Cool luminous stars: modelling their dynamical atmospheres and dusty winds

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in collaboration with
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and other members of the
EXWINGS* team

* EXplaining the WINds of cool Giant and Supergiant stars with global 3D models

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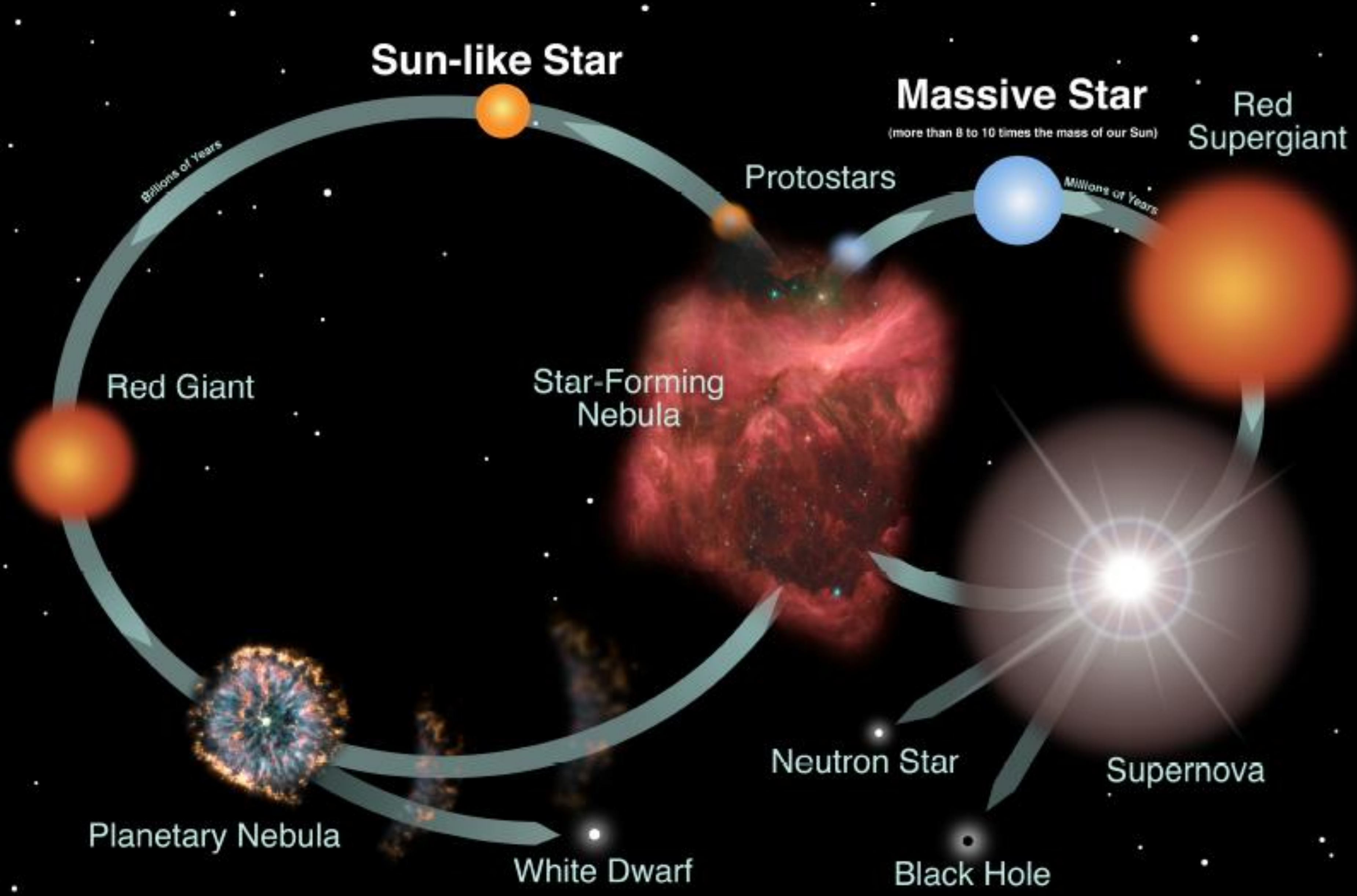
Cosmic Music - AnnKarina Vesterberg

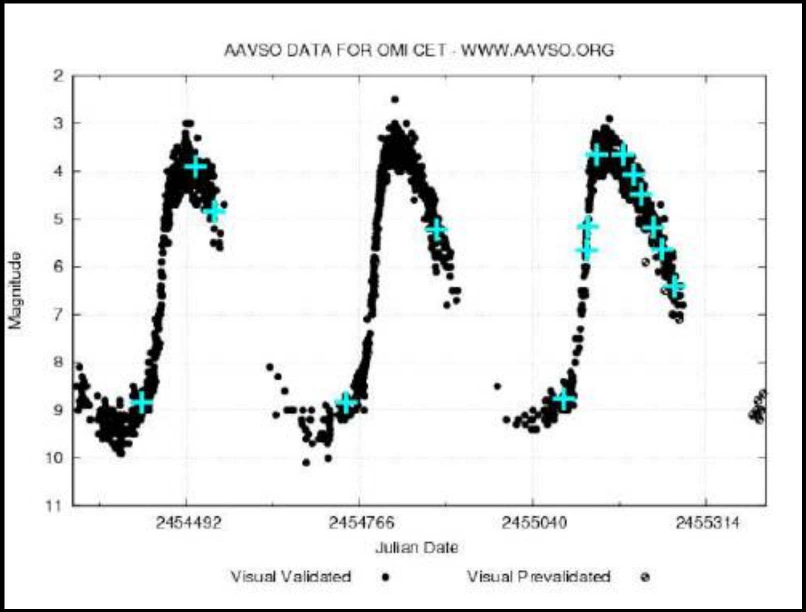
The life cycle of stars

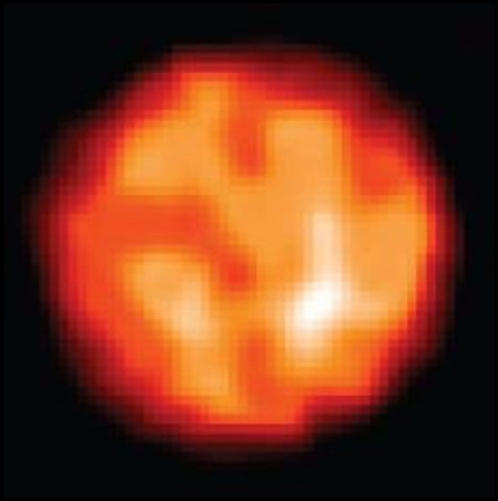


AGB stars: dynamical processes

- large-scale convection
- long-period pulsations
- atmospheric shocks
- dusty stellar winds

–> heavy mass loss

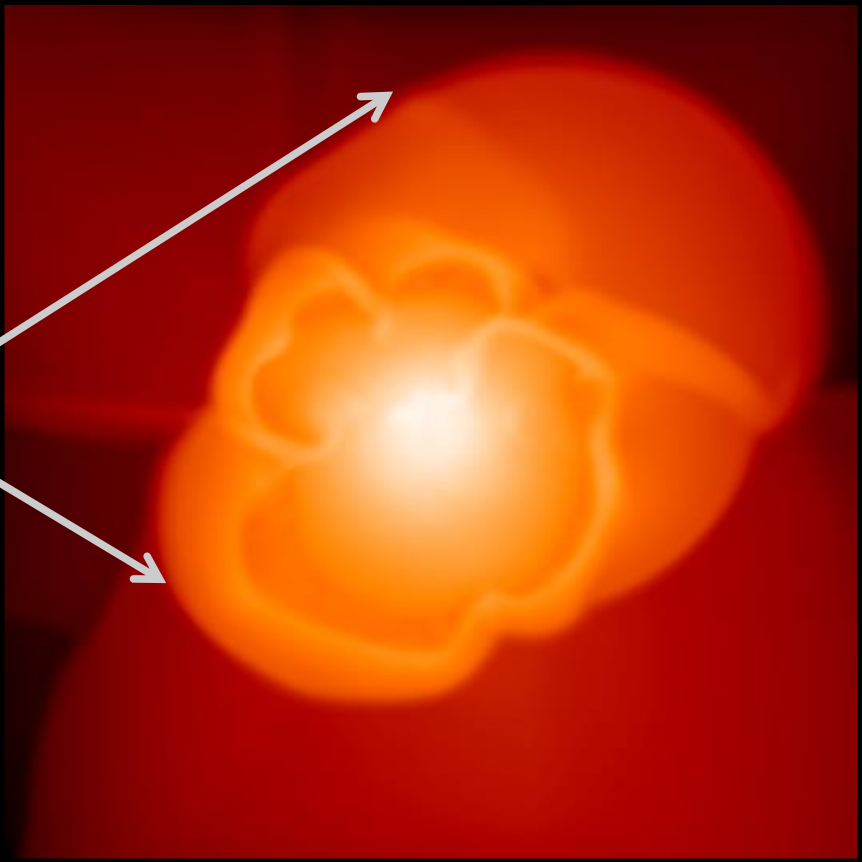




pi[1] Gru: H-band image reconstructed from VLTI/PIONIER data (Paladini et al. 2018)

Dust-driven winds: Ingredients

stellar pulsation
& convection
induce strong
shock waves
which propagate
outwards through
the gas
in the extended
stellar atmosphere

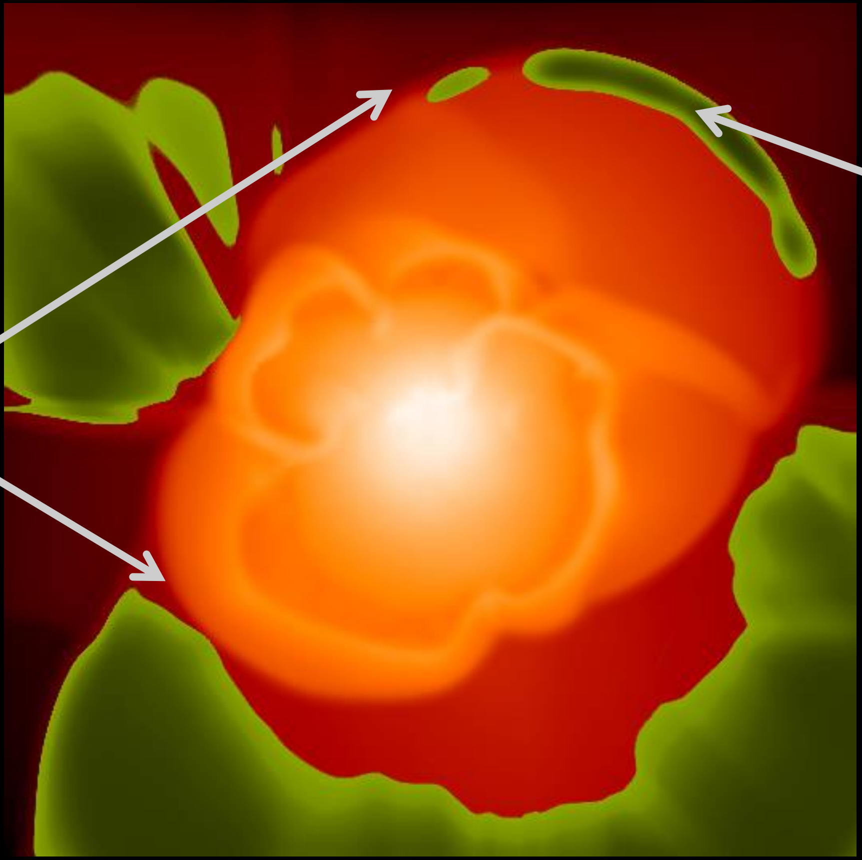


3D RHD model by Freytag & Höfner (2008)

Recent review on mass loss of AGB stars: Höfner & Olofsson (2018)

Dust-driven winds: Ingredients

stellar pulsation & convection induce strong shock waves which propagate outwards through the gas in the extended stellar atmosphere



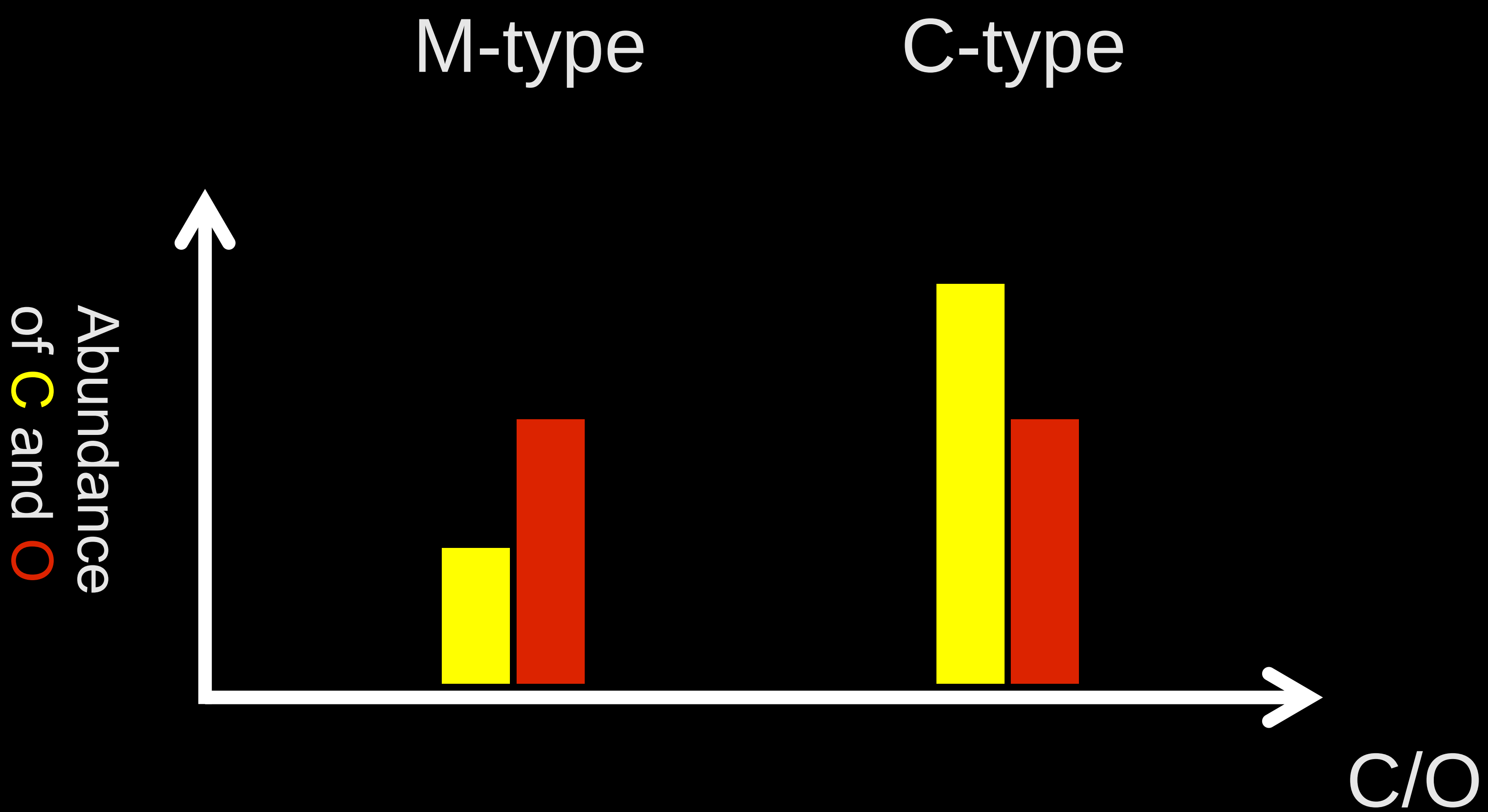
3D RHD model by Freytag & Höfner (2008)

dust forms in the wake of the shock at distances of 2-3 stellar radii and is accelerated outwards by radiation pressure, triggering a wind

PEDDRO scenario: Pulsation-Enhanced Dust-DRiven Outflow

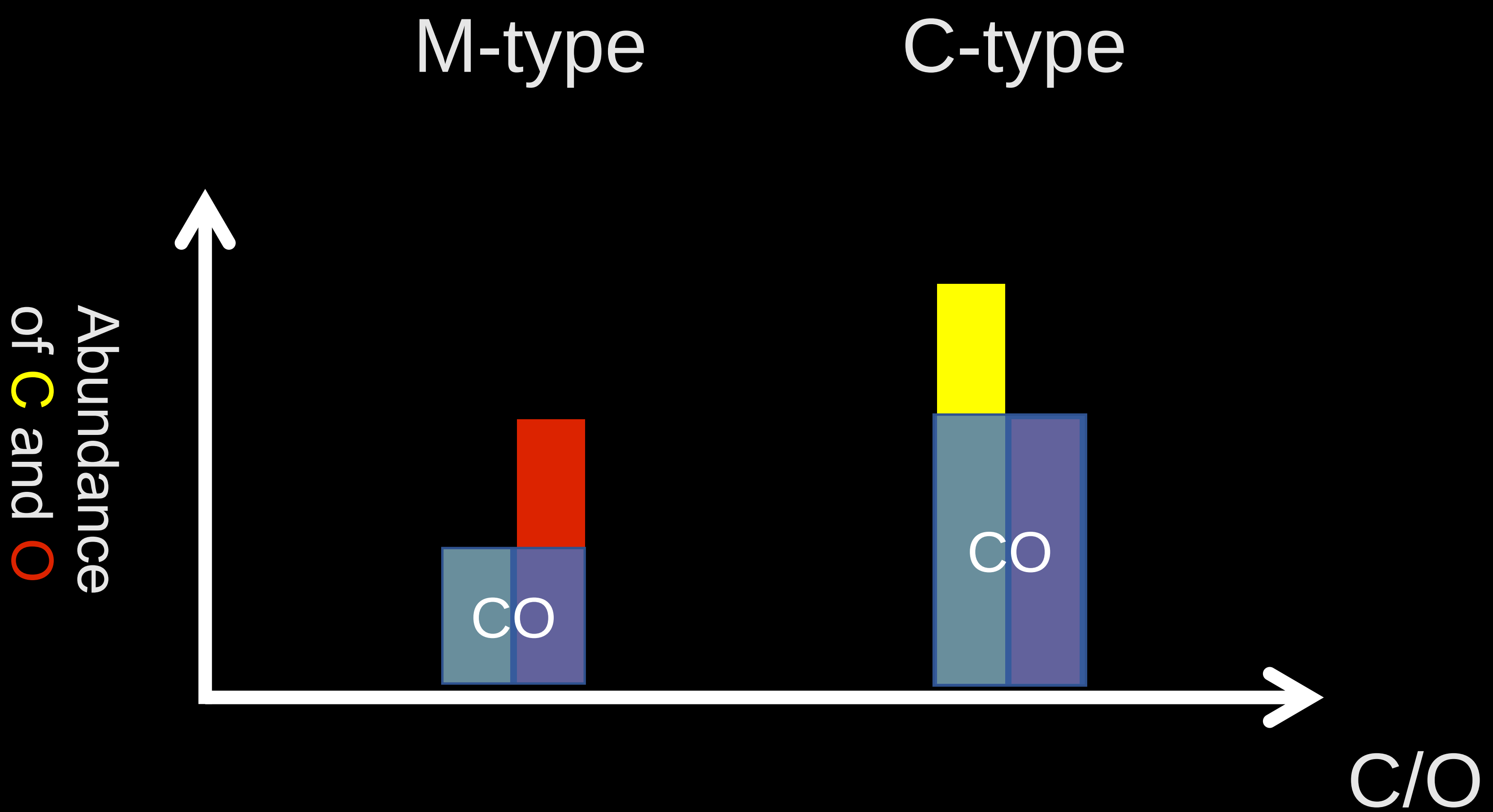
Recent review on mass loss of AGB stars: Höfner & Olofsson (2018)

Dust chemistry: the role of C/O



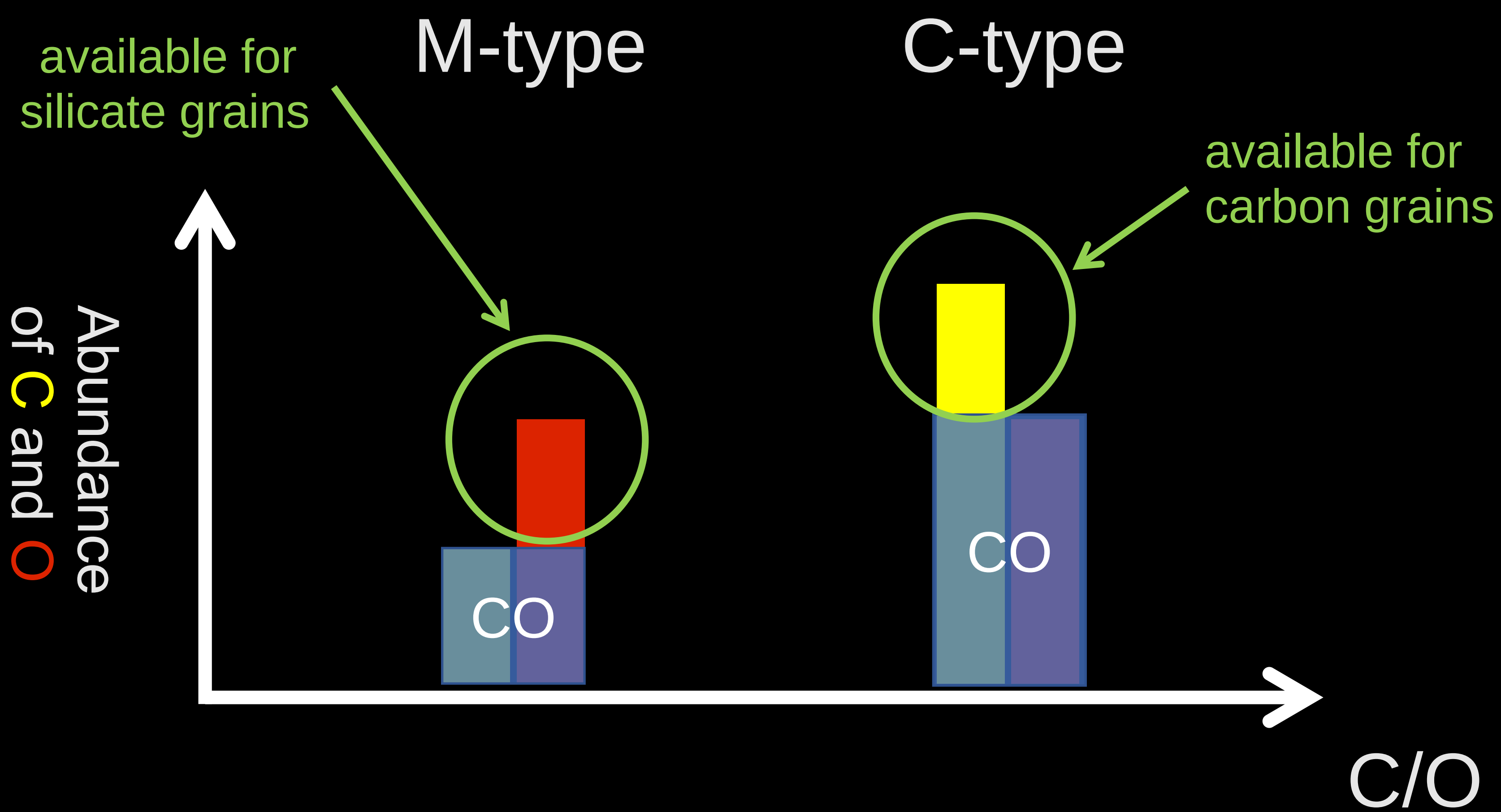
... changes during AGB evolution

Dust chemistry: the role of C/O



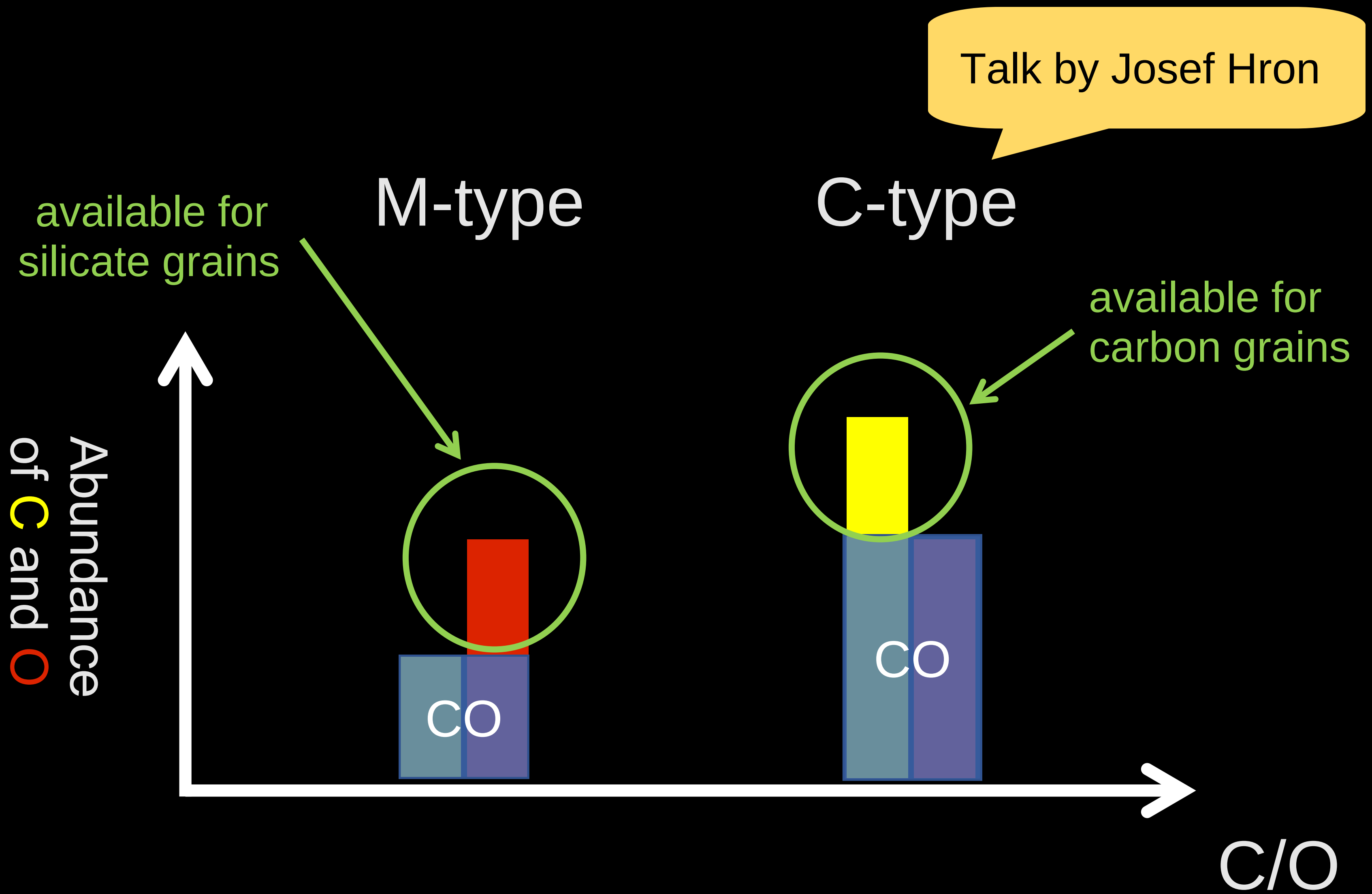
... changes during AGB evolution

Dust chemistry: the role of C/O



... changes during AGB evolution

Dust chemistry: the role of C/O

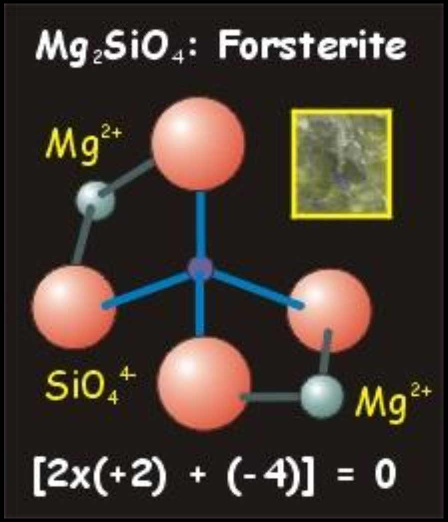


... changes during AGB evolution

Candidates for wind-driving grains

Observations of spectral features
at wavelengths of about 10 and 18 microns
in M-type AGB stars suggest
olivine- and/or pyroxene-type silicates

$Mg_{2x}Fe_{2(1-x)}\ SiO_4$ $Mg_xFe_{(1-x)}\ SiO_3$



- silicates consist of abundant elements
- can form at high temperatures
- typical Fe/Mg ratio ?

Composition of wind-driving grains

Mg_2SiO_4 $Fe_2\,SiO_4$

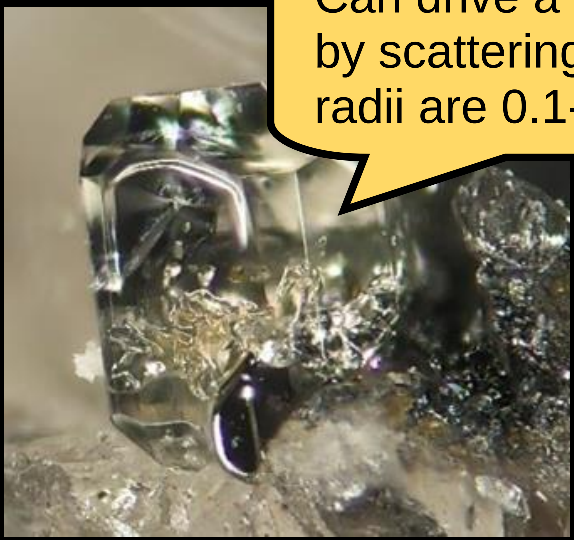
Mg-rich 1 ← X → 0 Fe-rich

low absorption high absorption
at visual and near-infrared wavelengths

dust temperature & condensation distance
smaller larger

Composition of wind-driving grains

Can drive a wind
by scattering if particle
radii are 0.1-1 micron



Mg_2SiO_4 $Fe_2\ SiO_4$

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Quantitative dynamic models

Dynamics

- pulsation & convection
- strong shock waves
- wind acceleration

Dust

- seed particles
- grain growth
- grain destruction

Radiation

- variable luminosity
- molecular opacities
- dust opacities

Wind properties

- mass loss rates
- wind velocities
- dust yields

Synthetic observables

- high-/low-res spectra
- light curves
- interferometric data

Quantitative dynamic models

Dynamics

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- variable luminosity
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3D RHD CO5BOLD* models

developed by Freytag et al.

interior & atmospheric dynamics (convection, pulsation, shocks); onset of dust-driven wind

necessary to study turbulence, and origin of complexity but computationally costly

* The kobold (occasionally cobold) is a sprite stemming from Germanic mythology. Most commonly, the creatures are house spirits of ambivalent nature; while they sometimes perform domestic chores, they play malicious tricks if insulted or neglected. (Source: Wikipedia)

Quantitative dynamic models

Dynamics

- pulsation & convection
- strong shock waves
- wind acceleration

Dust

- seed particles
- grain growth
- grain destruction

Radiation

- variable luminosity
- molecular opacities
- dust opacities

1D RHD DARWIN* models

Höfner et al. (2016, 2022)

dynamics of the atmosphere,
shocks and dust-driven wind,
parameterized pulsation effects

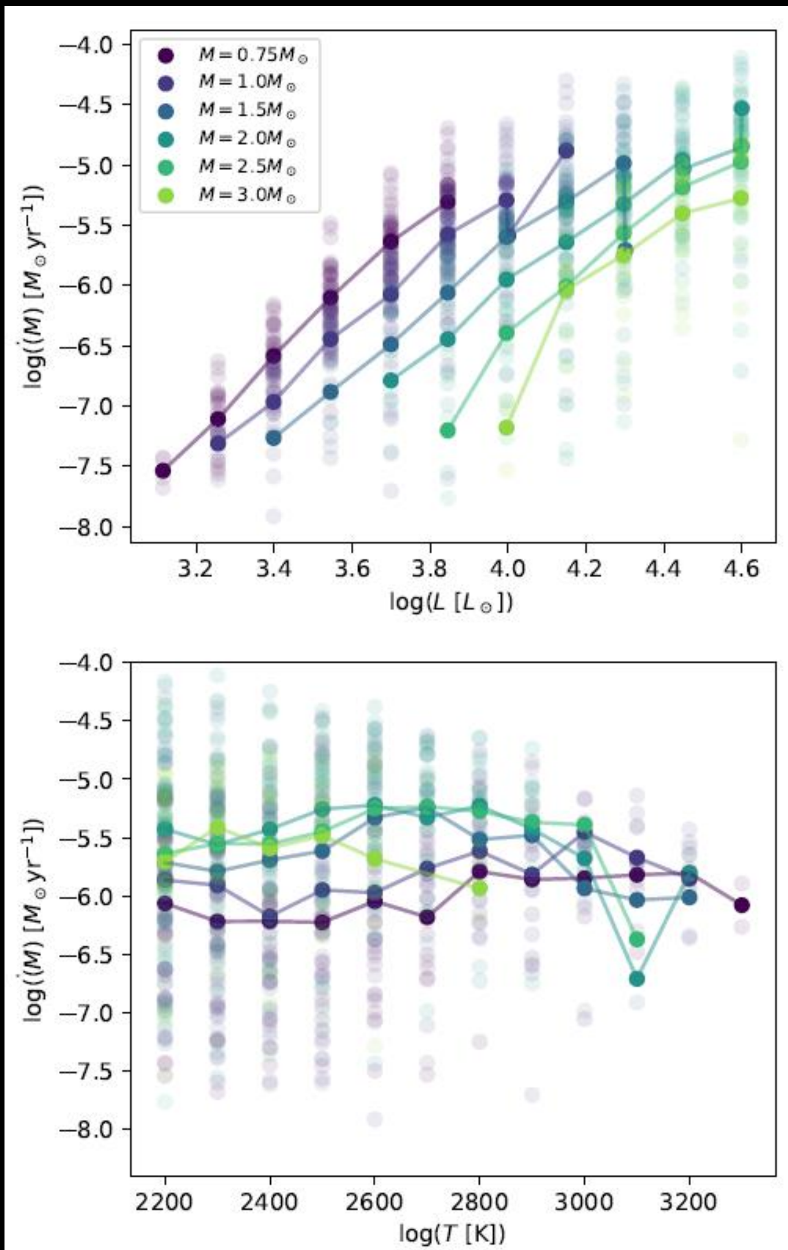
efficient → large grids
covering stellar parameter space

applications:

→ mass loss rates, spectra
→ stellar evolution
→ origin of chemical species

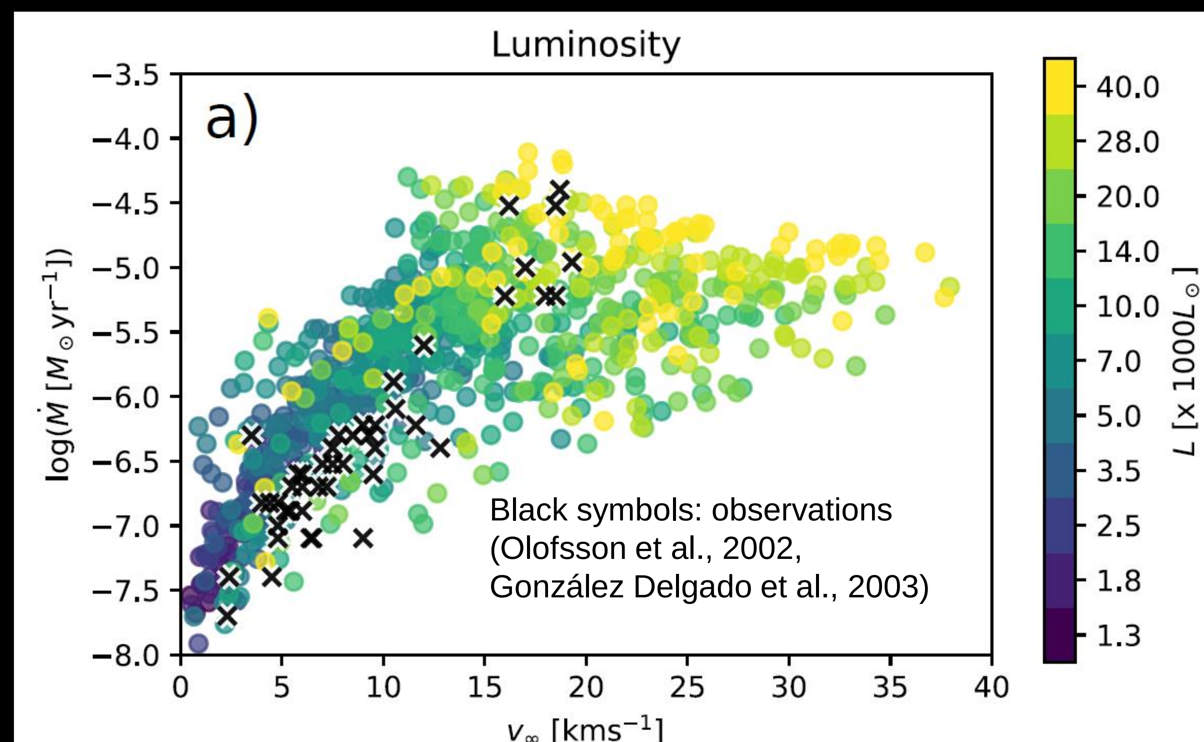
* Dynamic Atmosphere & Radiation-driven Wind models with Implicit Numerics

Dust-driven winds: DARWIN models

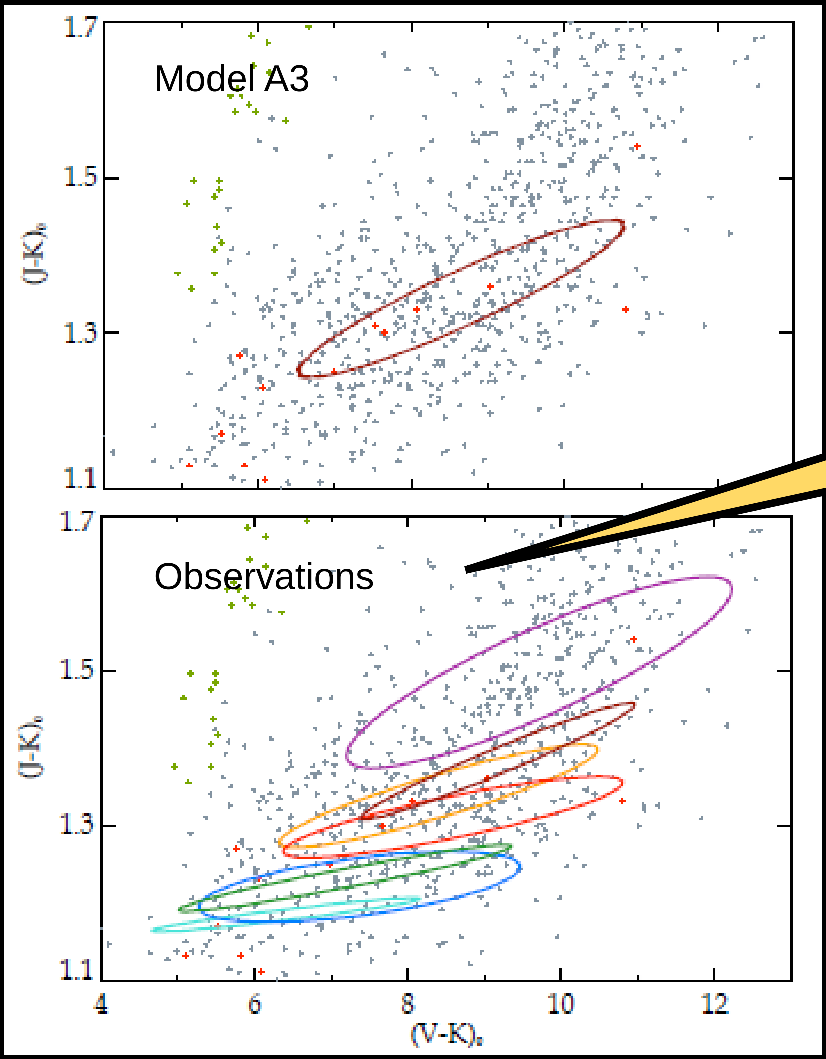


Winds driven by photon scattering on silicate grains with sizes of 0.1–1 micron (Höfner 2008, Bladh et al. 2015, 2019)

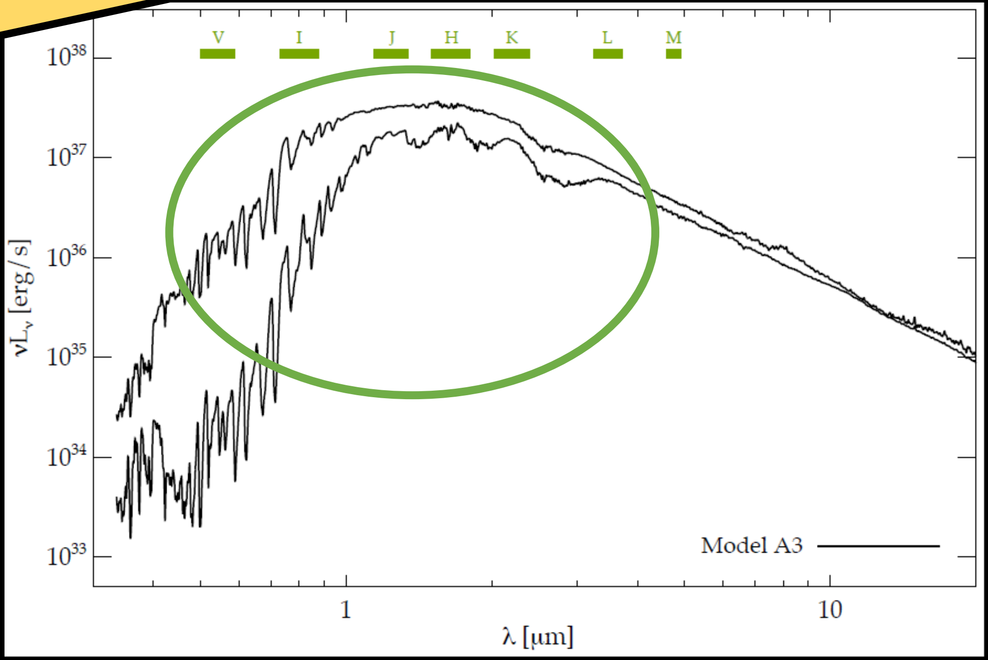
Large model grids predicting mass loss rates, wind velocities and dust properties for given stellar parameters and pulsation properties (period, amplitude)



Dust-driven winds: DARWIN models

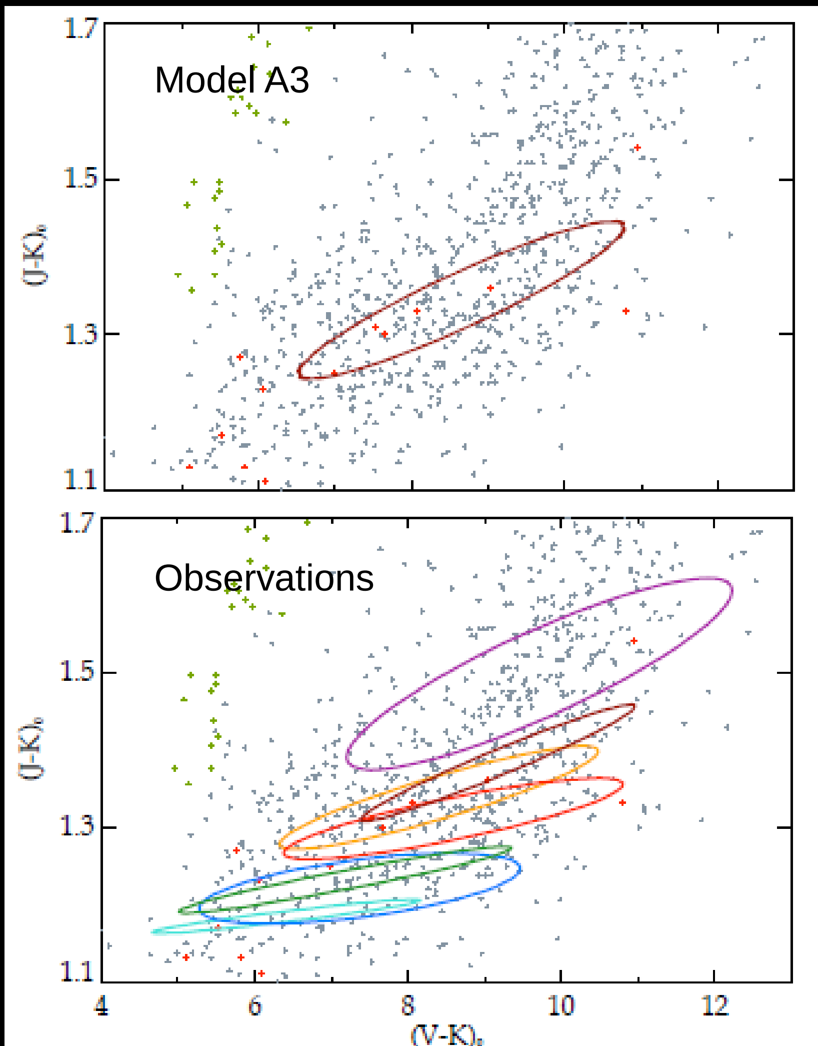


large variation with pulsation phase in (V-K) due to molecular features, but small variation in (J-K), indicates wind-driving grains with low absorption in visual and NIR (Mg_2SiO_4)

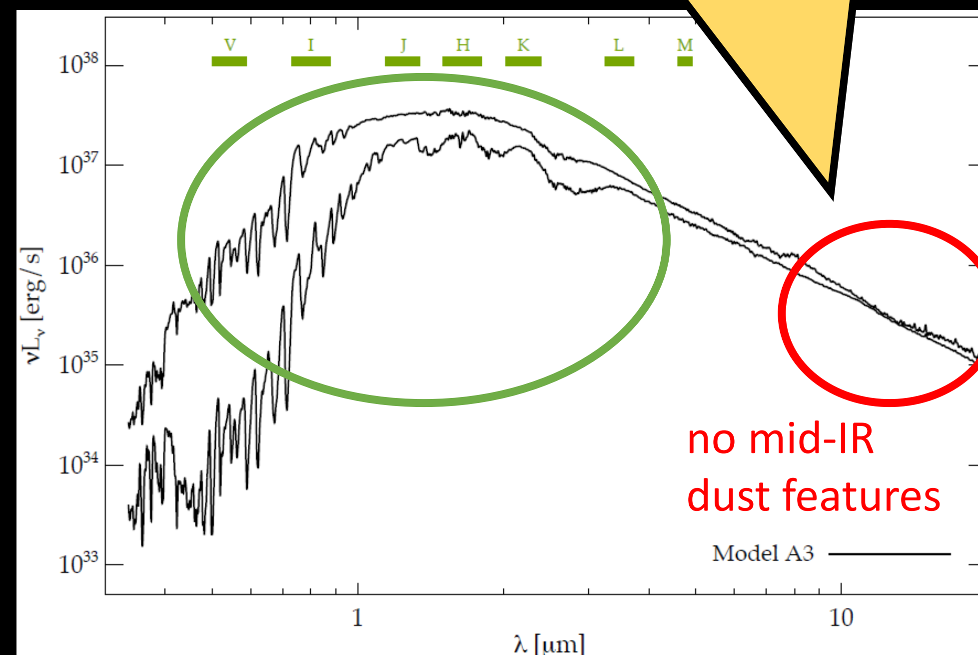


Models of winds driven by photon scattering on Fe-free silicate grains with sizes of 0.1–1 micron show realistic mass loss rates & wind velocities, V and near-IR spectra & photometry (Höfner 2008, Bladh et al. 2015, 2019)

Dust-driven winds: DARWIN models



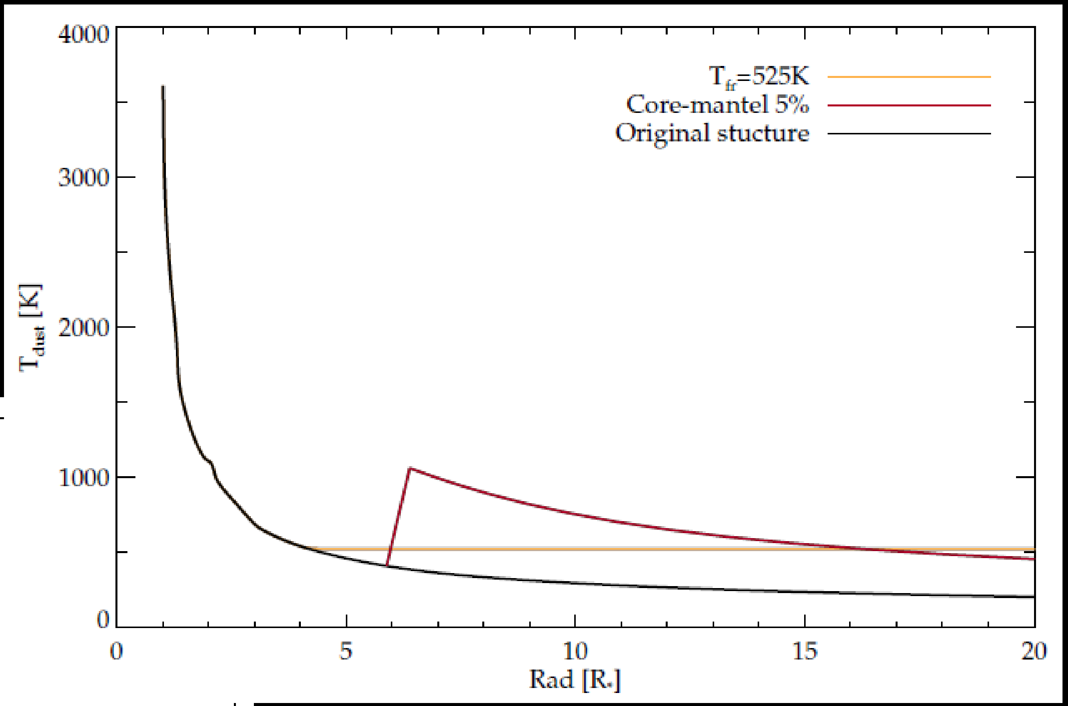
Low temperature of pure Mg_2SiO_4 grains due to low near-IR absorption, no discernible mid-IR features ...

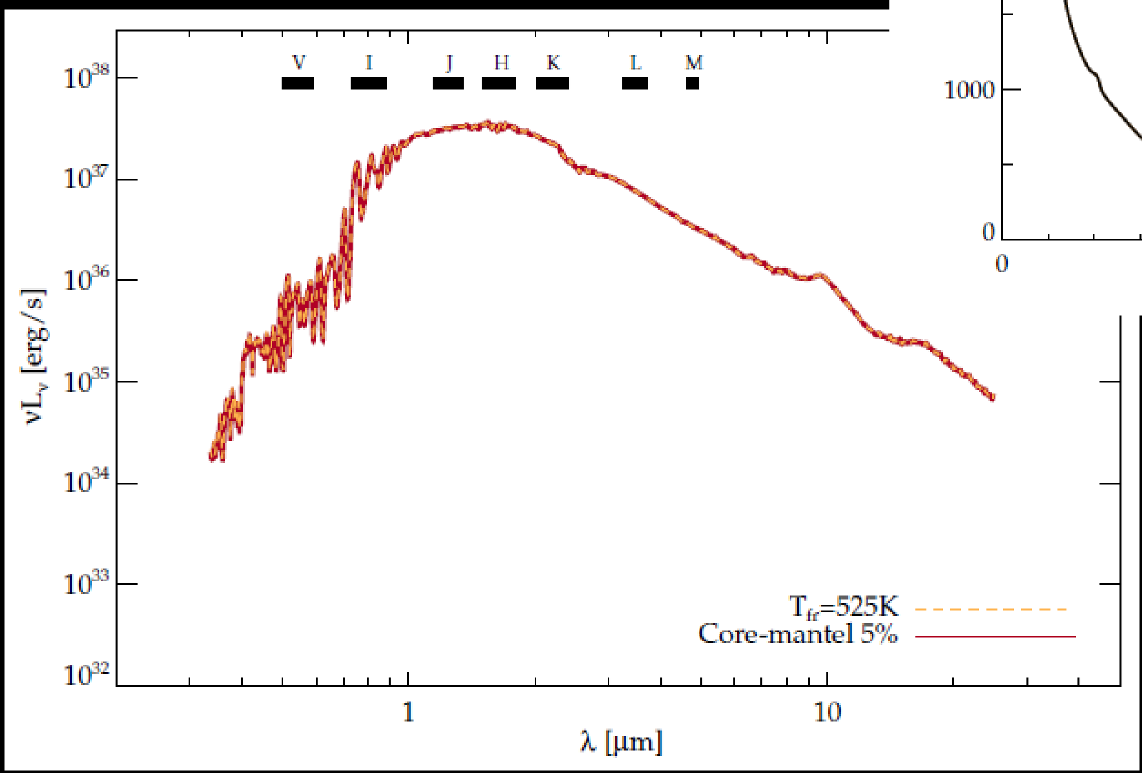


Models of winds driven by photon scattering on Fe-free silicate grains with sizes of 0.1–1 micron show realistic mass loss rates & wind velocities, V and near-IR spectra & photometry (Höfner 2008, Bladh et al. 2015, 2019)

Silicate features: Effects of Fe/Mg

Models with different dust temperature structures (different Fe-enrichment scenarios), but similar SED





MIR interferometry can distinguish different scenarios (Bladh et al. 2017)

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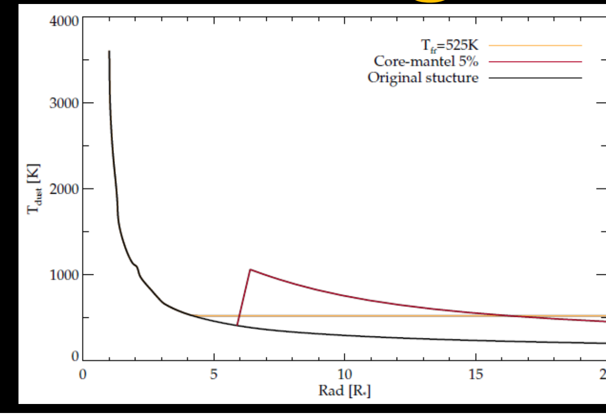


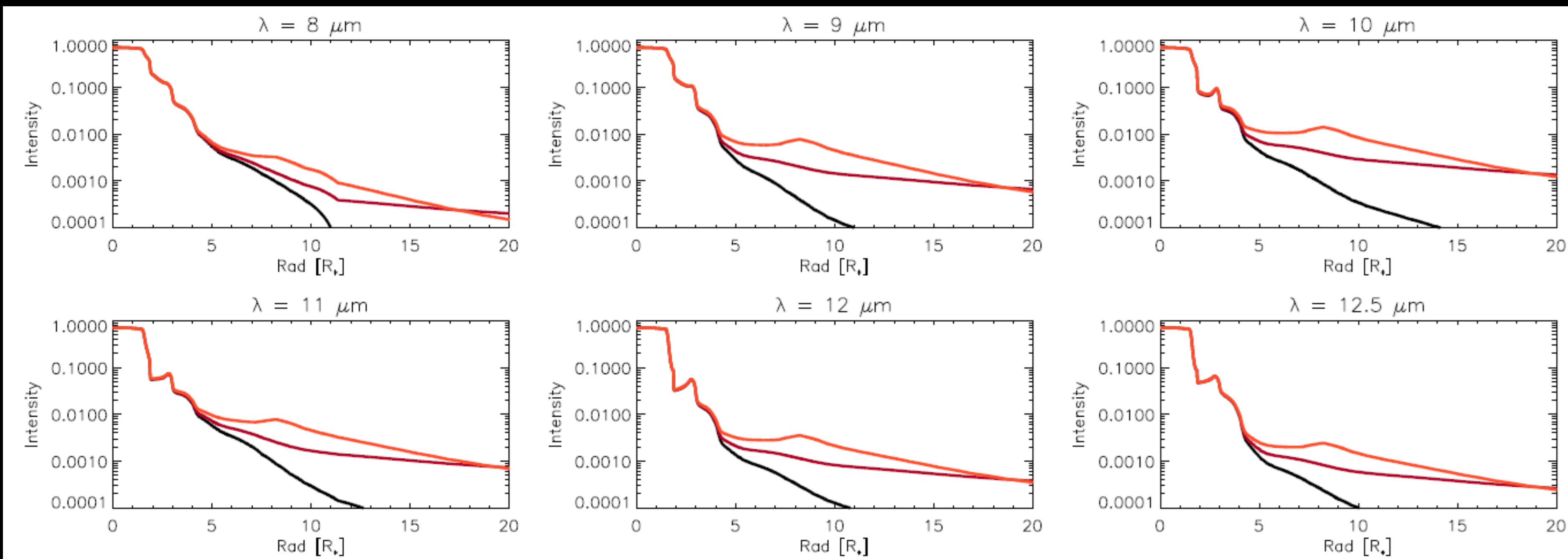


Fig. 6. Spatial intensity profile for the models shown in Fig. 4 (maximum luminosity phase). Every panel corresponds to a wavelength in the N-band interval [8-13 μm]. The red curve is from a snapshot with core-mantel grains of 5% thickness. The orange curve show the results from fitting the core-mantel spectra with snapshots of the atmosphere where we set the lower limit for the grain temperature to and 525 K.

MIR interferometry can distinguish different scenarios (Bladh et al. 2017)

Silicate features: Effects of Fe/Mg

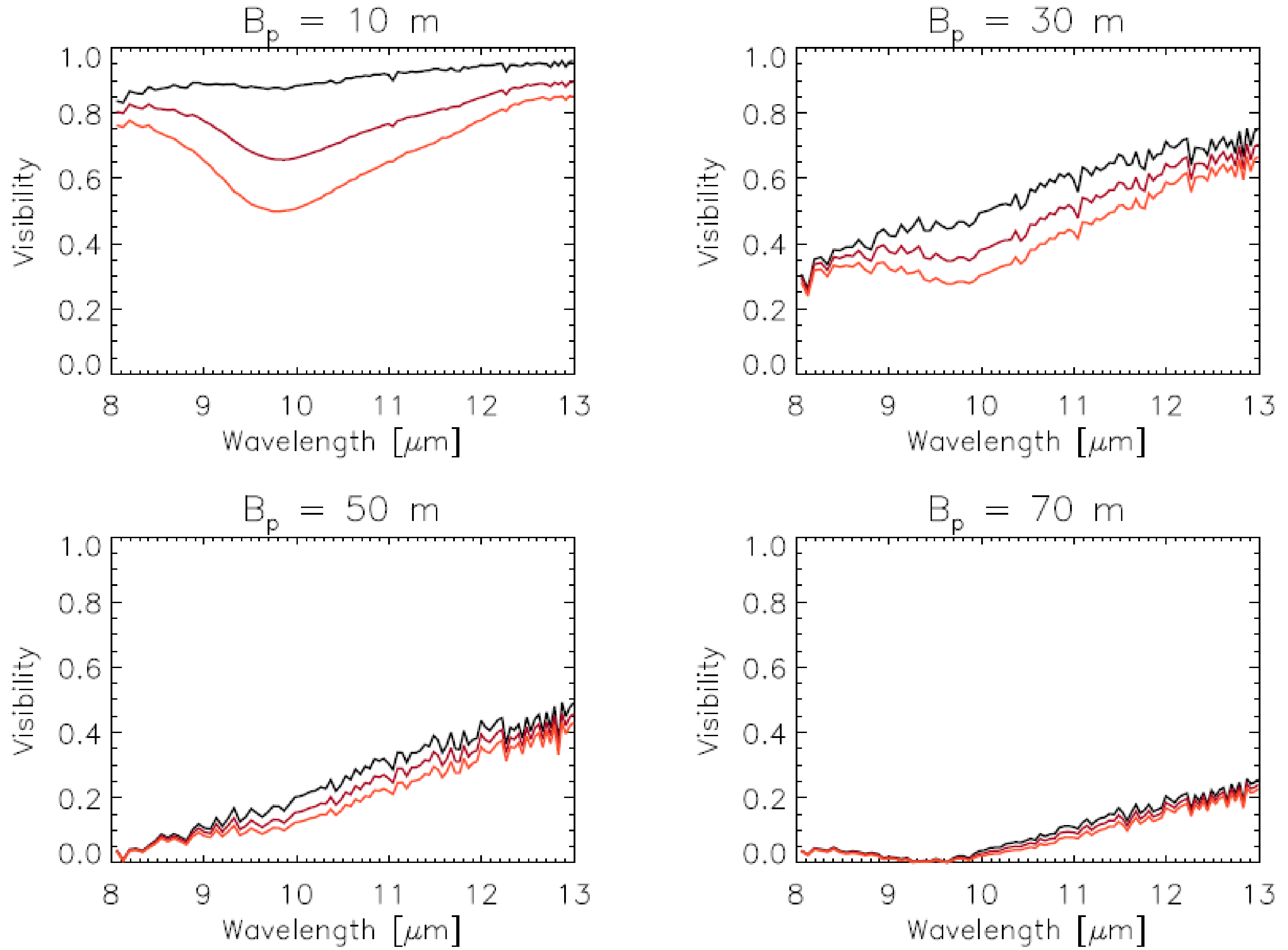
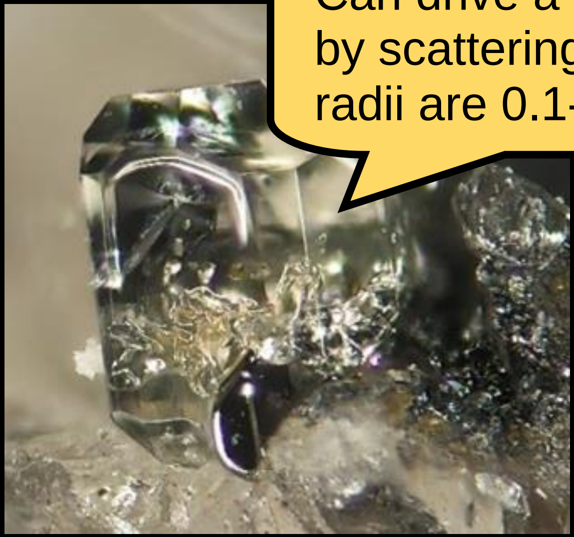


Fig. 7. Visibility spectrum across the N-band for the models shown in Fig. 4 (maximum luminosity phase). The panels represent observations simulated with different projected baselines (B_p = 10, 30, 50, and 70 m) regularly offered on the VLTI facility. Same color-coding as in Fig. 6.

MIR interferometry can distinguish different scenarios (Bladh et al. 2017)

Composition of wind-driving grains

Can drive a wind
by scattering if particle
radii are 0.1-1 micron



Mg_2SiO_4 $Fe_2\ SiO_4$

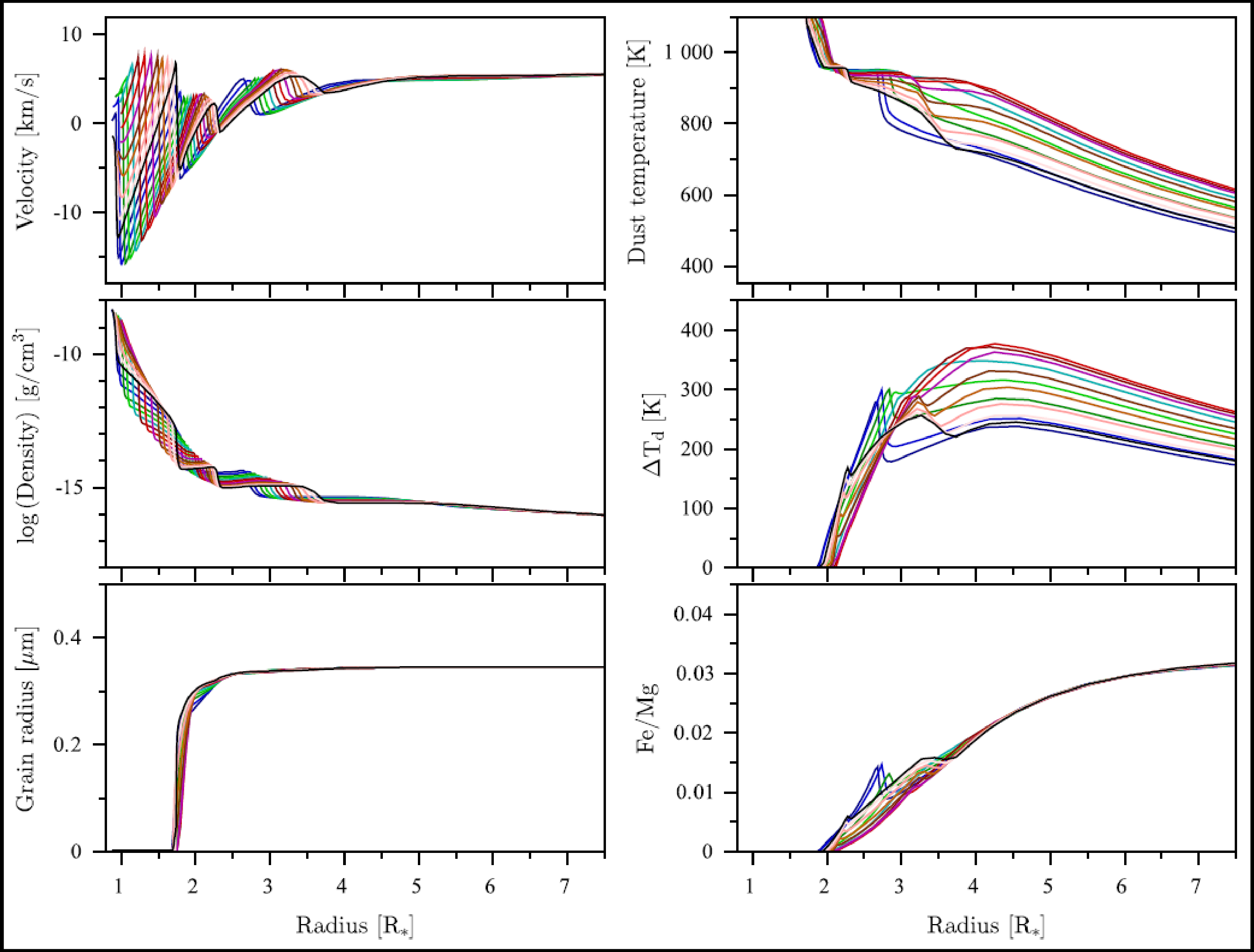
Mg-rich $1 \leftarrow X \rightarrow 0$ Fe-rich

low absorption high absorption

at visual and near-infrared wavelengths

Allow for Fe-enrichment of the wind-driving silicate grains,
subject to thermal stability → determine X from models

Composition of wind-driving grains



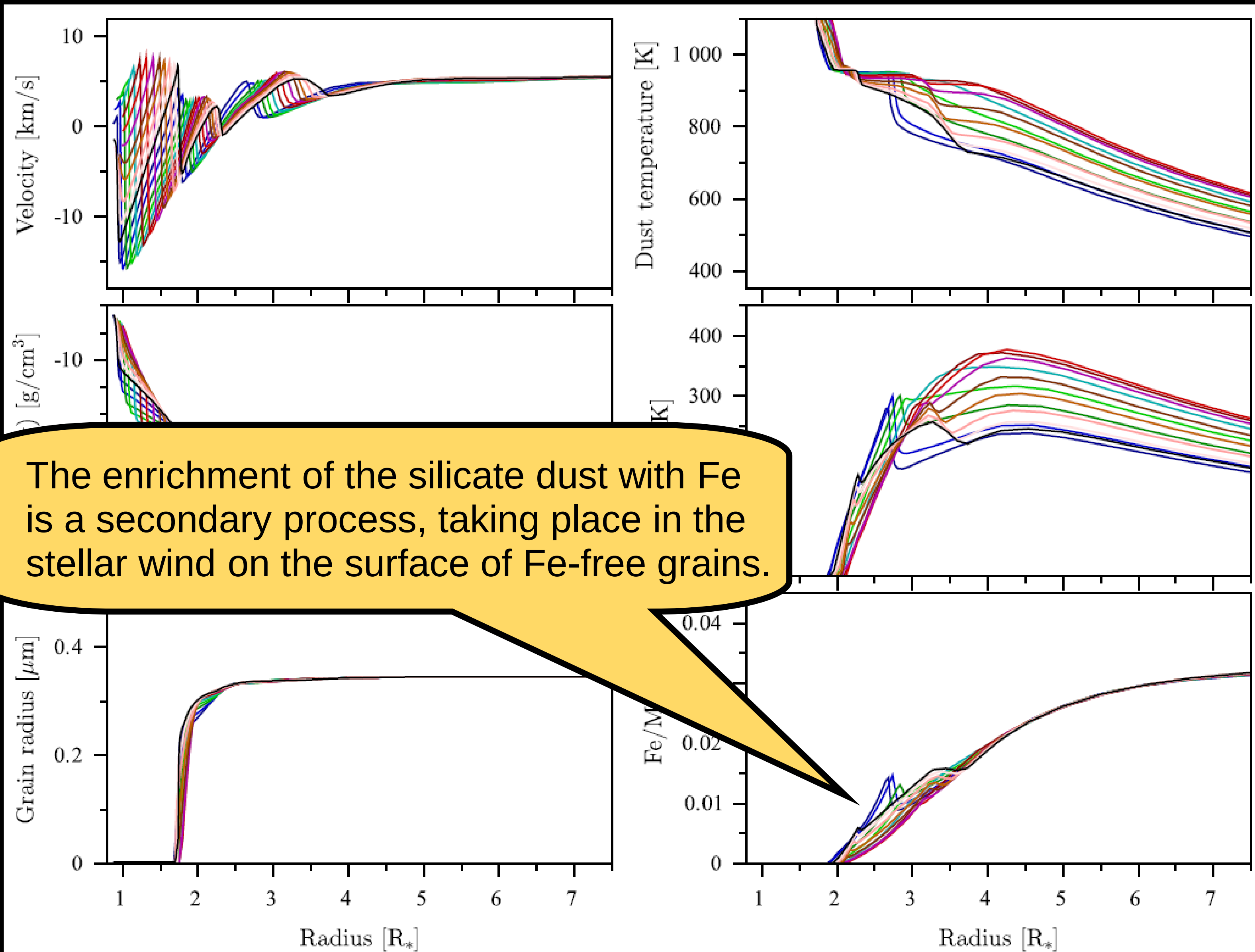
DARWIN models:

growth of silicate grains with variable Fe/Mg, self-regulation via grain temperature

Höfner et al., (2022)

Radial structure at different pulsation phases

Composition of wind-driving grains



The enrichment of the silicate dust with Fe is a secondary process, taking place in the stellar wind on the surface of Fe-free grains.

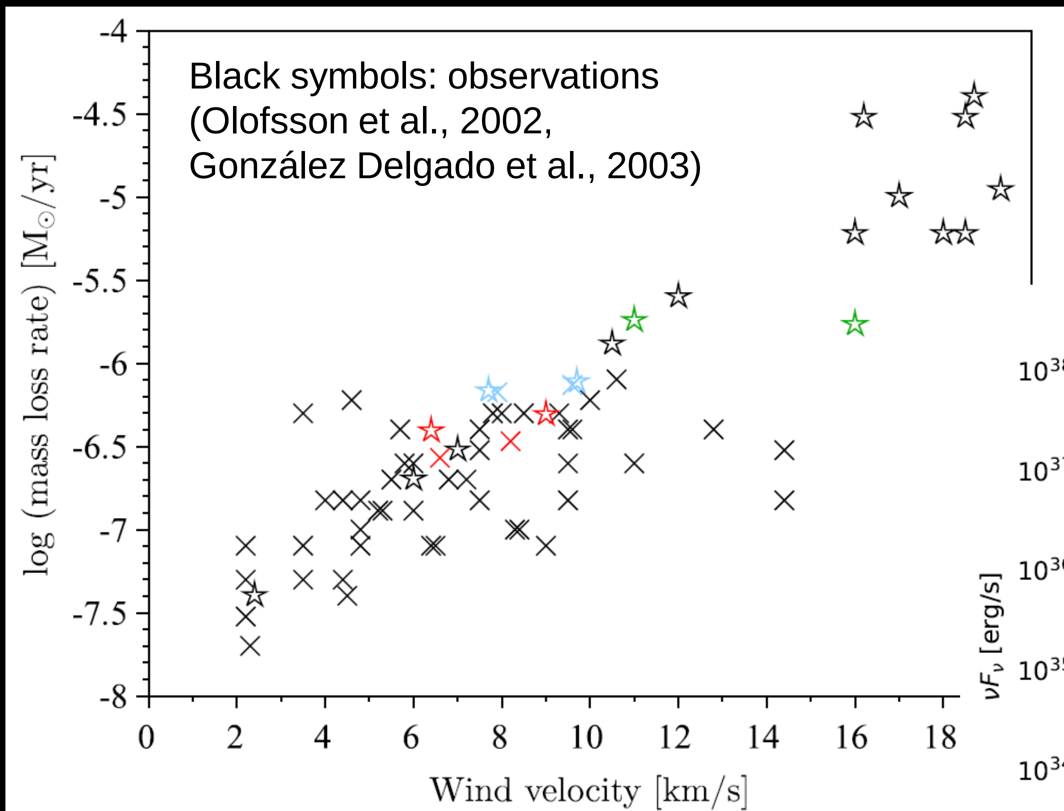
DARWIN models:

growth of silicate grains with variable Fe/Mg, self-regulation via grain temperature

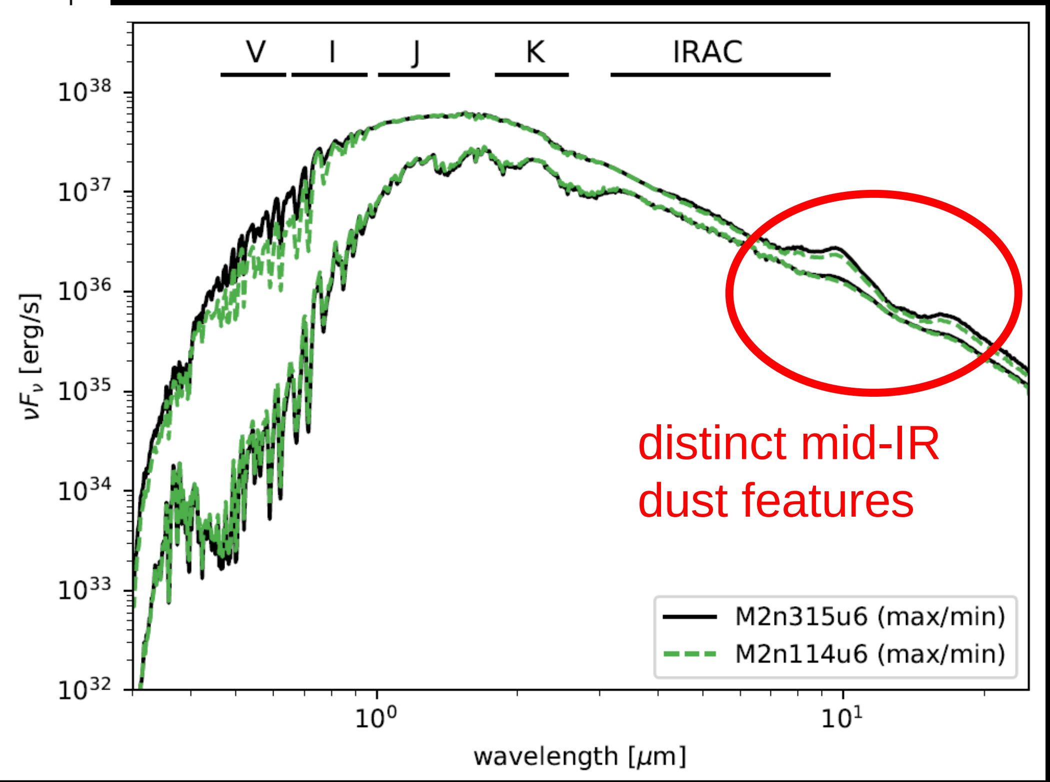
Höfner et al., (2022)

Radial structure at different pulsation phases

Dust-driven winds: DARWIN models



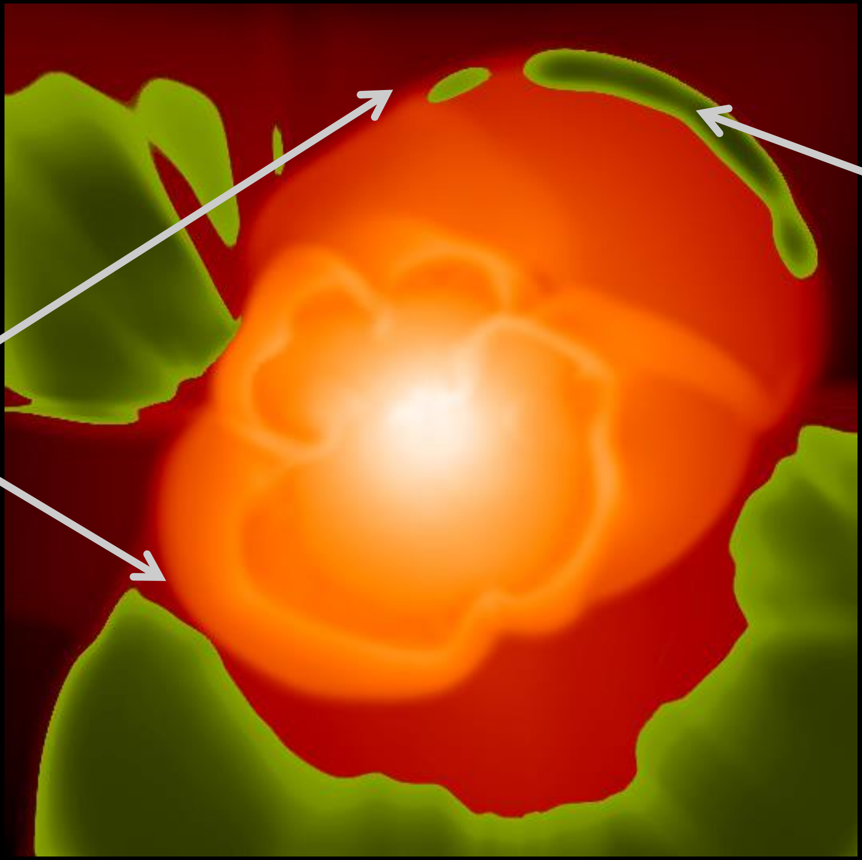
The self-regulating feedback between grain composition and radiative heating leads to low values of Fe/Mg, typically a few percent.



Models of winds driven by photon scattering on silicate grains with low Fe/Mg and sizes of 0.1–1 micron show realistic mass loss rates & wind velocities, visual, near-IR and mid-IR spectra & photometry (Höfner et al., 2022)

Dust-driven winds of AGB stars

stellar pulsation & convection induce strong shock waves which propagate outwards through the gas in the extended stellar atmosphere



dust forms in the wake of the shock at distances of 2-3 stellar radii and is accelerated outwards by radiation pressure, triggering a wind

dust distribution should show effects of convection cells, as gas density affects grain growth (Freytag & Höfner 2008, Höfner & Freytag 2019)

Clumpy circumstellar dust clouds

Ohnaka et al. (2017)

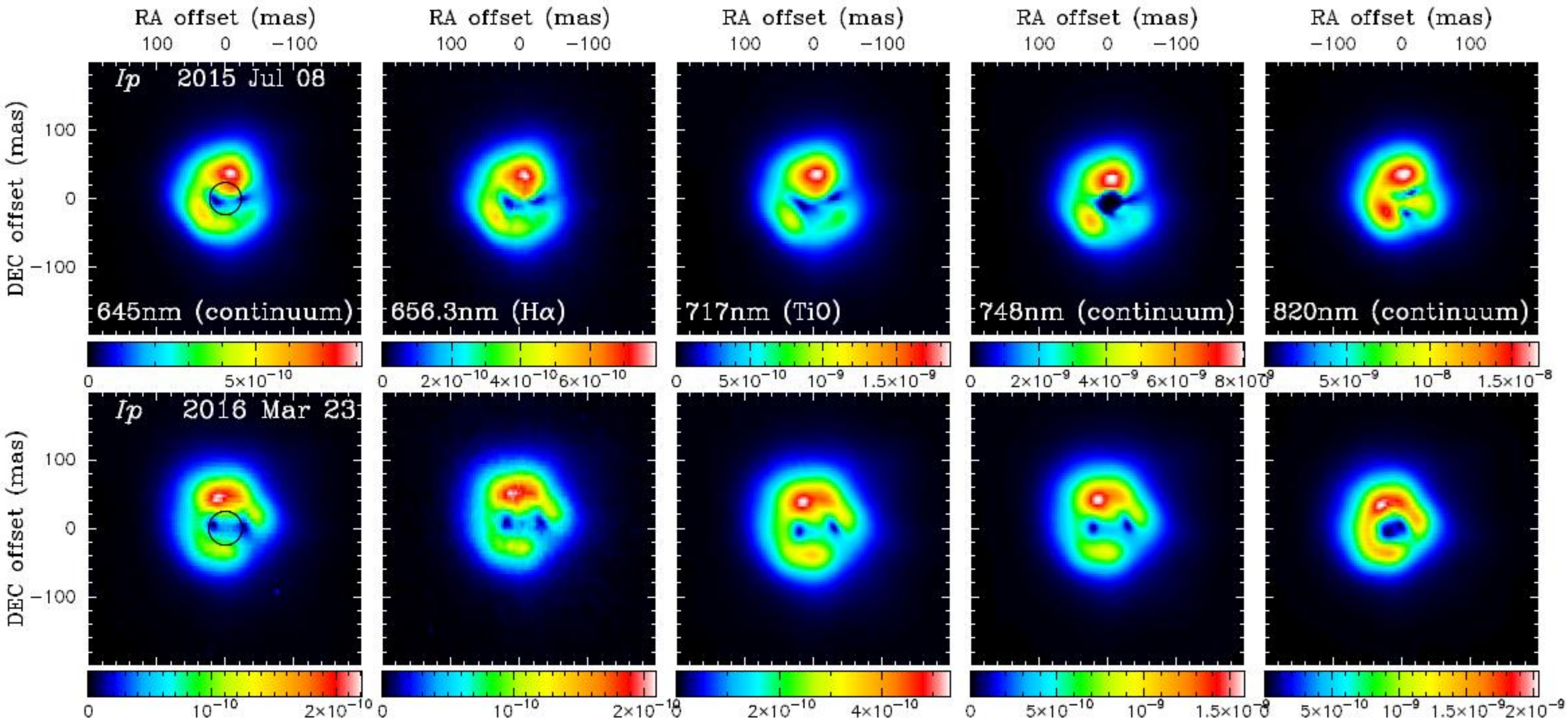


Fig. 2. Polarized intensity maps of W Hya observed with SPHERE-ZIMPOL. *The top and bottom rows* show the data of W Hya obtained on 2015 July 8 (phase 0.92, Paper I) and on 2016 March 23 (phase 0.54), respecti… (NHa, Hα), 717 nm (TiO717, TiO band), 748 nm (Cnt748, continuum), … North is up, east to the left in all panels. The 2016 data reveal the formation … in the SW in 2015 disappeared in 2016. The polarized intensity is shown … represent the size of the star measured in the continuum near 2.3 μm based on our VLTI/AMBER observations.

Grain sizes change with phase:
near L_{max}: 0.5 micron, L_{min}: 0.1 micron

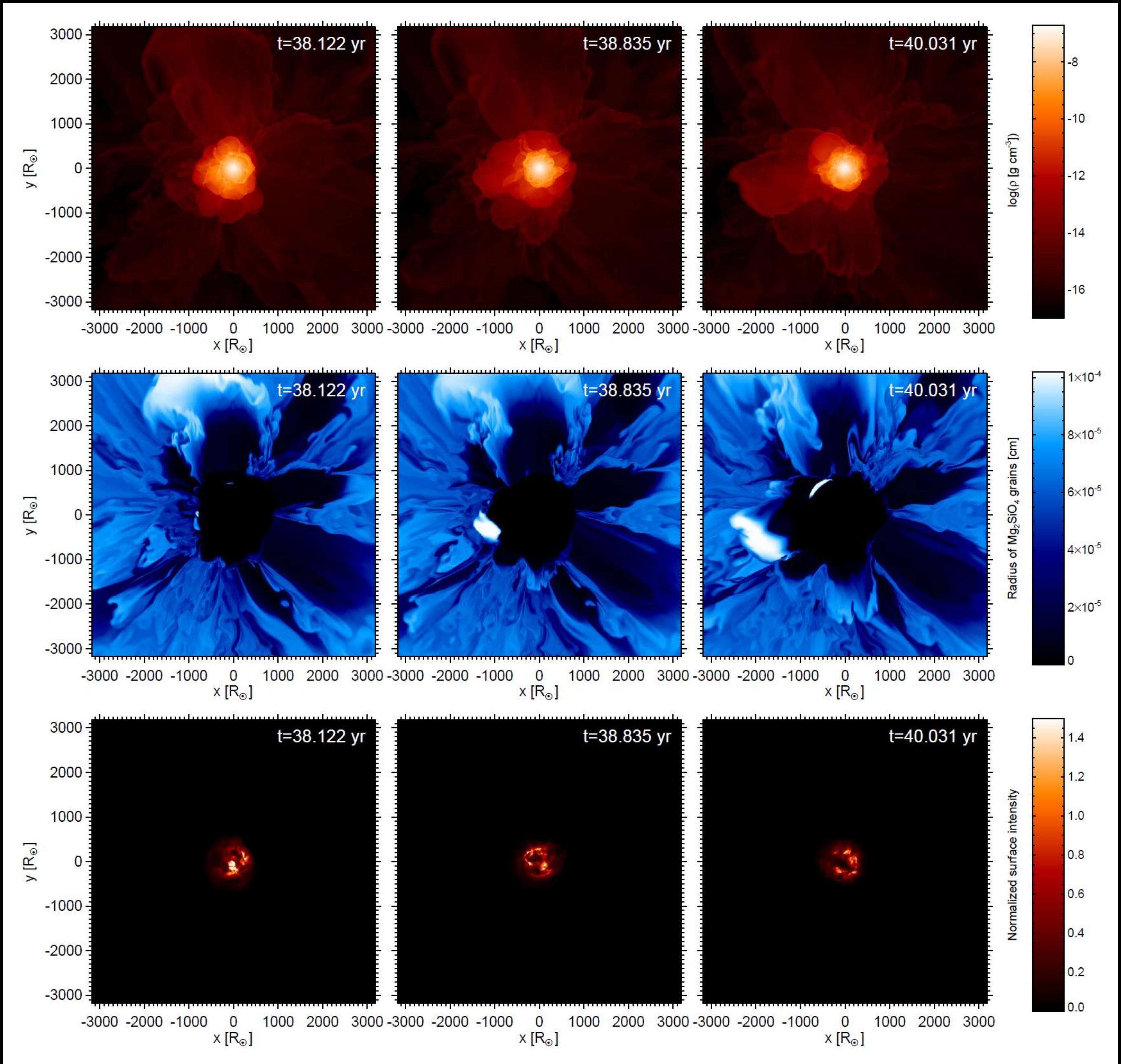
3D RHD models of AGB stars & winds

3D ‘star-and-wind-in-a-box’ model of an AGB star: snapshots showing gas density (left), dust concentration (middle) and radial velocity (right; red: inflow, blue outflow) for a slice through the center of the star (Freytag & Höfner 2023, A&A 669, A155)

The RHD model includes non-grey radiative transfer and a time-dependent description of silicate grain growth and evaporation.

Stellar parameters: 1.0 M_{sun}, 7000 L_{sun}, T_{eff} = 2800 K; resulting mass loss rate: 5 x 10^{-6}

3D RHD models of AGB stars & winds



3D 'star-and-wind-in-a-box' model of an AGB star: a time sequence of 3 snapshots, showing gas density (top), grain radius (middle) and stellar surface intensity (bottom).

The RHD model includes non-grey radiative transfer and a time-dependent description of silicate grain growth and evaporation.

Freytag & Höfner (2023, A&A 669, A155)

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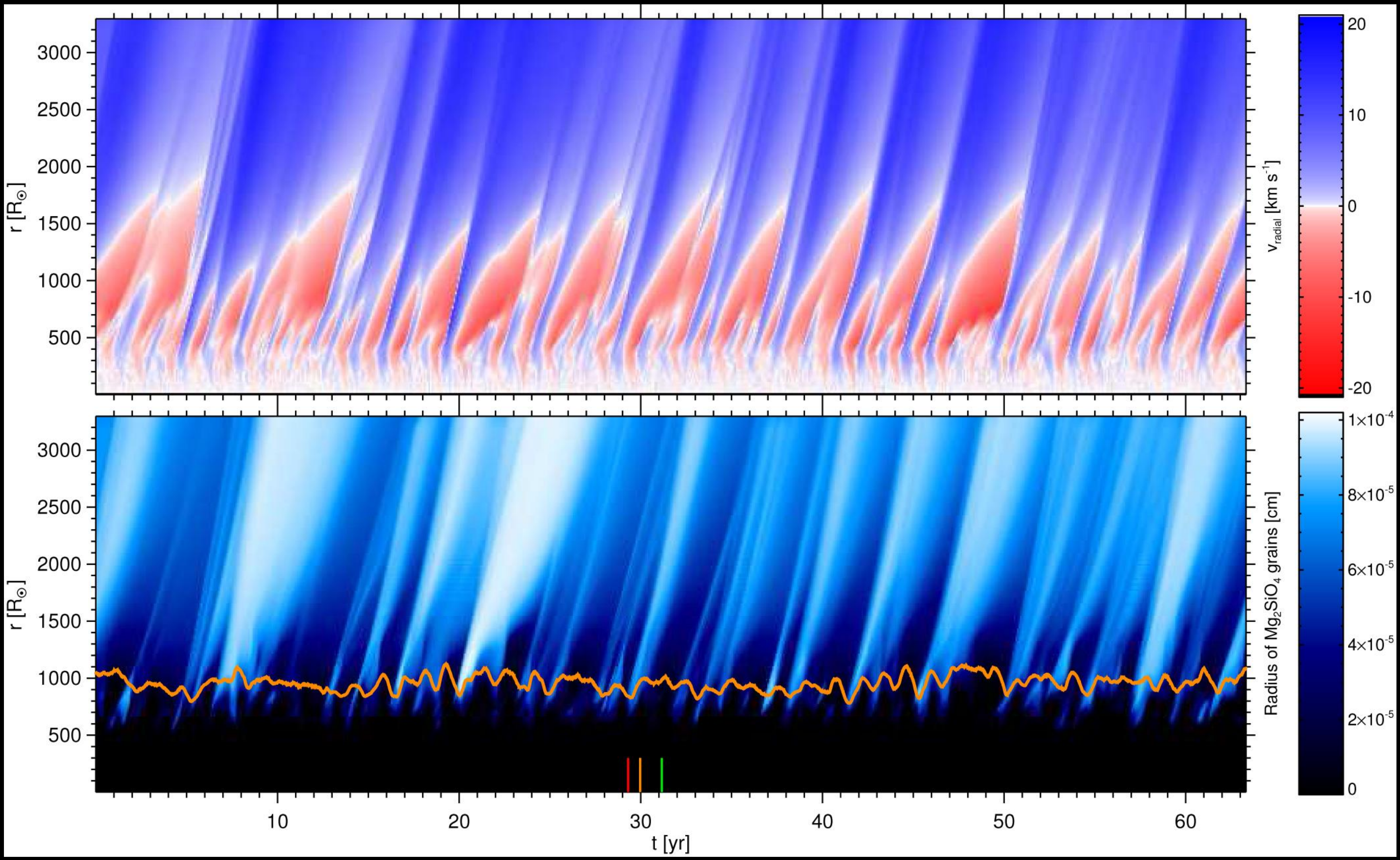
3D RHD models of AGB stars & winds



3D 'star-and-wind-in-a-box' model of an AGB star (1.0 M_{sun}, 7000 L_{sun}, T_{eff} = 2800 K): spherical means of radial velocity and grain radius (Freytag & Höfner 2023)

3D RHD models: images of dust clouds

Wiegert, J., et al.: A&A, 690, A162 (2024)

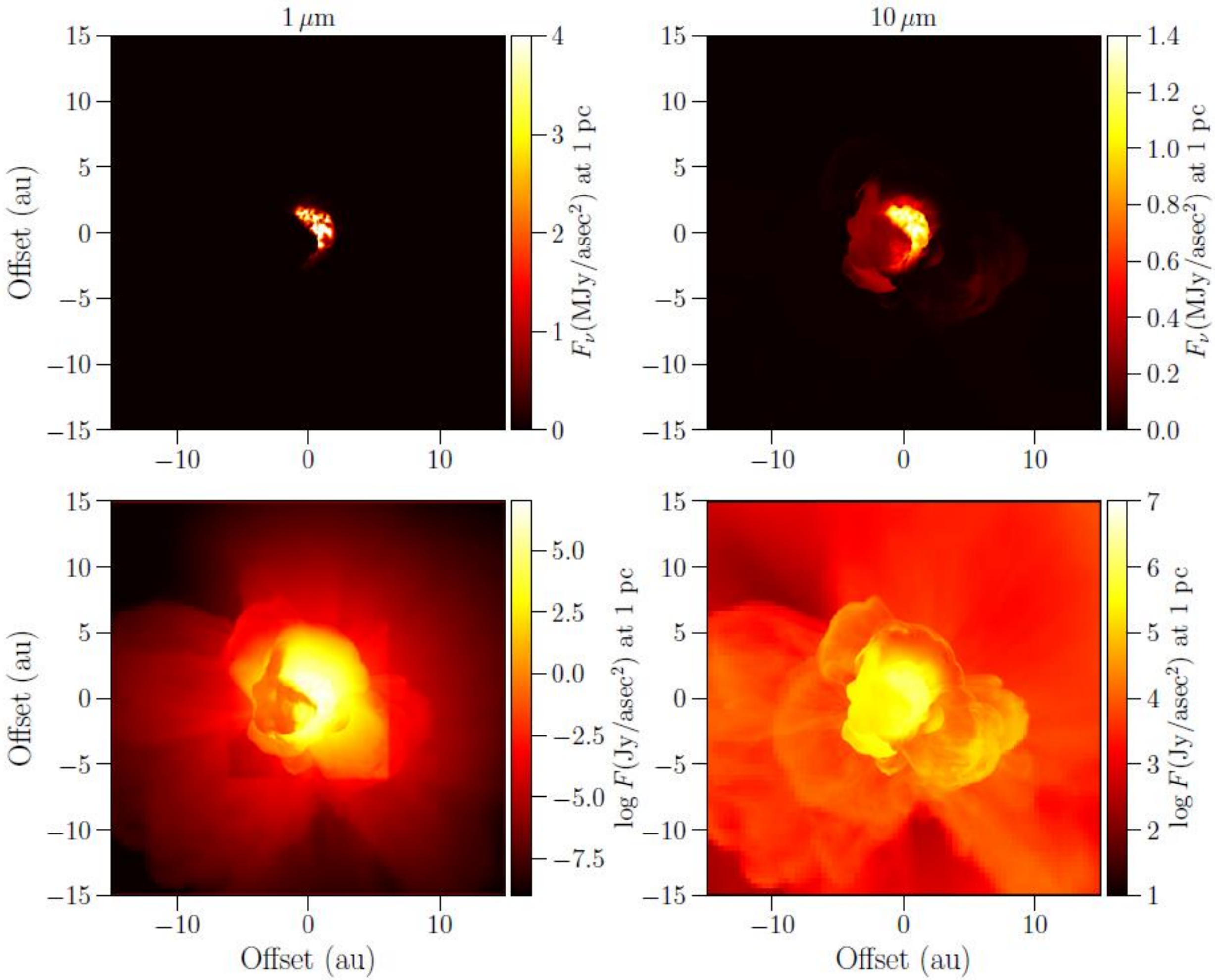


Fig. 7. Images created with RADMC-3D from `st28gm06n052` at 1 and 10 μm and as seen from the 0–0 angles ($i = 0°$ and $\phi = 0°$). The top row has a linear flux scale, and the bottom row has a logarithmic flux scale as indicated by the colour bars where the flux densities are normalised to a distance of 1 pc.

Synthetic images of a 3D 'star-and-wind-in-a-box' CO5BOLD model of an AGB star ($1.0\ M_{sun}$, $7000\ L_{sun}$, $T_{eff} = 2800$ K)

The images show extinction by dust at 1 micron (left) and silicate emission at 10 micron (right)

Wiegert et al. (2024, A&A 690, A162)

Summary – Dust & AGB star winds

- The mechanism behind dust-driven winds of AGB stars involves 2 steps:
  - shock waves triggered by pulsation and convection lift material to distances where temperatures are low enough for dust formation
  - radiation pressure on dust causes the outflow
- Large dust grains with radii of 0.1 - 0.5 micron are observed at about 2 stellar radii around AGB stars, as required for driving winds by photon scattering on near-transparent silicate grains with low Fe/Mg
- 1D DARWIN models develop winds with realistic velocities and mass-loss rates; they show distinctive mid-IR silicate features even for low Fe/Mg
- High-angular-resolution imaging of scattered visual and near-IR light shows clumpy dust clouds surrounding AGB stars
- Clumpy dust clouds emerge naturally in 3D “star-and-wind-in-a-box” CO5BOLD models, as a consequence of giant convection cells
- The first global 3D models of AGB stars, combining convection, self-excited pulsation and dust-driven winds, indicate a complex morphology of the outflows