Atmospheric Dynamics & Winds of AGB stars:

A Theorist's View

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Overview

- Dynamical atmospheres
  - convection, pulsation, extended structures
  - 1D vs. 2D/3D models
- Dust formation and winds
  - basic mechanisms, detailed models and constraints from observations
- Mass Loss and Evolution

Dynamical atmospheres

Sun

surface convection
small-scale compared to star

effects on
- abundance determination

3D box-in-a-star models

AGB stars

giant convection cells
deep-reaching, global dynamics

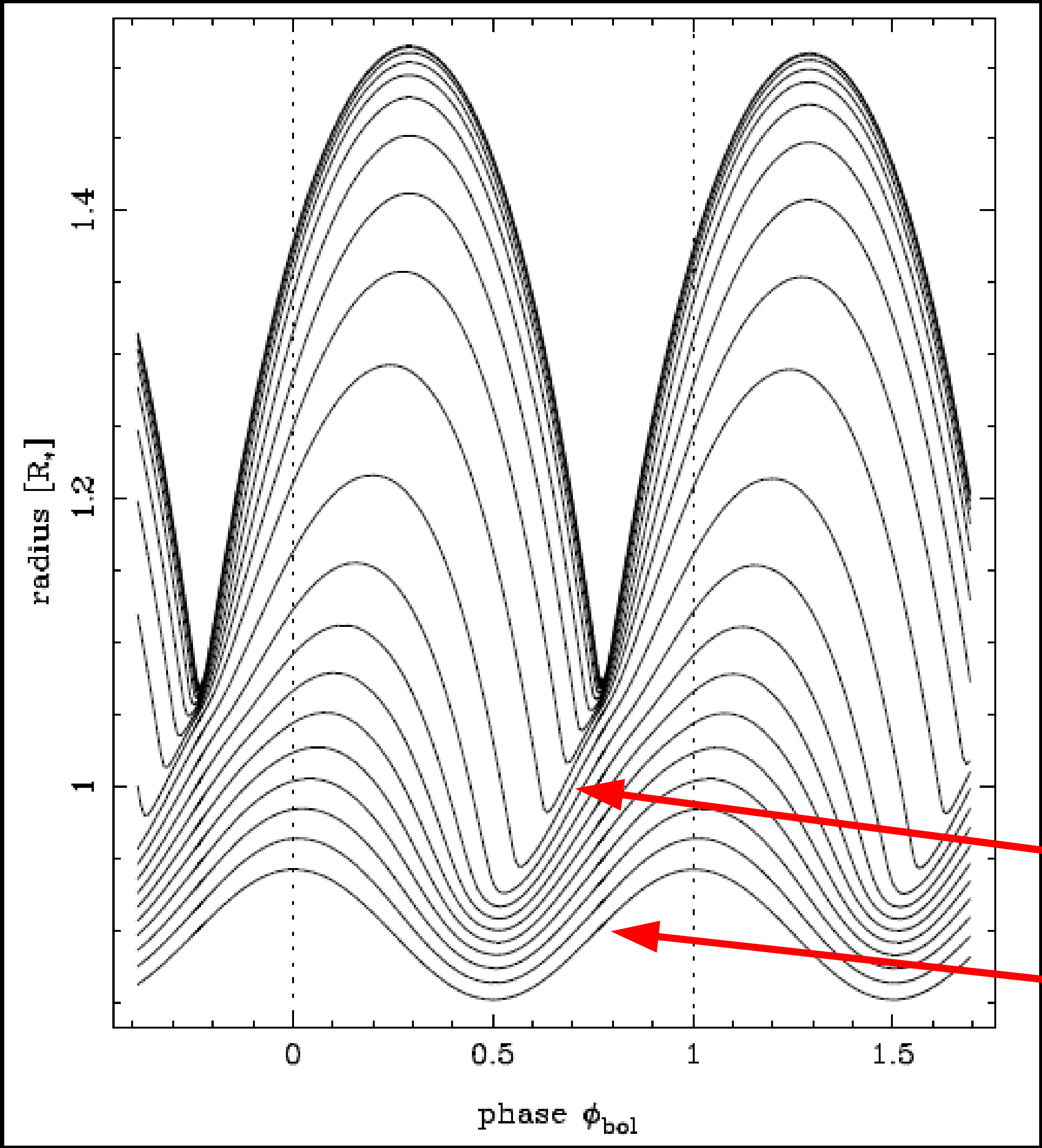
stellar pulsation

strong effects on
- abundances (dredge-up, C/O)
- mass loss

3D star-in-a-box models
- simplified physics

1D atmosphere & wind models
- more detailed physics
- larger spatial range
- longer time series

Effects of pulsation and shocks

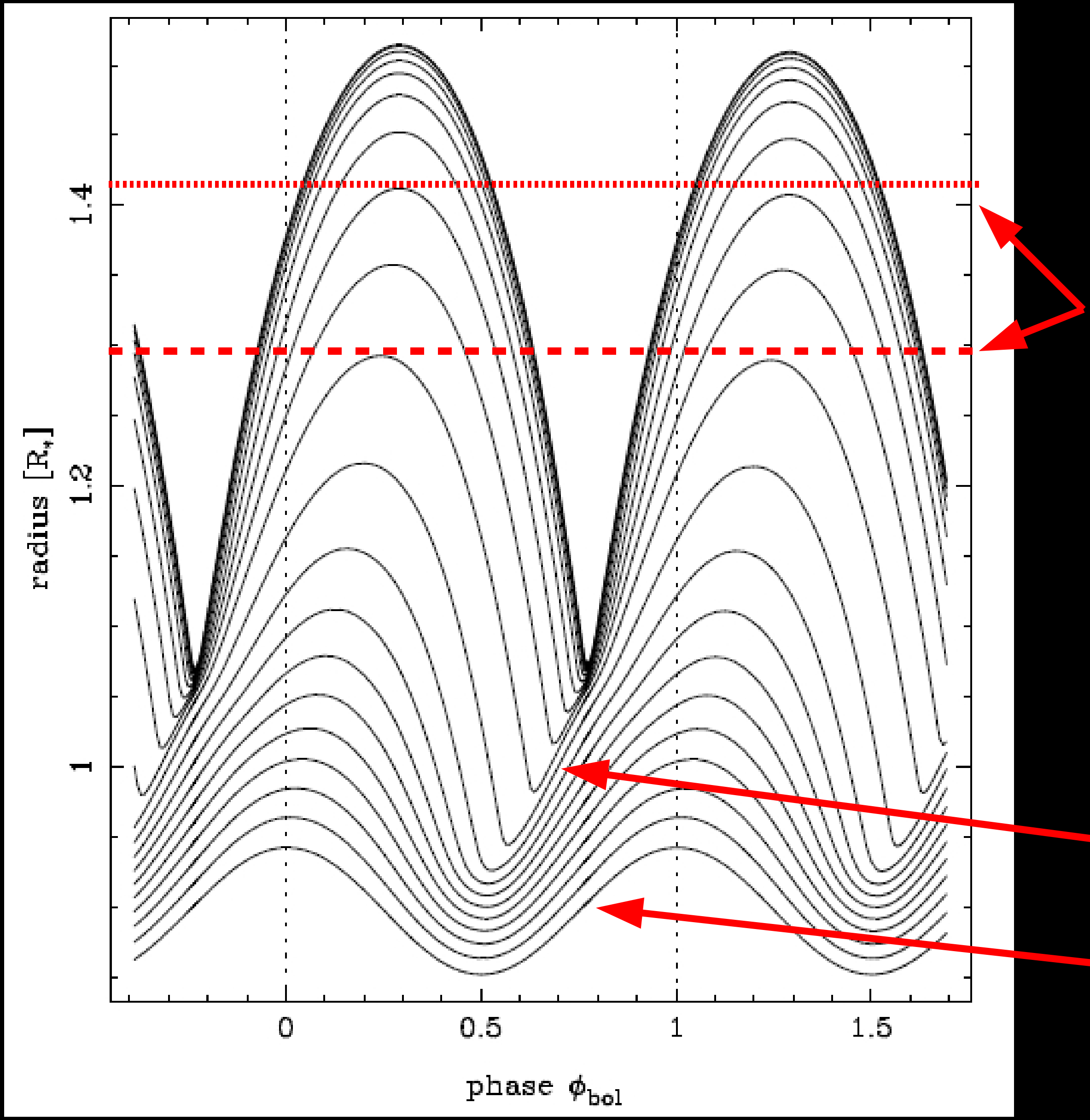


movement of mass shells
in a detailed dynamical
model atmosphere

formation and
propagation of
shock waves

pulsation

Effects of pulsation and shocks



movement of mass shells in a detailed dynamical model atmosphere

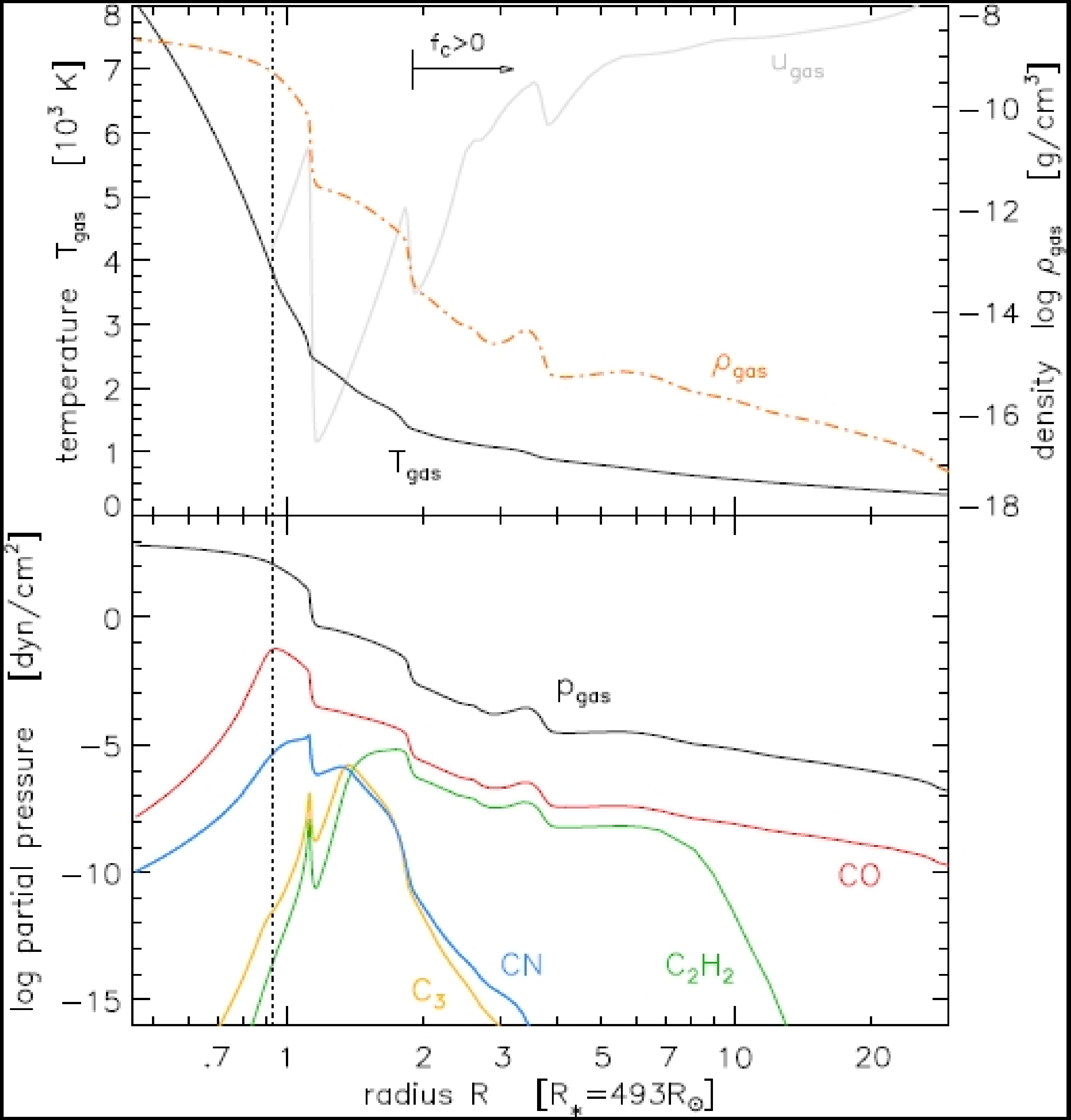
outer atmospheric layers: about 70 (50) percent of the time in the upper half (quarter) of the trajectory

⇒ levitation, extended cool atmosphere

formation and propagation of shock waves

pulsation

Extended dynamical atmospheres



Spatial structure of a detailed dynamical model (incl. frequency-dependent RT and dust formation)

top: density and gas temperature

bottom: partial pressures of various molecules

Note the effects of shock waves.

Nowotny et al. (2010)

Extended dynamical atmospheres

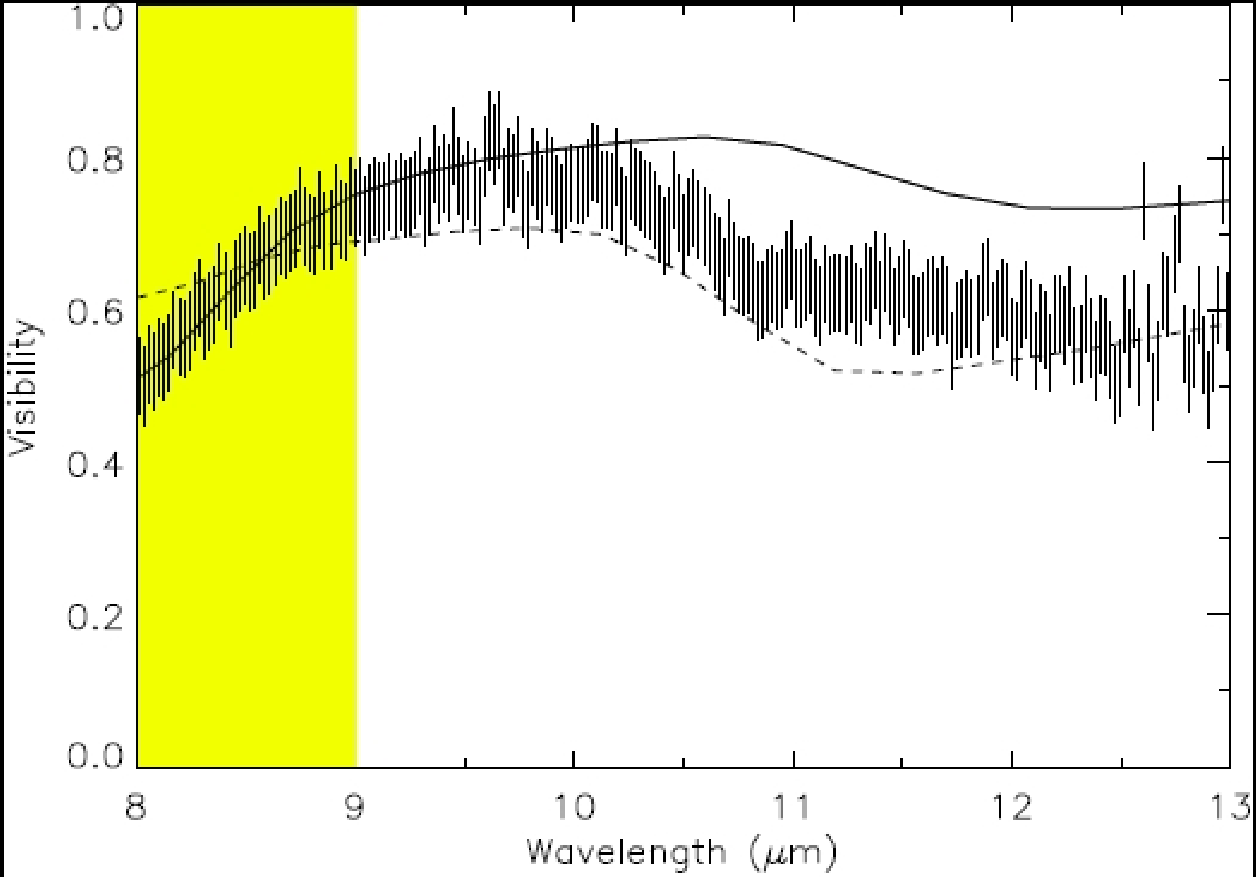


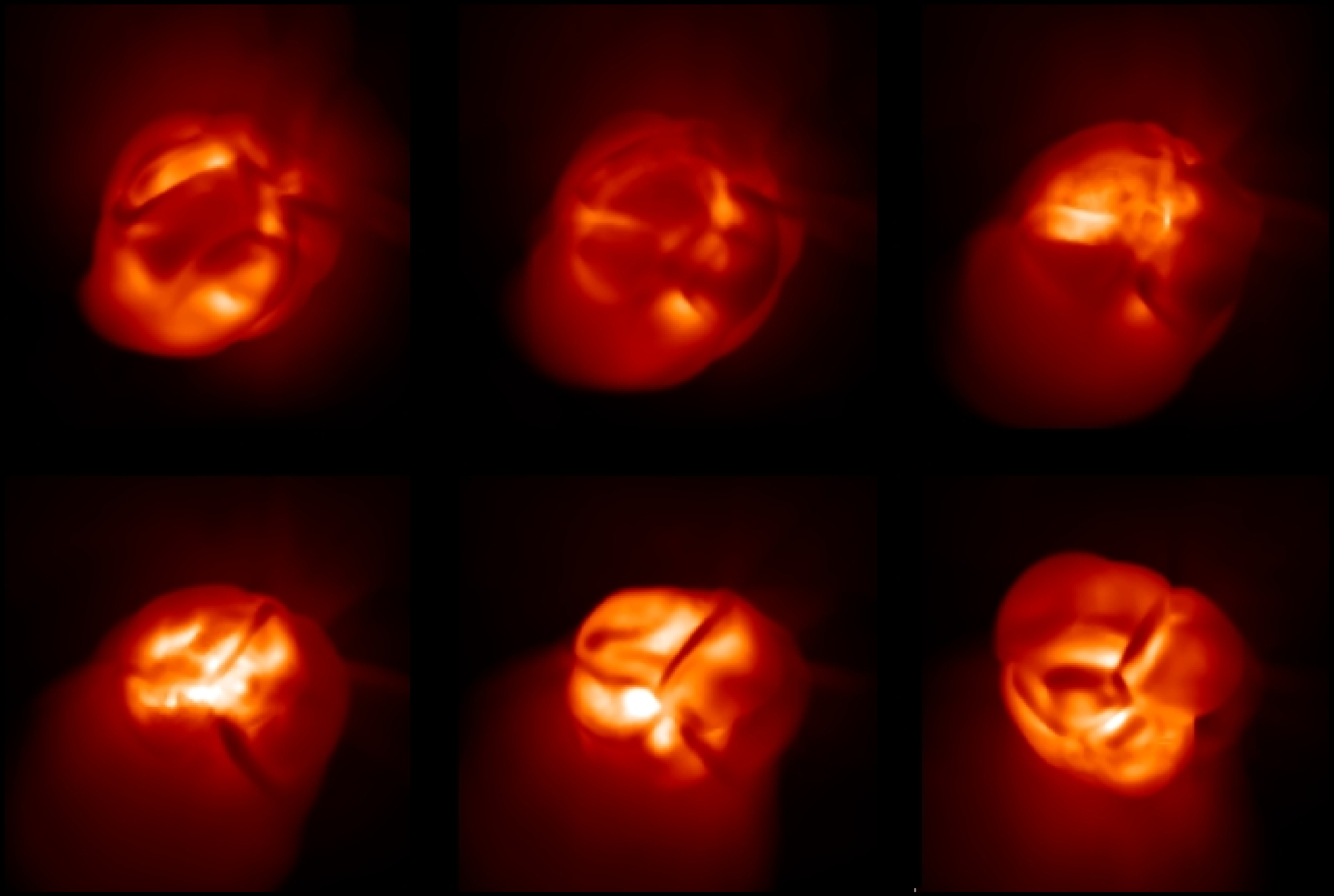
Fig. 21. Comparison of the visibility of the best dynamic model (solid line) with the best fitting COMARCS+DUSTY model (dashed line; see Sect. 4.2.1) superimposed on the 60 meter MIDI visibility data (error bars) at phase 0.23. The yellow zone corresponds to the region dominated by the presence of warm molecular layers.

Observations of the C-rich AGB star R Scl with VLTI/MIDI, compared with different models.

Sacuto et al., submitted to A&A

Related talks by Stephane Sacuto, Claudia Paladini

'Star-in-a-box' models of AGB stars

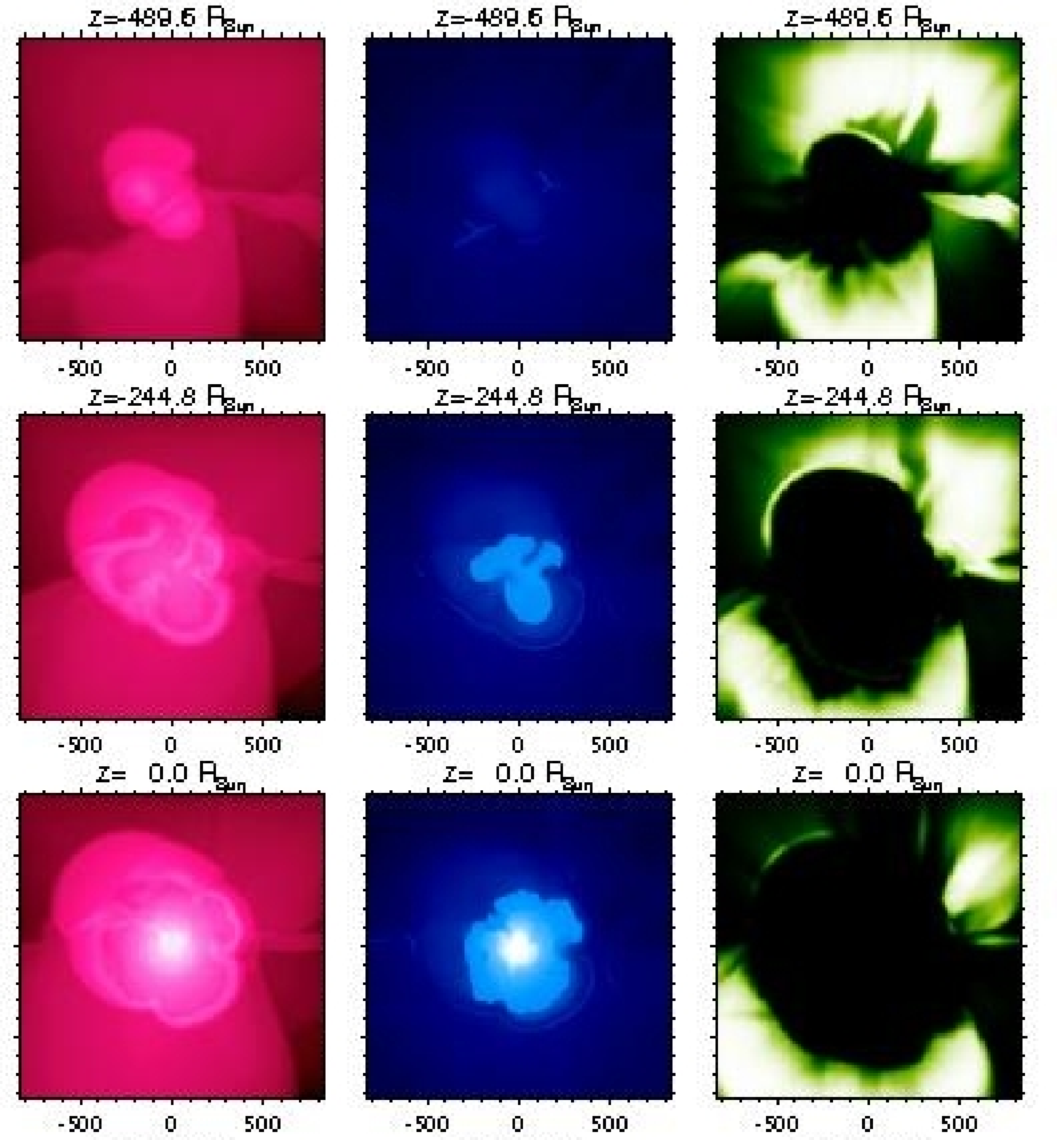


3D star-in-a-box surface intensity

a time series showing the development of giant convection cells

Freytag & Höfner (2008)

Effects of giant convection cells



density temperature dust

3D star-in-a-box

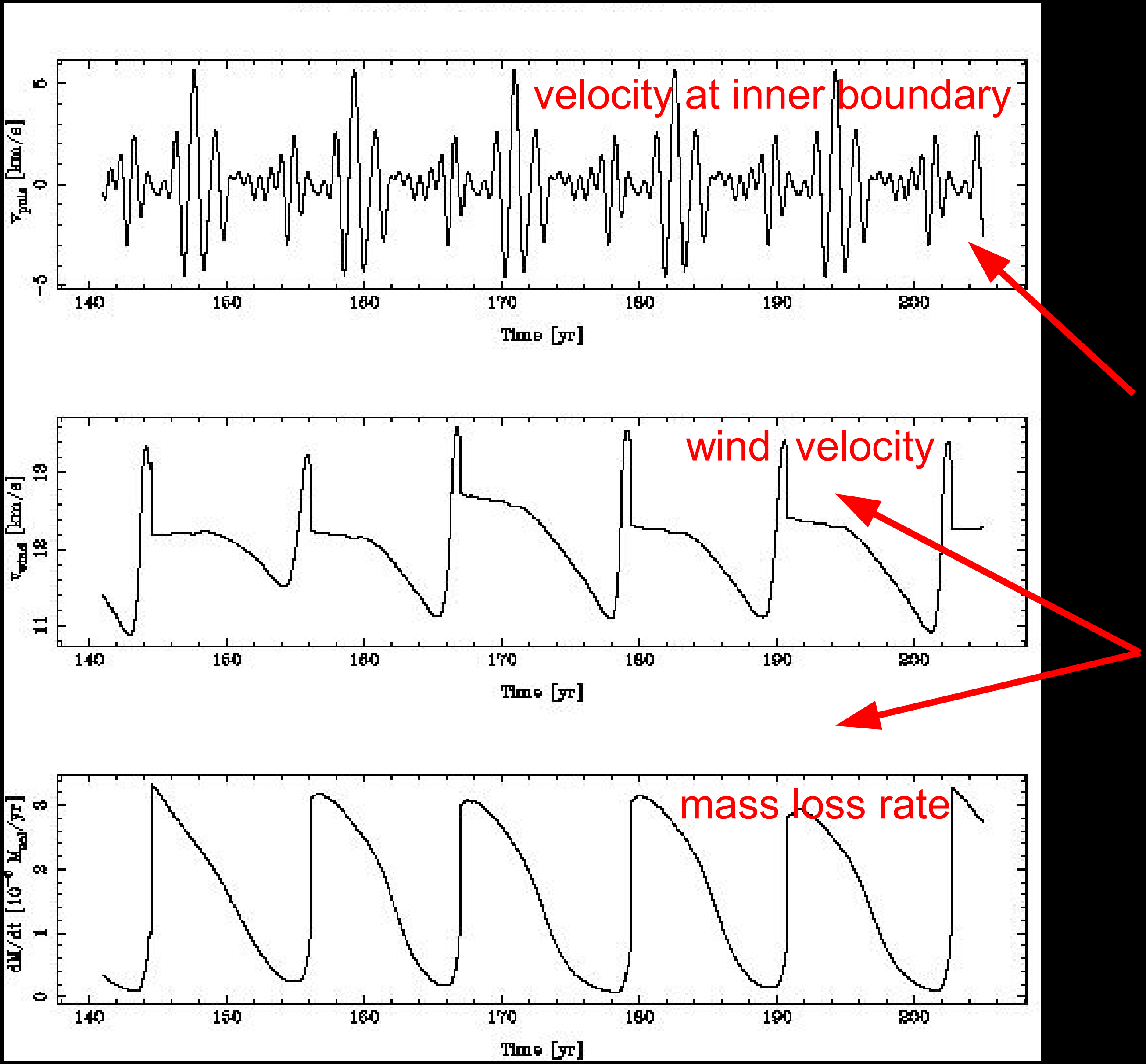
convection
dust formation

tomography of
star & envelope:
slices at different
distances from
center of box

Freytag & Höfner
(2008)

See also poster
by Wachter et al.

Effects of giant convection cells



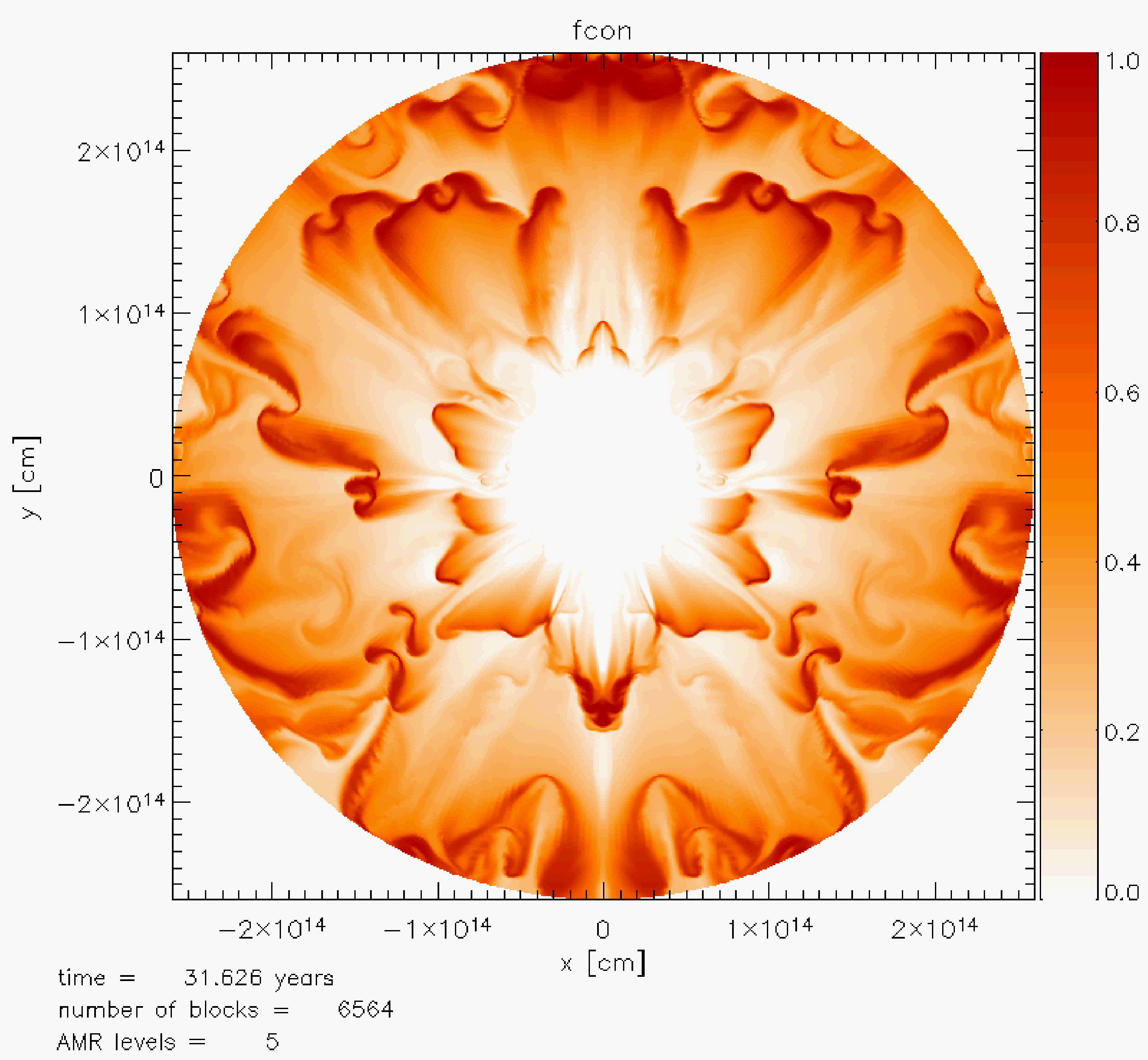
3D star-in-a-box

convection
dust formation

movement of mass shell in 3D model converted into a boundary condition for a 1D spherical atmosphere and wind model

Freytag & Höfner (2008)

Dust-induced CSE structures



2D circumstellar envelope models

structure formation in dust-driven winds

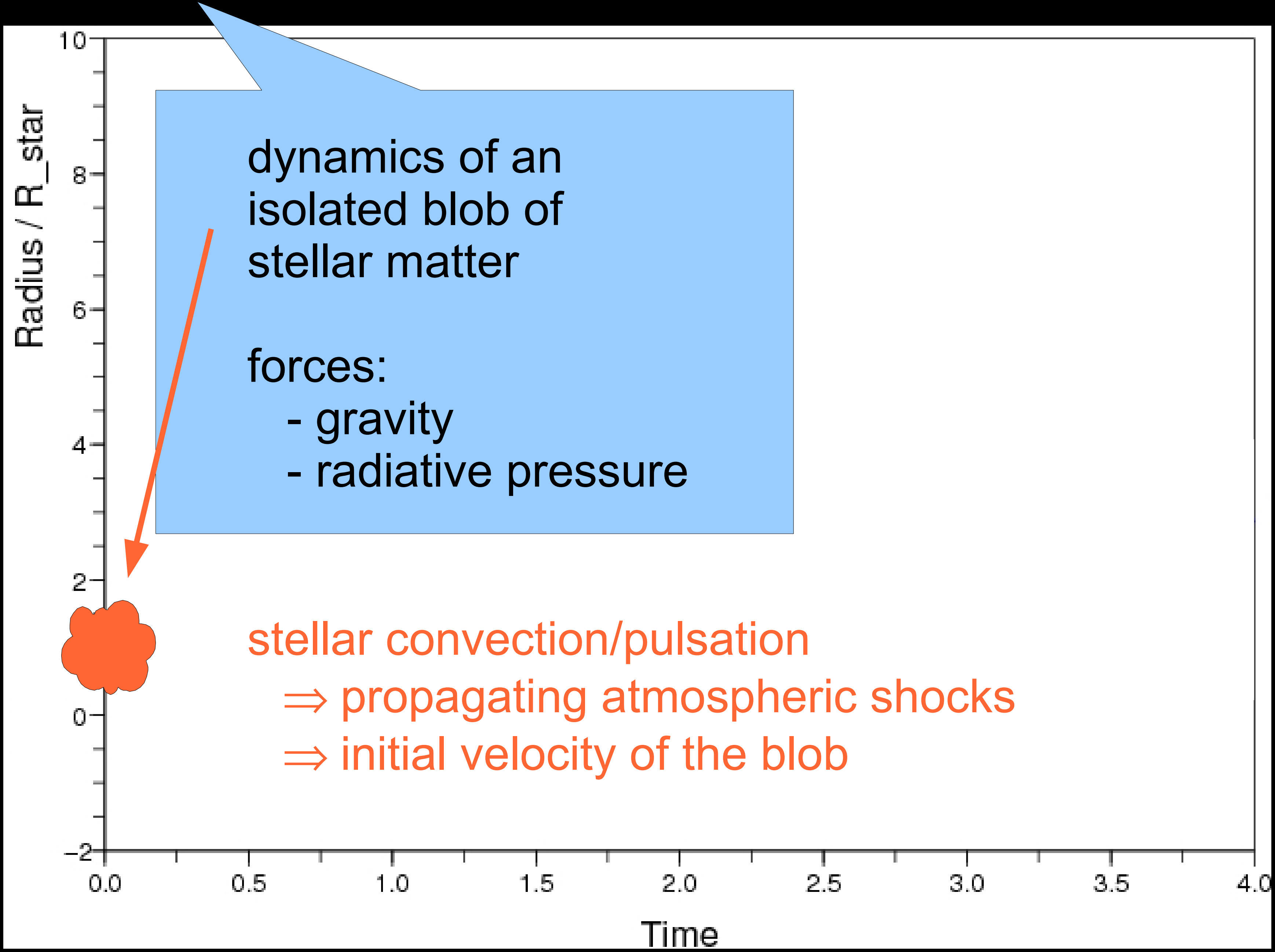
Woitke & Niccolini (2005)

Woitke (2006)

Dynamical Atmospheres Summary

- Pulsation and convection induce strong radiating shocks which propagate outwards.
- Dynamical levitation due to shocks leads to extended cool variable structures.
- The formation of molecules and dust is strongly influenced by dynamics.
- Radial structures and convection-induced patterns are accessible to interferometry.

A toy model: shocks, dust & wind

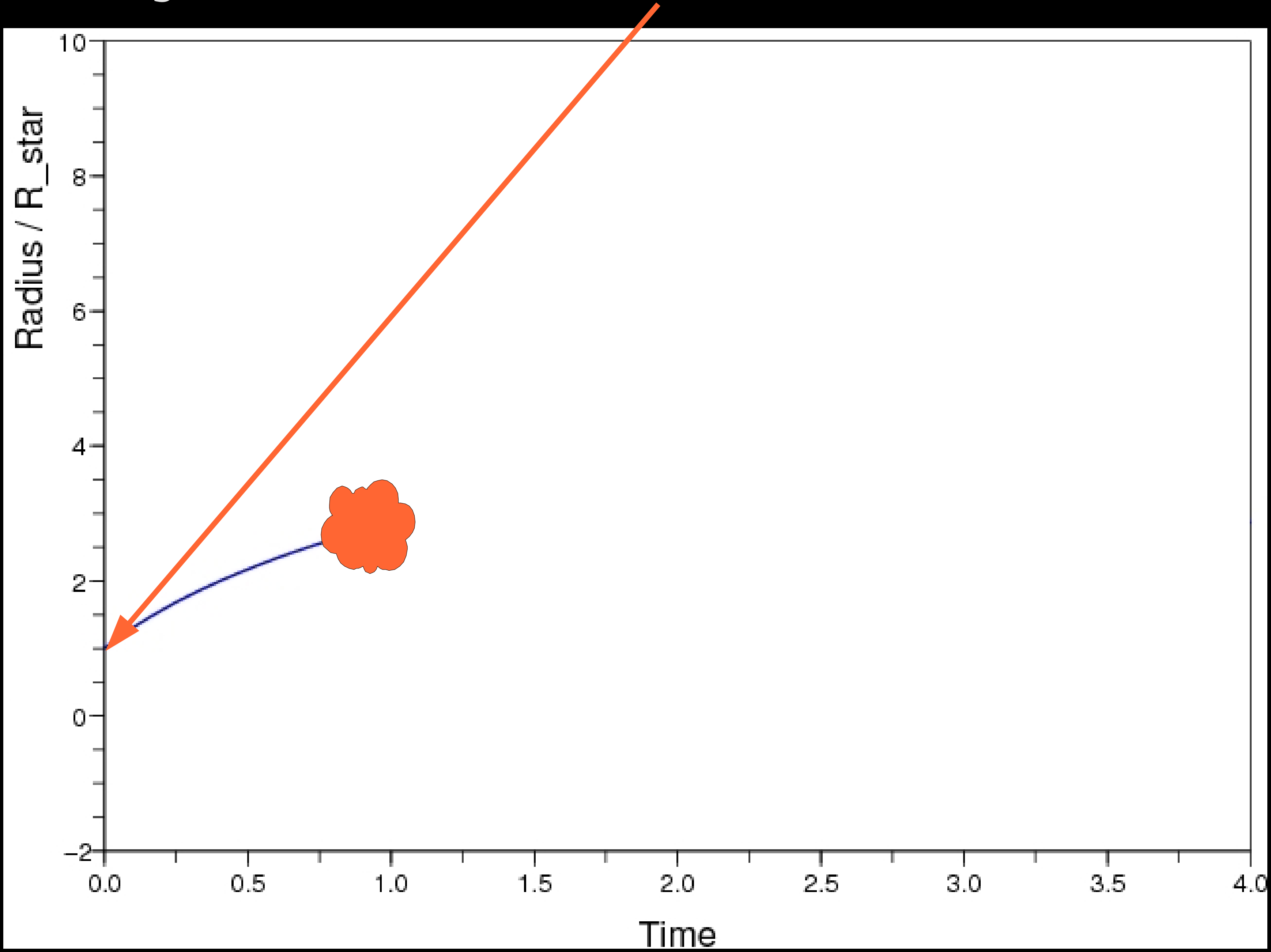


dynamics of an isolated blob of stellar matter

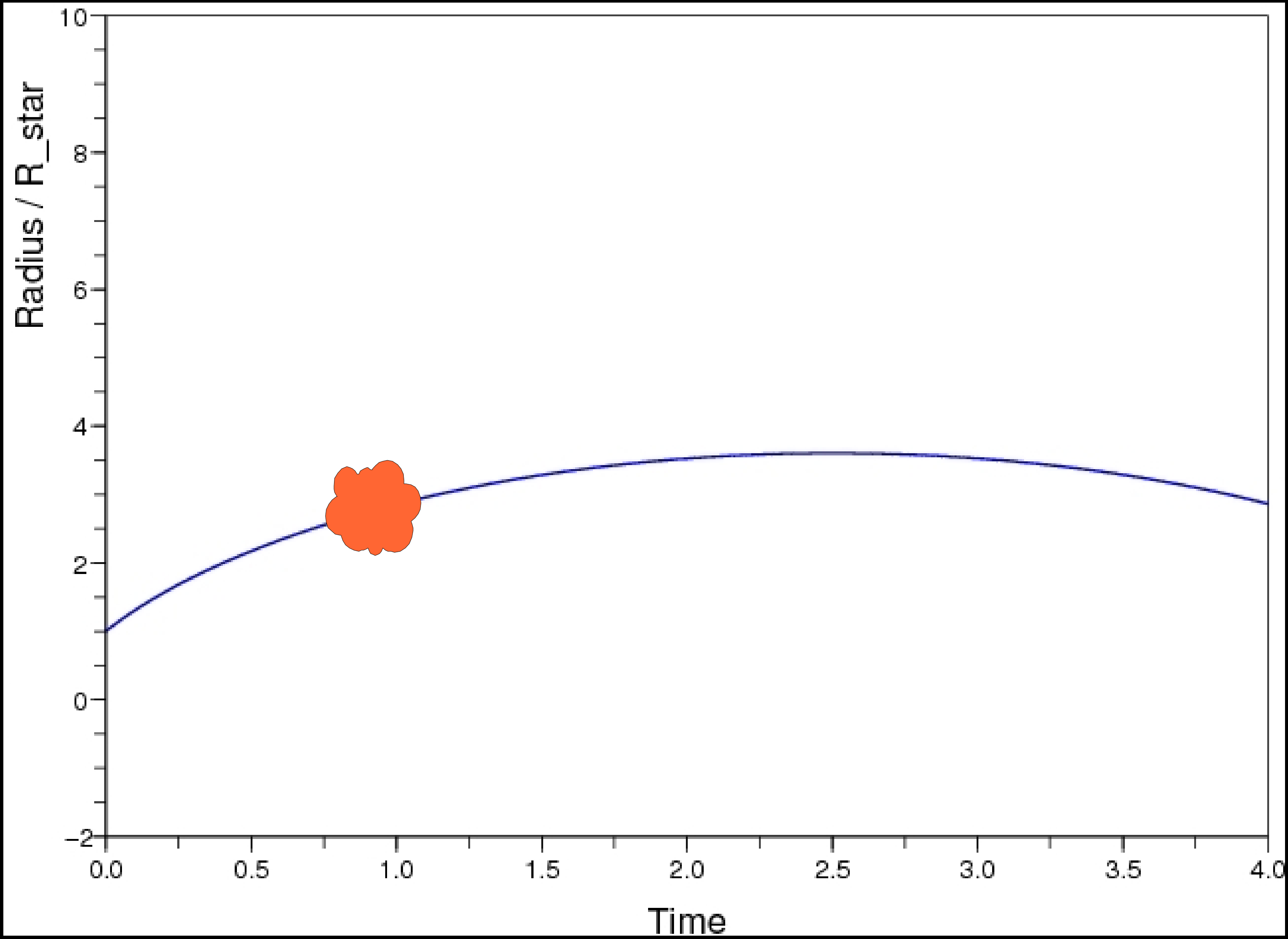
forces:
- gravity
- radiative pressure

stellar convection/pulsation
  ⇒ propagating atmospheric shocks
  ⇒ initial velocity of the blob

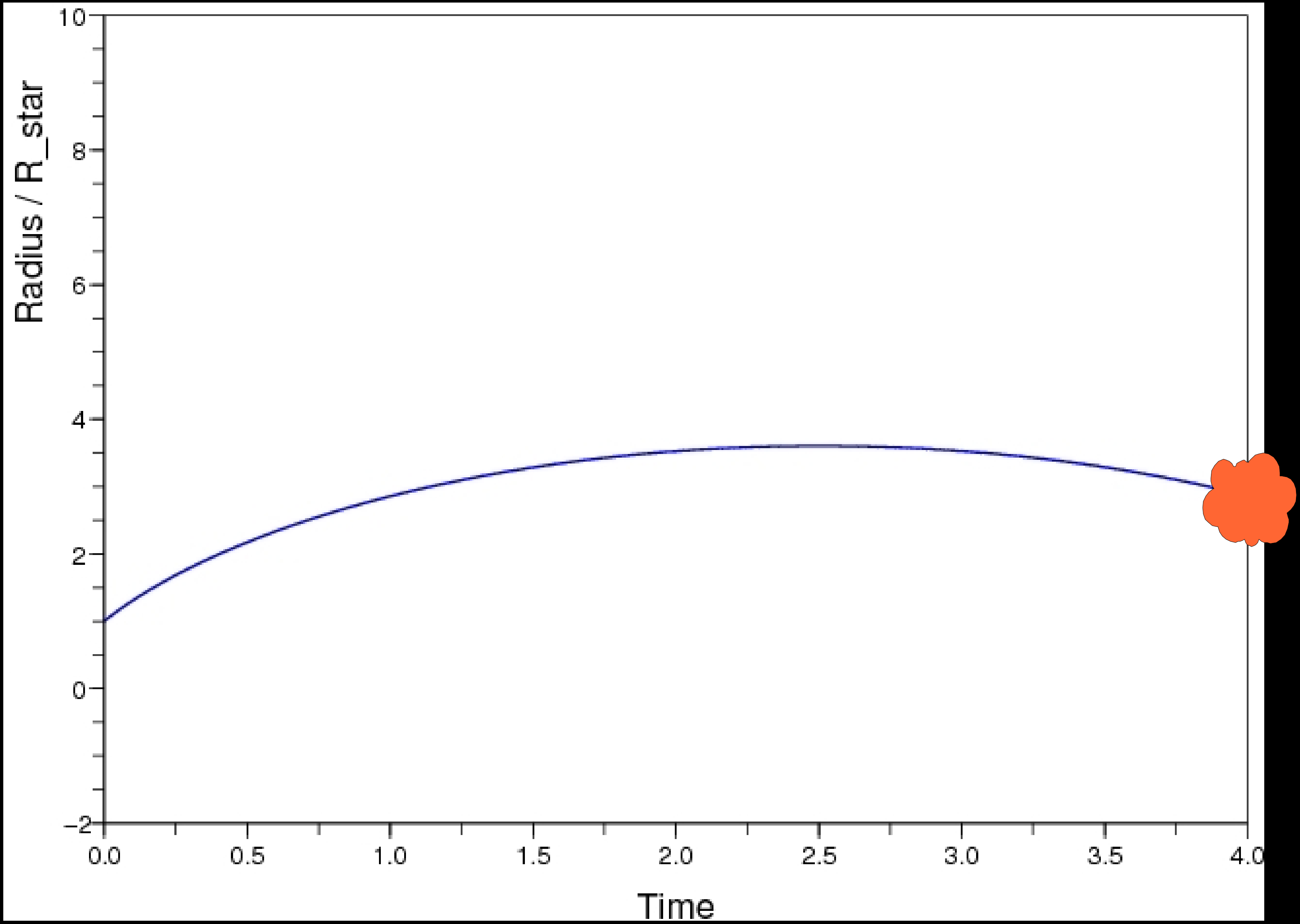
A toy model: shocks, dust & wind



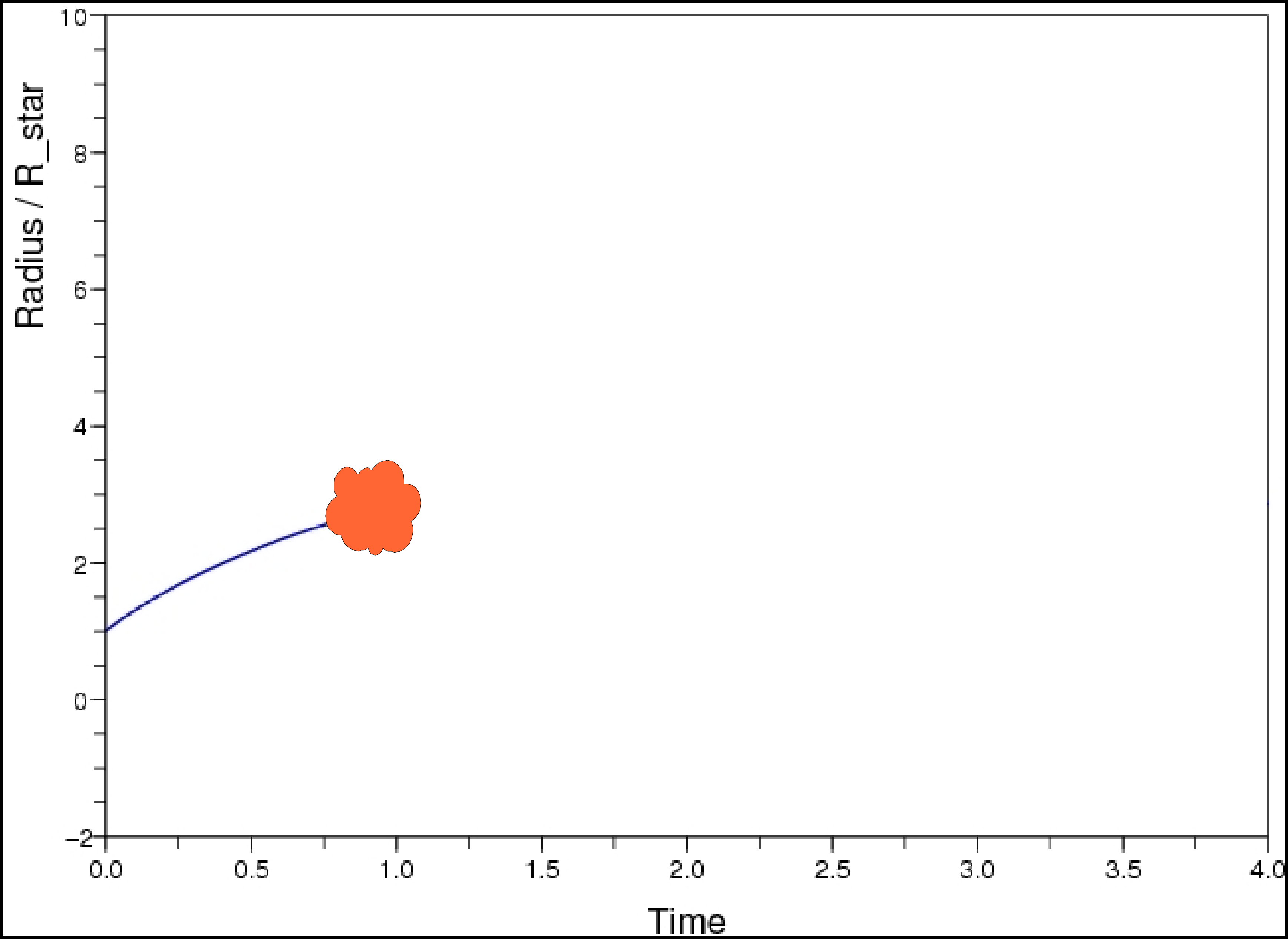
A toy model: shocks, dust & wind



A toy model: shocks, dust & wind



A toy model: shocks, dust & wind



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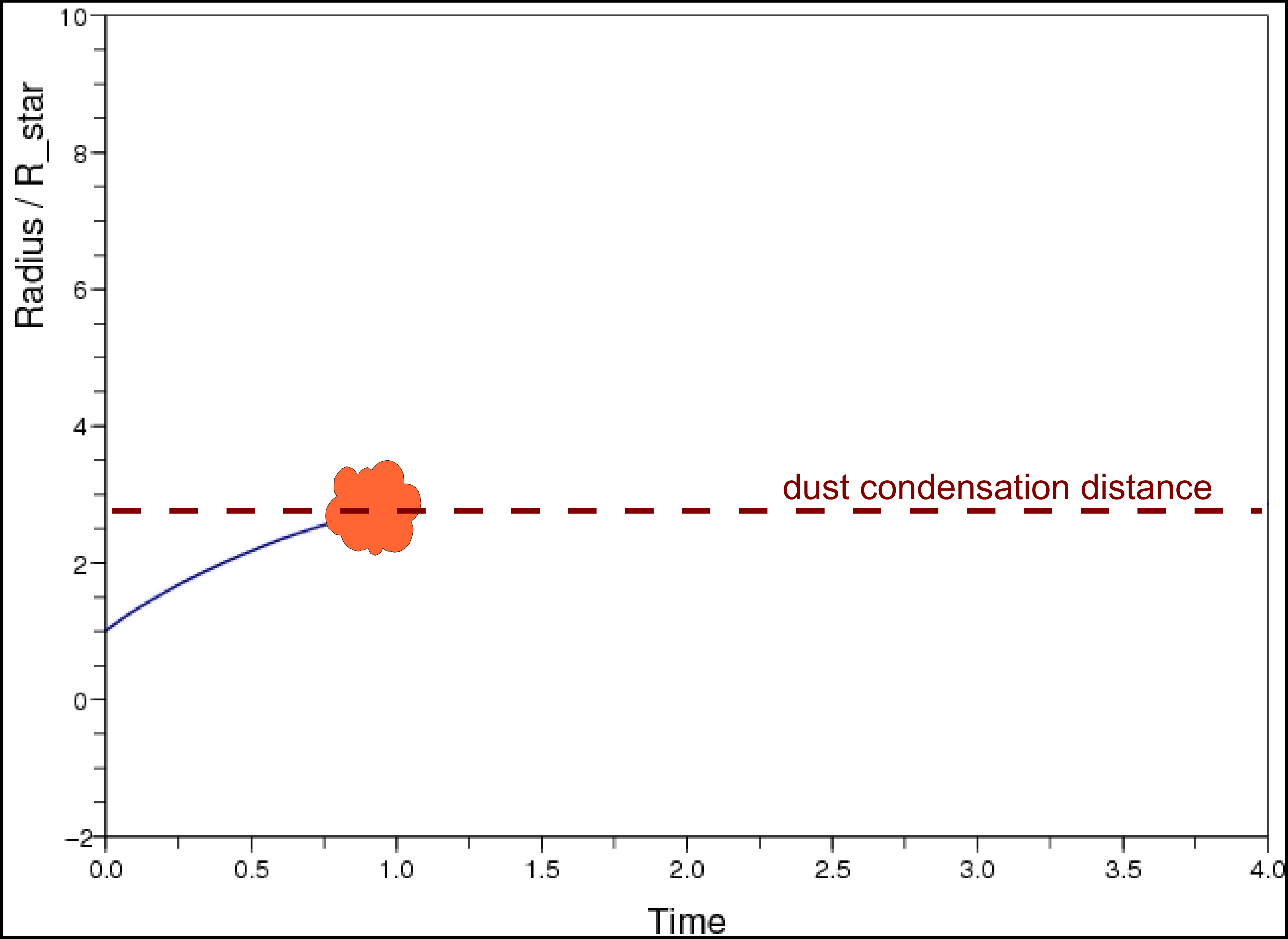
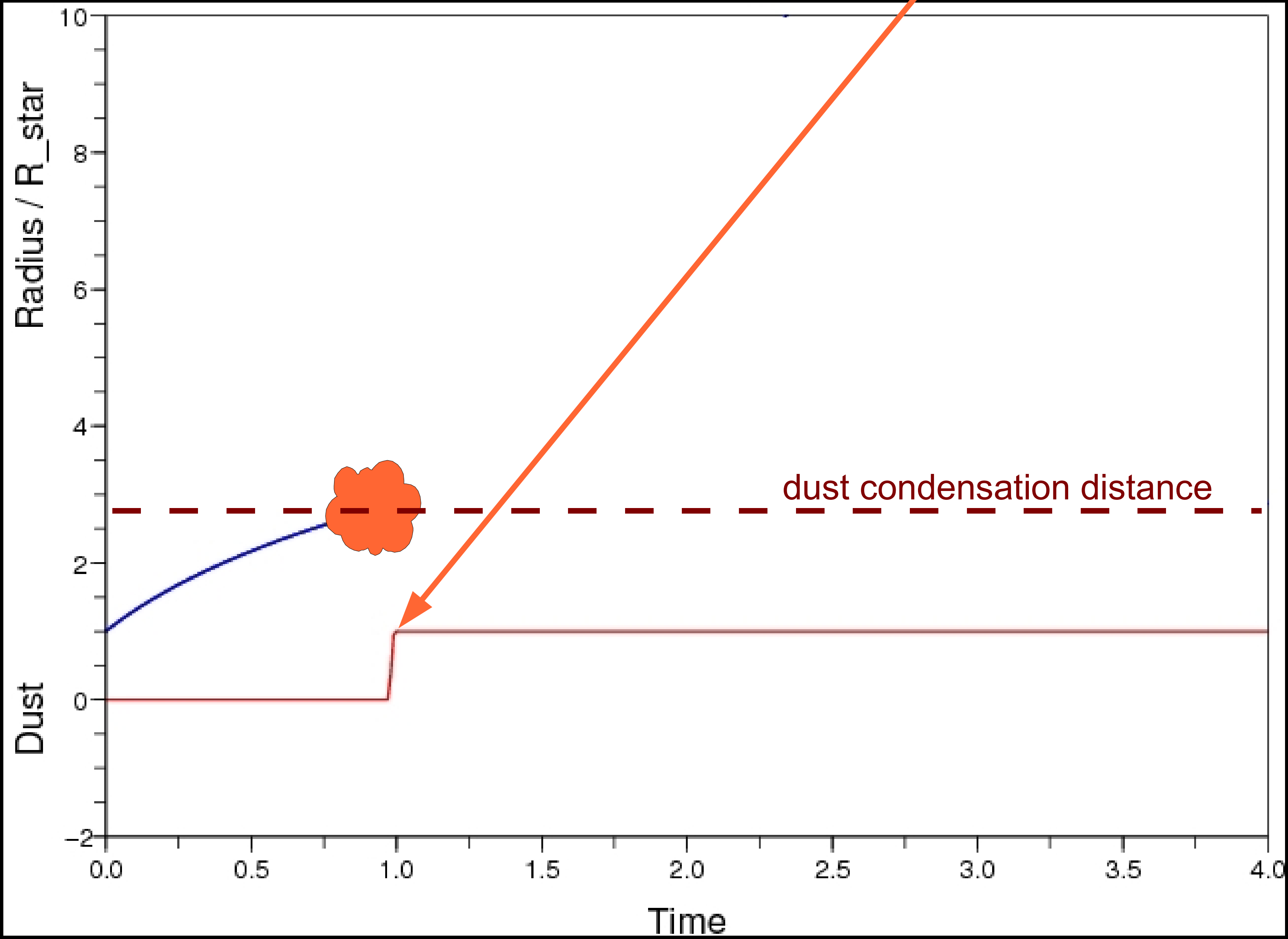
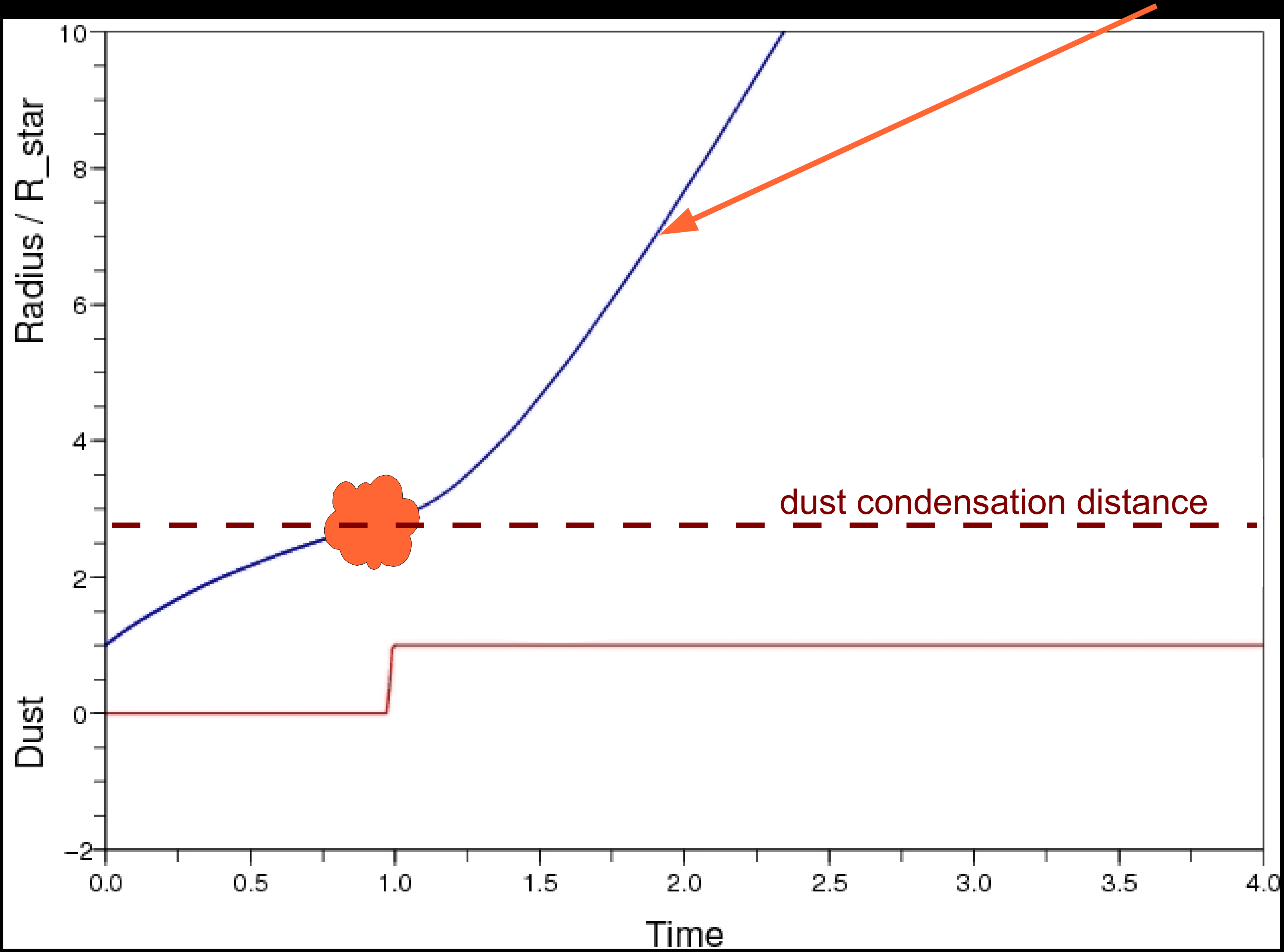


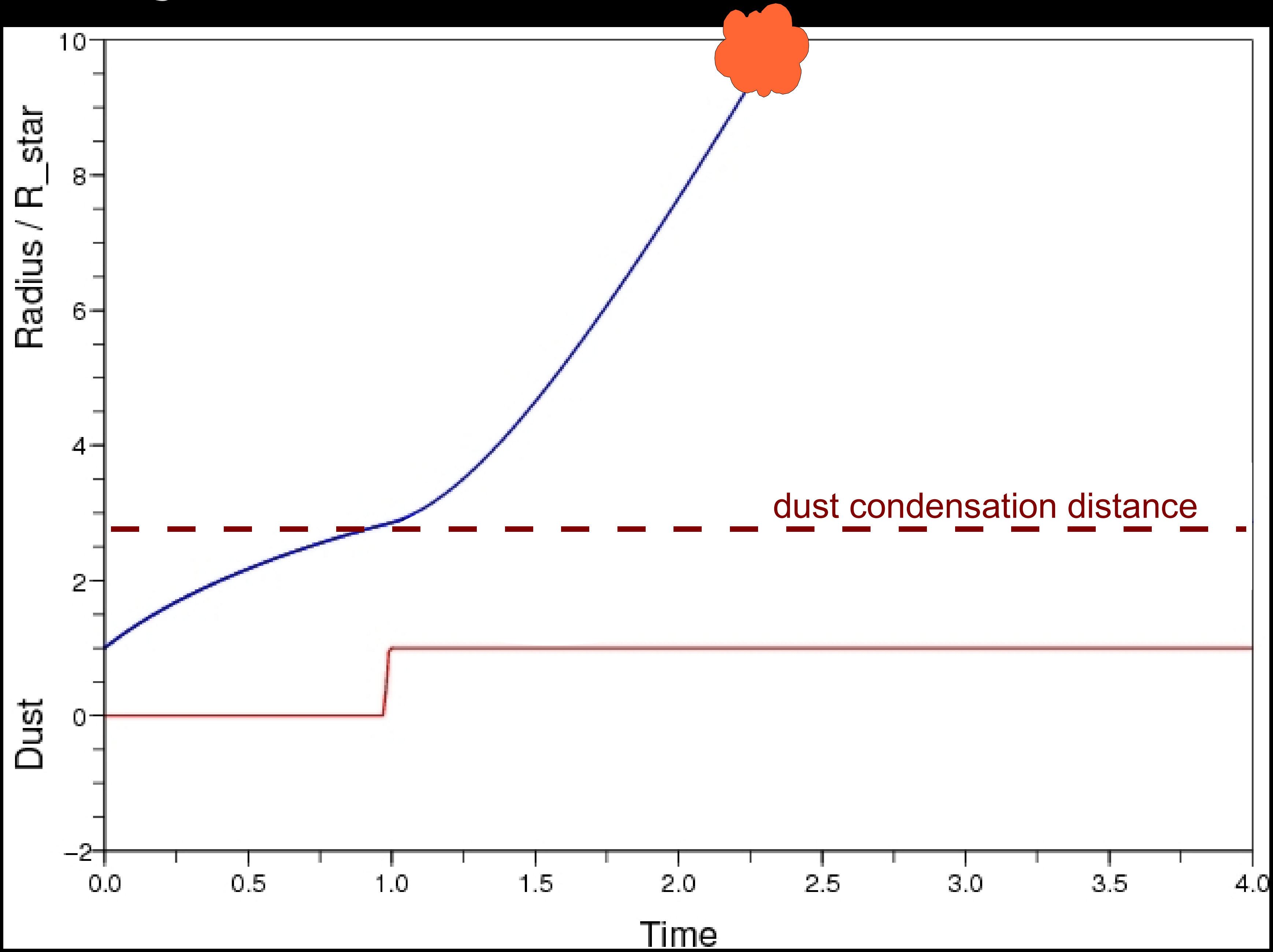
A toy model: shocks, dust & wind



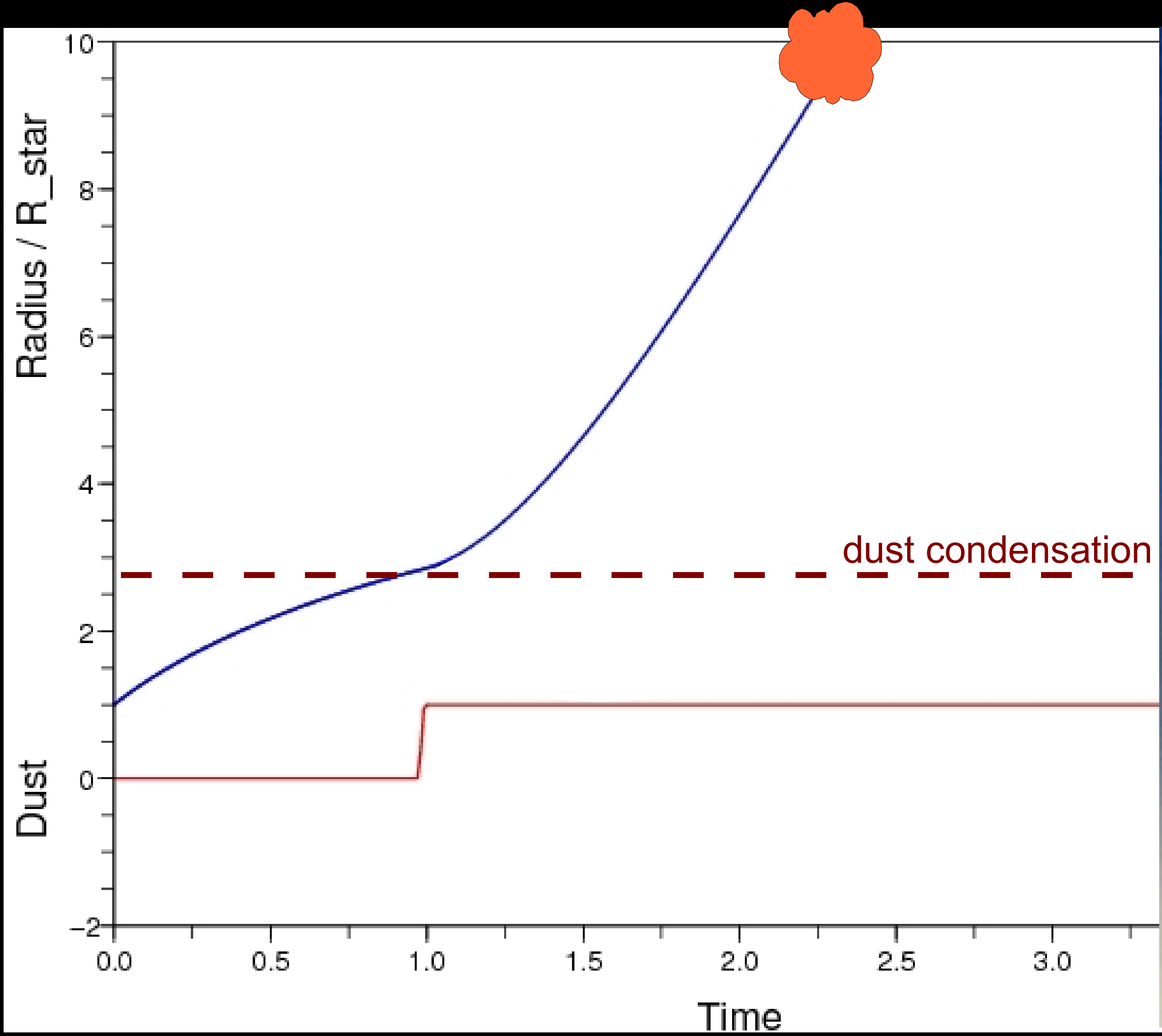
A toy model: shocks, dust & wind



A toy model: shocks, dust & wind



A toy model: shocks, dust & wind



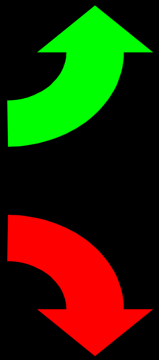
Radiative acceleration: basics

radiative / gravitational acceleration:

$$\Gamma = \frac{\kappa_H \ L_*}{4 \pi c G M_*}$$

> 1

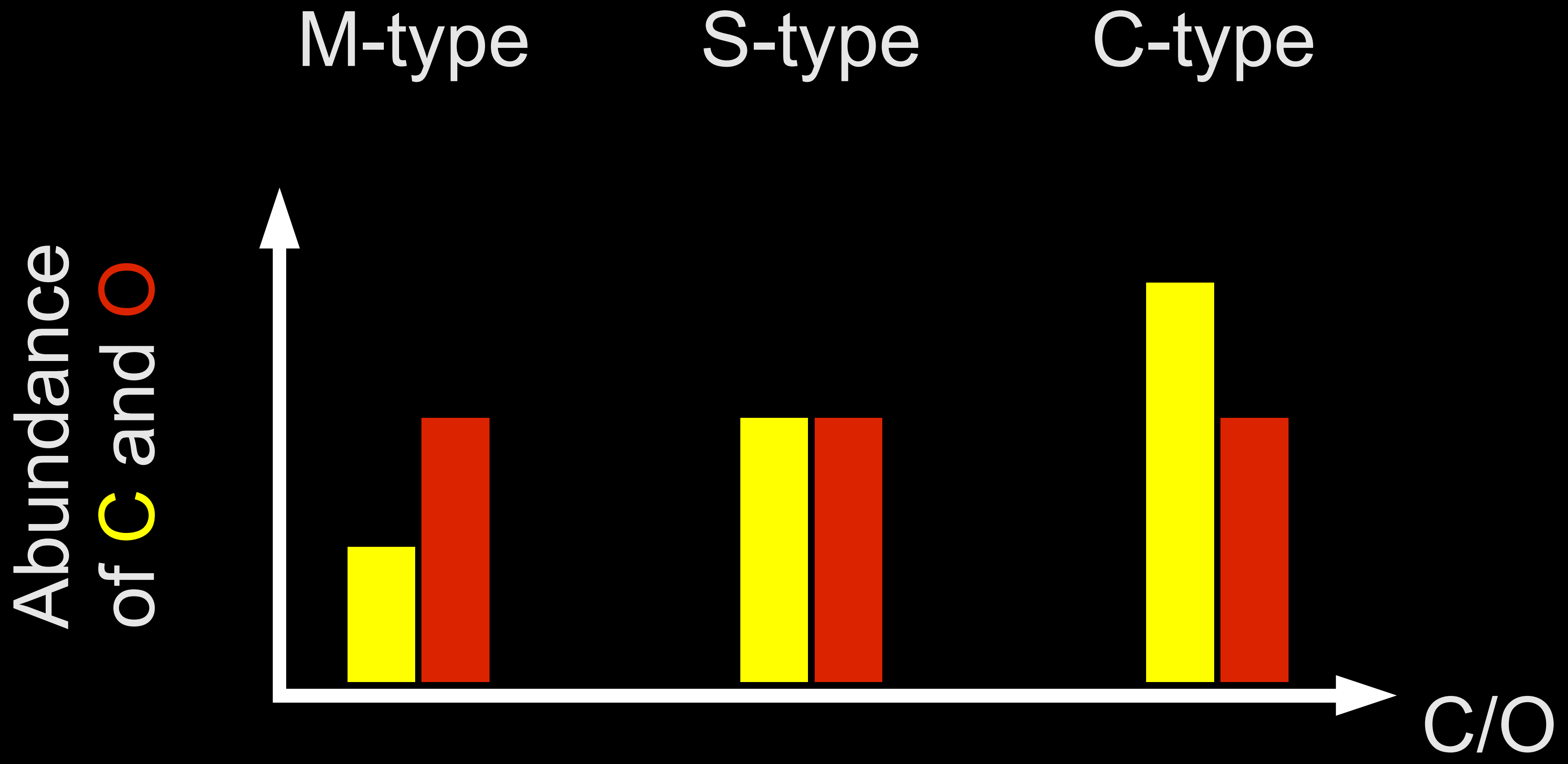
< 1



critical value = 1 $\Rightarrow$ critical flux mean opacity:

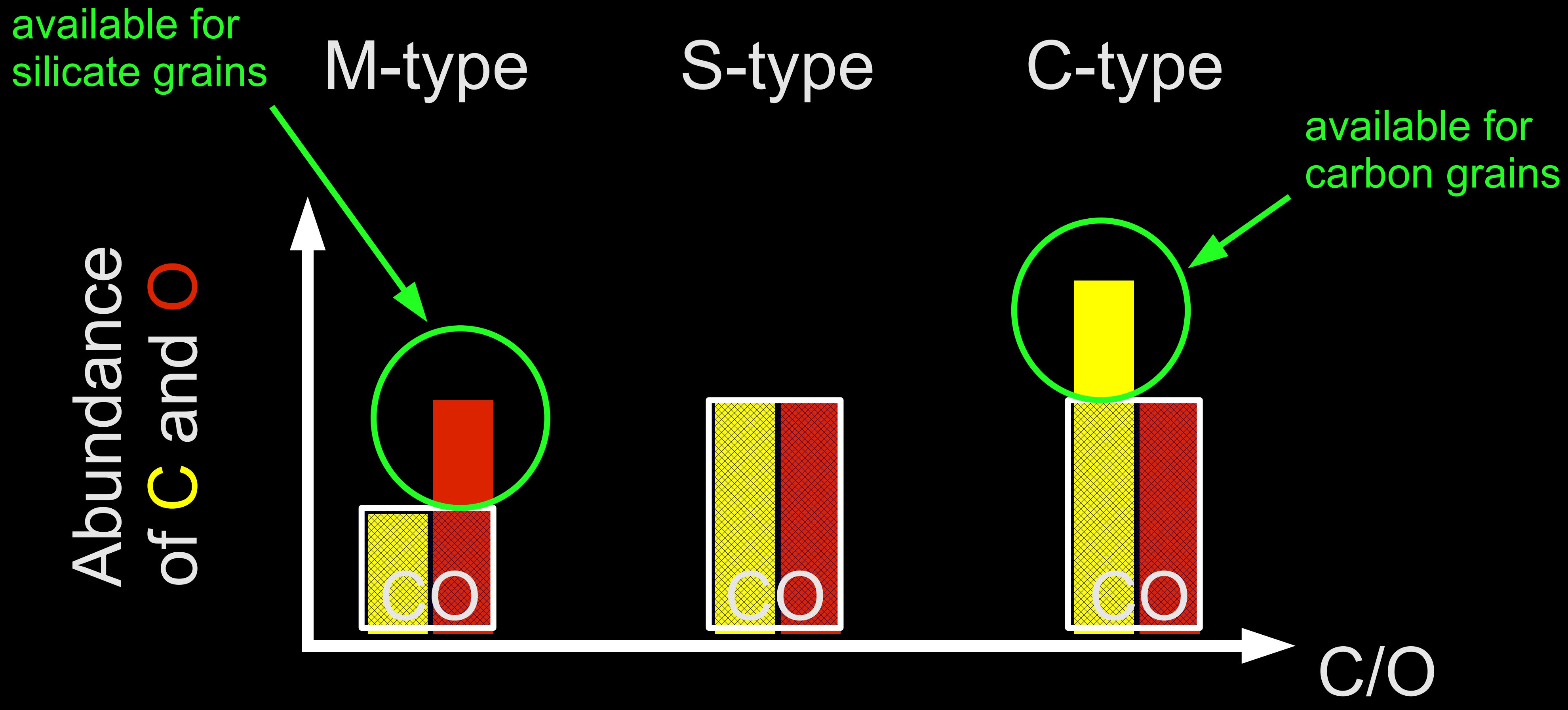
$$\kappa_{crit} = 4 \pi c G M_* / L_*$$

Chemistry: the simple picture



... changes during AGB evolution

Chemistry: the simple picture



... changes during AGB evolution

Dust: grain temperature

simple estimate for grain temperature:

- radiative equilibrium
- Planckian radiation field, geom. diluted
- dust opacity approximated by power law

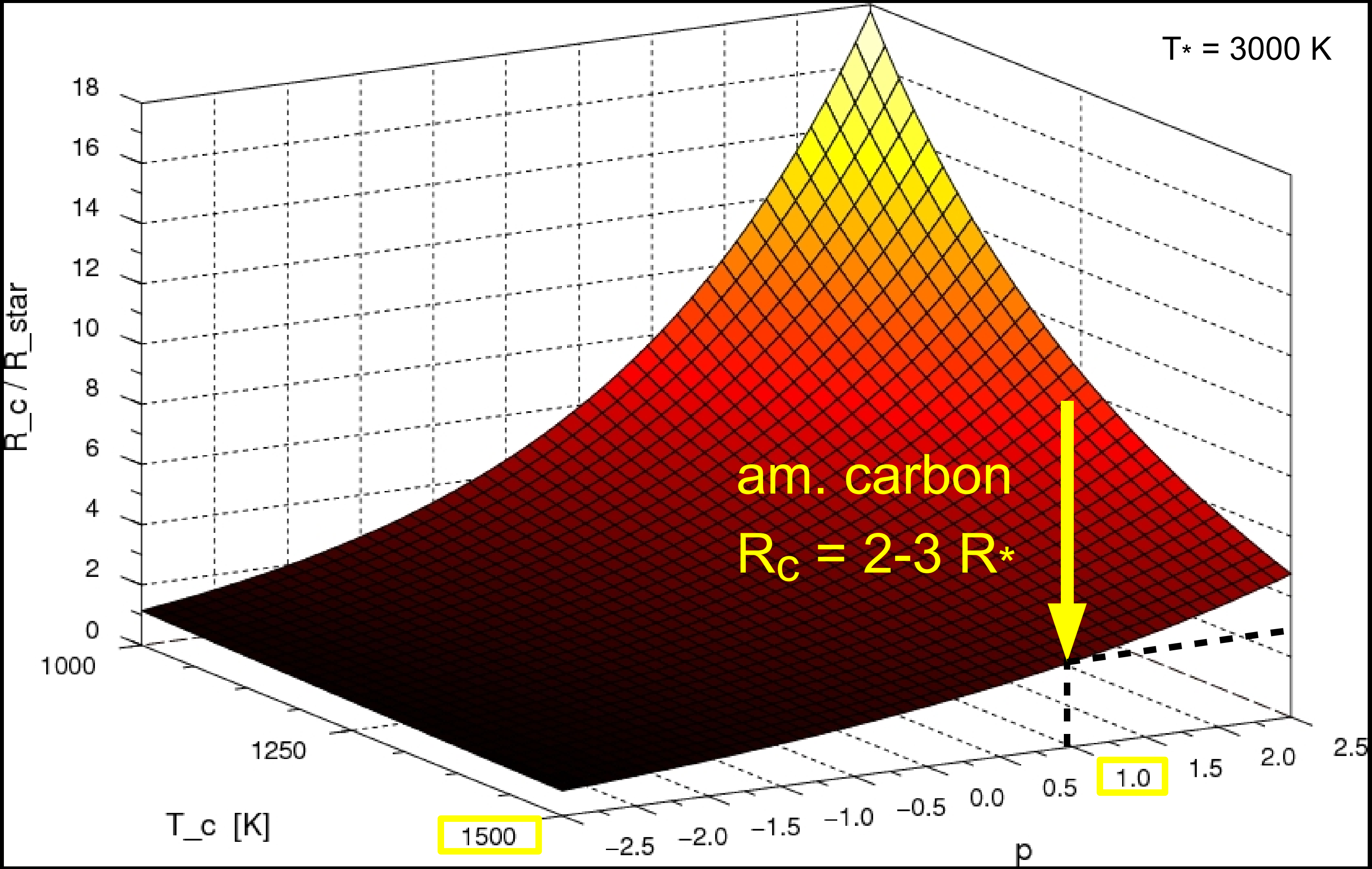
condensation distance: $T_{\text{grain}} = T_c$

condensation temperature (material property)

$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

$$\kappa_\lambda \propto \lambda^{-p}$$

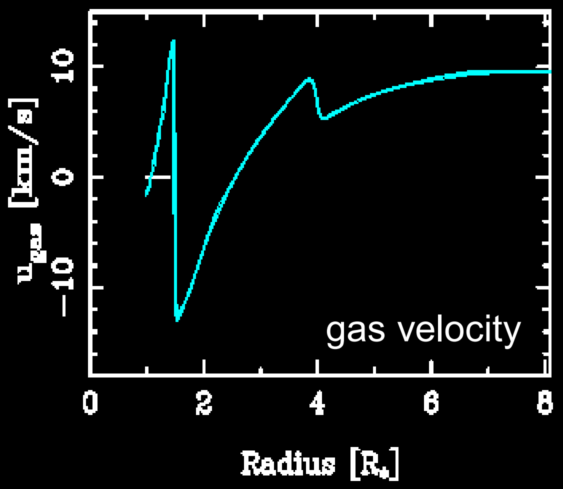
Condensation distance: C/O > 1

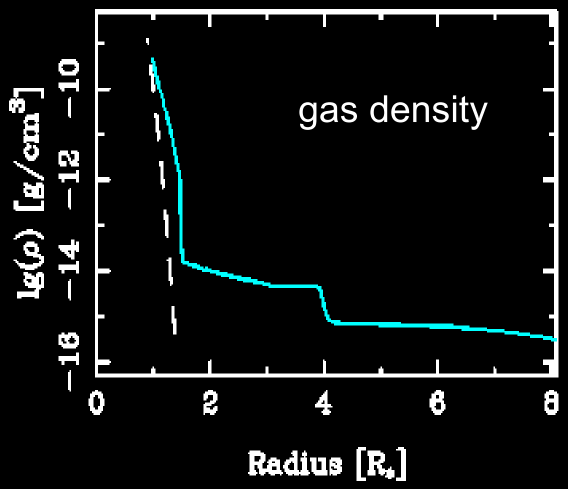


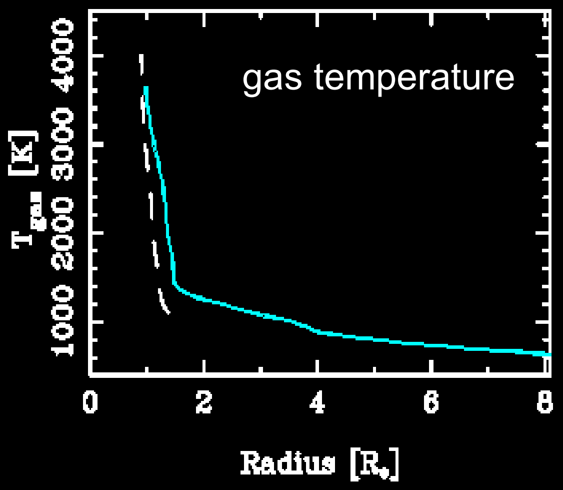
$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

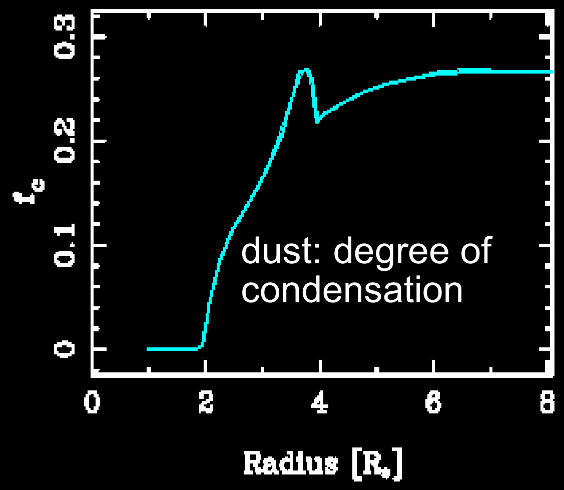
$$\kappa_\lambda \propto \lambda^{-p}$$

Dust-driven wind models: C/O > 1









winds of pulsating carbon stars:

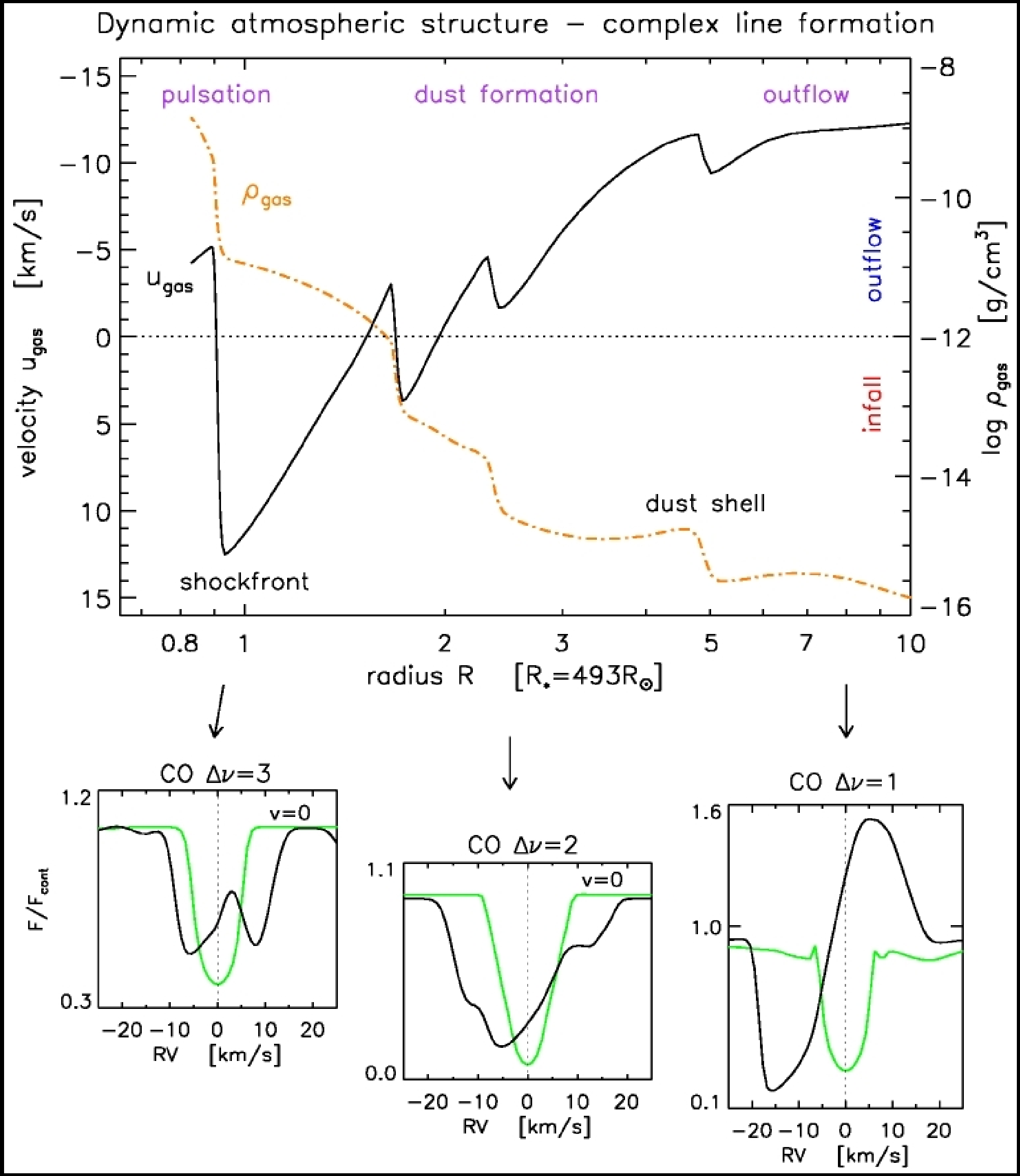
detailed models with frequency-dependent radiative transfer and non-equilibrium dust formation

snapshot of a typical radial structure

Höfner et al. (2003)

Gautschy-Loidl et al. (2004)

Dust-driven wind models: C/O > 1

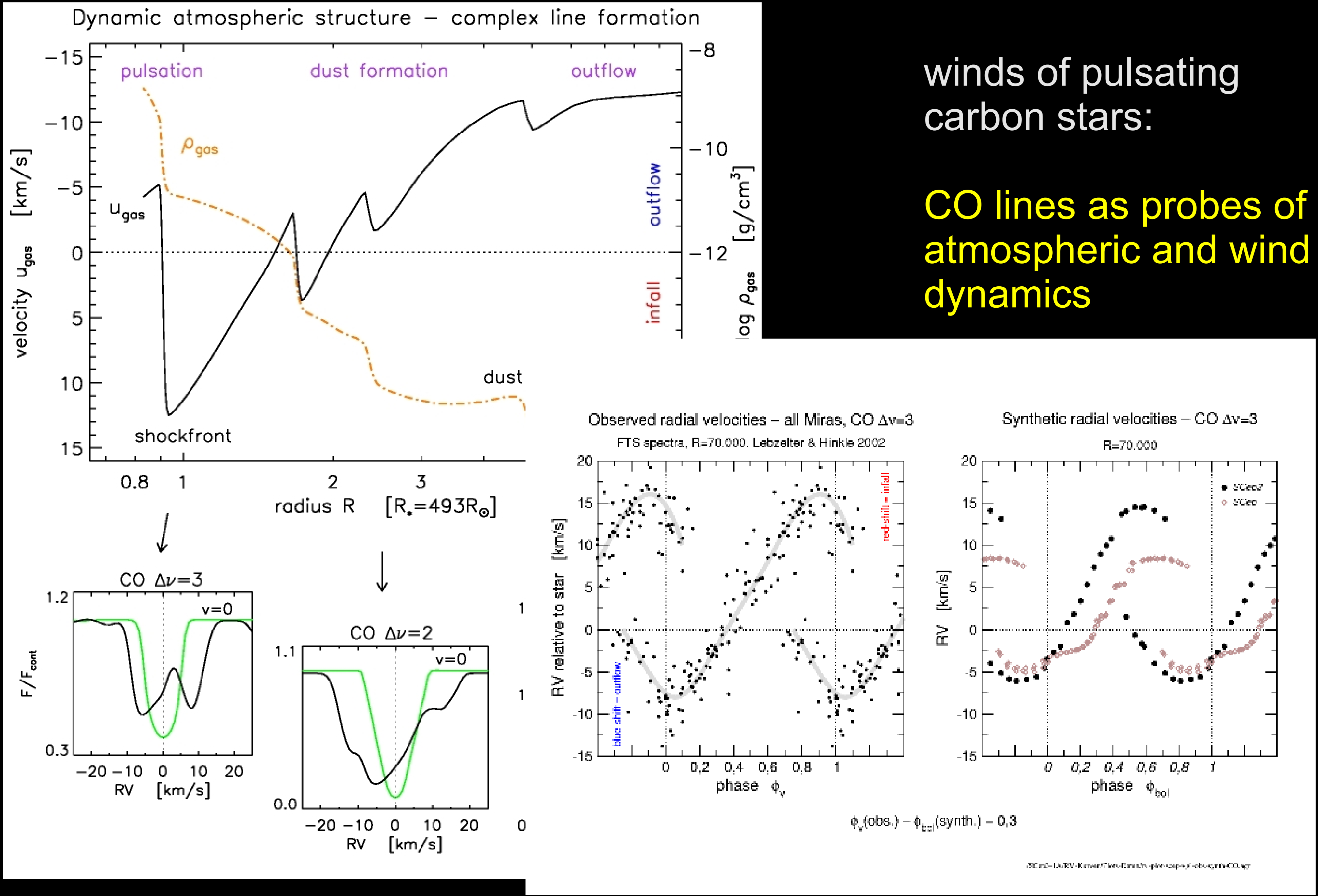


winds of pulsating carbon stars:

CO lines as probes of atmospheric and wind dynamics

Nowotny et al. (2005, 2010)

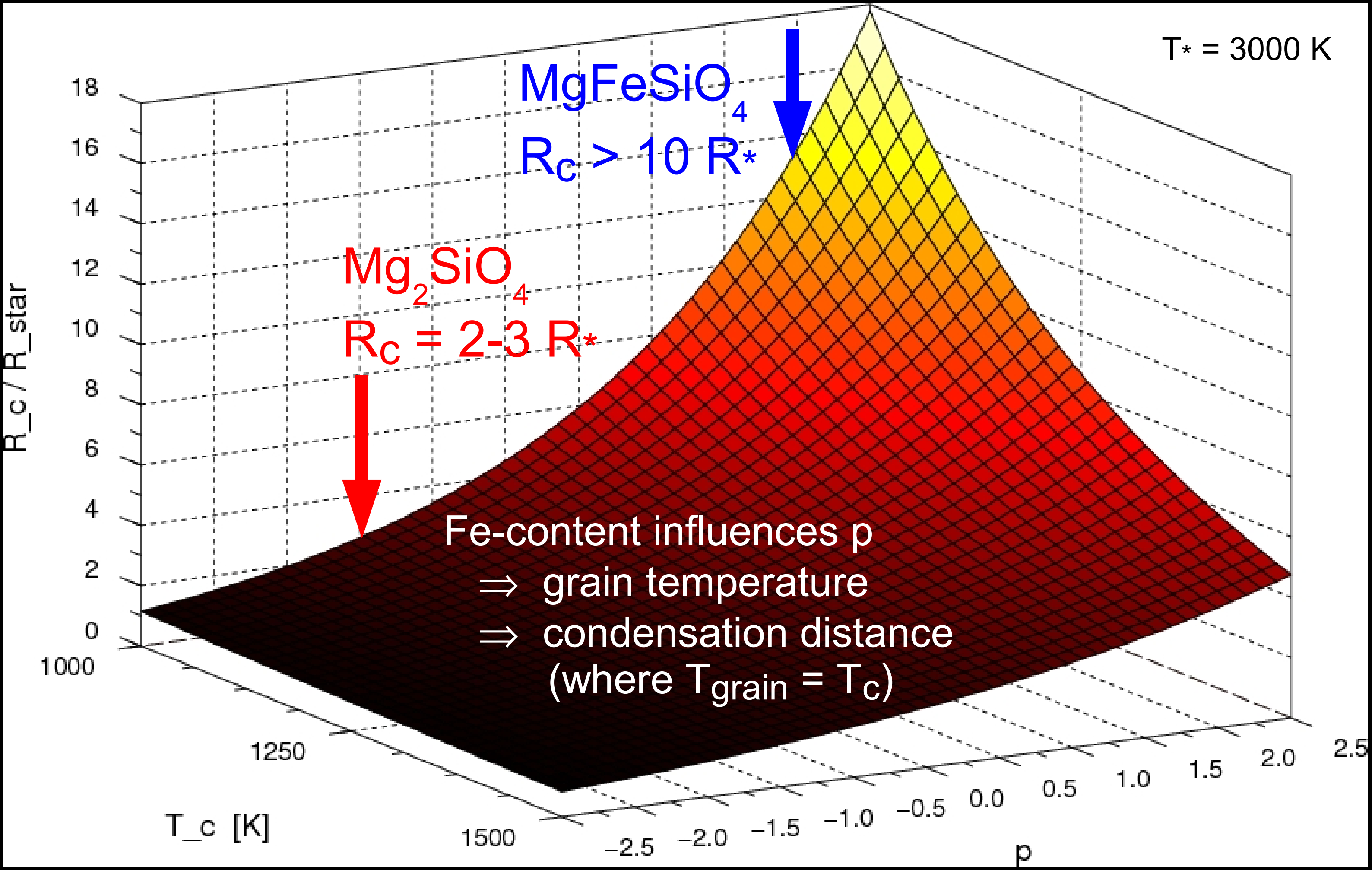
Dust-driven wind models: C/O > 1



winds of pulsating carbon stars:

CO lines as probes of atmospheric and wind dynamics

Condensation distance: C/O < 1



$MgFeSiO_4$

$R_c > 10\ R_*$

Mg_2SiO_4

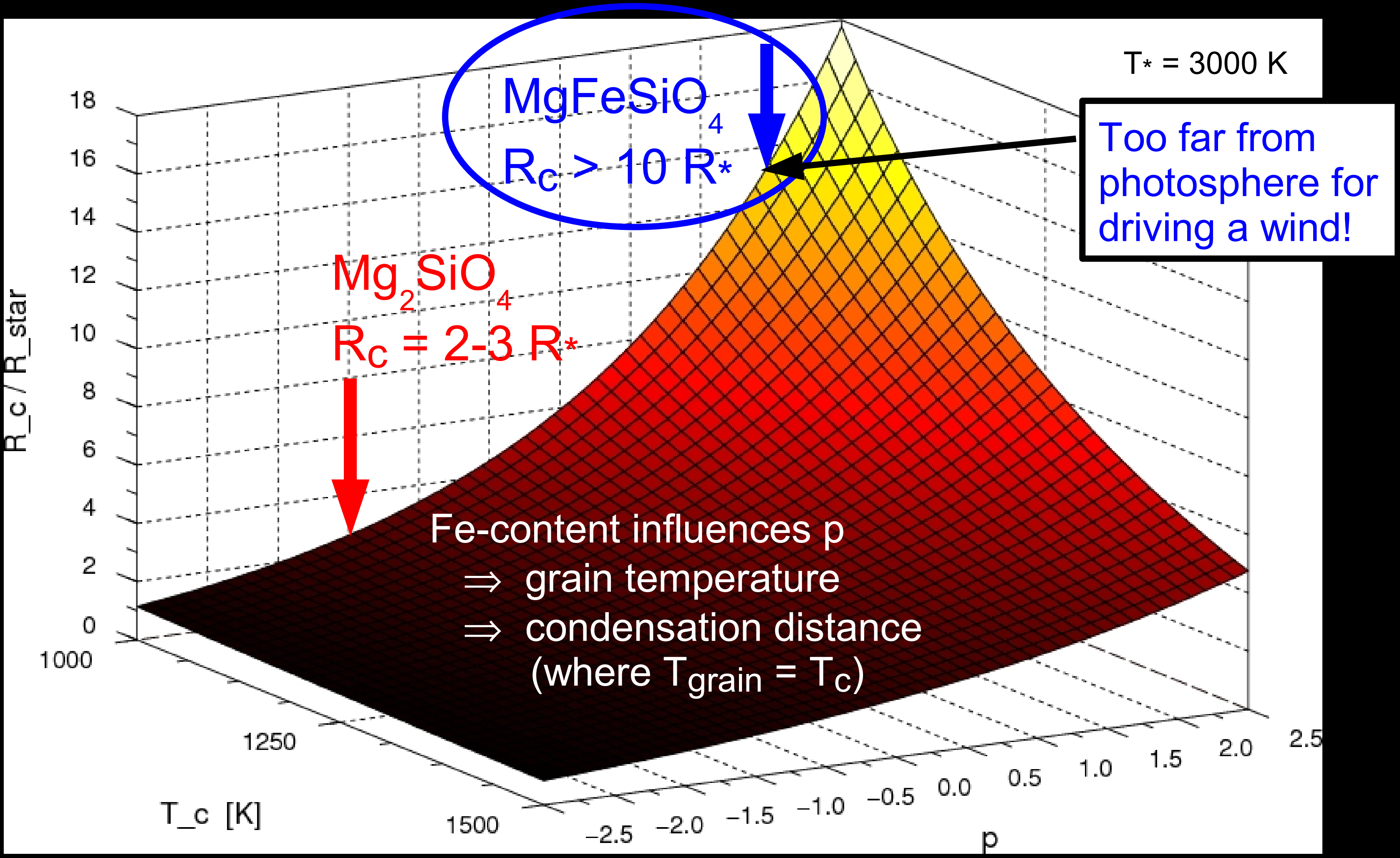
$R_c = 2\text{-}3\ R_*$

Fe-content influences p
⇒ grain temperature
⇒ condensation distance
(where $T_{grain} = T_c$)

$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

$$\kappa_\lambda \propto \lambda^{-p}$$

Condensation distance: C/O < 1



$MgFeSiO_4$

$R_c > 10\ R_*$

Too far from photosphere for driving a wind!

Mg_2SiO_4

$R_c = 2\text{-}3\ R_*$

Fe-content influences p

$\Rightarrow$ grain temperature

$\Rightarrow$ condensation distance (where $T_{grain} = T_c$)

$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

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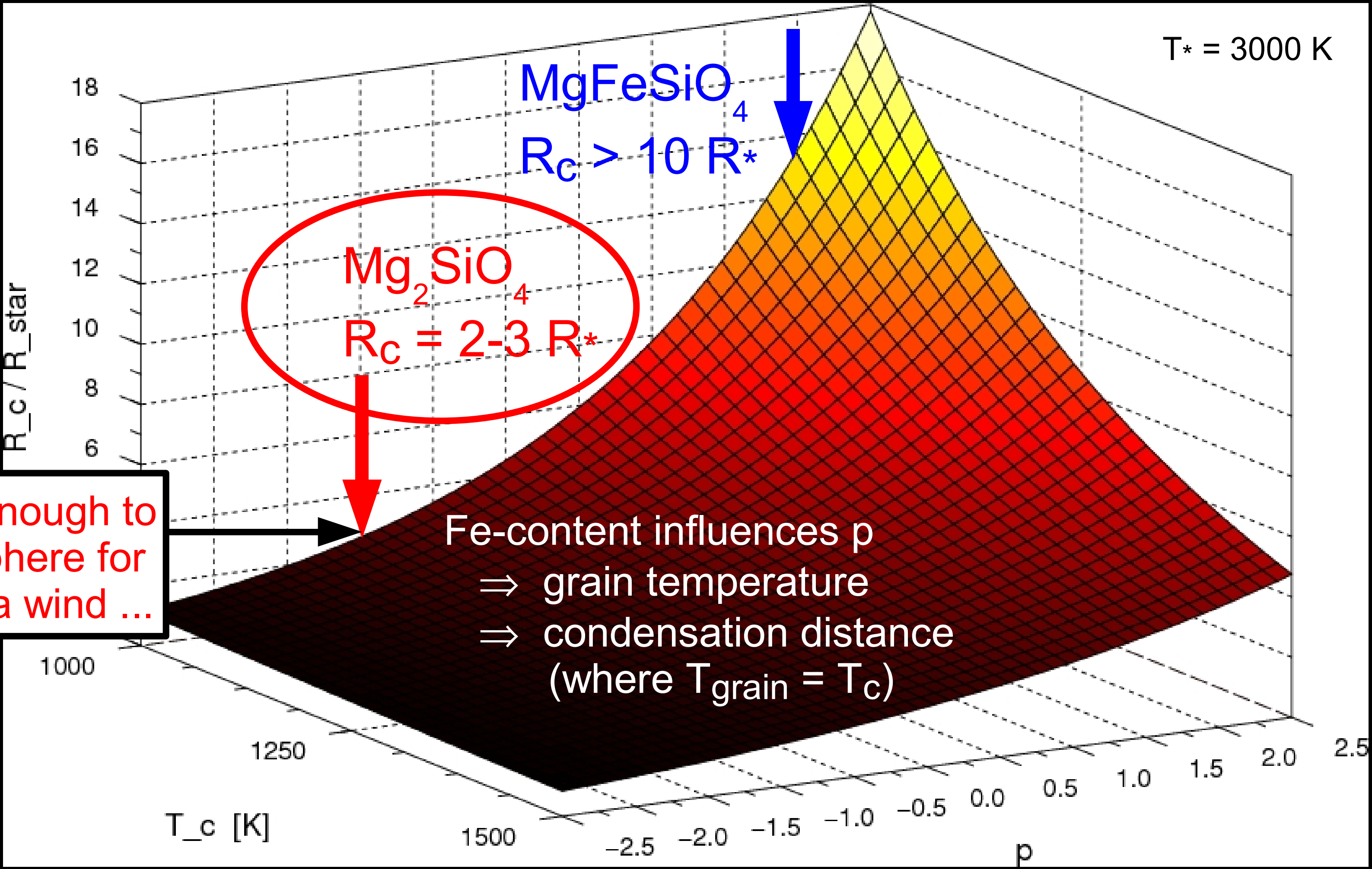
Condensation distance: C/O < 1



$MgFeSiO_4$

$R_c > 10\ R_*$

Mg_2SiO_4

$R_c = 2\text{-}3\ R_*$

Close enough to photosphere for driving a wind ...

Fe-content influences p

⇒ grain temperature

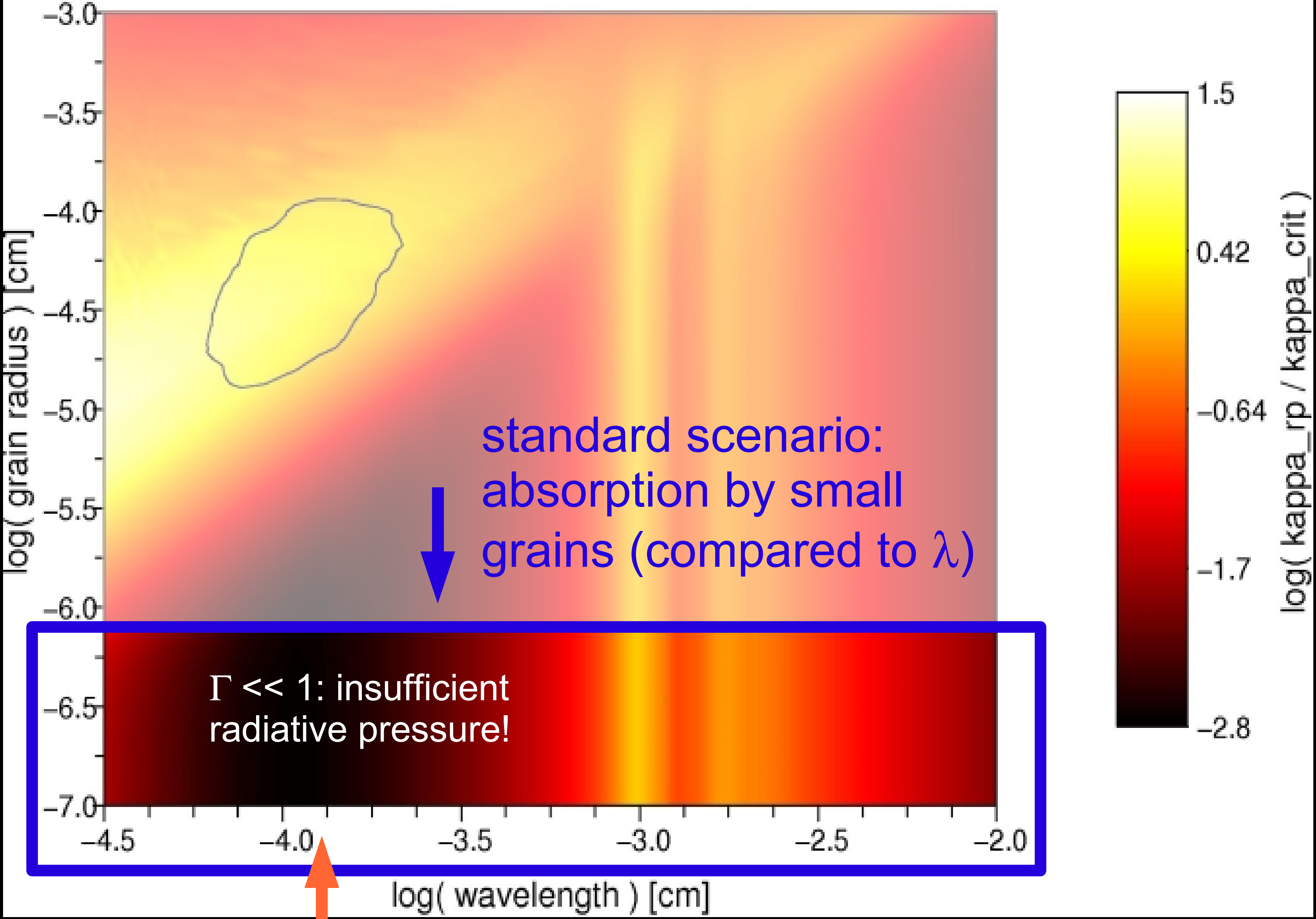
⇒ condensation distance

(where $T_{grain} = T_c$)

$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

$$\kappa_\lambda \propto \lambda^{-p}$$

Radiative pressure on Mg_2SiO_4

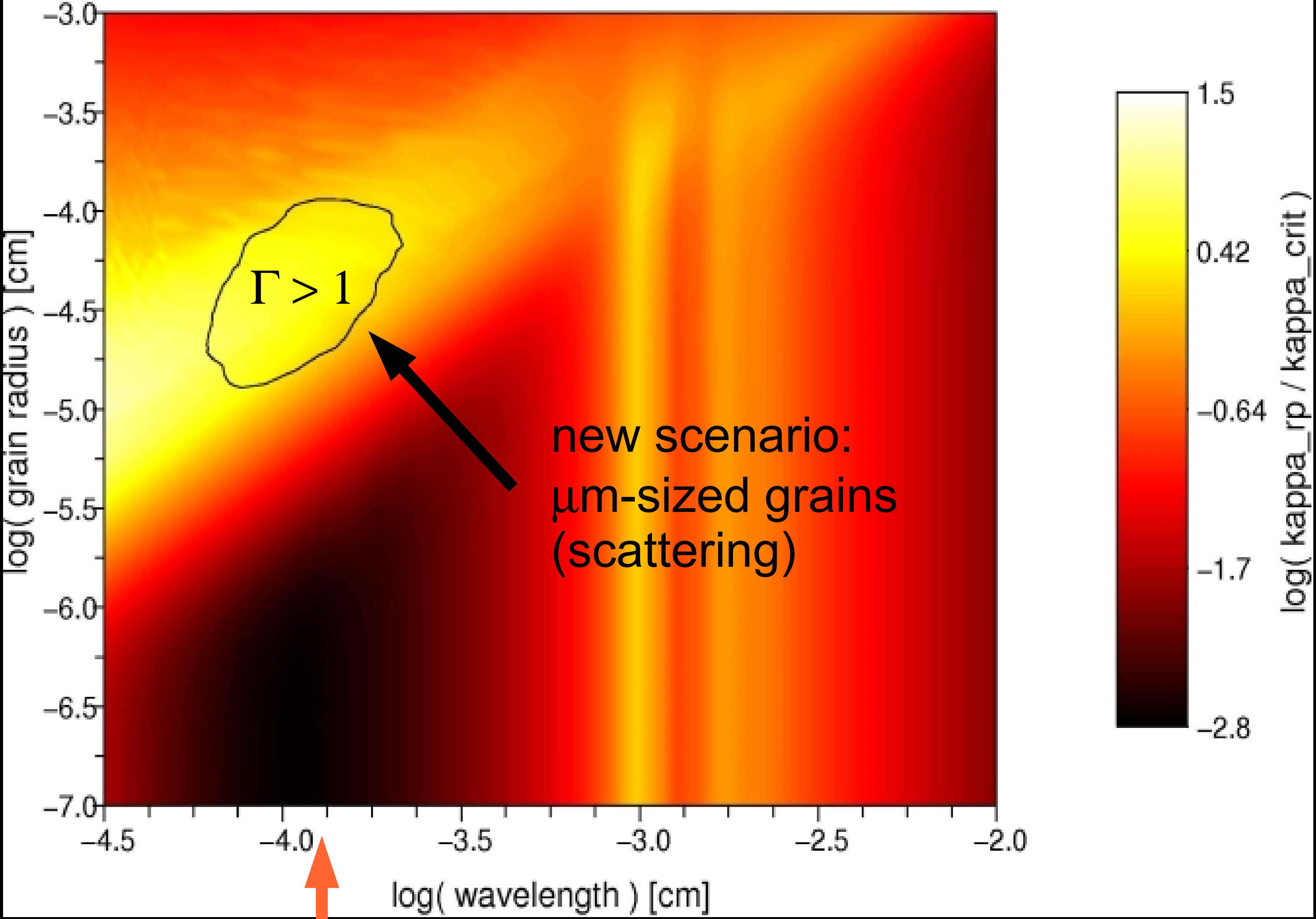


standard scenario: absorption by small grains (compared to λ)

$\Gamma << 1$: insufficient radiative pressure!

stellar flux maximum ↔ κ_H

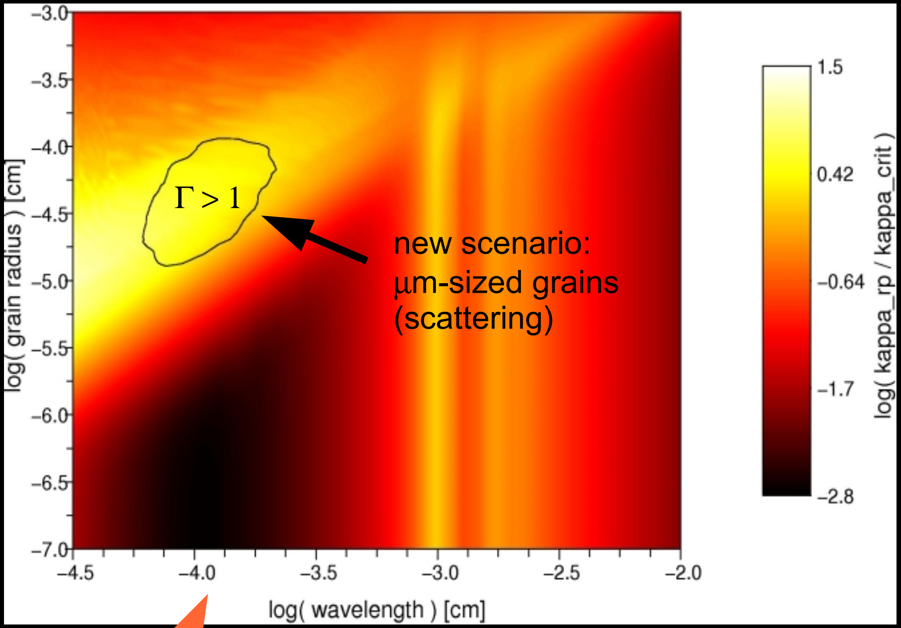
Radiative pressure on Mg_2SiO_4



new scenario:
μm-sized grains
(scattering)

stellar flux maximum ↔ κ_H

Dust-driven AGB winds for C/O < 1

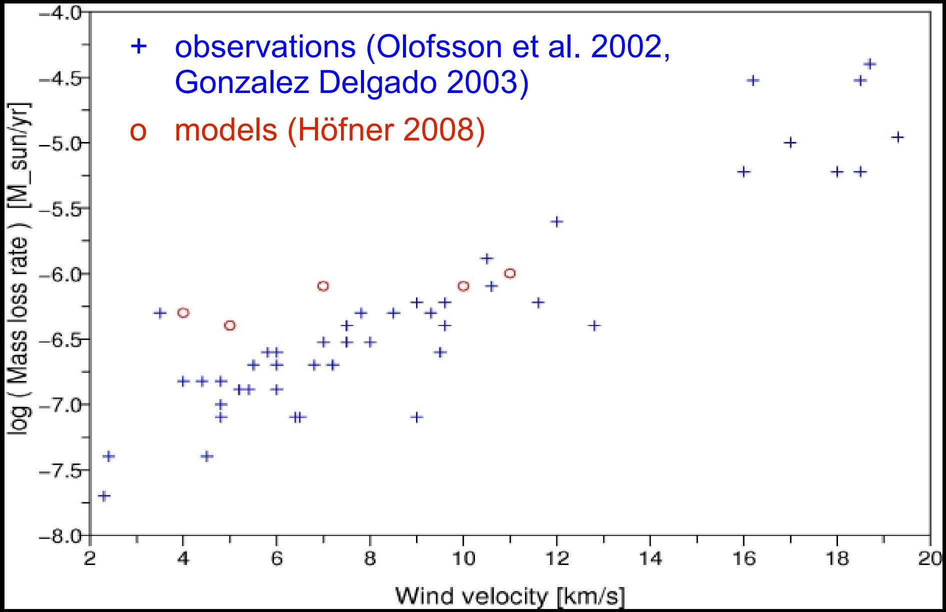


new scenario:
µm-sized grains
(scattering)

stellar flux maximum

opacity of Mg_2SiO_4
as a function of
wavelength and
grain radius

black contour marks
where radiative
pressure exceeds
gravity for a typical
AGB star



comparison of
mass loss rates and
wind velocities with
observations

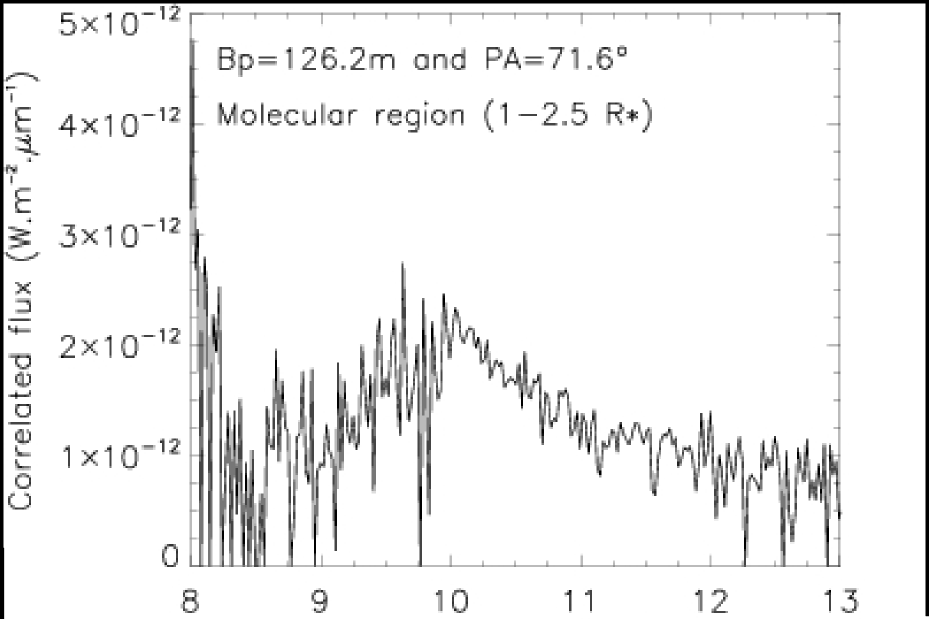
new scenario for
winds of pulsating
M-type AGB stars

detailed models with
frequency-dependent
radiative transfer
and non-equilibrium
dust formation
(Mg_2SiO_4)

wind driven by
Fe-free, micron-sized
silicate grains

Höfner 2008
(A&A 491, L1)

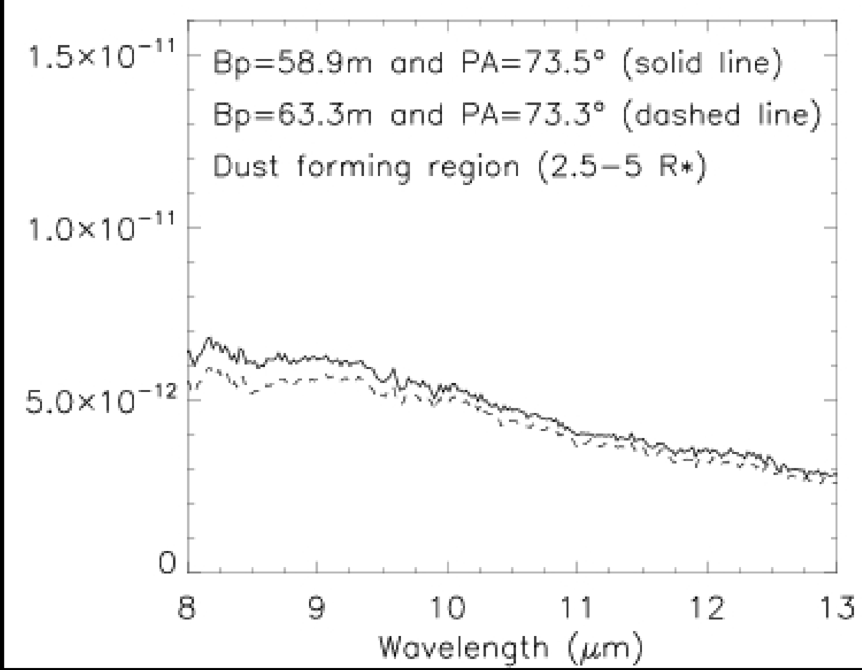
Dust-driven AGB winds for C/O < 1

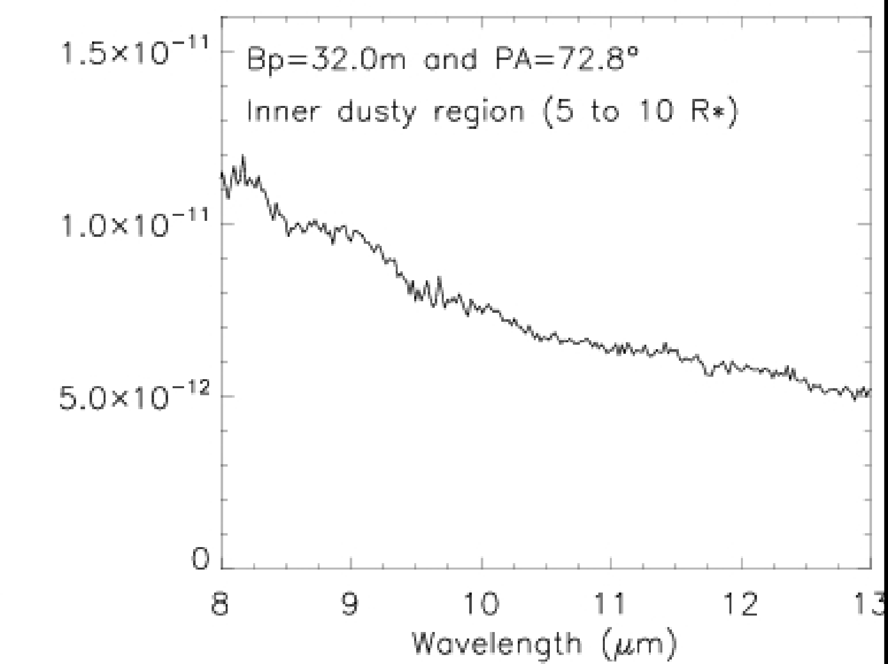


Testing the new scenario:
observations of RT Vir with VLTI/MIDI, 3 different baselines

work in progress by
Ramstedt, Sacuto et al.

For more information see
Sofia Ramstedt's talk ...

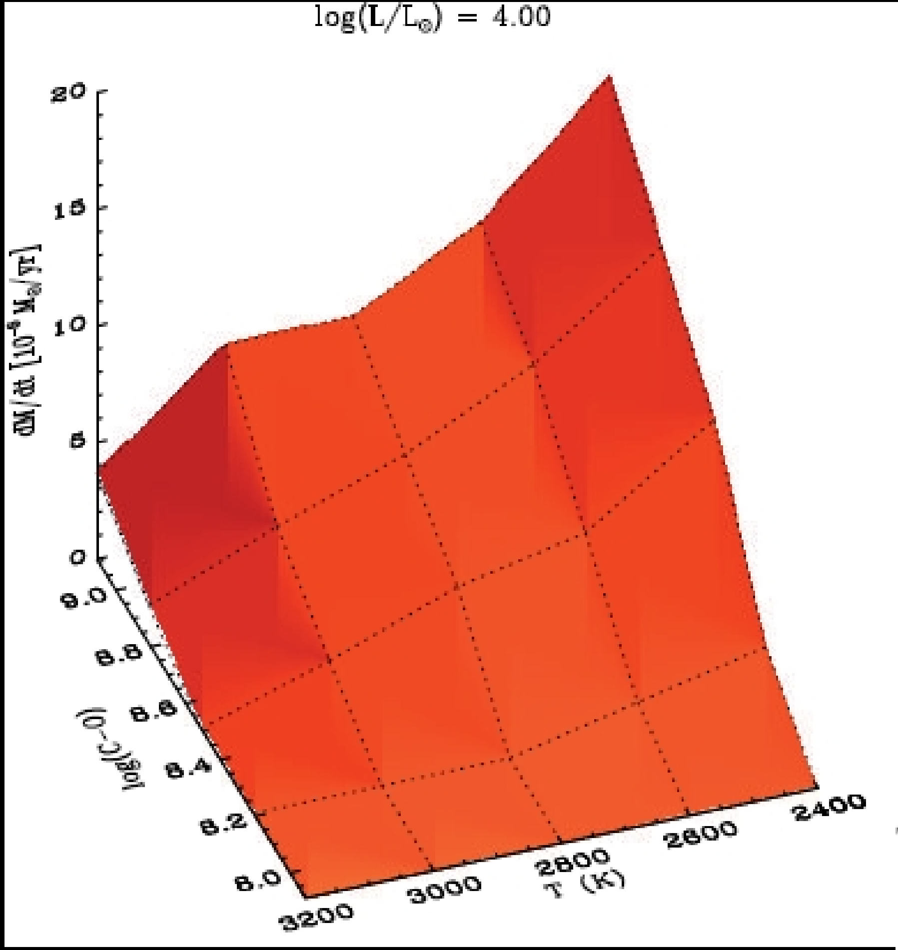


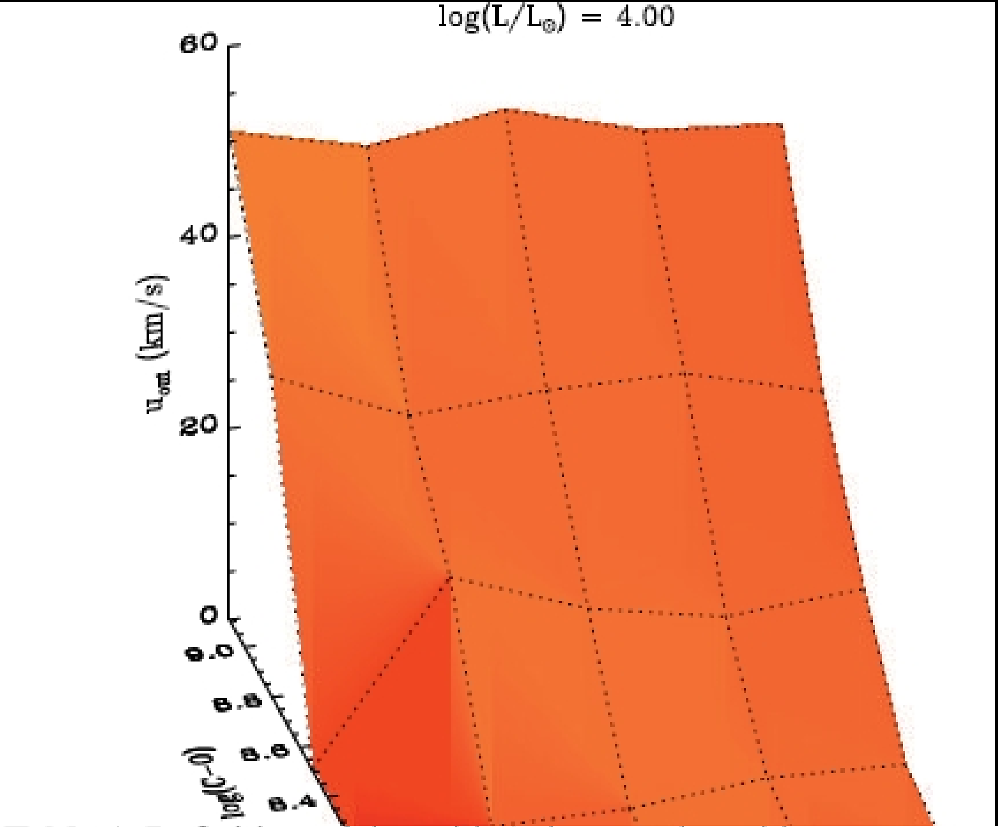


Dust & Winds - Summary

- C/O > 1: winds driven by carbon grains,
  good agreement of detailed
  non-grey models with observations
- C/O < 1: non-grey RT → Fe-free silicates
  → too low radiative pressure for
  small grains (cf. Woitke 2006)
  → winds possibly driven by
  μm-sized Fe-free silicate grains
- More observational constraints for models!

A new mass loss grid for C/O > 1





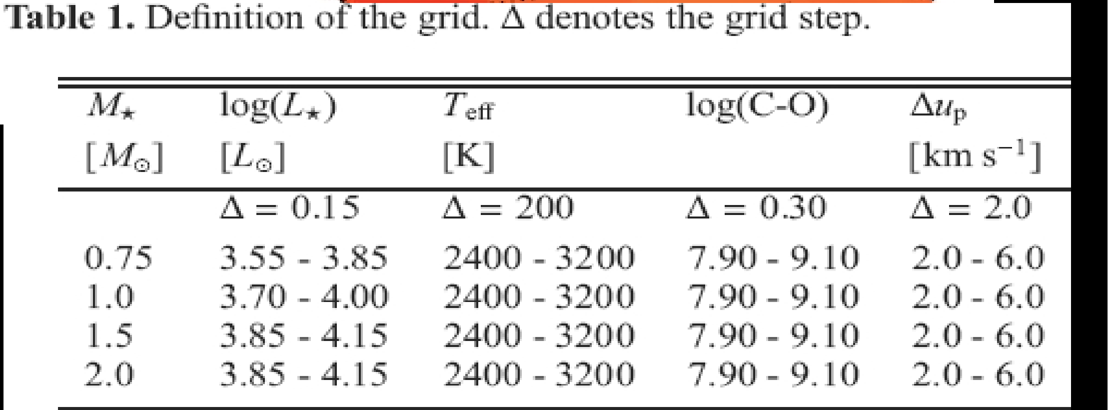
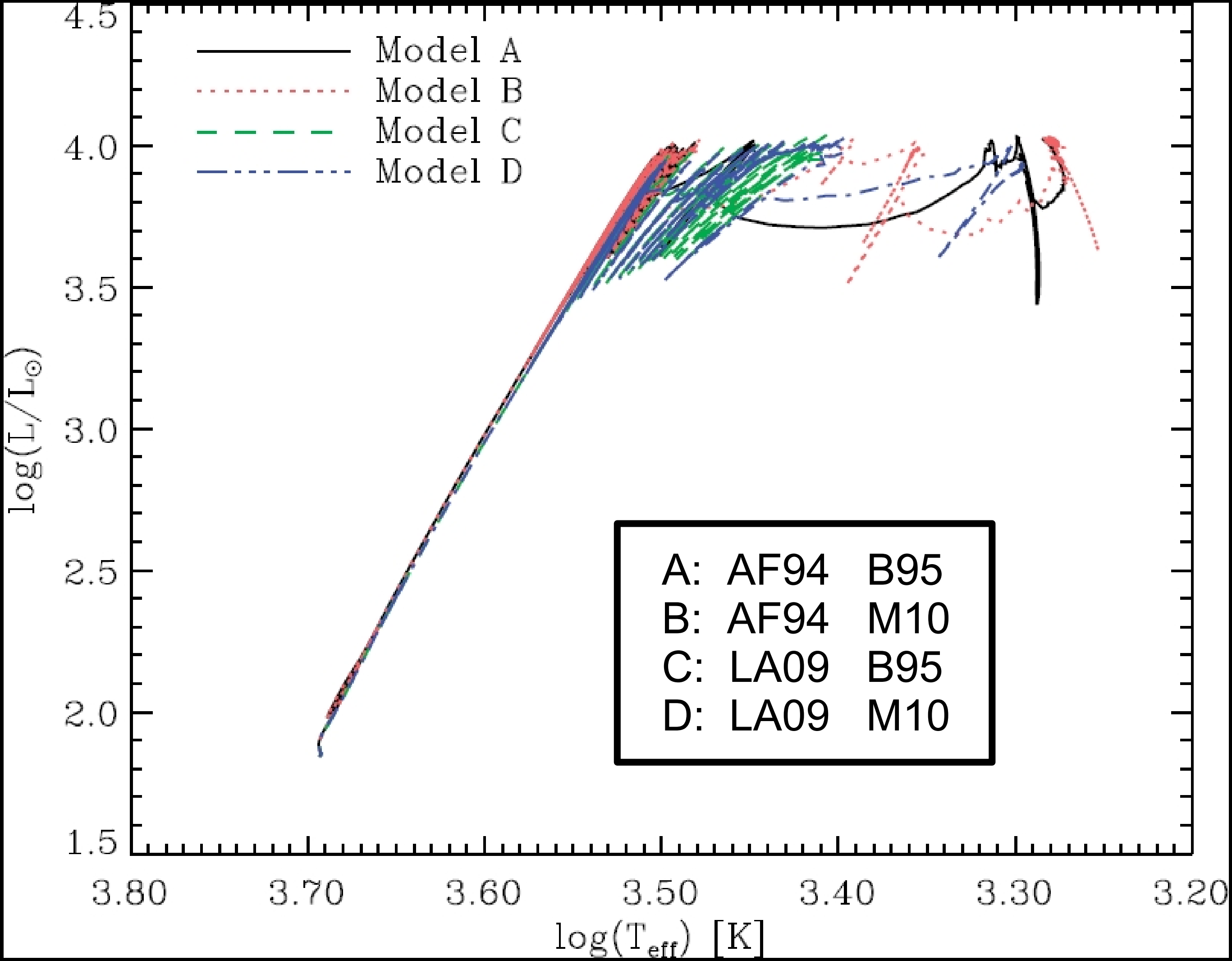


Table 1. Definition of the grid. Δ denotes the grid step.

$M_\star$ $[M_\odot]$	$\log(L_\star)$ $[L_\odot]$	$T_{\rm eff}$ [K]	log(C-O)	$\Delta u_{\rm p}$ $[{\rm km\,s^{-1}}]$
	Δ = 0.15	Δ = 200	Δ = 0.30	Δ = 2.0
0.75	3.55 - 3.85	2400 - 3200	7.90 - 9.10	2.0 - 6.0
1.0	3.70 - 4.00	2400 - 3200	7.90 - 9.10	2.0 - 6.0
1.5	3.85 - 4.15	2400 - 3200	7.90 - 9.10	2.0 - 6.0
2.0	3.85 - 4.15	2400 - 3200	7.90 - 9.10	2.0 - 6.0

based on frequency-dependent RHD models with detailed dust description (Mattsson et al. 2010)

Mass loss and stellar evolution



A:	AF94	B95
B:	AF94	M10
C:	LA09	B95
D:	LA09	M10

Mattsson et al., in prep.

AGB evolution models with MESA

influence of input physics

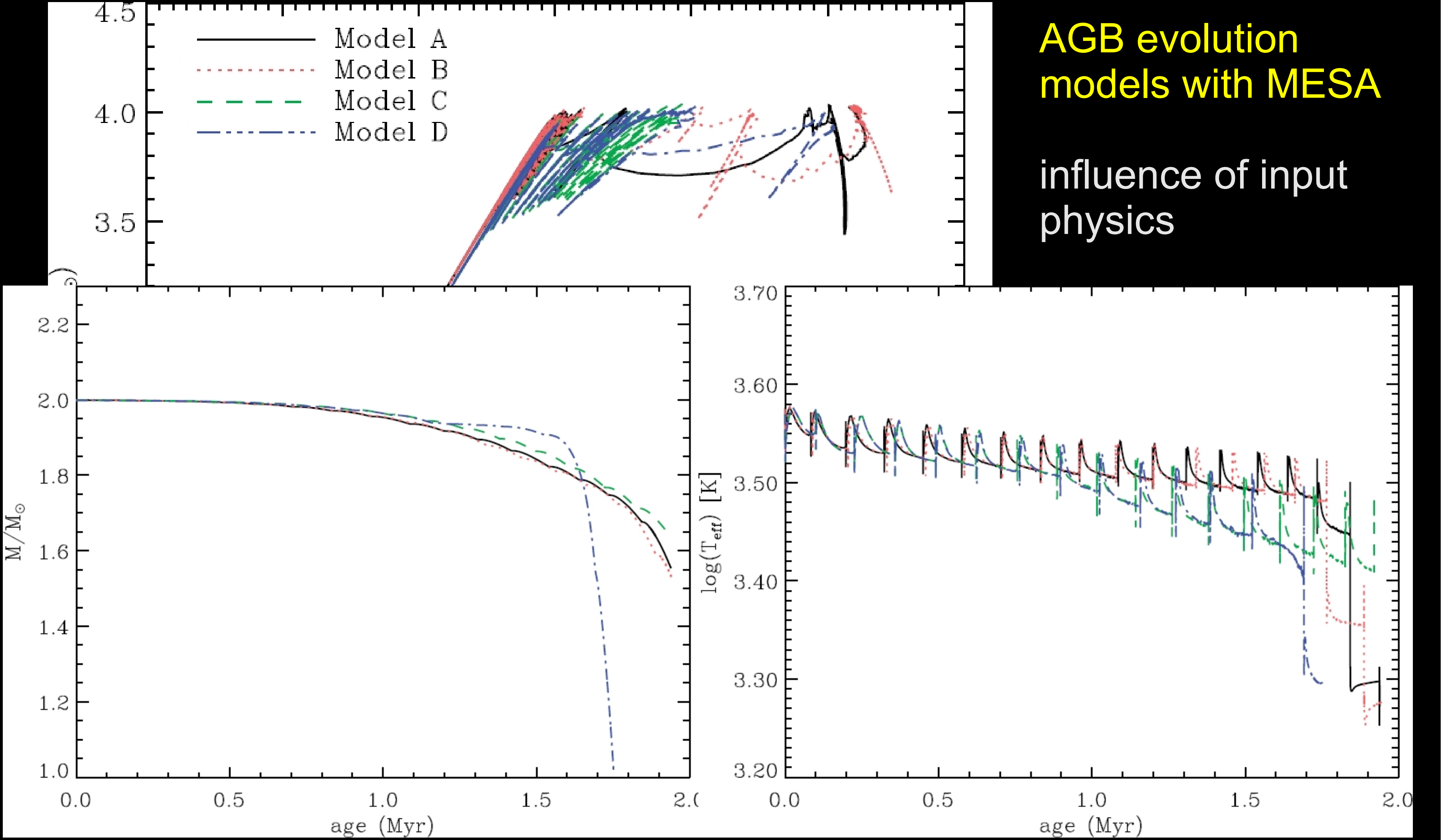
- gas opacities:

Alexander & Ferguson (1994) vs. Lederer & Aringer (2009)

- mass loss:

Blöcker (1995) vs. Mattsson et al. (2010, for C/O>1)

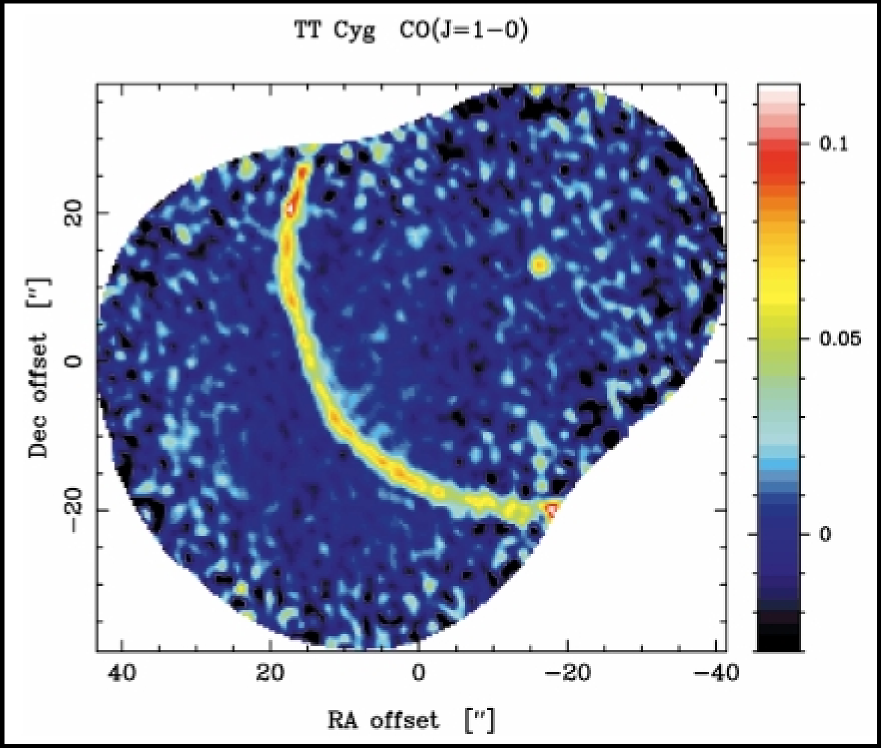
Mass loss and stellar evolution



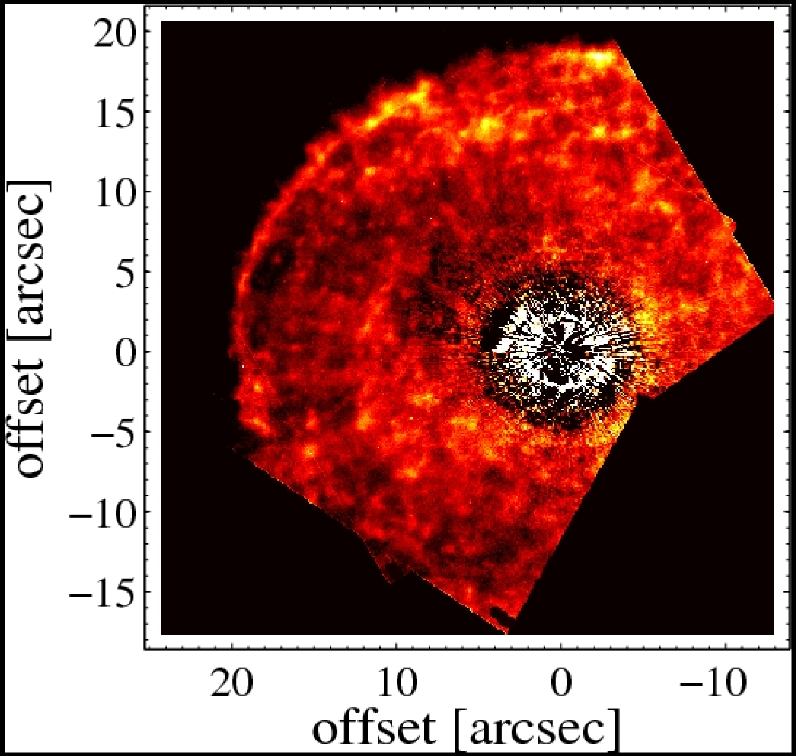
AGB evolution models with MESA

influence of input physics

Observations of detached shells



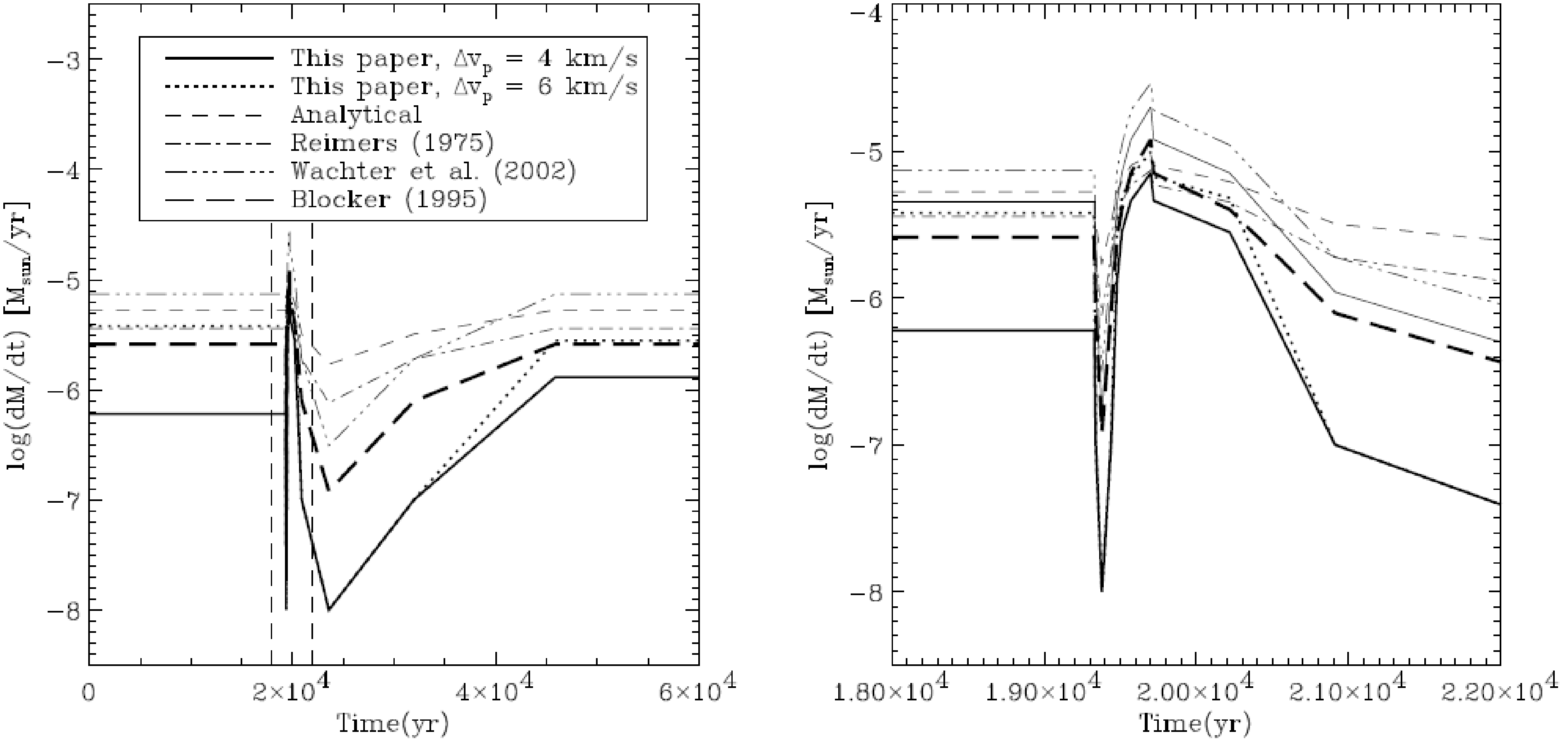
Thin molecular shell around
TT Cyg (Olofsson et al. 1998)



Circumstellar envelope of
R Scl (Olofsson et al. 2010)

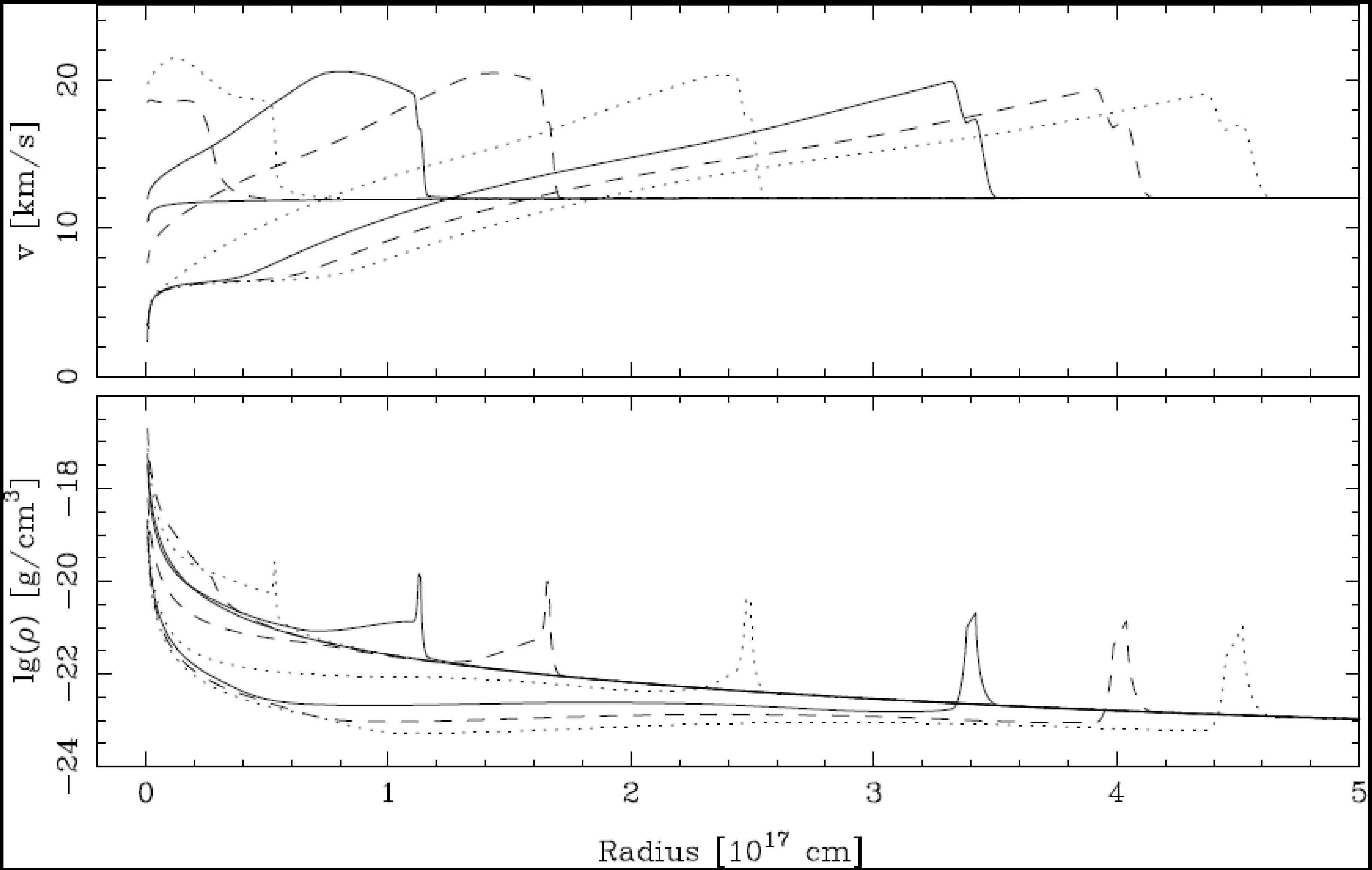
More about this topic: talk by Matthias Maercker ...

Mass loss during a He-shell flash



variation of mass loss during a He-shell flash: comparison of models (Mattsson, Höfner & Herwig 2007)

Mass loss during a He-shell flash



variation of wind properties leading to the formation of a detached shell: snapshots of velocity (top) and density (bottom) (Mattsson et al. 2007)

Mass Loss and AGB Evolution Summary

- Descriptions of mass loss and gas opacities (incl. molecules, changes in abundances) are crucial input for stellar evolution models.
- A consistent combination of these two is critical, as mass loss is very sensitive to certain stellar parameters, and vice versa.
- Detached shells around C-type AGB stars are an interesting test case for the interplay of mass loss and evolution.

Conclusions

- Dynamics caused by pulsation / convection produces intricate variable structures in atmospheres and circumstellar envelopes.
- Spatially resolved observations are important for constraining 3D models of convection and dusty envelopes (giant convection cells, patchy dust formation)
- The debate on the wind mechanism(s) of M-type AGB stars needs observational input.