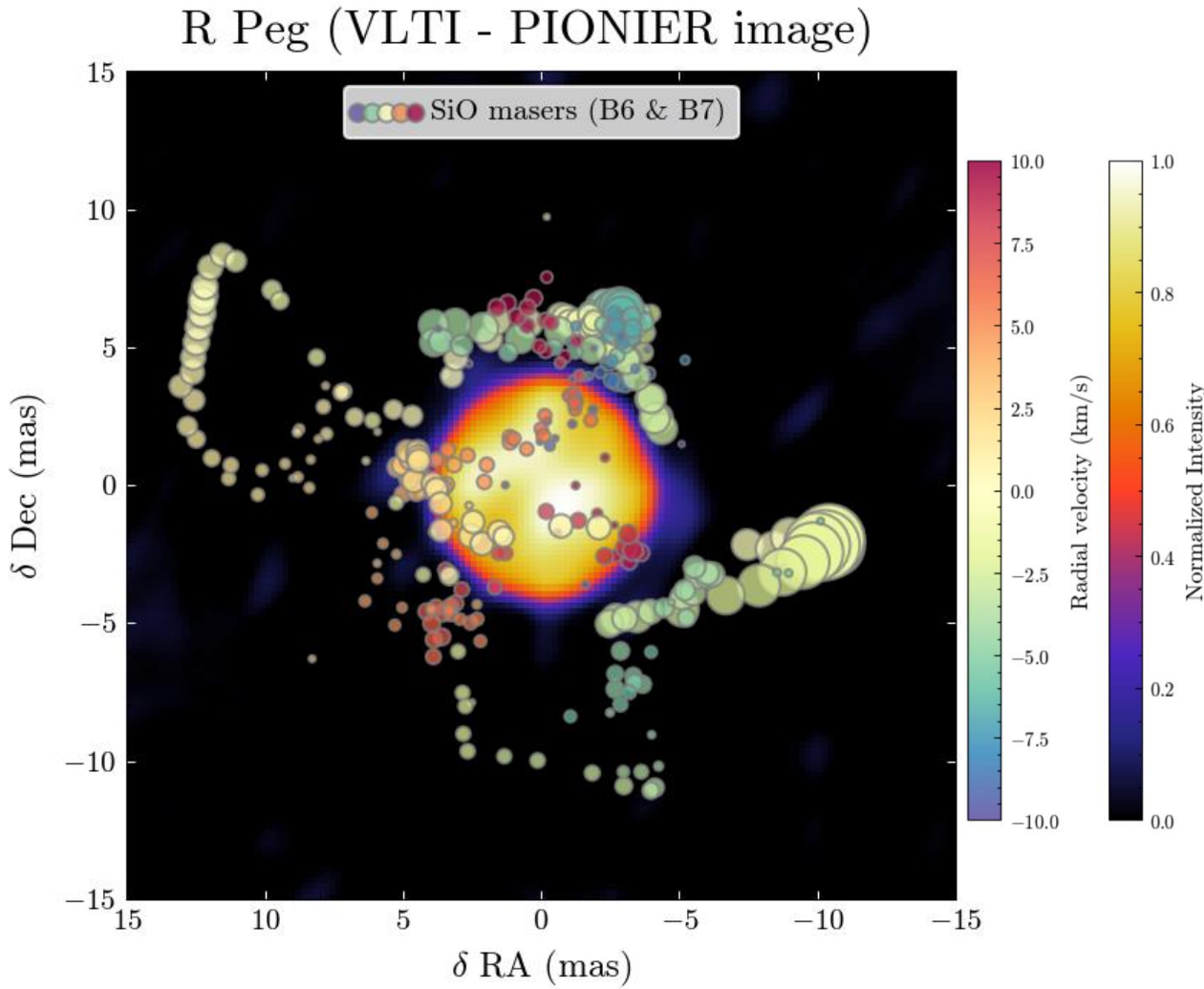


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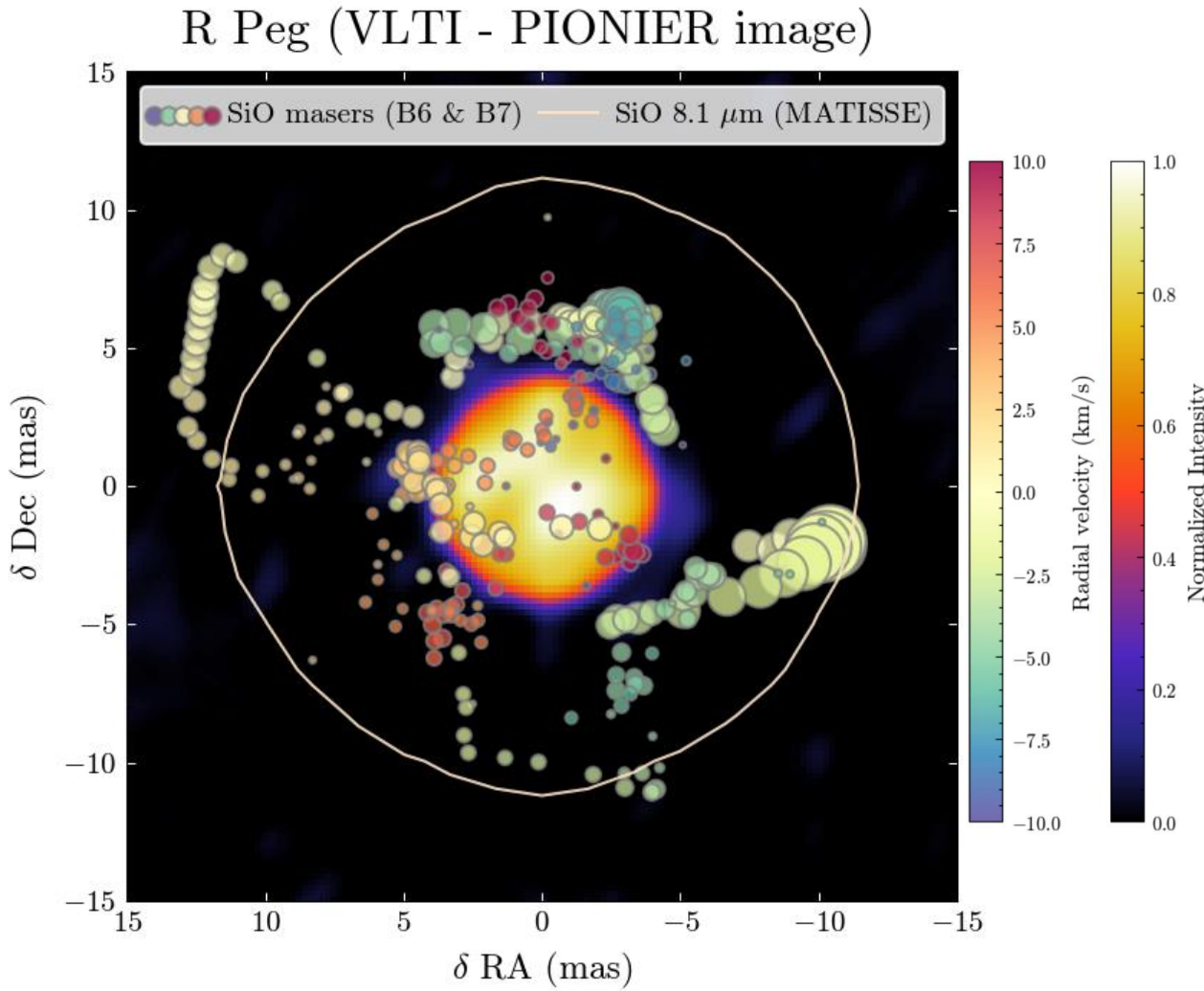


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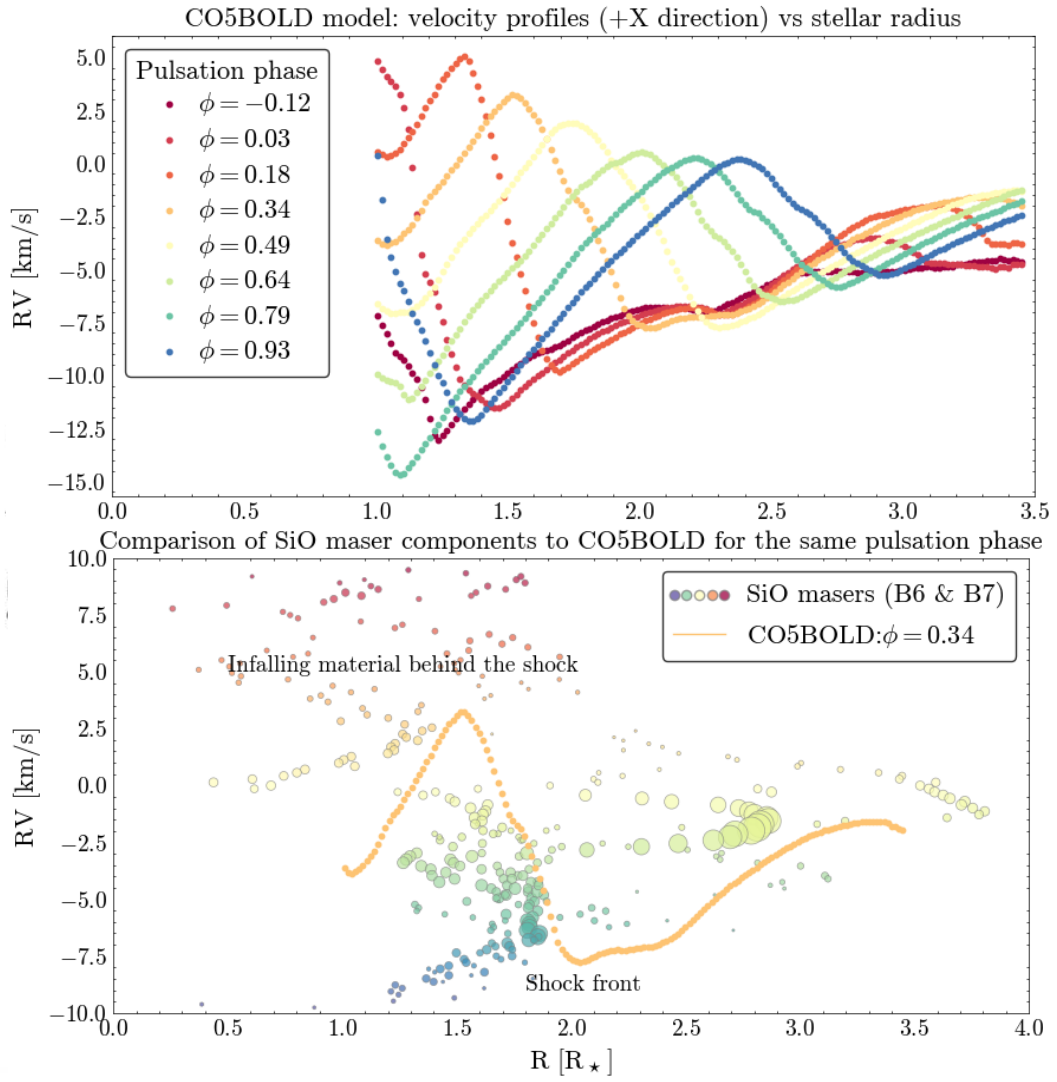


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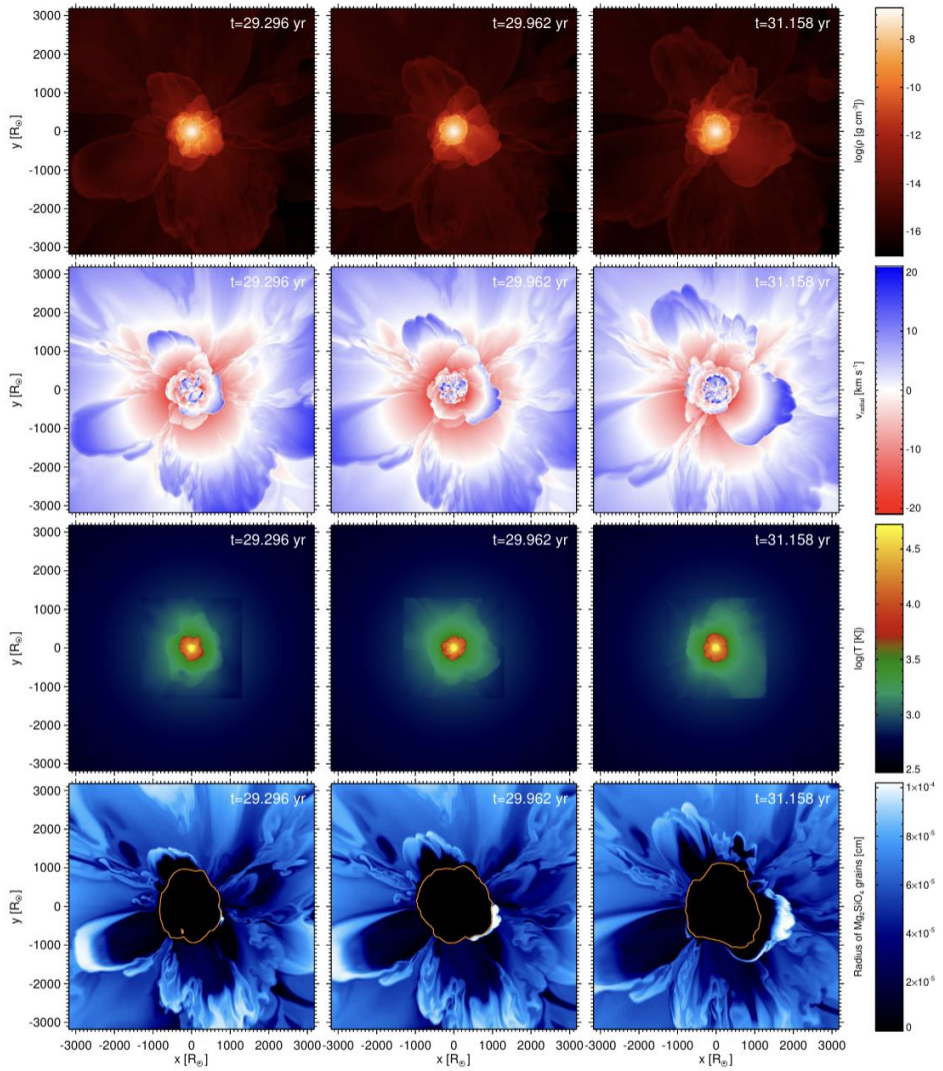


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Comparison to dynamical models

CO5BOLD 3D RHD (Freytag et al. 2008, 2023)

- „star-in-a-box“ approach, radiative hydrodynamics (RHD) simulation, **self-excited radial pulsations**, convective cells, but computationally expensive; only a small grid available (~2-3 new models/year)
- the main grid used a gray-opacity approximation (problems for molecular/dust formation), new models include **frequency-dependent opacity** → better agreement with mass loss (Freytag+2023)
- **large-scale shocks due to pulsations and convection**, resulting in asymmetric mass los
- other models: 3D Athena++ (Goldberg+2022), 1D DARWIN models (Bladh+2019, Hofner+2022) → also promising results

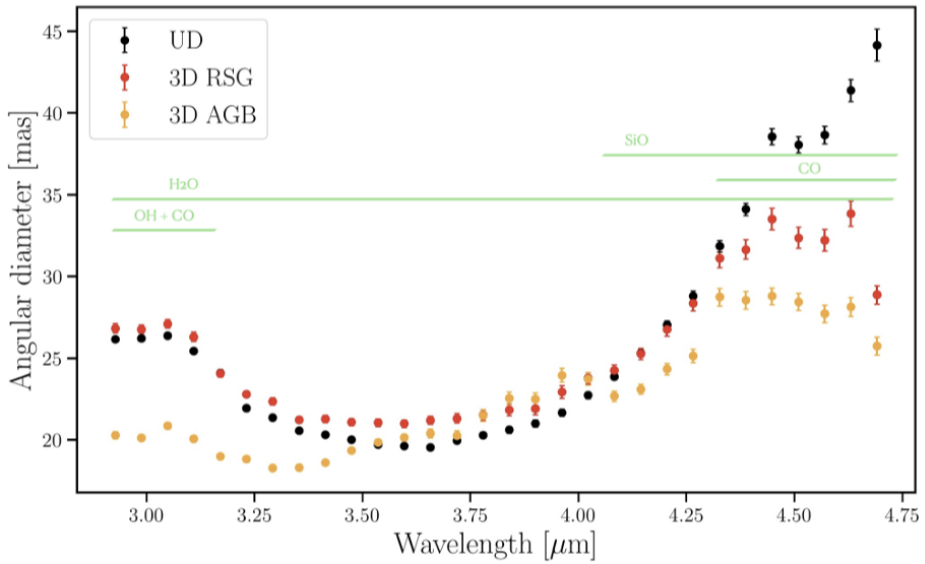


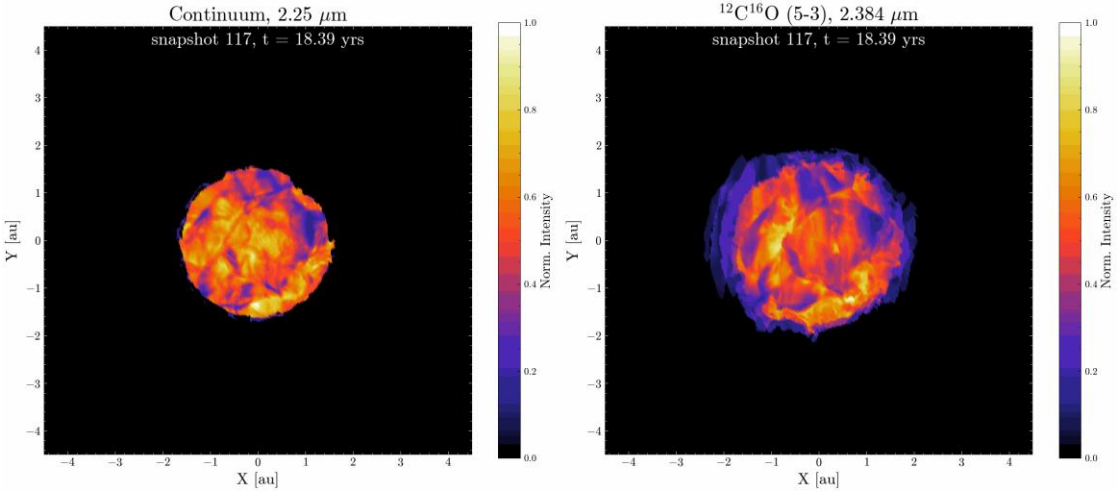
Figures: Freytag+2023, movies: https://www.astro.uu.se/~bf/movie/AGBmovie.html

3D RHD CO^{5}BOLD simulations

Reproducing interferometric observables

- agreement with the **observed surface structures**, but problems with variability and atmospheric extension
- **atmospheric extension**: cool evolved stars show extended atmospheres due to molecular and dust layers, not always well reproduced by the models, especially for RSGs (e.g., Arroyo-Torres+2015, Chiavassa+2022)
- **pulsations**: some models show Mira-like pulsations (Ahmad+2022), but the max *R* may occur at different phase shifts Φ_{Vis} (Jadlovský+2026a)



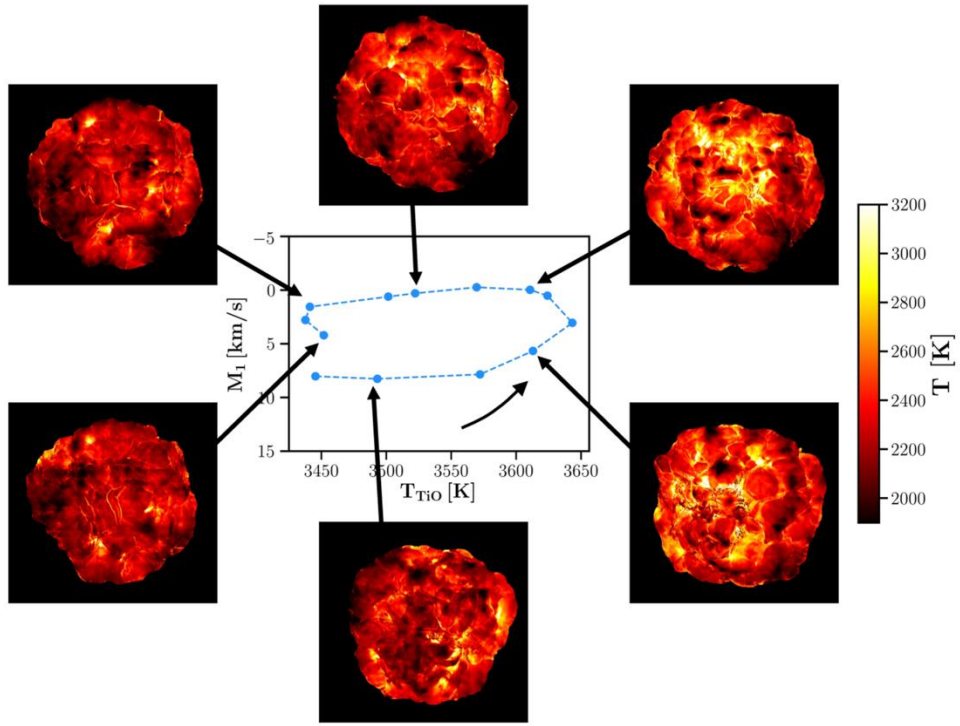


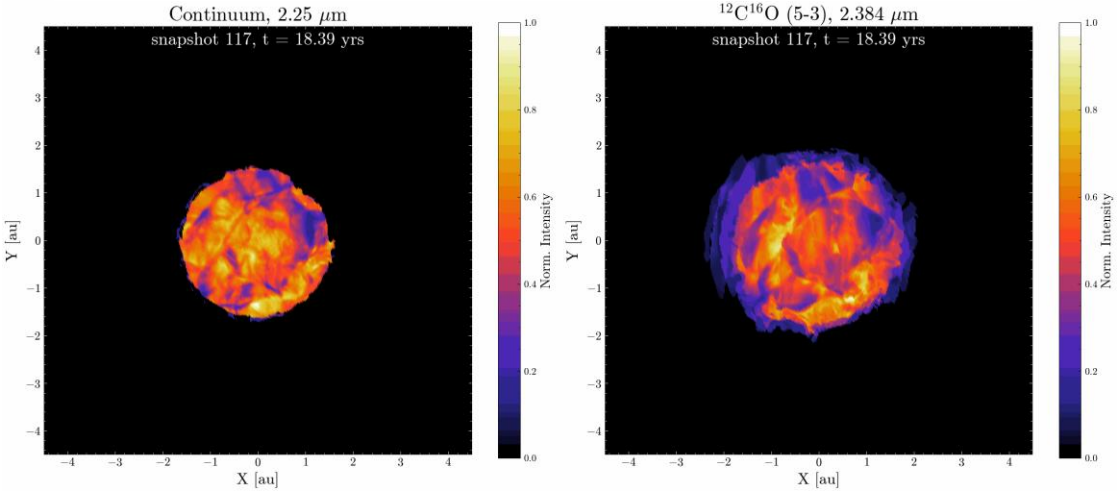
Upper: angular diameter vs wavelength (AGB vs RSG model), lower: movie for the continuum and CO (5-3). Sources: Kravchenko+2019, Chiavassa+2022, Jadlovský+2026a

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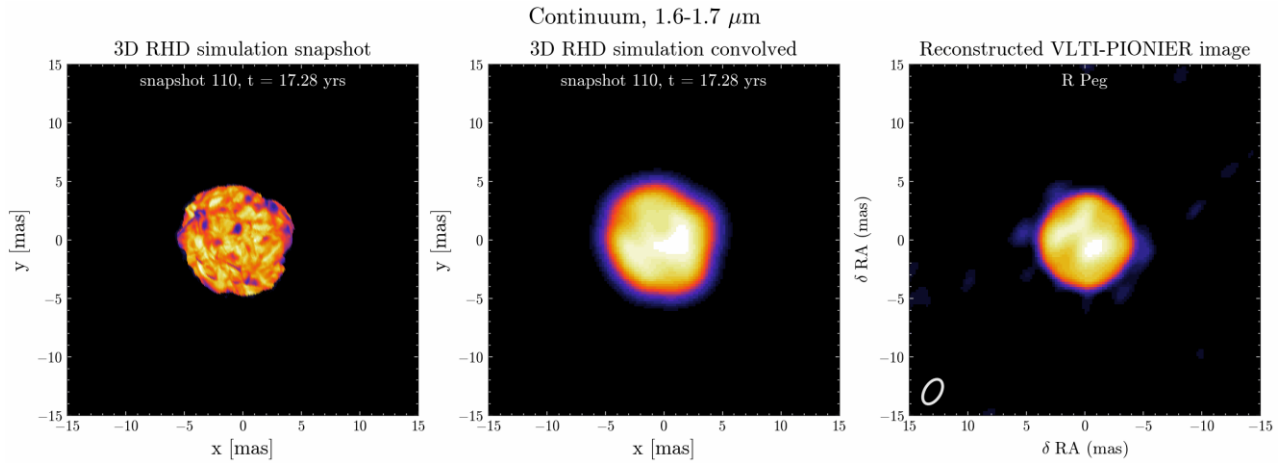


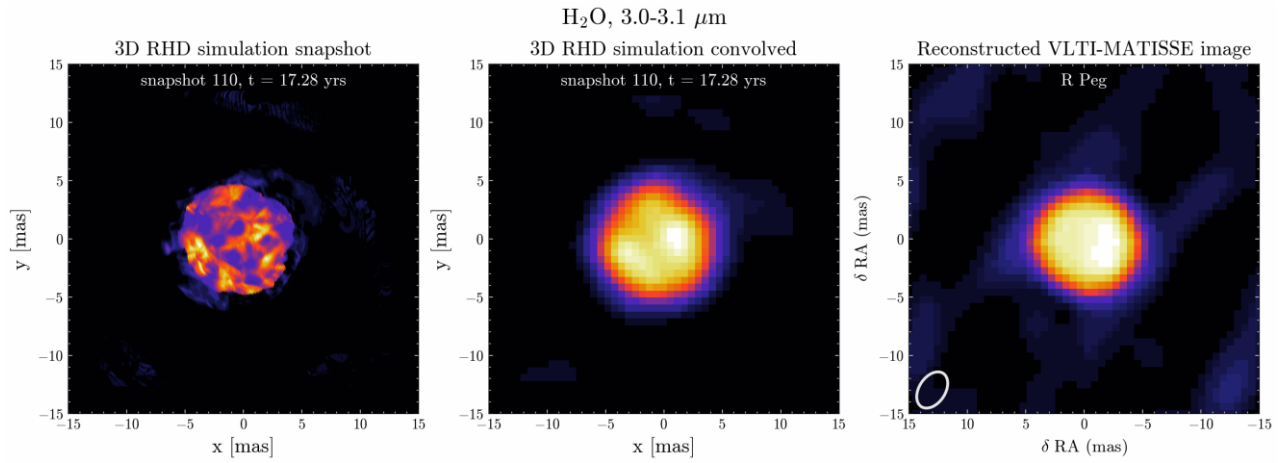
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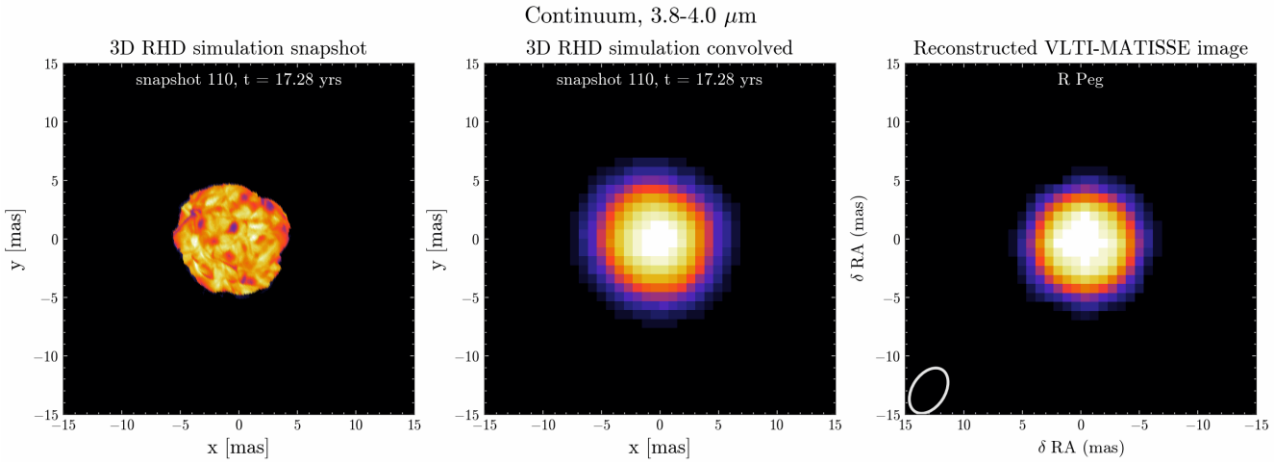
Comparison based on surface morphology

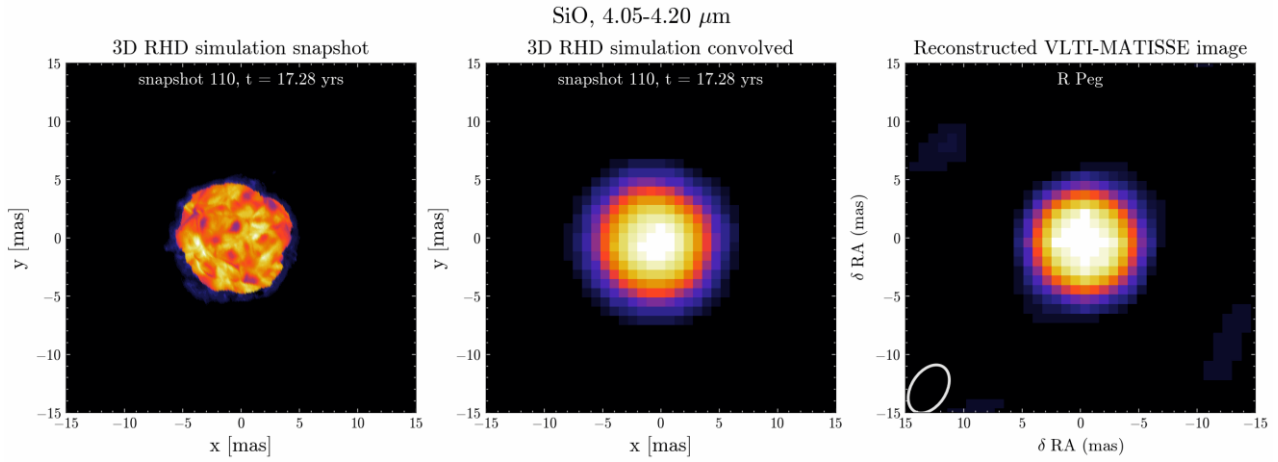
Compared to observations of R Peg (right panels)

- Intensity calculated for the same spectral bins as interferometric observations









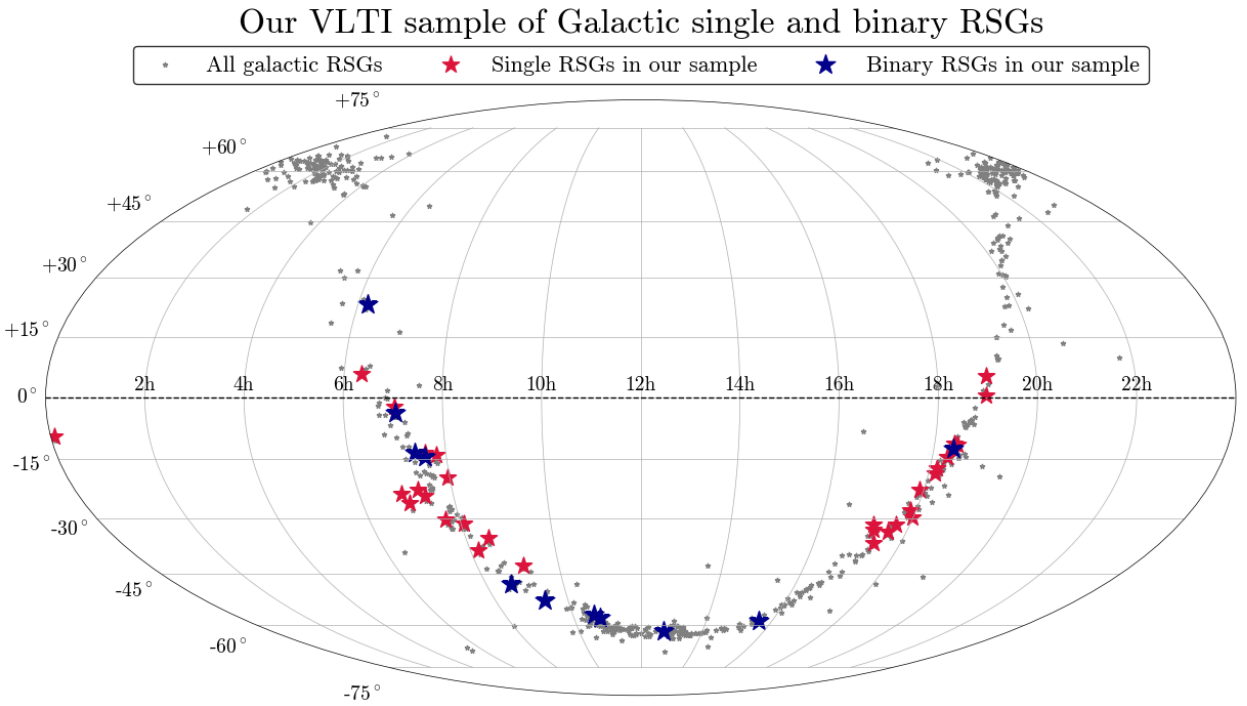
Left panels: 3D simulation (original resolution), middle panels: convolved to the angular resolution of VLTI, right panels: VLTI observations (Jadlovský+in prep)

Pulsation properties of red supergiants

Our VLTI-GRAVITY survey of southern RSGs

In order to systematically unveil the mass-loss process, we need a larger sample (of "normal" RSGs)

- about 40 RSGs with VLTI → constraining the pulsations, atmospheric extension and multiplicity
- coordinated with the STELLA (AIP, Tenerife) and PLATOSpec (La Silla) optical spectrographs
- observations in optical and near-IR → more accurate stellar parameters and mass-loss rates
- **Successful proposals (2024-2026)**:
  - VLTI-GRAVITY (PI: Jadlovský): about 300 hrs allocated(!), STELLA: about 500 hrs, observations finish this year → **new results incoming**
  - Additional MATISSE observations (PI: González i Torà) → molecular and dust layers in mid-IR



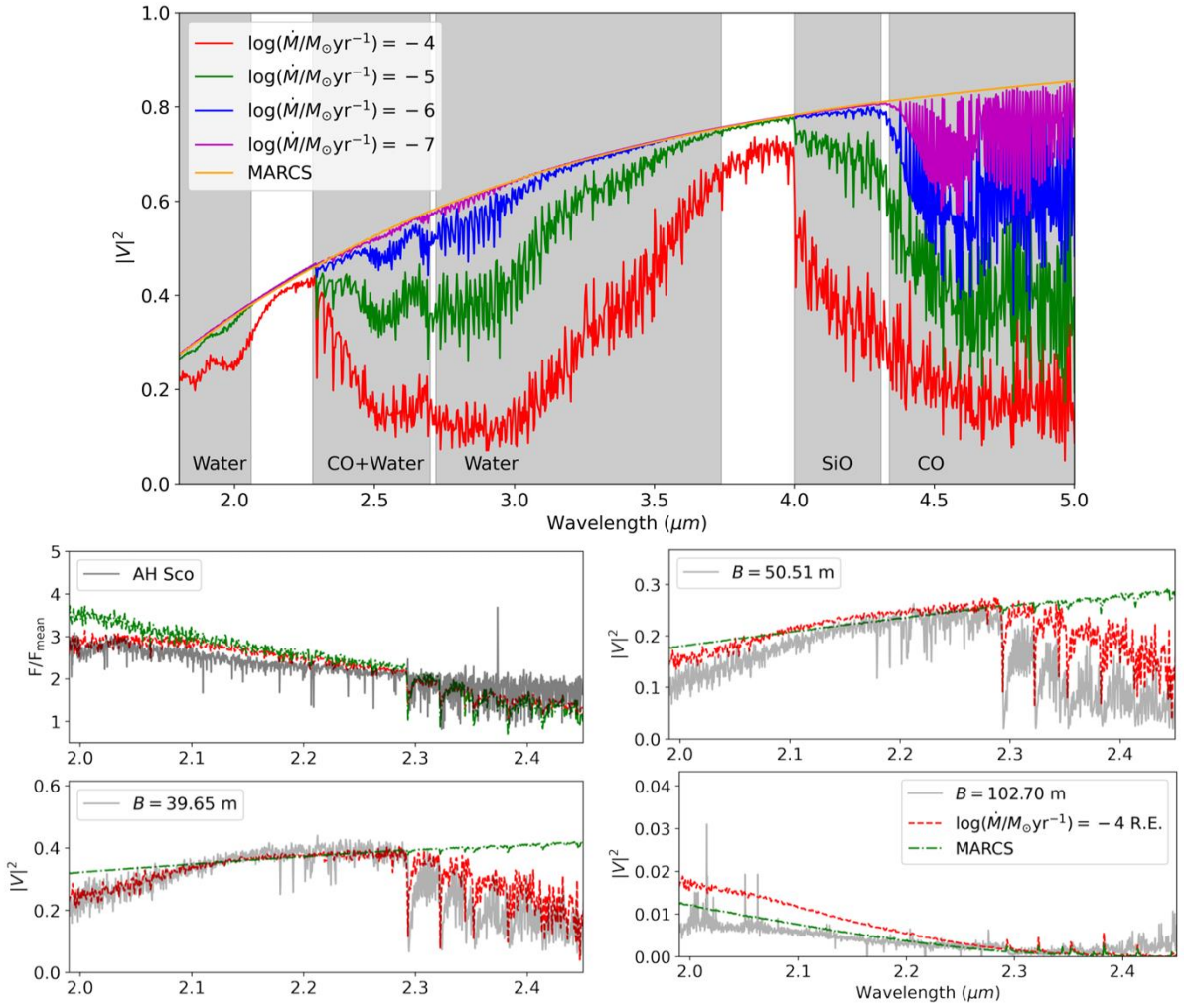
Distribution of Galactic red supergiants on the sky, our sample highlighted

Main goals

Preliminary results (papers in preparation)

- the sample will allow us to determine photospheric radii, pulsation properties and luminosities for the full RSG sample (+ periods from photometry) → **constraining pulsation and evolutionary models**
- variability in the photosphere and the extended atmosphere → **episodic mass-loss events** vs stable outflows, the connection to pulsation mode changes (FM ←→ 1O)
- AGB and RSG stars show extended atmospheres (up to several stellar radii in mid-IR) → adding the atmospheric extension in 1D models can be used to to determine **mass-loss rates** (González-Torà+2023, 2024)

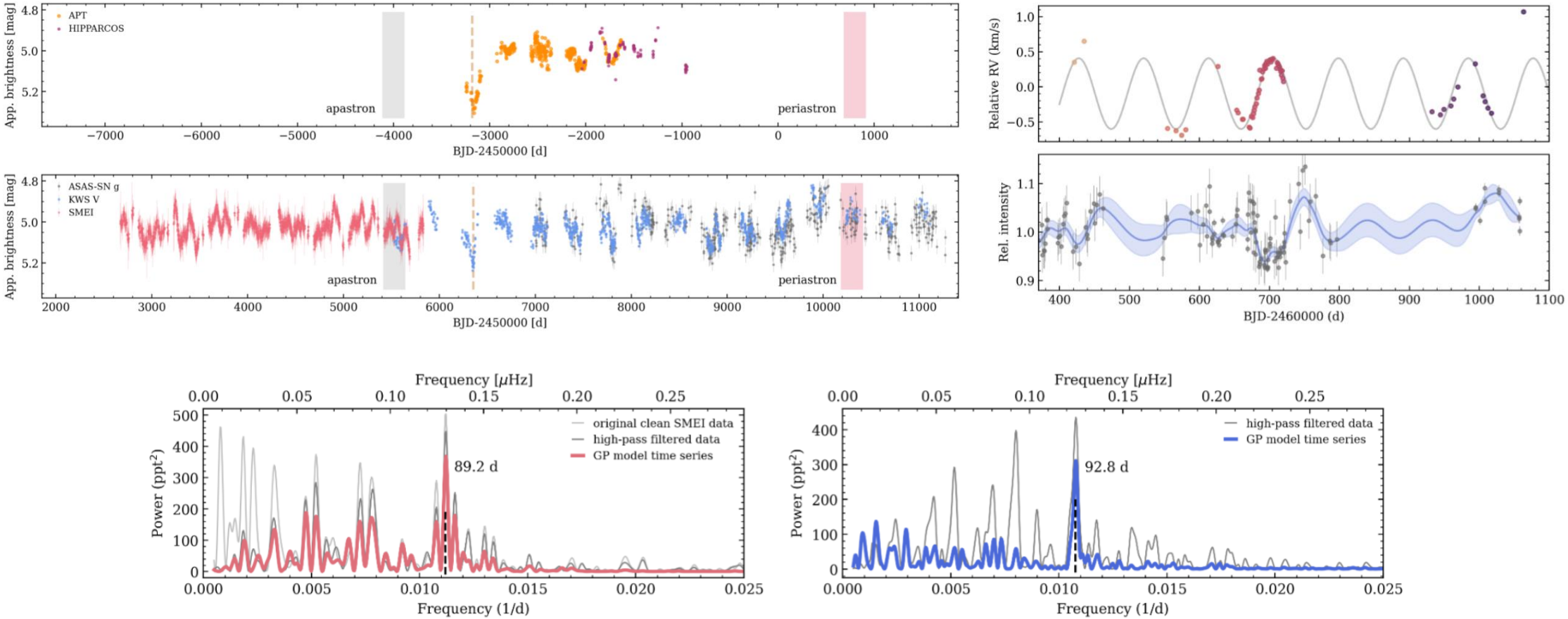
→ significant constraints on the properties of RSGs



Upper: effect of mass loss on atmospheric extension, lower: mass-loss determination (González-Torà+2023, 2024)

Data coverage example

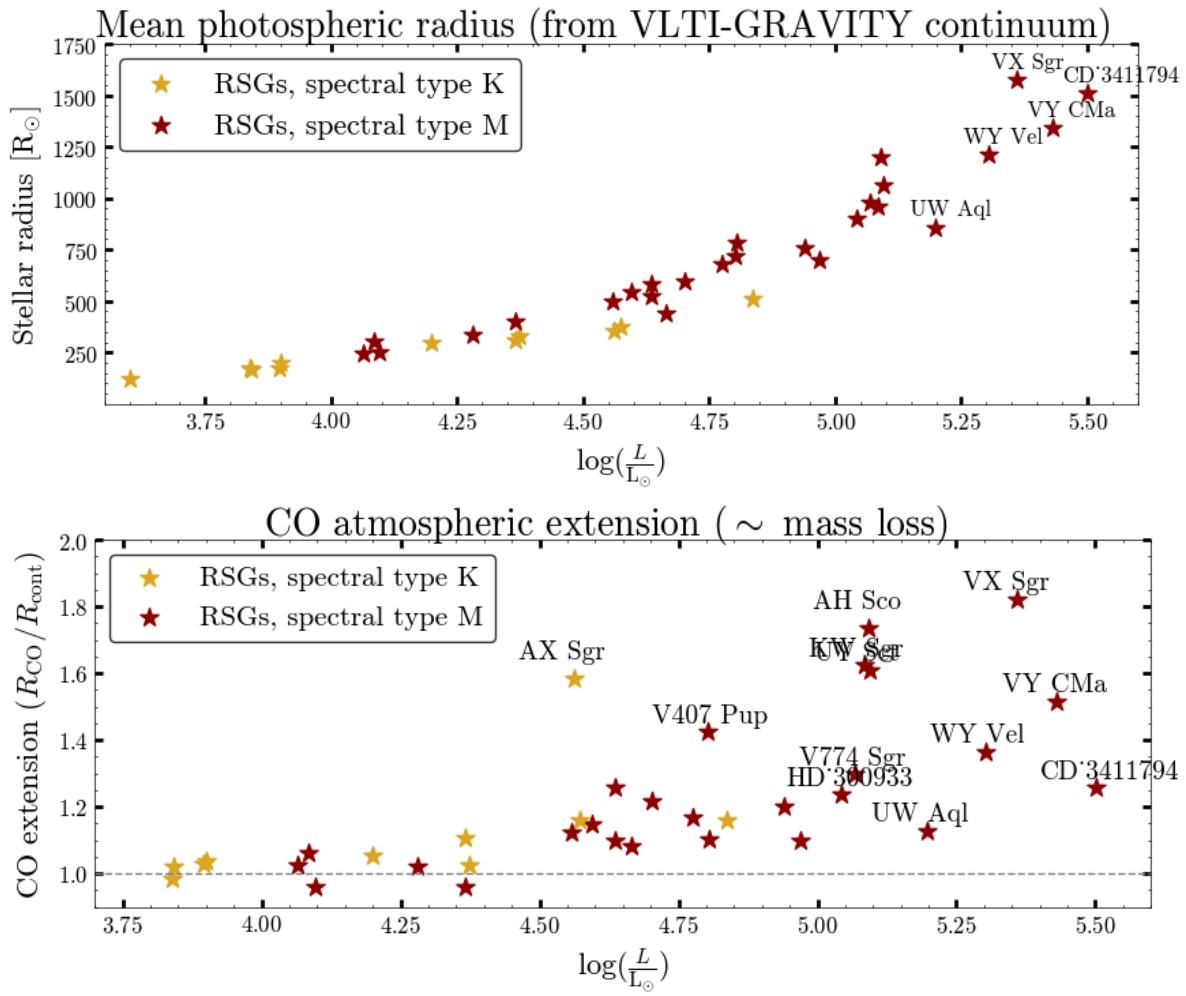
Archival photometry and new RVs (KQ Pup, Molnár+in prep.)



First results

Radius and luminosity relations

- the sample covers less-evolved supergiants (spectral type K), as well as more evolved supergiants (late M)
- angular diameter determined for the whole sample (from ~200 $R_\odot$ to ~1600 $R_\odot$) → physical radius shows a **strong correlation with luminosity**
- CO atmospheric extension (~ mass-loss rate) also correlated, but more scattered → less luminous RSGs do not form molecules?
- VLTI time-series (TBD) → angular diameter variations to be combined with the RVs



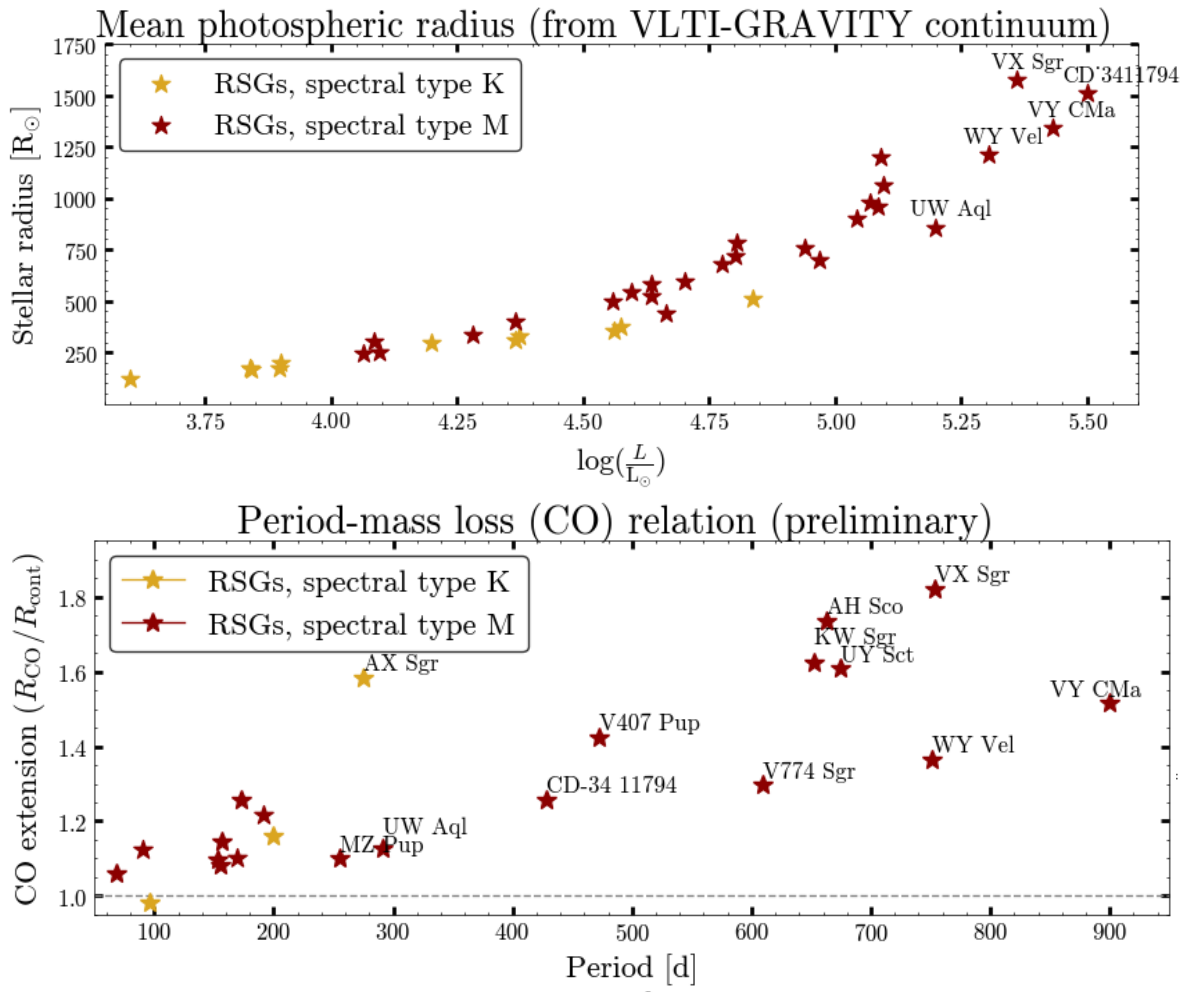
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→ RSGs need large-amplitude pulsations to drive the mass loss!

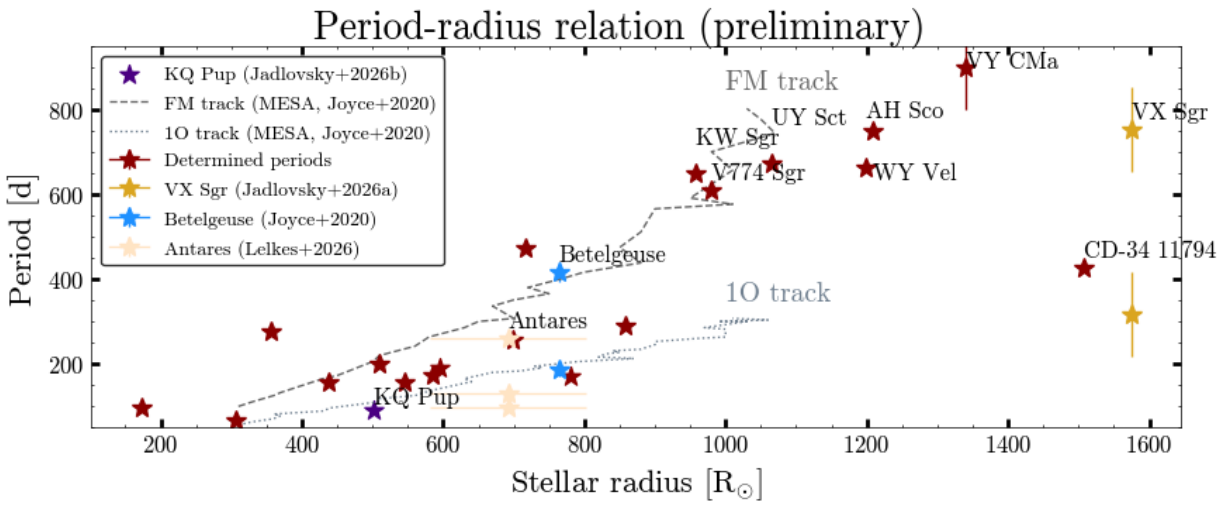


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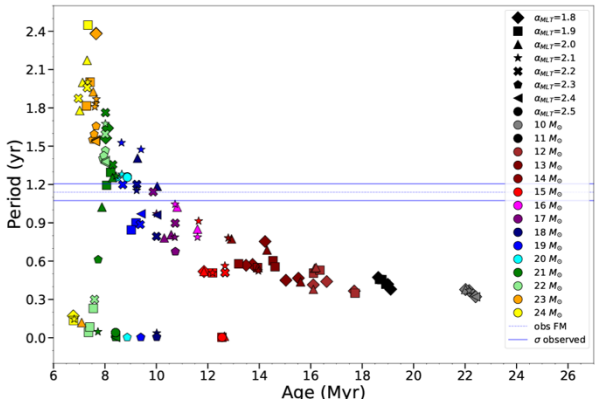
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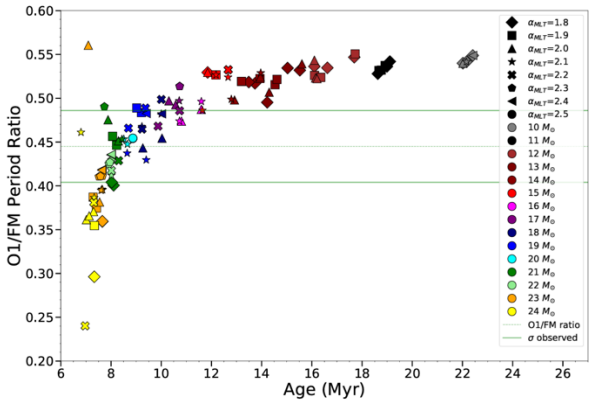
Radius and period relations

- periods (WIP) based on archival photometry (AAVSO, ASAS, KWS, …), combined with high-cadence RVs from STELLA
- previous works (e.g., Kiss+2006, Chatys+2019) typically reported longer periods
- we find **low-amplitude short pulsations** for many stars in our sample → many RSGs (e.g., Antares, KQ Pup, …) are pulsating in the first overtone (1O), possibly also higher overtones?
- max pulsation period is well correlated with the determined *R* (about ~900 d for ~1600 $R_\odot$)
- similar values to pulsation models by Joyce+2020 → comparison to **pulsation models**, especially FM/1O ratio



Pulsation models (MESA-GYRE, Joyce+2020)



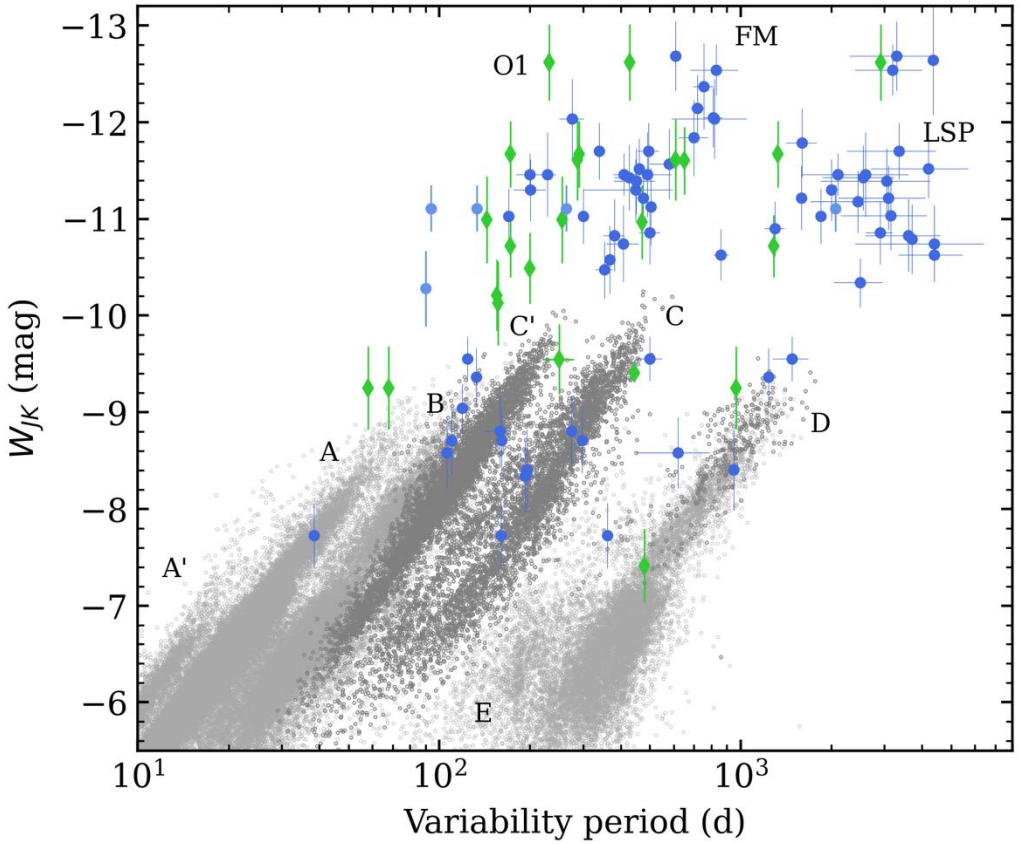


Upper: Period vs our determined photospheric radius (part of the sample with determined periods), lower: pulsation models from Joyce+2020

First results

Period-luminosity relations

- long-period variables (RGB, AGBs, …) form tracks in the period-luminosity relation, corresponding to different **pulsation modes**
- RSGs connect to the period sequences, with likely FM and 1O tracks, supporting the pulsation mechanism as the origin of variability
- luminosity estimates may improve with distances from Gaia DR4/DR5 and better periods with new photometric surveys
- LSP/D sequence are an extension of E (eclipsing binaries) → likely not pulsations
- **several other talks will cover the P-L relations and the LSPs!** (e.g. P. Kołaczek-Szymański, P. Iwanek, L. Planquart, D. Dionese, R Urago, F. Jiménez-Esteban, …)



Period-Wesenheit luminosity relations (Goldberg+2024, Kiss+2006, Chatys+2019, Soszyński+2021), showing long-period variables (grey), Betelgeuse (red), Galactic RSGs (blue) and some stars in our sample (green)

Companions of cool evolved stars

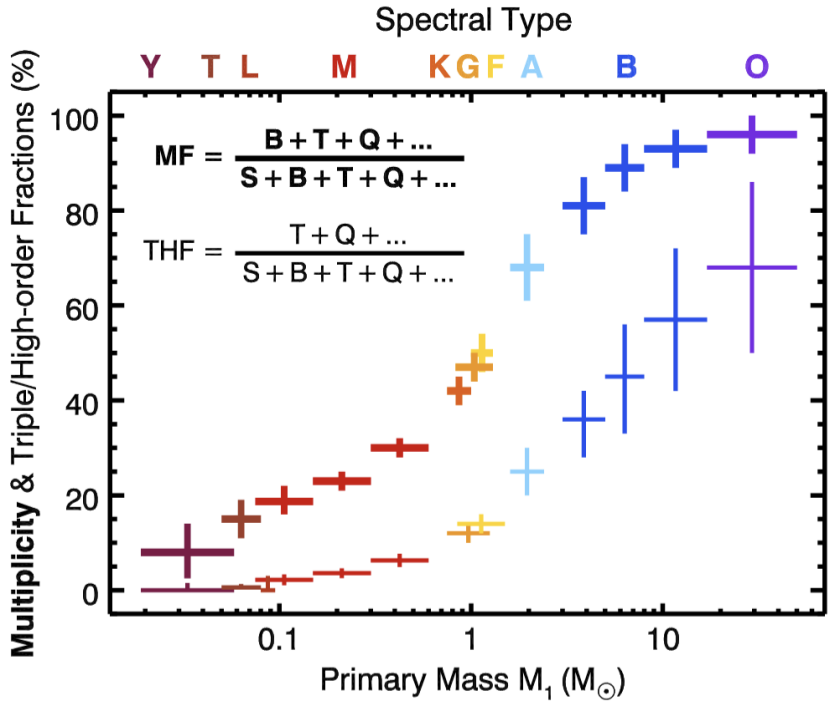
Multiplicity fraction

Binarity interaction shapes the evolution of stars (Sana+2012)

- multiplicity surveys of main-sequence stars report a high number of binaries/triples (e.g., Offner+2022, Frost+2025), from about 50% for 1 $M_{\odot}$ stars, to nearly 100% for the most massive ones
- yet, **the reported multiplicity fractions of AGB/RSG stars drop significantly**

→ **where are all the companions?**

- the few known binary systems (typically SB1) were identified based on extreme properties of their interacting/accreting companions (e.g., emission lines in symbiotic stars)
- the shortest orbital periods are typically at least a few years → requires **multi-year monitoring**!

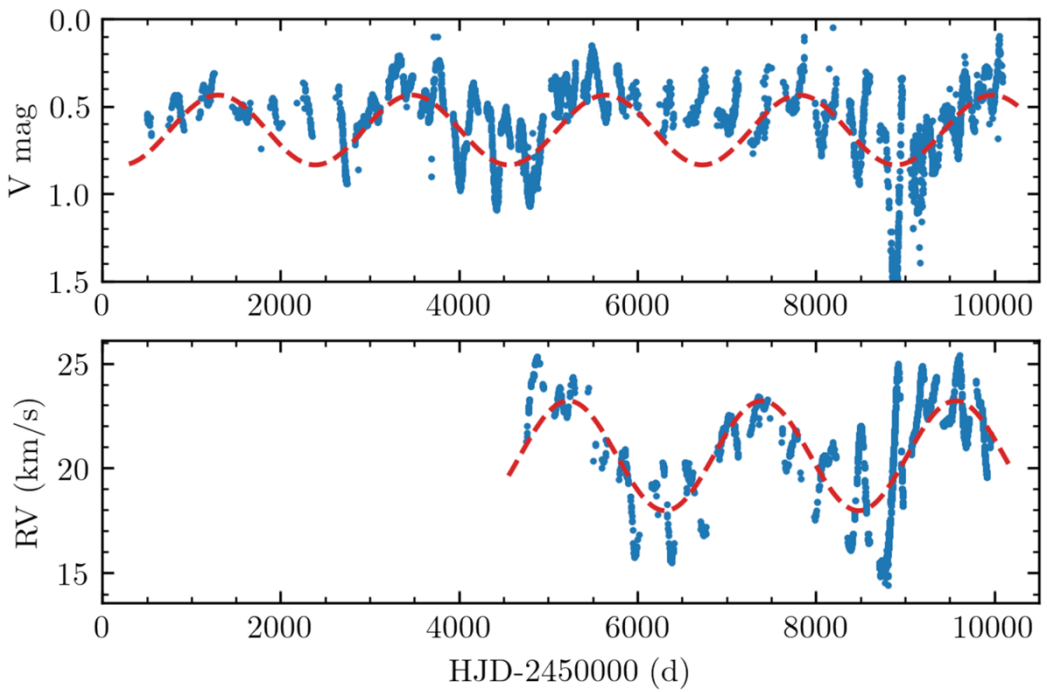


Bias-corrected multiplicity fraction for main-sequence stars (Offner+2022)

Long secondary periods

The binary companion Betelgeuse confirmed!

- about 1/3 of long-period variables (Kiss+2006, Soszyński+2021) show photometric periods of several years: the long secondary period (LSP)
- recently hypothesized to be caused by **close-by low-mass companions**, which modulate the amount of dust (Soszyński+2021)
- **Betelgeuse (RSG):**
  - LSP ~ 6 years, also present in the RVs (Granzer+2022, Jadlovský+2024) → the companion proposed by Goldberg+2024 and MacLeod+2025
  - tentatively detected by Howell+2025, and finally confirmed by Montargès+2026 using VLT/SPHERE
  - likely mass: ~ 1 $M_\odot$ (e.g. Goldberg+2026) or 2-3 $M_\odot$ (Montargès+2026)

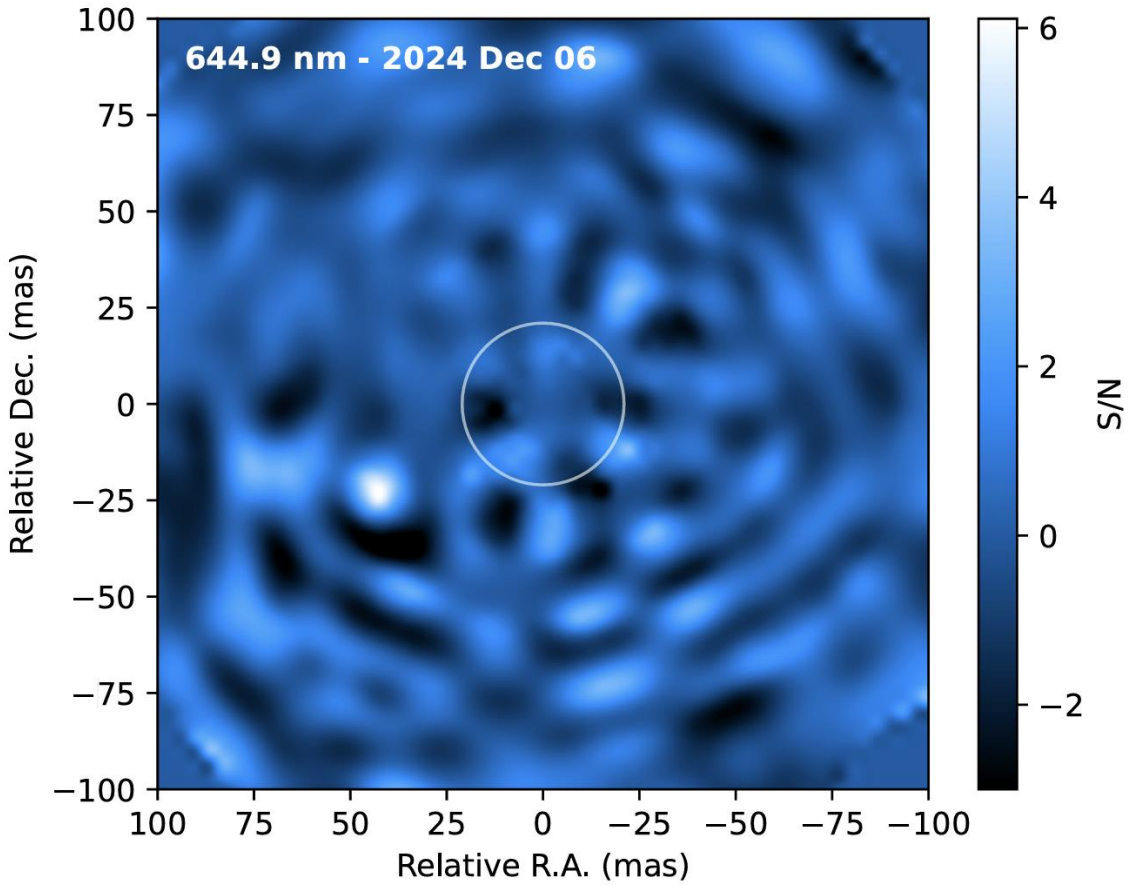


First: Photometric and RV variations of Betelgeuse, showing LSP (Goldberg+2024). Second: Betelgeuse B detection by Montargès+2026

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- recently hypothesized to be caused by **close-by low-mass companions**, which modulate the amount of dust (Soszyński+2021)
- **Betelgeuse (RSG):**
  - LSP ~ 6 years, also present in the RVs (Granzer+2022, Jadlovský+2024) → the companion proposed by Goldberg+2024 and MacLeod+2025
  - tentatively detected by Howell+2025, and finally confirmed by Montargès+2026 using VLT/SPHERE
  - likely mass: ~ 1 $M_\odot$ (e.g. Goldberg+2026) or 2-3 $M_\odot$ (Montargès+2026)



First: Photometric and RV variations of Betelgeuse, showing LSP (Goldberg+2024). Second: Betelgeuse B detection by Montargès+2026

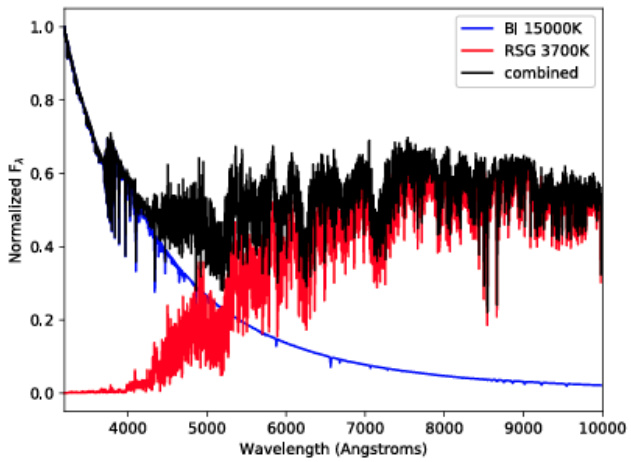
Red supergiants in binaries

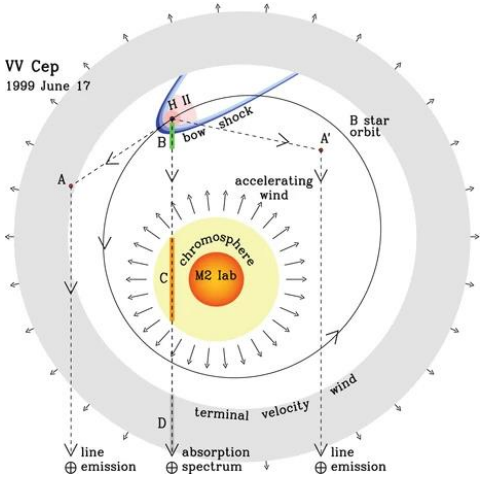
Quite a lot of confusion in the community about if and how many binary RSGs do we know…

- recently, many new RSG+B binary systems have been found in the Local Group → **RSG binary fraction up to ~15- 40%** (e.g., Neugent+2021)
- however, masses and orbital parameters are **not constrained** for the majority of the systems!
- majority of better-studied systems belong to **VV Cephei** type (Cowley1969) - wide wind-interacting RSG+B systems, Balmer emission, eccentric orbits of several years or decades
- **hot companions of RSGs:**
  - nearly all are B stars – unclear classification, the ones in VV Cephei show Be/B[e] properties
  - spectrum below cca 4000 Å dominated by the hot component, no clear diagnostics in optical

Table 1: Orbital configurations of RSG binary systems with constraints on orbital solutions.

ID	Alt. ID	Components	Period	$\log L_{RSG}/L_{\odot}$ [dex]	M_{RSG} [$M_{\odot}$]	$q = M_2/M_1$
32 Cyg	HR 7751	K5 Ib + B6 V	1148 d	3.82 ± 0.08	7.5–10	0.5
V766 Cen	HR 5171 A	RSG + YSG	1304 d	5.8 ± 0.4	27–36	$0.16^{+0.4}_{-0.07}$
AZ Cas	–	K5 Iab-Ib + B	3406 d	4.2	–	–
VV Cep	–	M2 Iab + B0-2 V	7431 d	5.3 ± 0.2	20	~ 1
KQ Pup	HD60414 Boss 1985	M1 Iab + B2	9752 d	4.6	13–20	~ 1
HD 42474	WY Gem	M1 Ib + B2	> 40 yr	4.6	20	0.75 – 1
5 Lac	HD 213310	K6-M0 I + B7/8	41.95 yr	4.4	5.1	–
HD 203338	V381 Cep Boss 5481	M1 Ib + B2	~ 75 yr	5.2	–	
α Sco	Antares	M1.5 Iab + B2.5 V	2700 yr	5.0	18	0.4





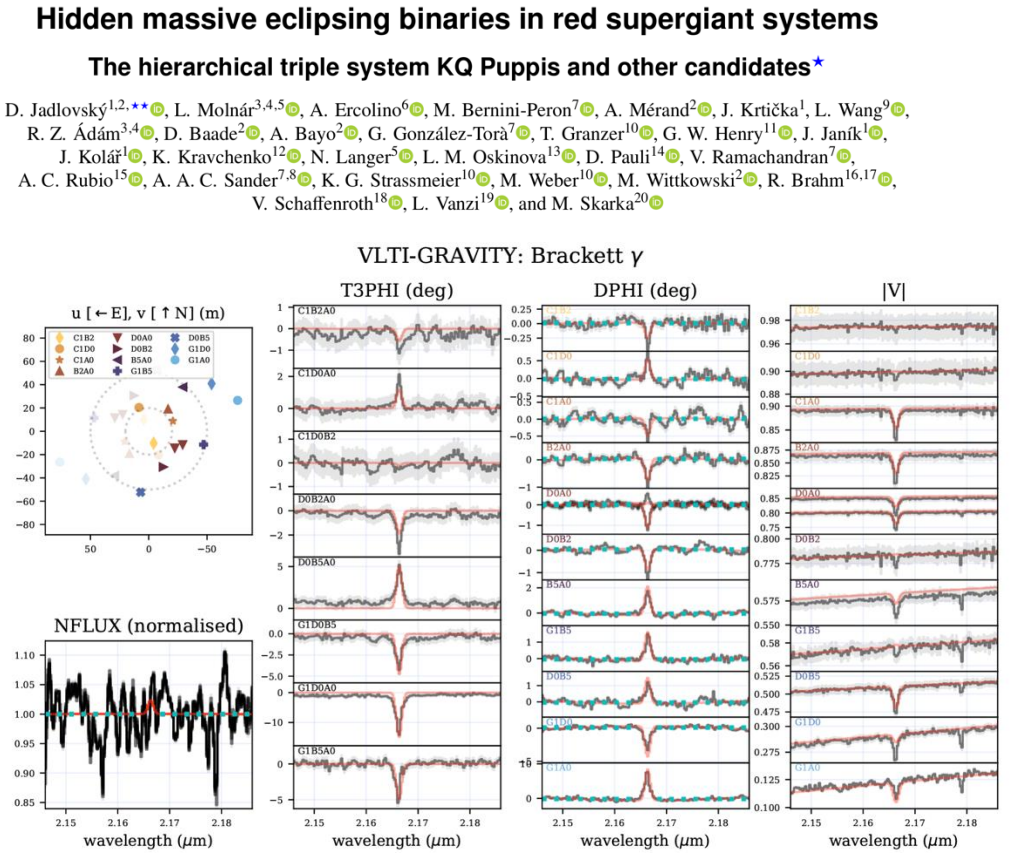
Sources: Ake+2015, Neugent+2018, Patrick+2024

Constraining orbital parameters of interacting systems with VLTI-GRAVITY

KQ Pup (Jadlovský, D., et al., 2026, A&A, 712, A30)

- KQ Pup: interacting RSG system (VV Cephei) with hydrogen emission lines, originating in the accretion disk of the hot companion
- **Brγ emission** in the VLTI-GRAVITY data → relative astrometry of B relative to A → **orbital parameters** (RSG A, ~10 $M_\odot$ + hot companion B, ~14 $M_\odot$)
- wide eccentric orbit (P_{A+B} ~ 26 yr), with accretion to B only during periastron, but the RSG photosphere fills the Roche Lobe only by ~ 70% → **wind Roche-Lobe Overflow** due to the extended atmosphere!

→ VLTI can be used to study RSG binaries, using **Brγ** to trace **wind-accreting companions** and determine astrometric orbits → **masses and parallaxes**



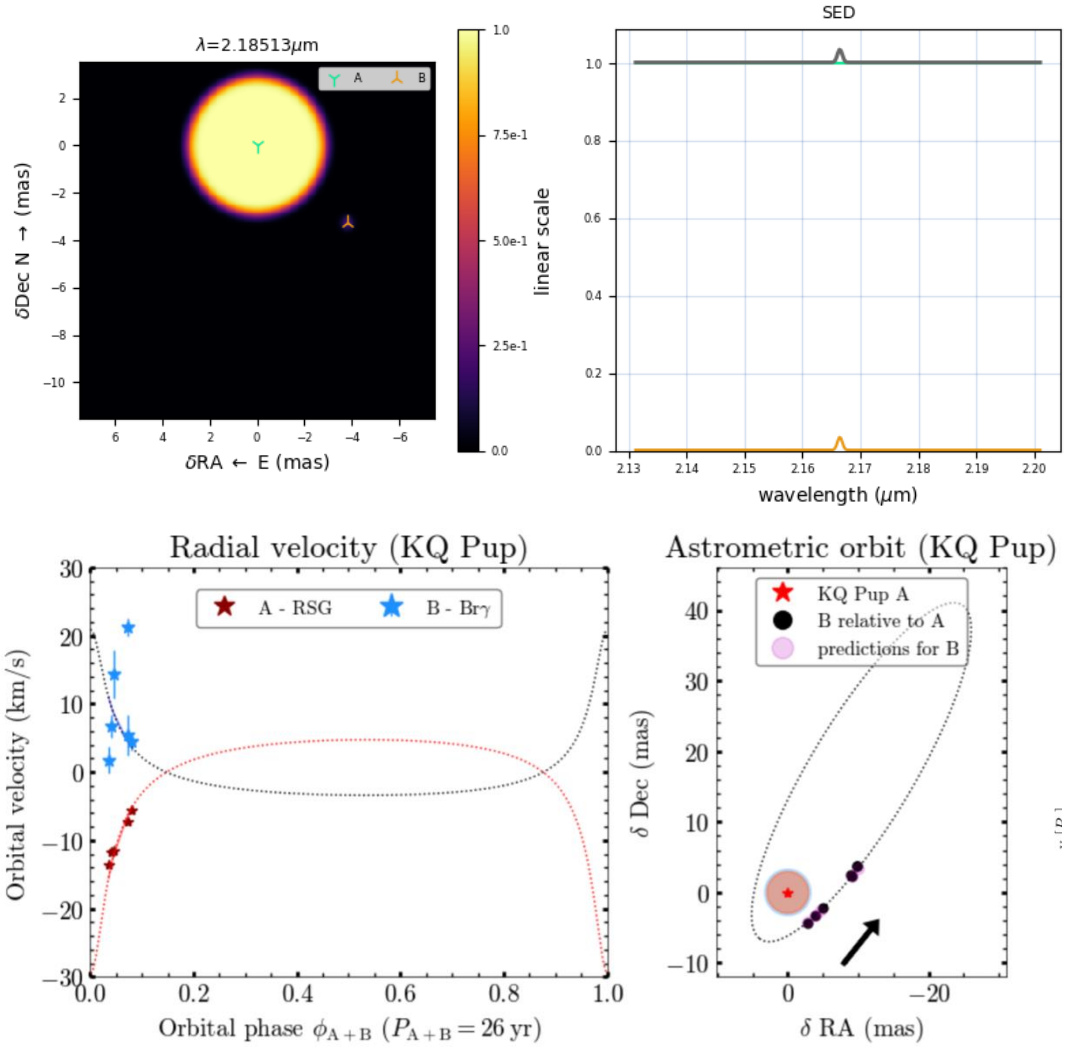
First: detection of Brγ line and relative astrometry with VLTI-GRAVITY data (PMOIRED). Second: astrometric orbit.

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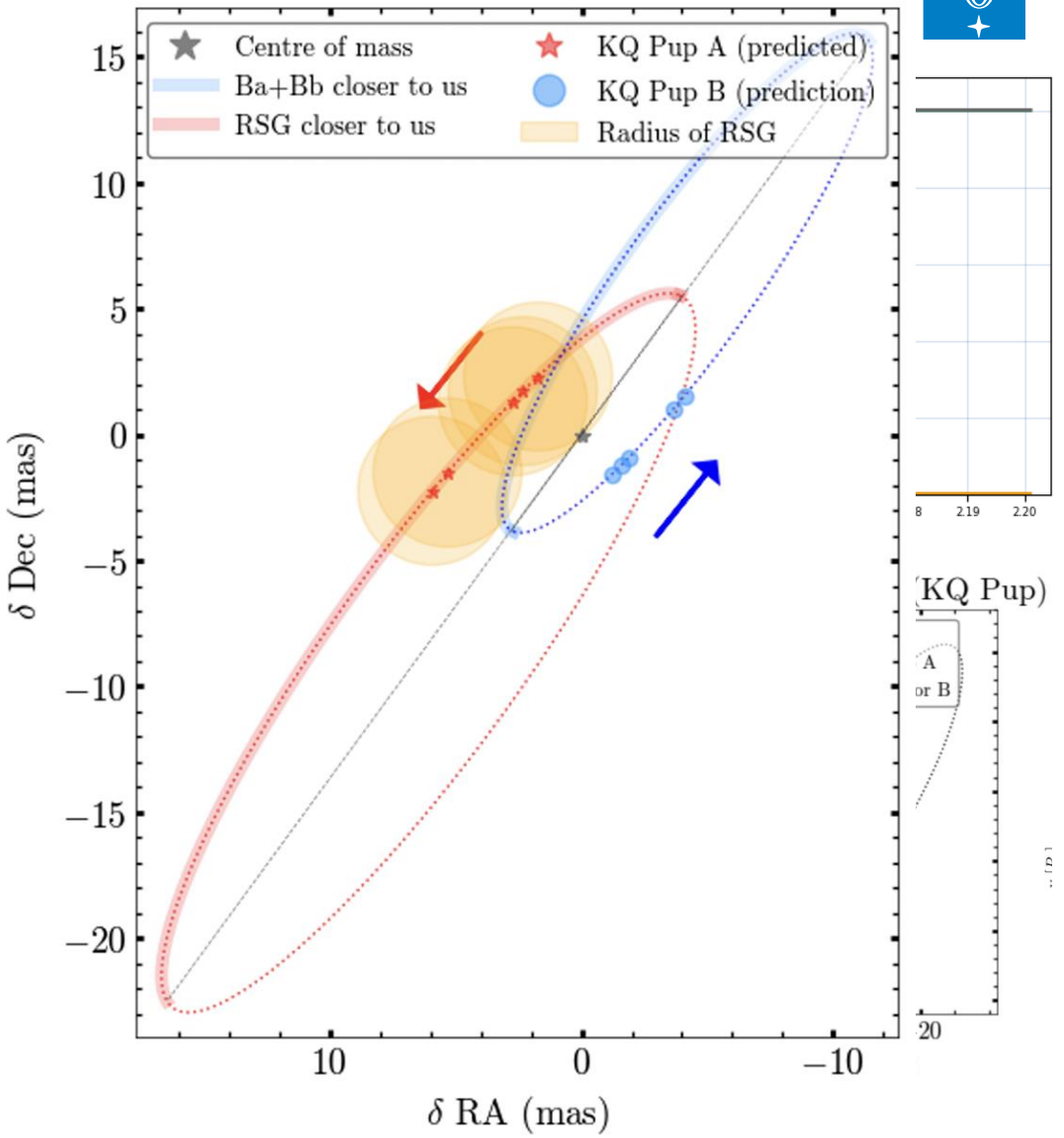
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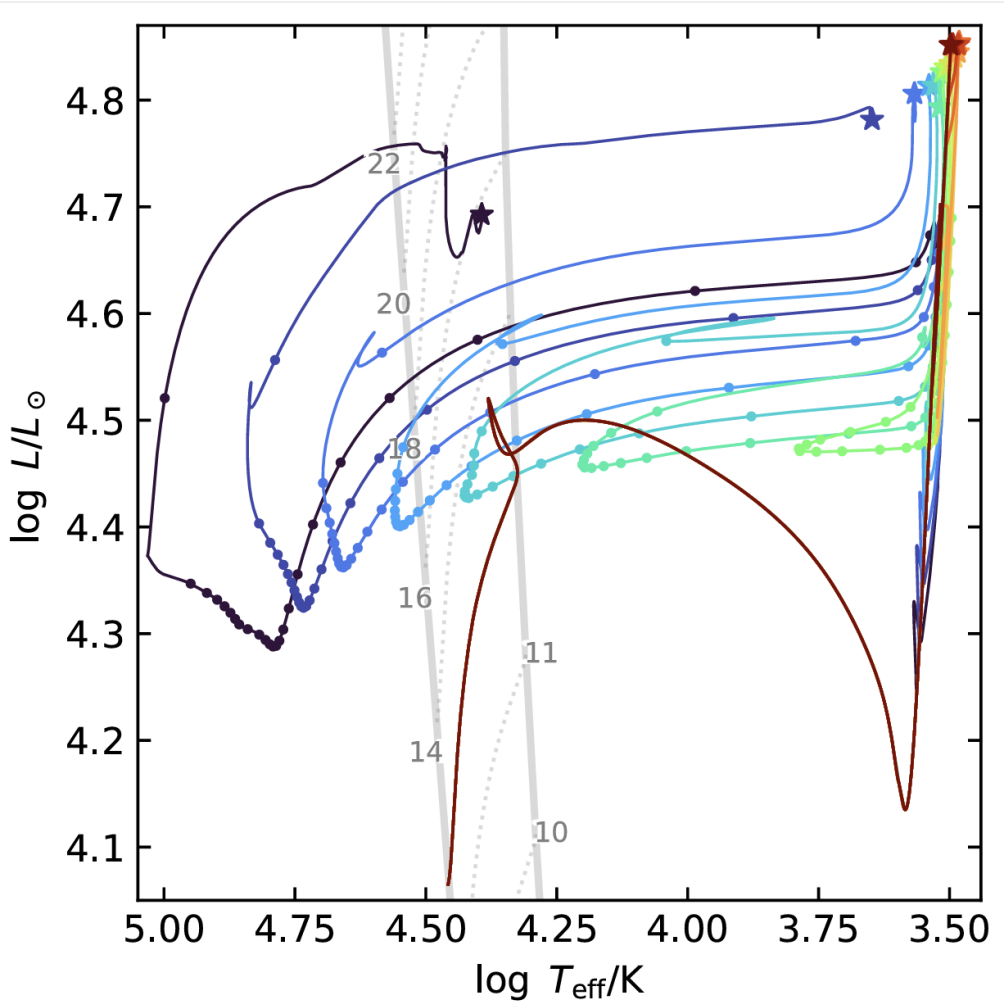


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Extended atmospheres as a paradigm shift in the binary evolution models?

So far neglected - effects of adding extended atmosphere discussed in Ercolino+2024

- binary evolution models typically used only the photospheric radius as a parameter for initiating **Roche Lobe Overflow** (RLOF)
- extended atmosphere → significant increase in the hydrostatic radius, **wind-RLOF**
- Ercolino+2024: considered isothermal stratification (slight increase of radius) → **wider systems can interact**, causing the primary to take „blue loops“
- if the observed extended atmospheres were added (up to ~10 stellar radii), **RSG systems with orbital periods of decades and even hundreds of yrs may interact** → could help explain the *RSG problem?*
- (very) recent results on AGB/symbiotic systems support wind-RLOF: Merc+2025, Drevon+2026

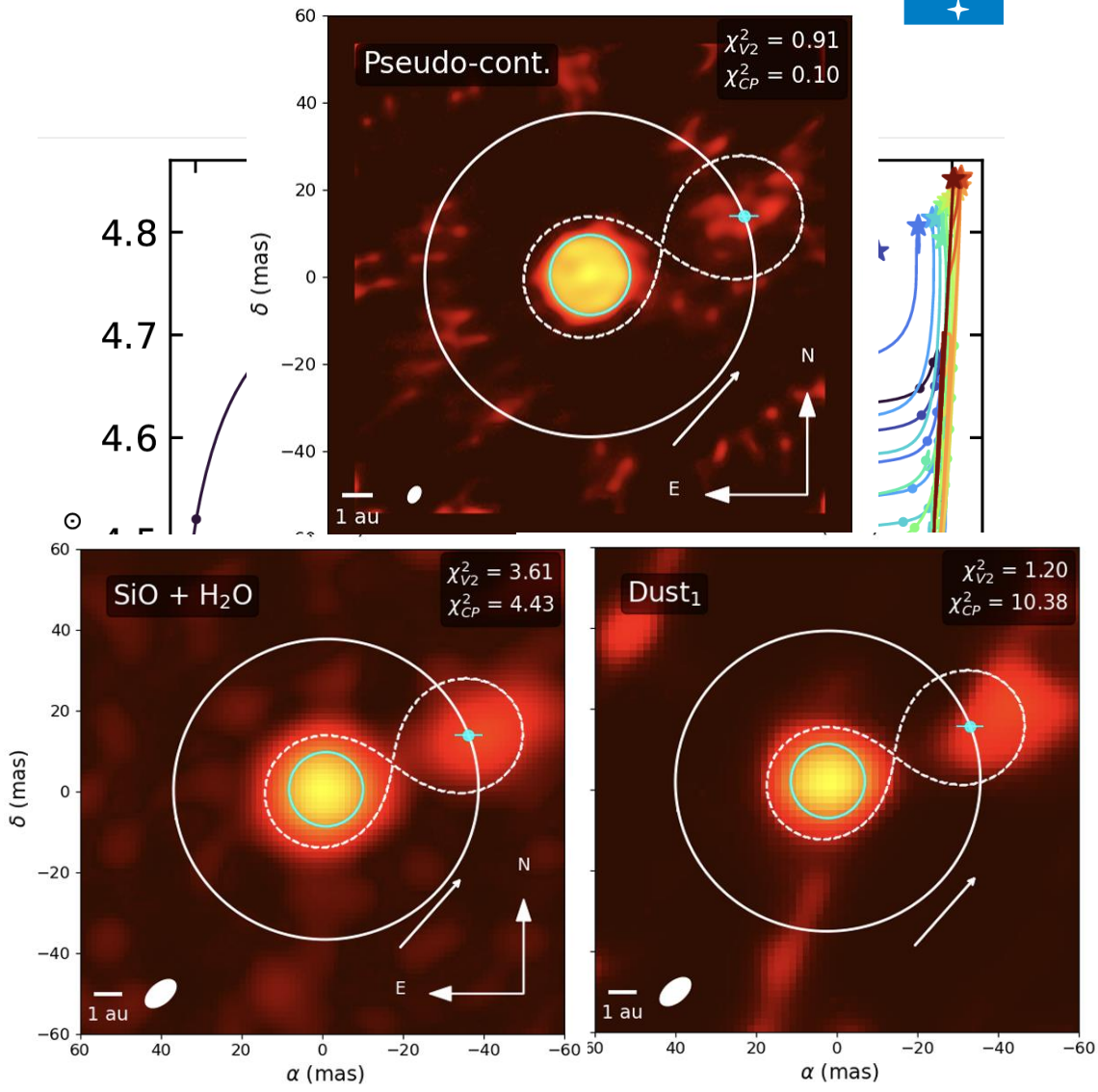


Evolutionary tracks for RSGs in binaries (Ercolino+24), demonstration of wind-RLOF for AGB system π^1 Gru (Drevon+2026).

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Conclusions

VLTI and ALMA play a crucial role in uncovering the mass loss and the hidden companions

- high spectral and angular resolution observations – atmospheric extension in atomic and molecular species (tomography) → constraints on pulsations, winds, and propagation of shocks
- our **VLTI-GRAVITY sample of RSGs**: statistical properties of the RSG population → calibrating the pulsation and evolutionary models + improving our knowledge of the mass-loss process
- RSGs often show low-amplitude overtone oscillations → high-cadence observations required
- **stable mass loss** for Miras vs **episodic mass-loss events** for RSGs → do RSGs require large-amplitude pulsation (and mode changes FM ←→ 1O) to drive the wind?
- new 1D and 3D models with extended atmosphere and molecules/dust can better reproduce the interferometric observations (e.g., González-Torà+2023, 2024, Freytag+2024)
- **GRAVITY+ upgrade:** fainter and more distant AGB and RSG stars are now accessible to VLTI
- **Gaia DR4/DR5**: expected to detect many new hidden companions (for typical orbits of $\gtrsim$ 5 yr)

Thank you!

Finishing my PhD next year (summer 2027); interested to hear about postdoc opportunities ☺

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Bonus slides