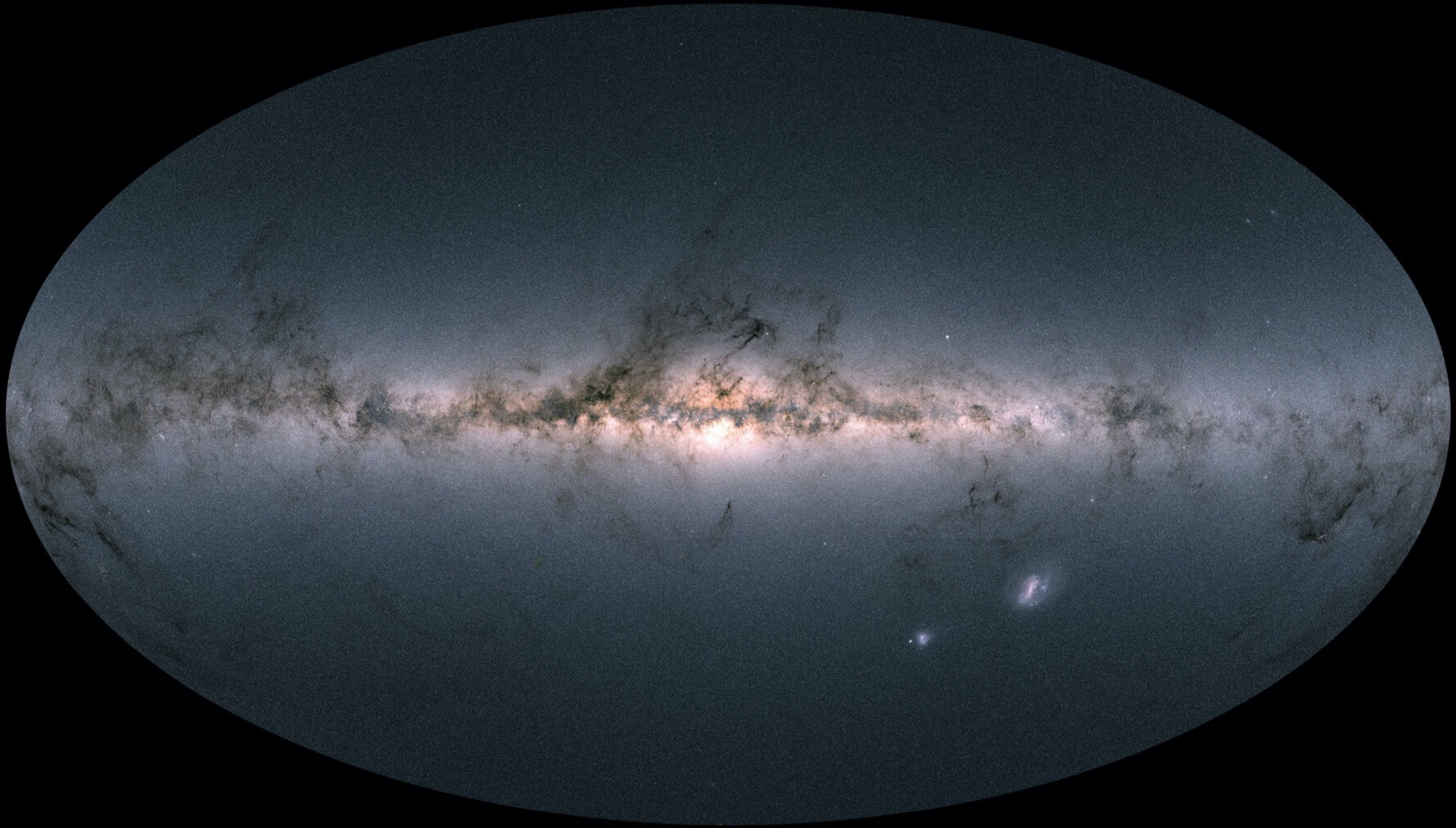
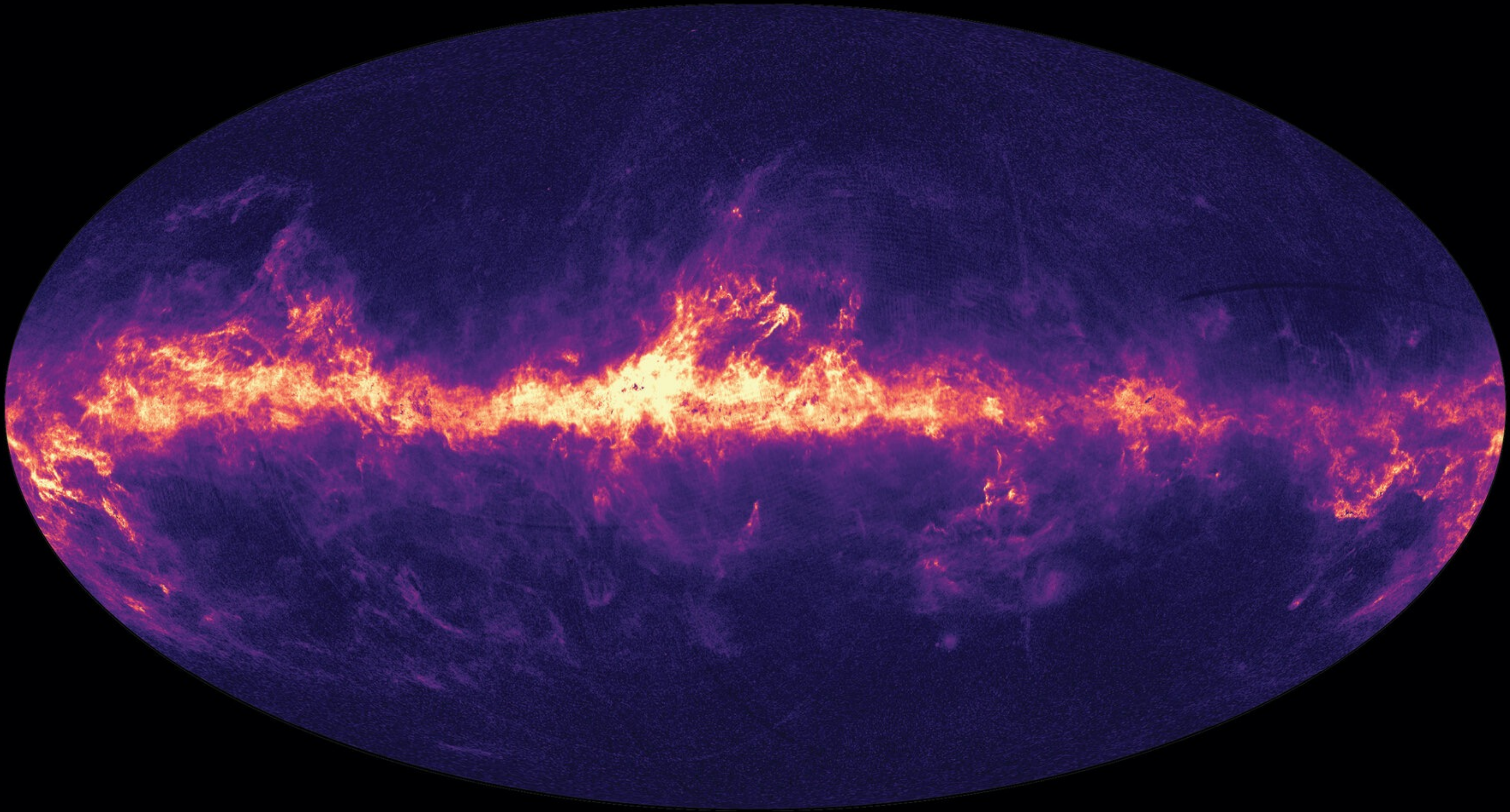
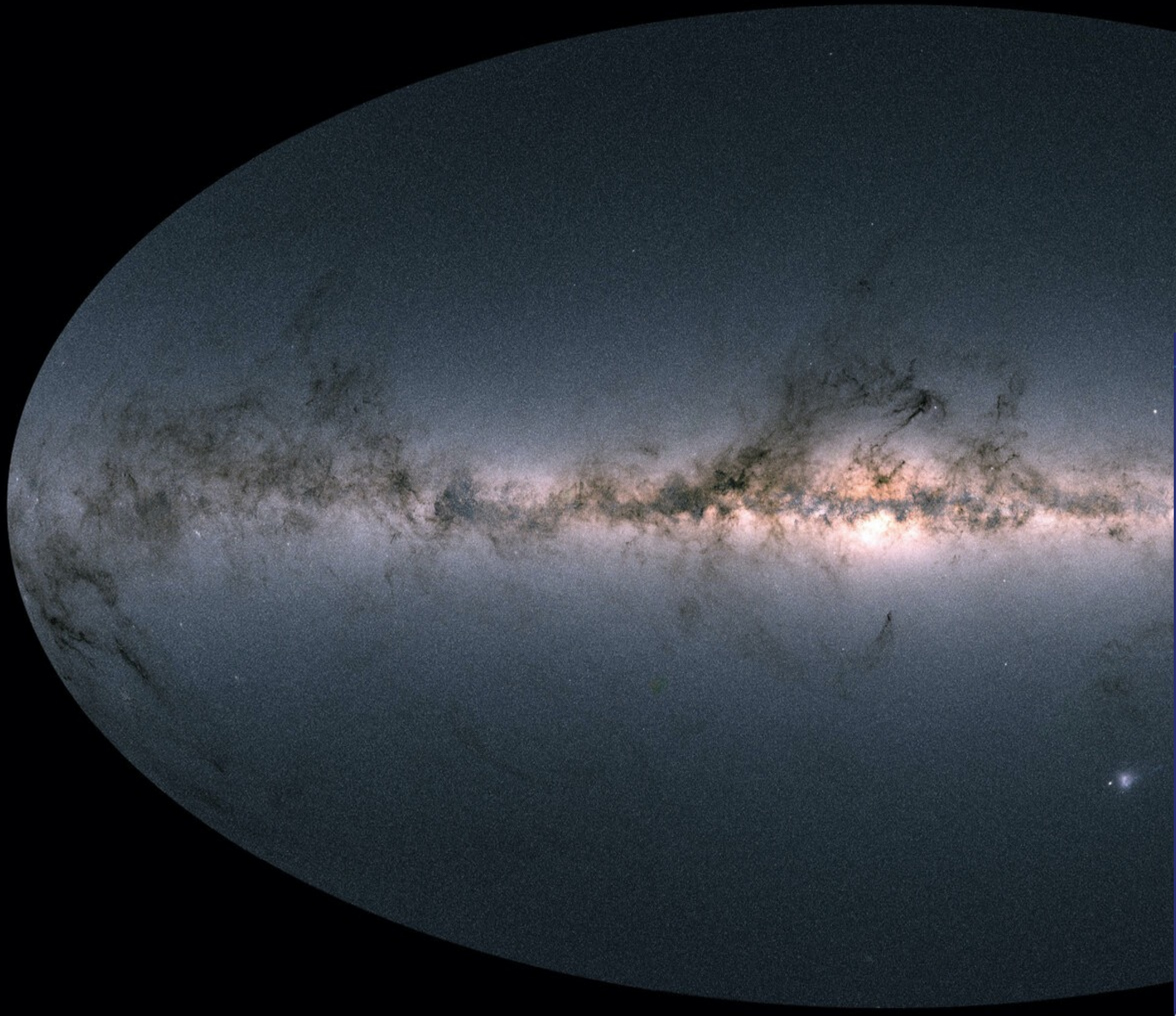
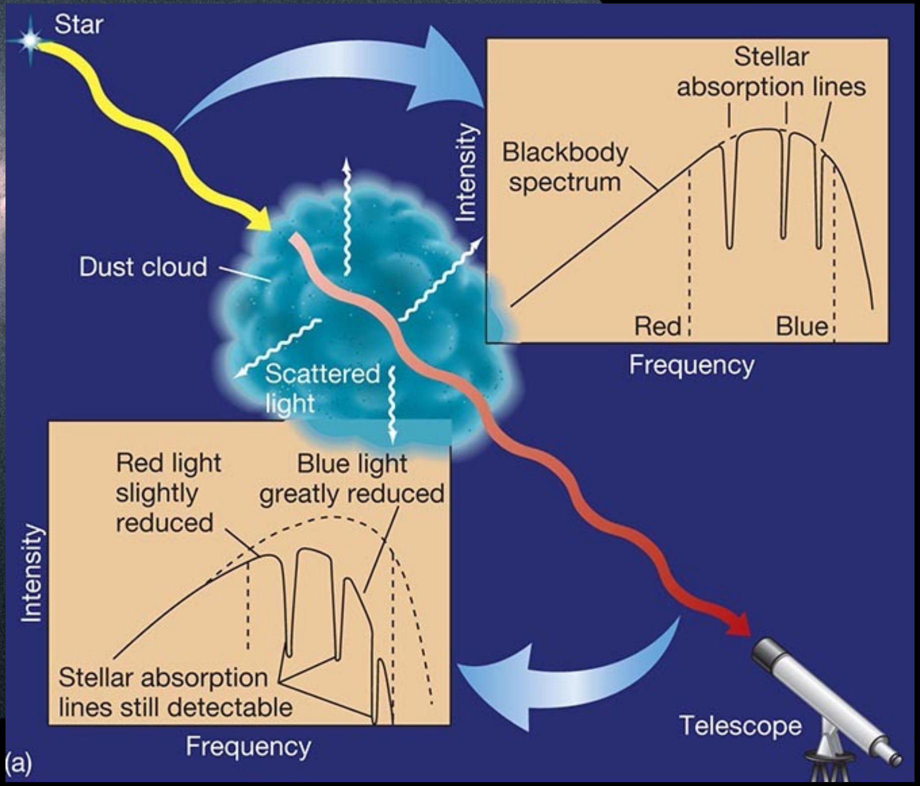
Dust formation around evolved stars

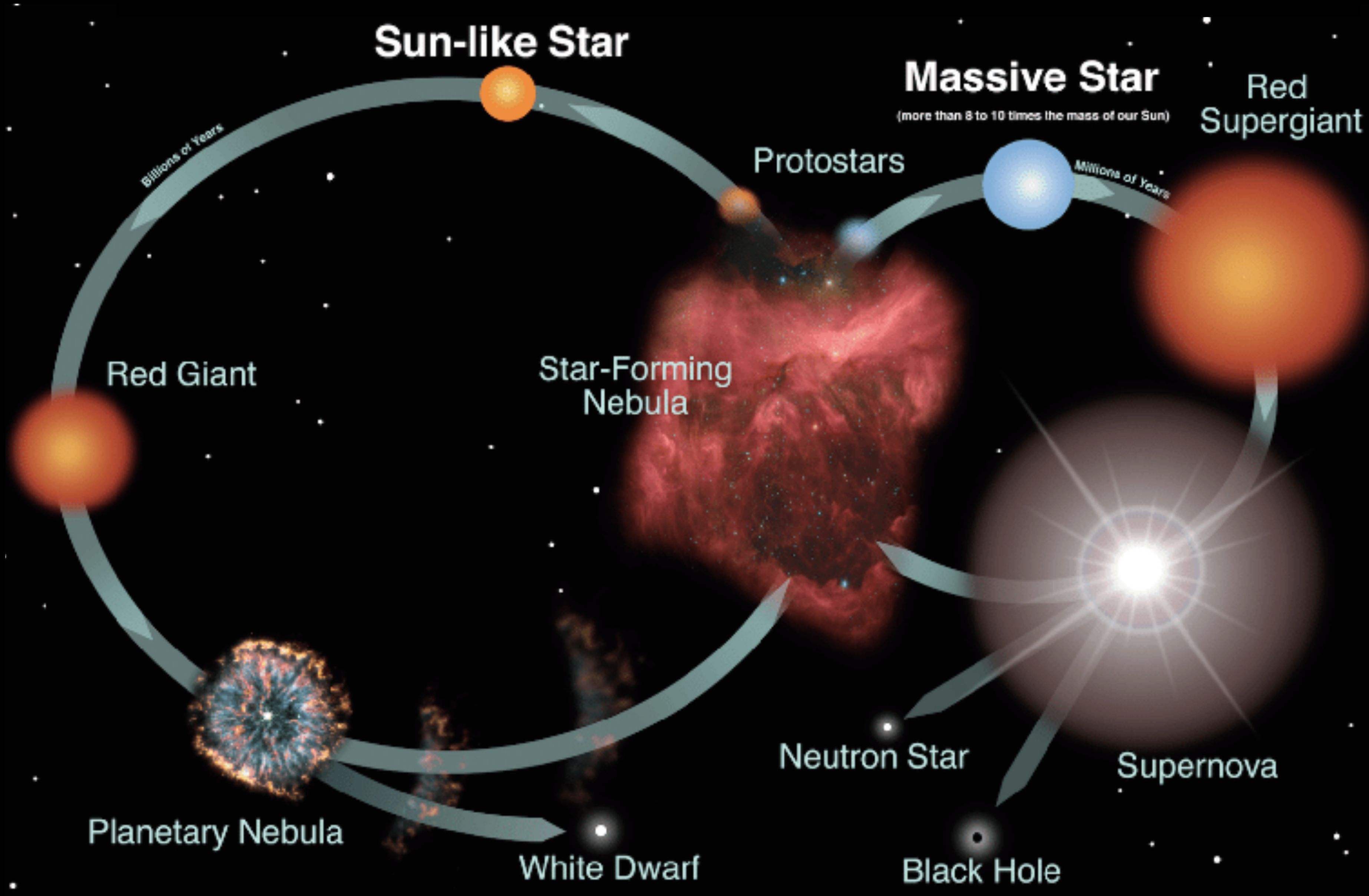
Flavia Dell'Agli - INAF Observatory of Rome



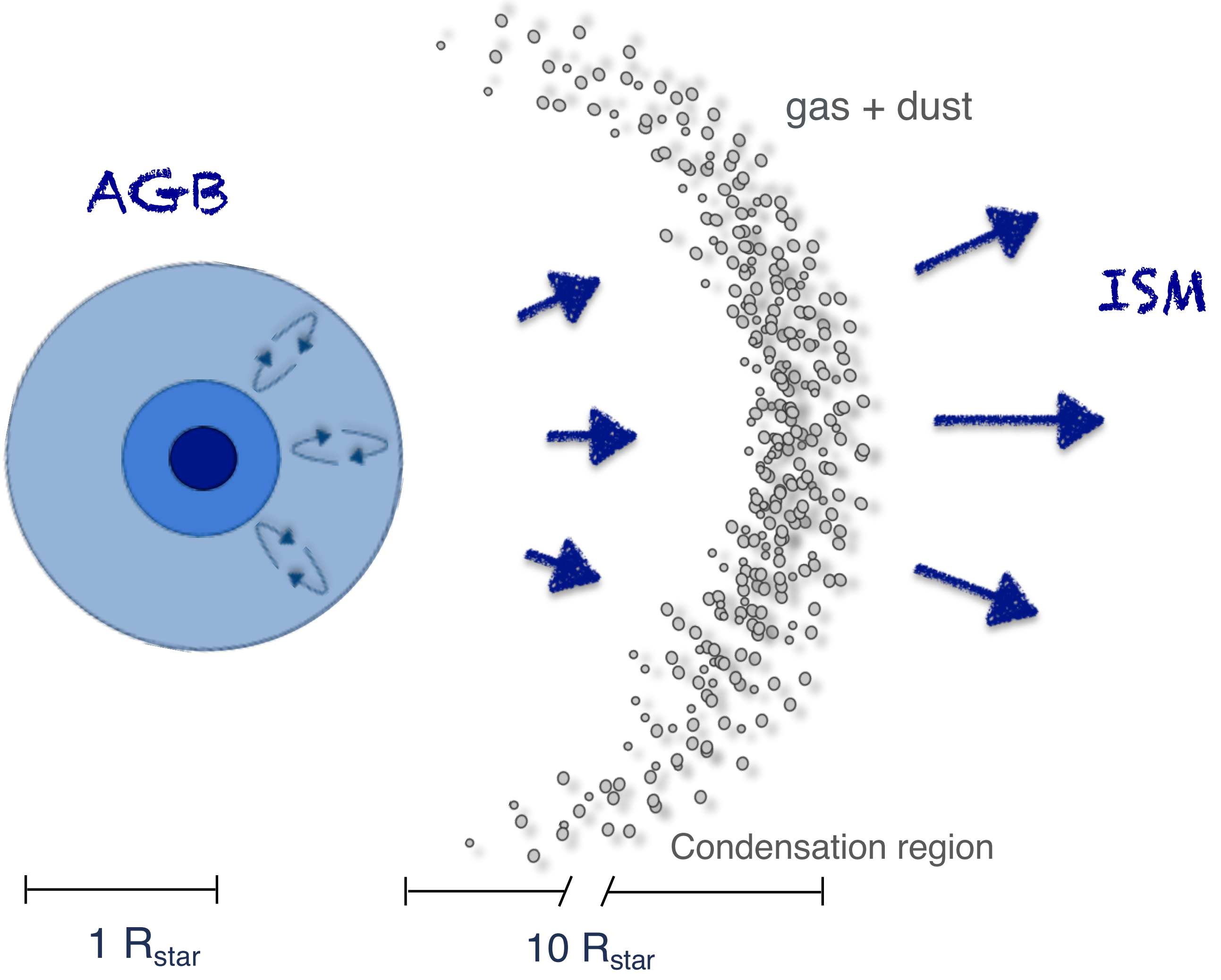




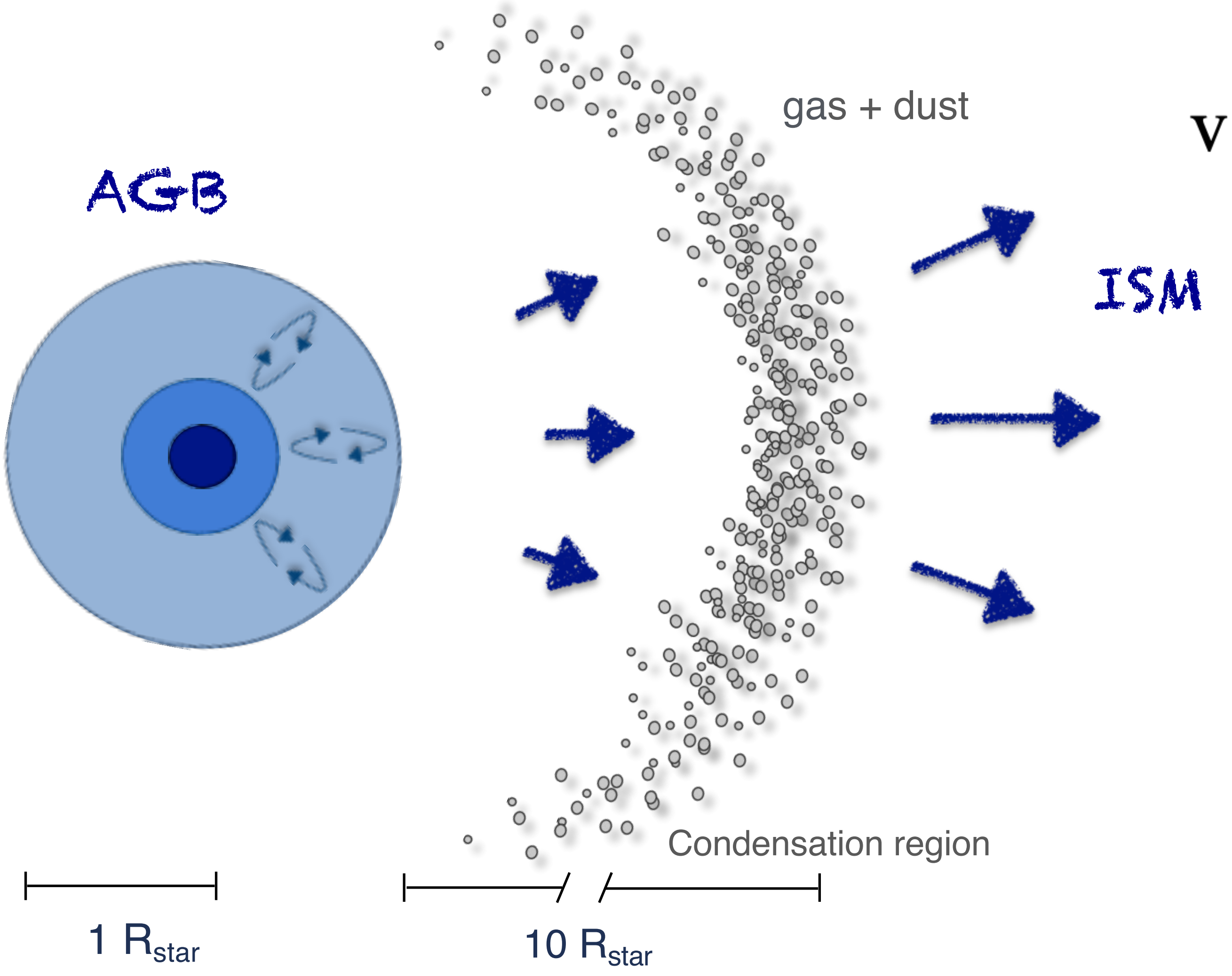

Star
Stellar absorption lines
Blackbody spectrum
Intensity
Red
Blue
Frequency
Dust cloud
Scattered light
Red light slightly reduced
Blue light greatly reduced
Intensity
Stellar absorption lines still detectable
Frequency
Telescope
(a)


Sun-like Star
Billions of Years
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Millions of Years
Red Giant
Star-Forming Nebula
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Black Hole

DUST FORMATION IN THE CIRCUMSTELLAR ENVELOPE



DUST FORMATION IN THE CIRCUMSTELLAR ENVELOPE



$$v\frac{\partial v}{\partial r} = -\frac{GM_*}{r^2}(1-\Gamma)$$

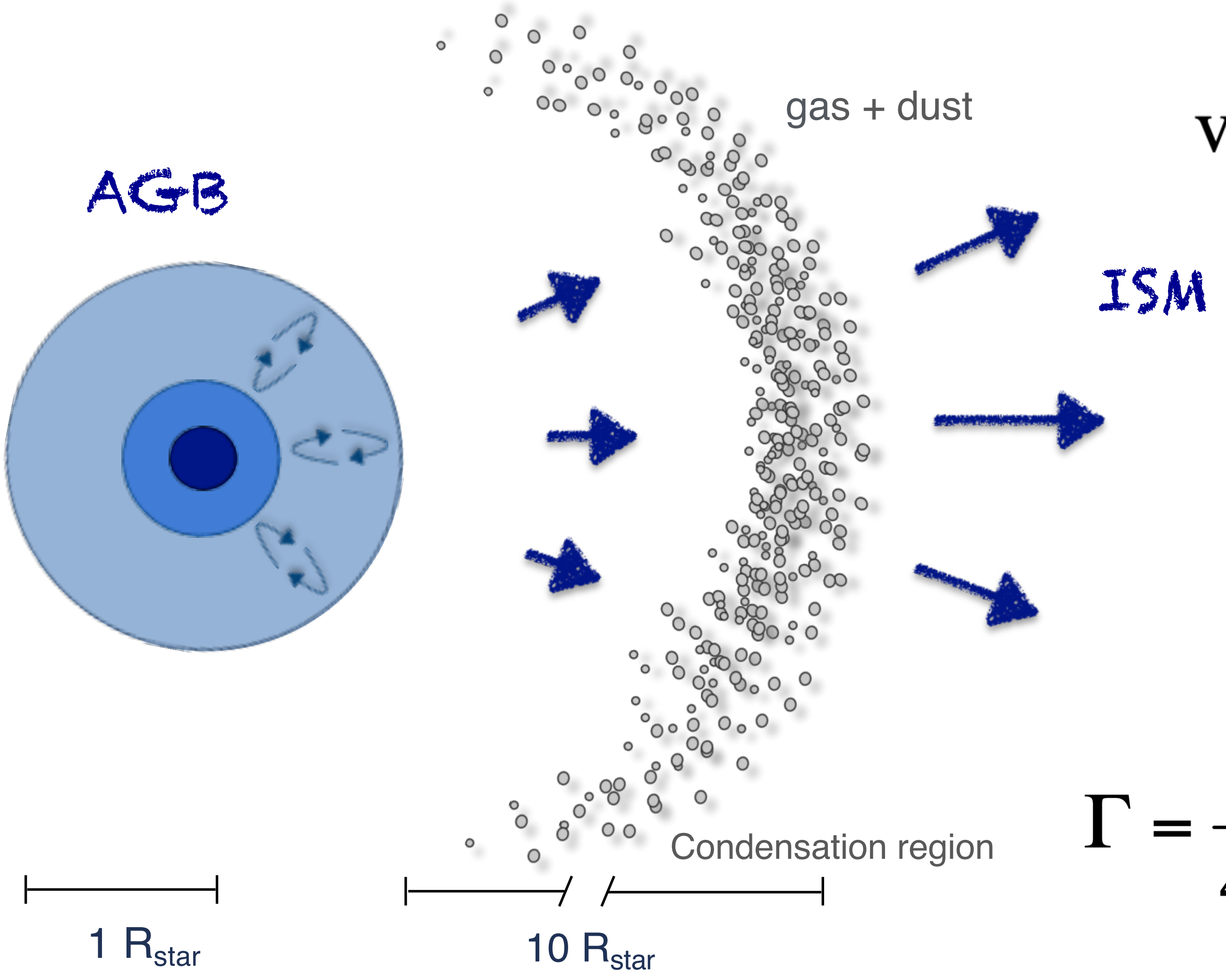
Momentum equation for a stationary and spherically symmetric wind

$$\Gamma = \frac{L_*}{4\pi c G M}k$$

$$\frac{\text{Radiation pressure}}{\text{Gravitational attraction}}$$

Ferrarotti & Gail 2006

DUST FORMATION IN THE CIRCUMSTELLAR ENVELOPE



$$\mathrm{v}\frac{\partial \mathrm{v}}{\partial r} = -\frac{GM_*}{r^2}(1-\Gamma)$$ Momentum equation for a stationary and spherically symmetric wind

$$\Gamma = \frac{L_*}{4\pi c GM}k$$ $\frac{\text{Radiation pressure}}{\text{Gravitational attraction}}$

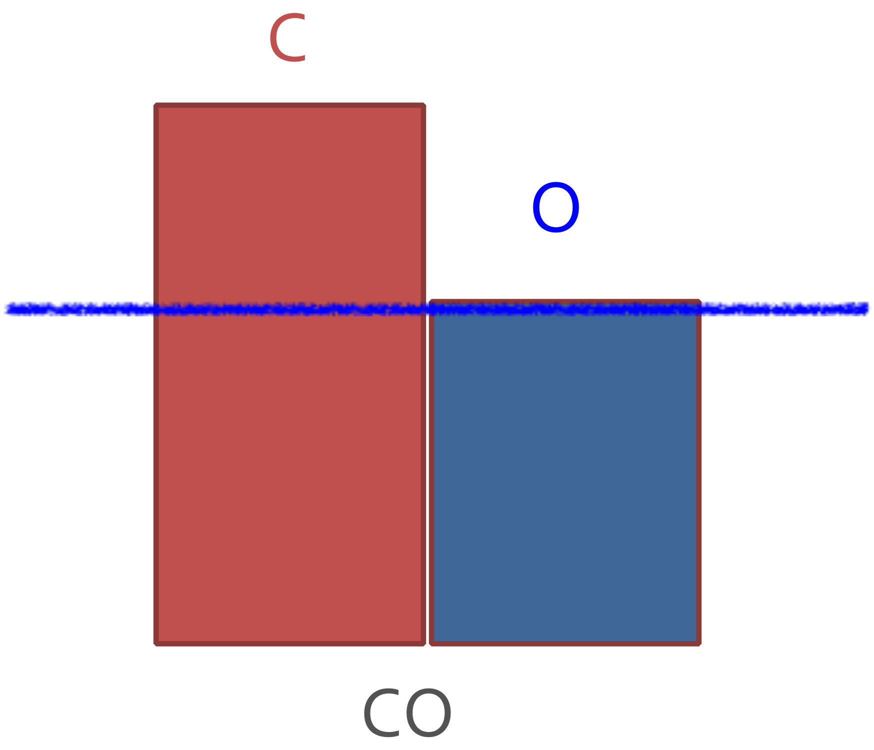
$$k = k_{gas} + \sum_i f_i k_i$$ Extinction coefficient

$$\Gamma = \frac{L_*}{4\pi c GM}k > 1$$ → Acceleration of the wind!

Ferrarotti & Gail 2006

WHICH DUST SPECIES CAN BE FORMED?

It depends on:



1) the surface chemistry of the stars

   The CO molecule is extremely stable

   → The element in excess between C and O is available to form dust.

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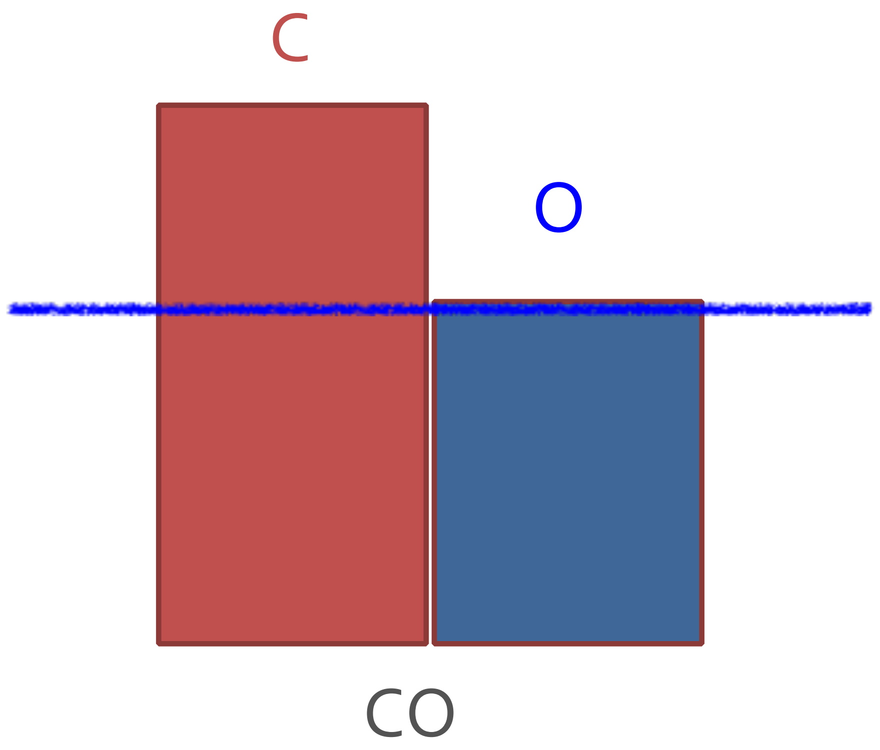


1) the surface chemistry of the stars

   The CO molecule is extremely stable

   → The element in excess between C and O is available to form dust.

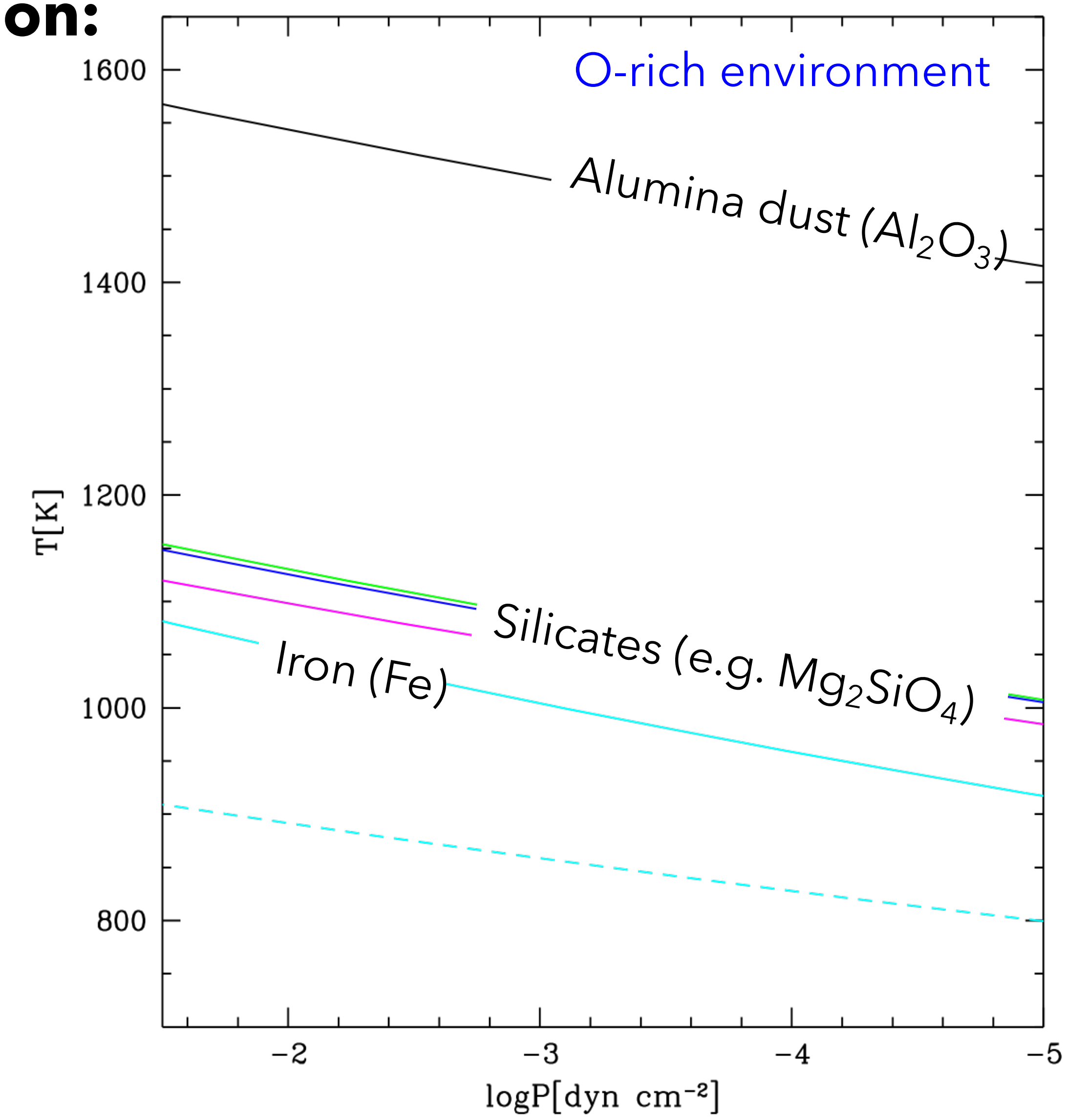
   M<4Msun stars that experience several **third dredge up (TDU)** episodes can reach the carbon star stage (**C/O>1**)

   M>4Msun stars that activate the **hot bottom burning (HBB)** burn ^{12}C via the proton capture nucleosynthesis (**C/O<1**)

WHICH DUST SPECIES CAN BE FORMED?

It depends on:

2) the stability of the different species that can be formed in the wind we are considering



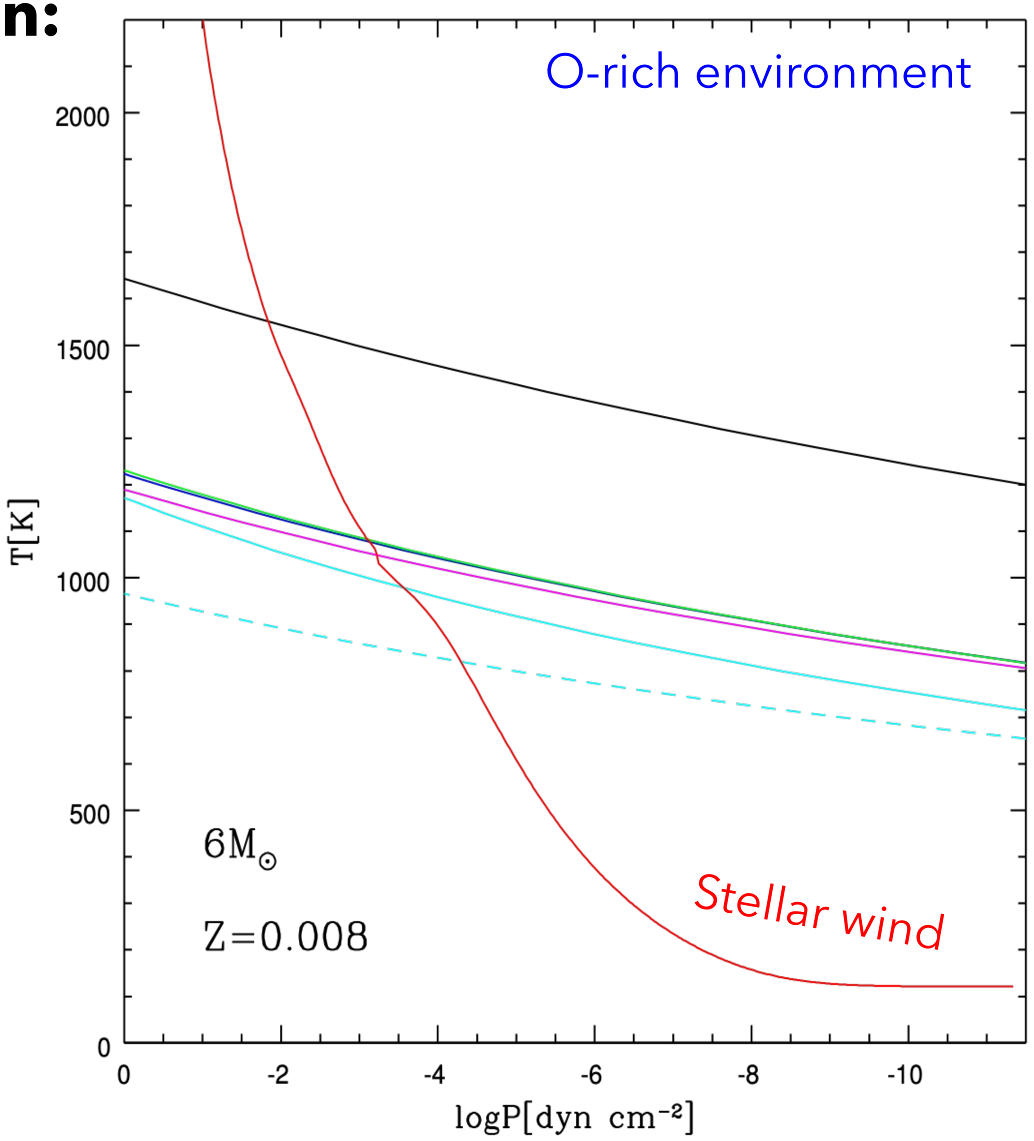
WHICH DUST SPECIES CAN BE FORMED?

It depends on:

2) the stability of the different species that can be formed in the wind we are considering

O-rich atmospheres:
Oxygen-based dust species
- Alumina dust (T_c ~1400 K)
- Silicates (T_c ~1100 K)
- Solid Iron (T_c ~800 K)

C-rich atmospheres:
Carbon-based dust species
- SiC (T_c ~1400 K)
- Solid Carbon (T_c ~1100 K)
- Solid Iron (T_c ~800 K)



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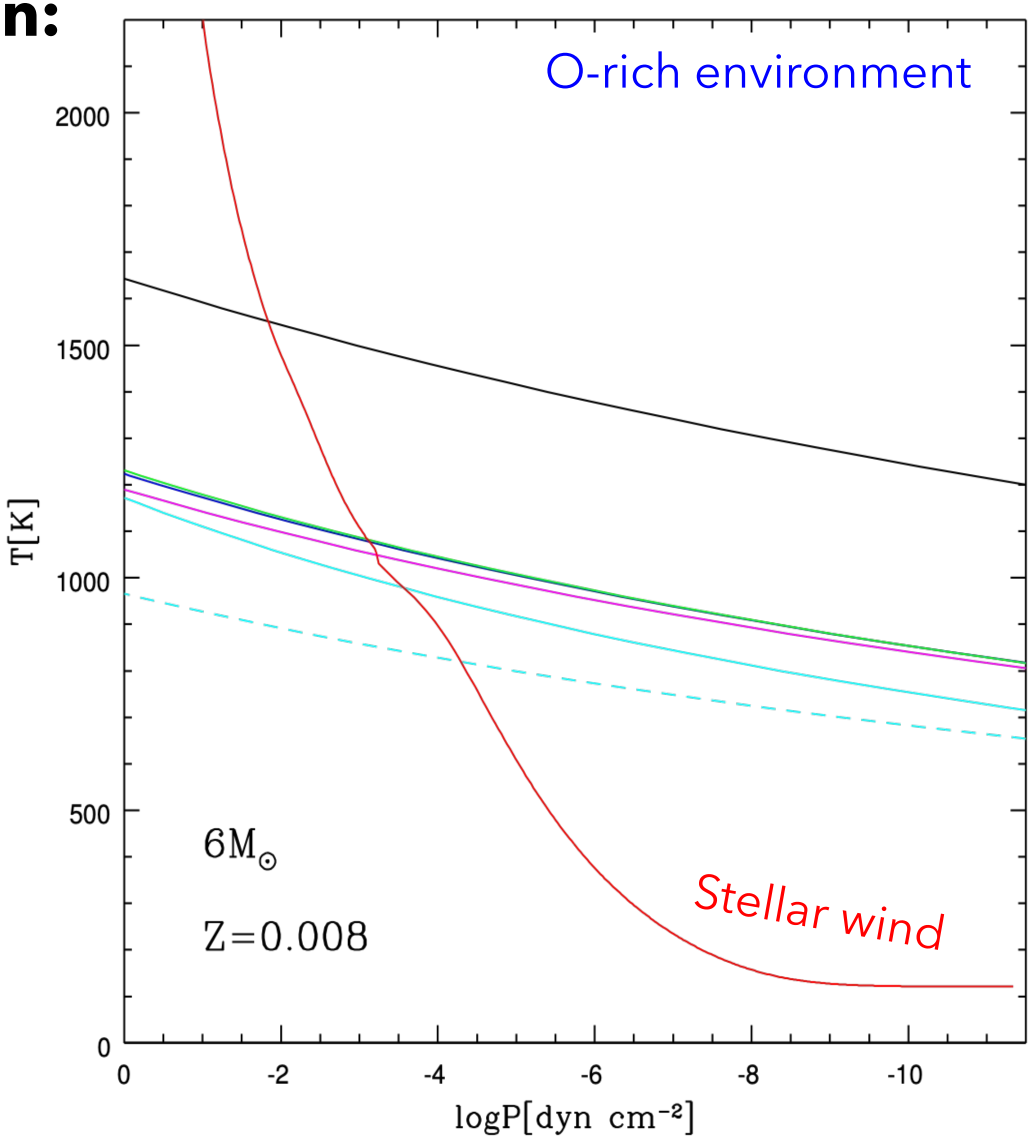
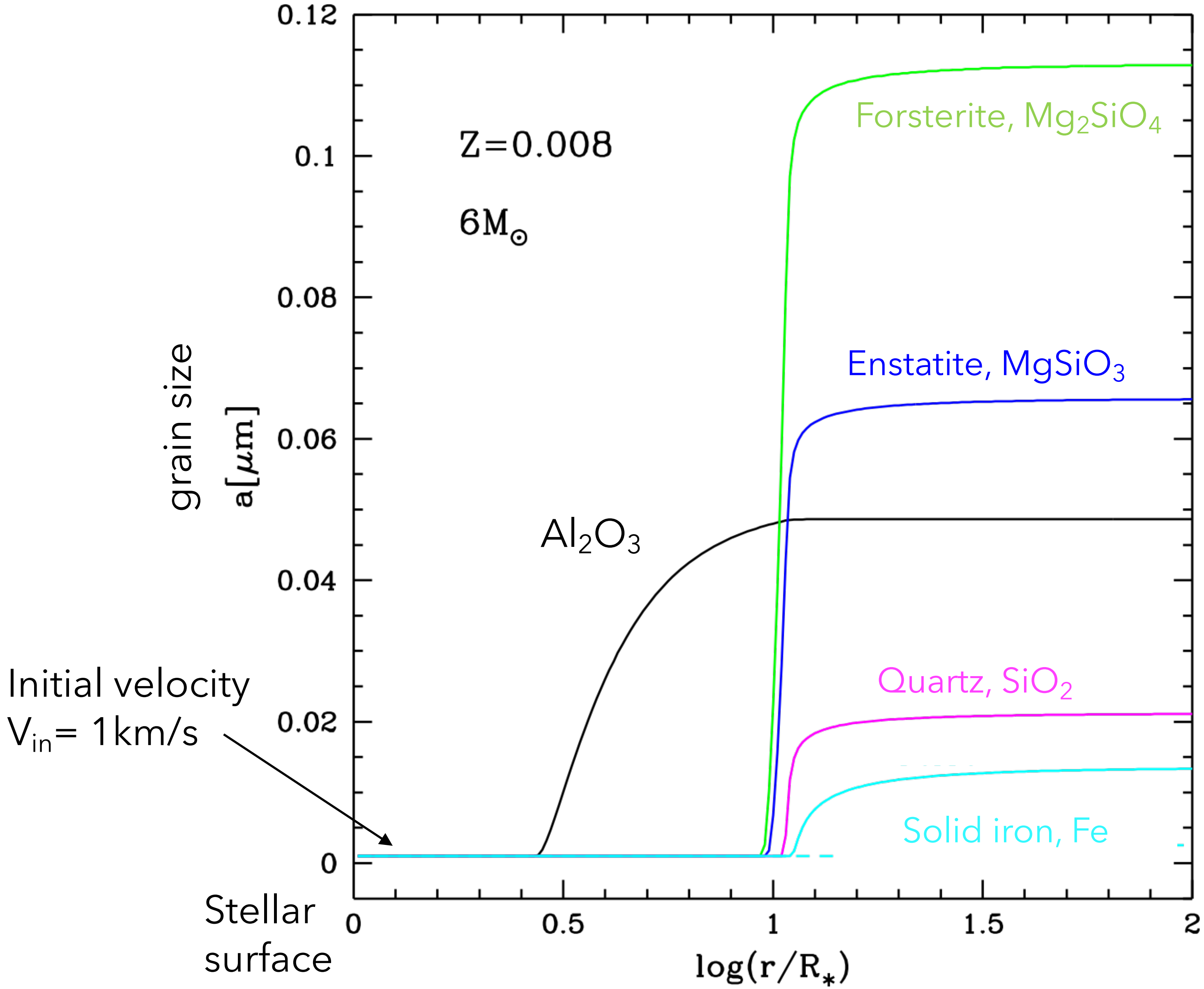
C-rich atmospheres:
Carbon-based dust species
- SiC (T_c ~1400 K)
- Solid Carbon (T_c ~1100 K)
- Solid Iron (T_c ~800 K)

3) the availability of the less abundant element (key-element) of the dust species we are considering: e.g. Si for silicates and SiC, Al for alumina dust

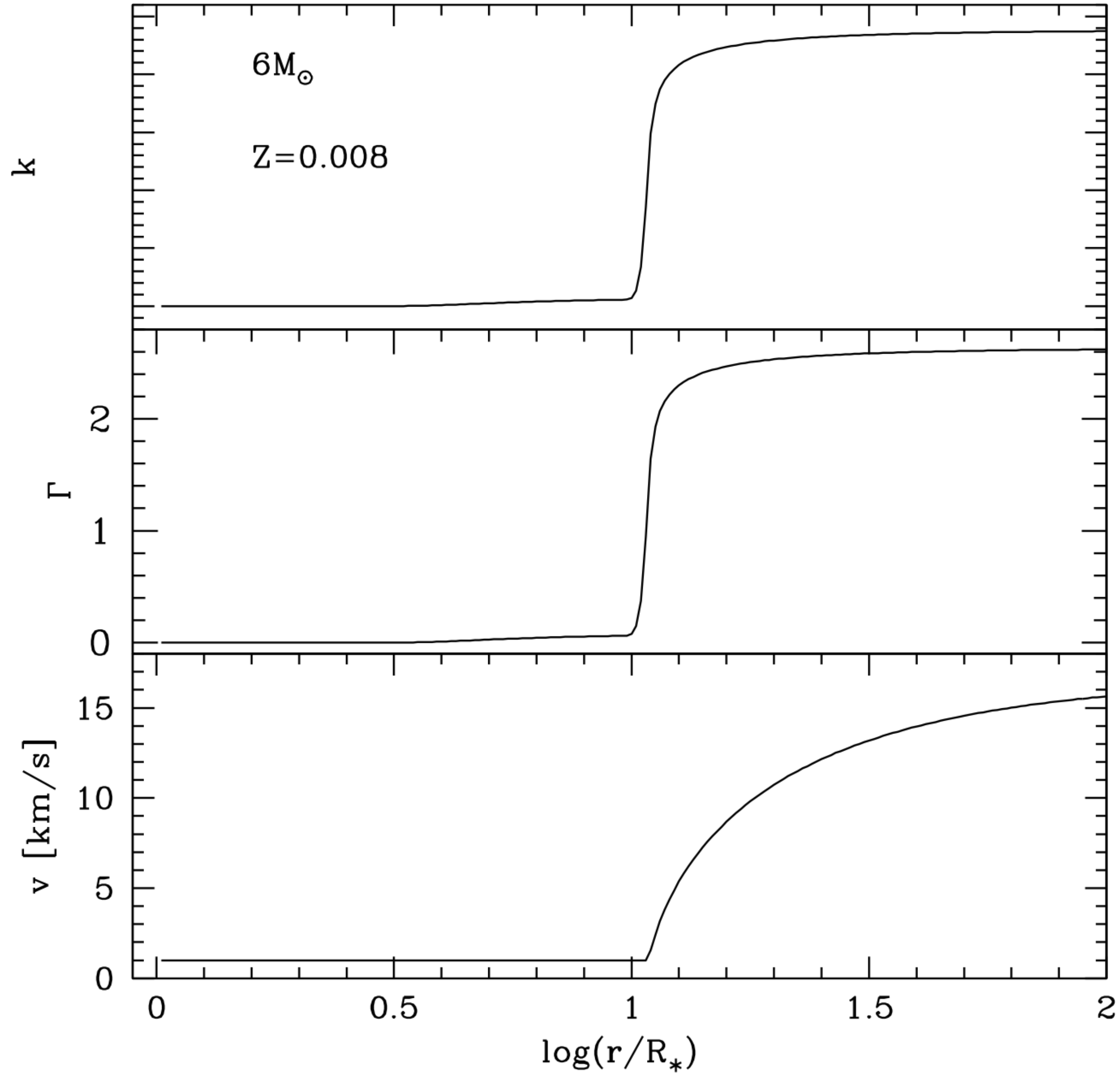


DUST GROWTH



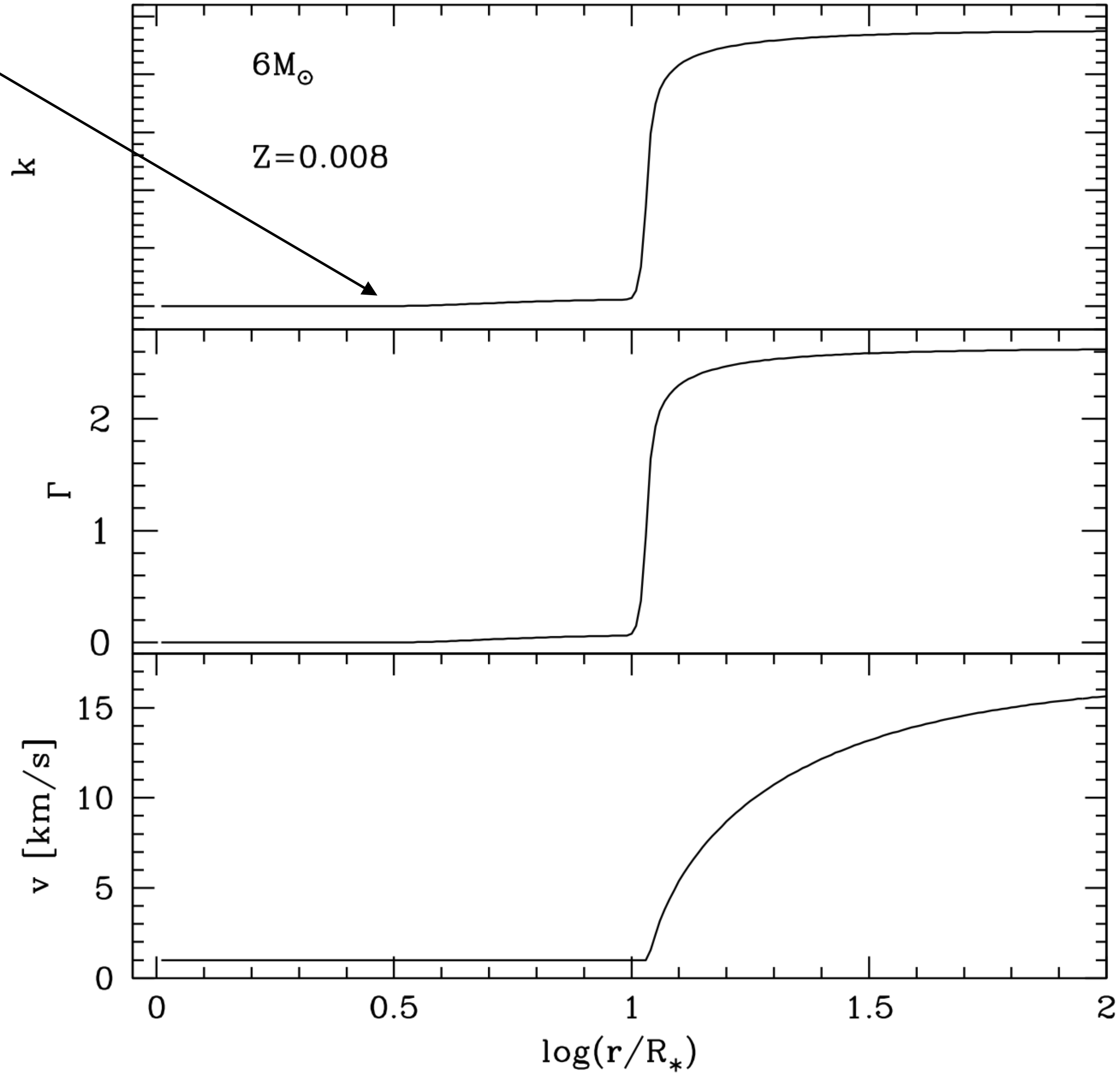
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
Z=0.008
6M☉
Forsterite, Mg_2SiO_4
Enstatite, $MgSiO_3$
Al_2O_3
Quartz, SiO_2
Solid iron, Fe
grain size
a[μm]
log(r/R*)
Initial velocity
V_{in}= 1km/s
Stellar
surface

WIND STRUCTURE

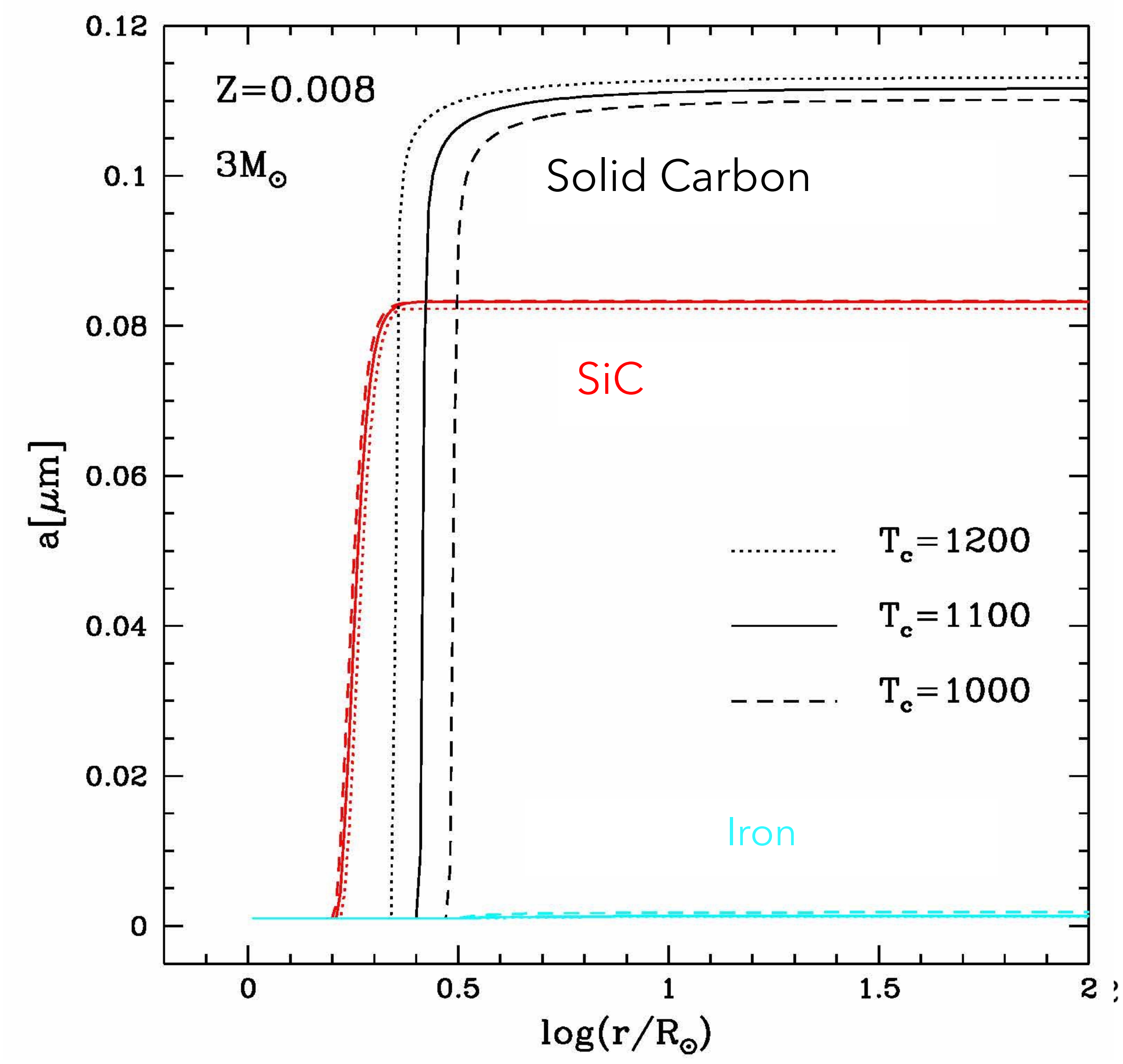


WIND STRUCTURE

The wind is transparent to alumina dust formation

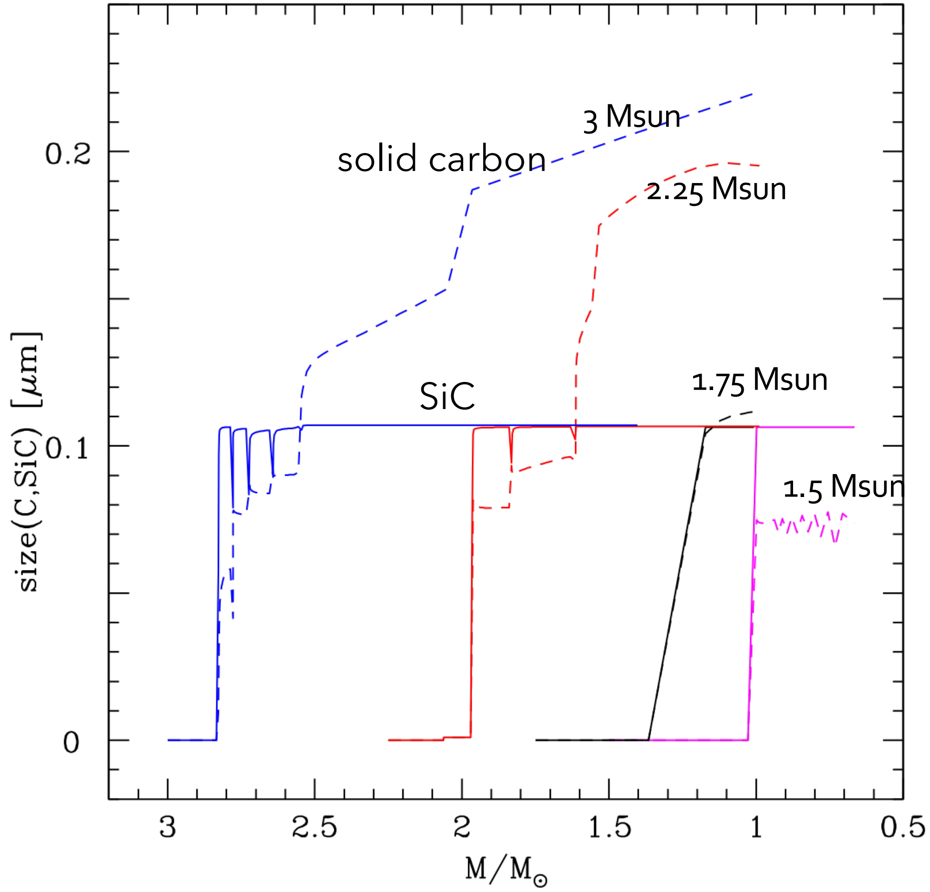


WIND STRUCTURE



DUST GROWTH EVOLUTION DURING THE AGB PHASE

carbon stars (<4Msun) TDU



DUST GROWTH EVOLUTION DURING THE AGB PHASE

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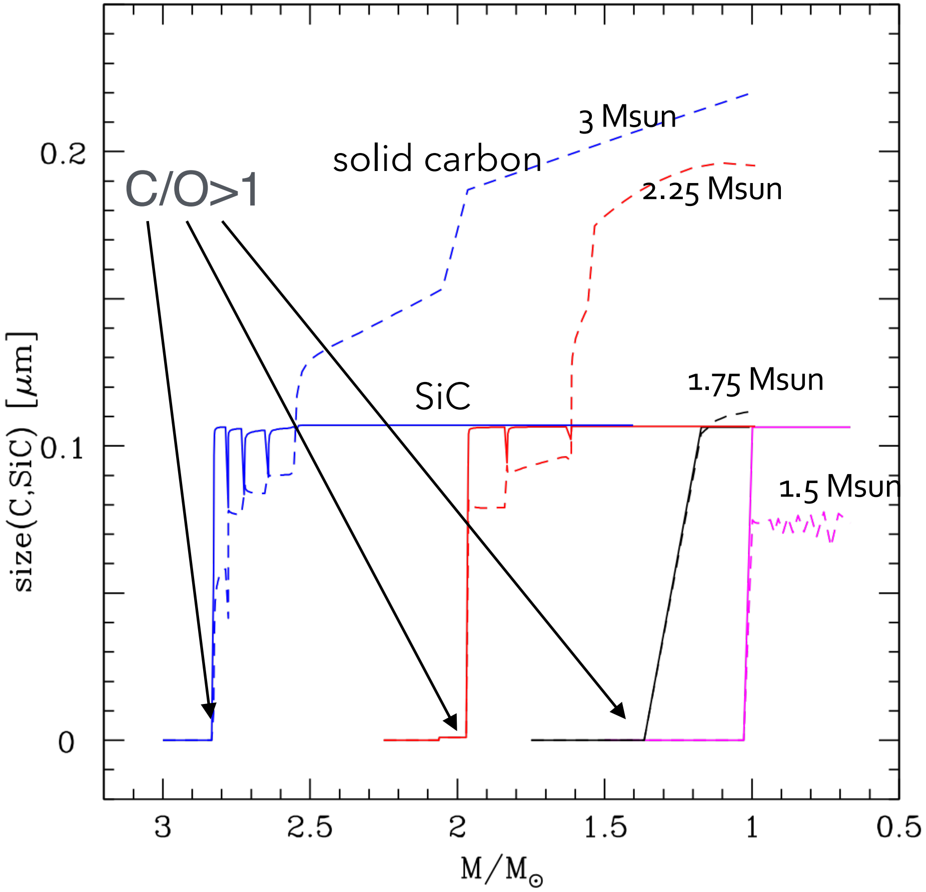

DUST GROWTH EVOLUTION DURING THE AGB PHASE

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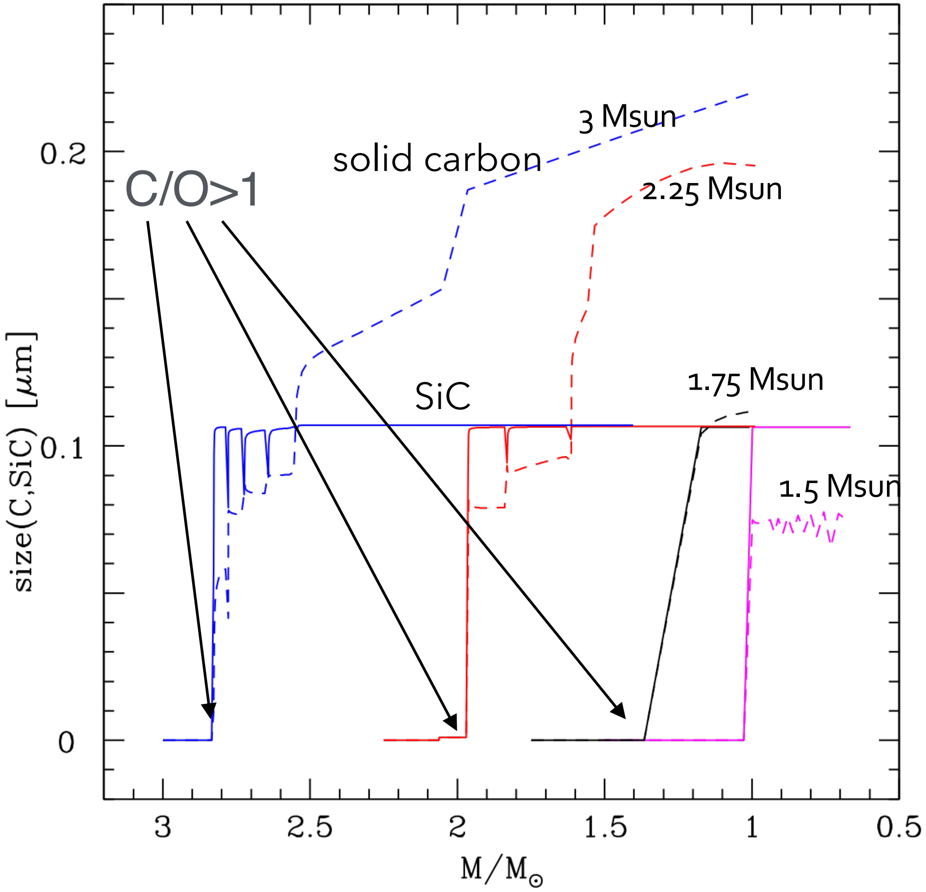
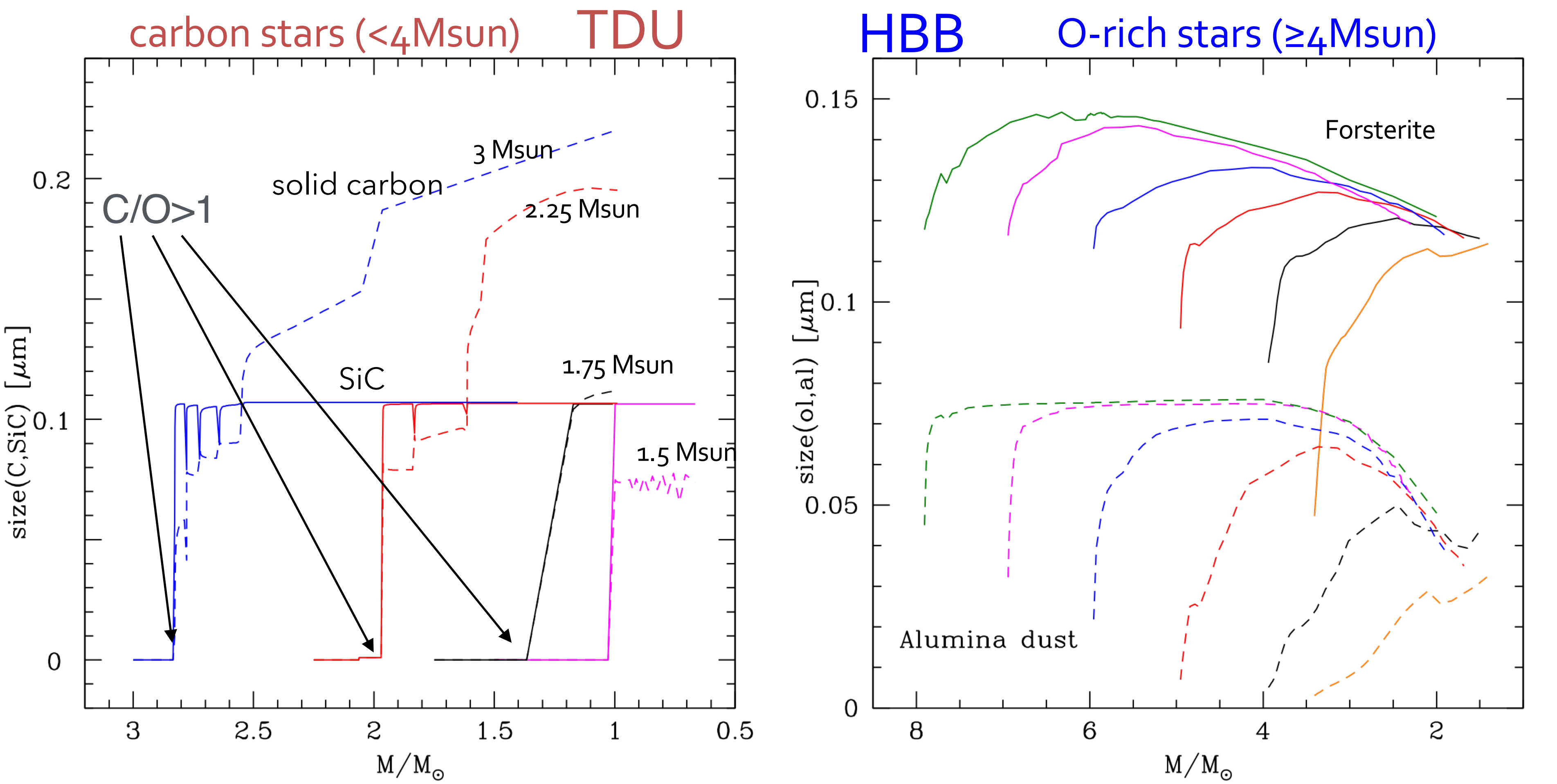
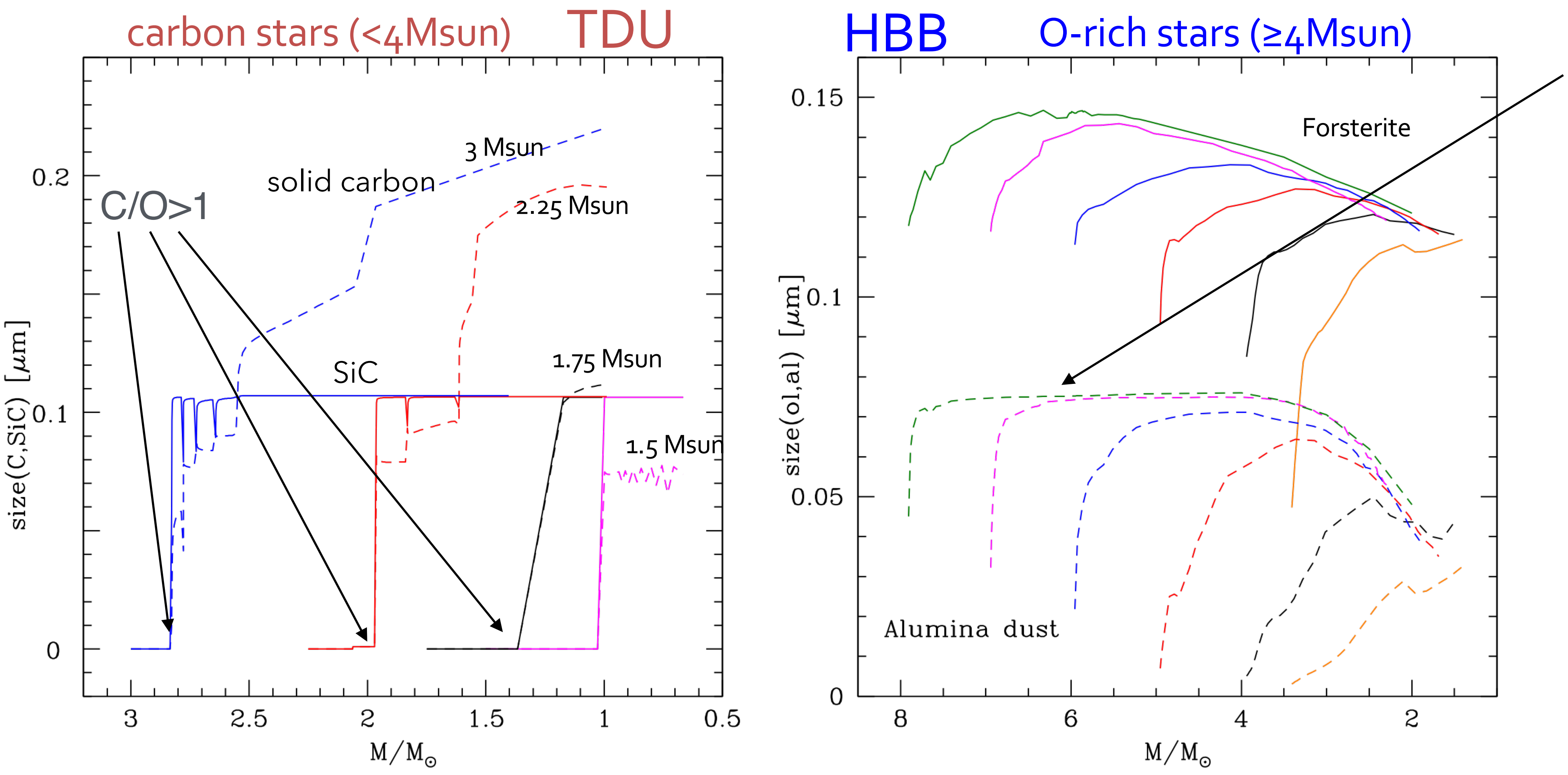


More TDU episodes → more solid carbon dust

DUST GROWTH EVOLUTION DURING THE AGB PHASE

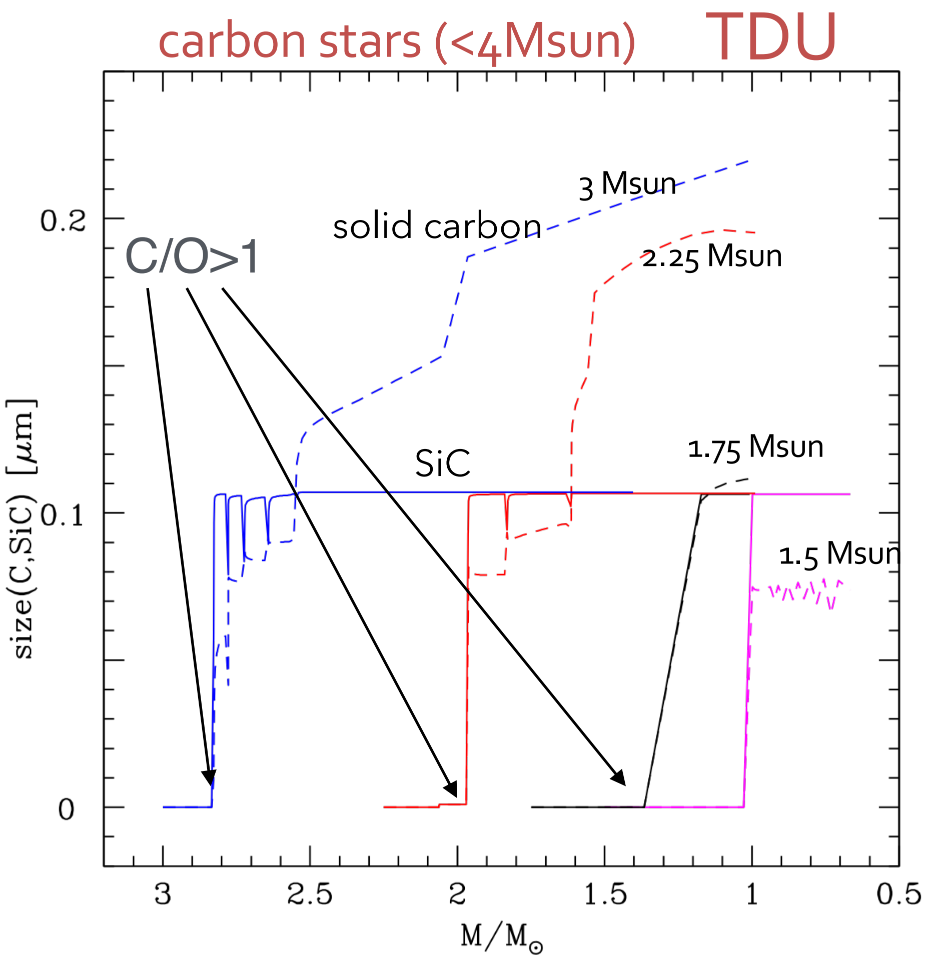


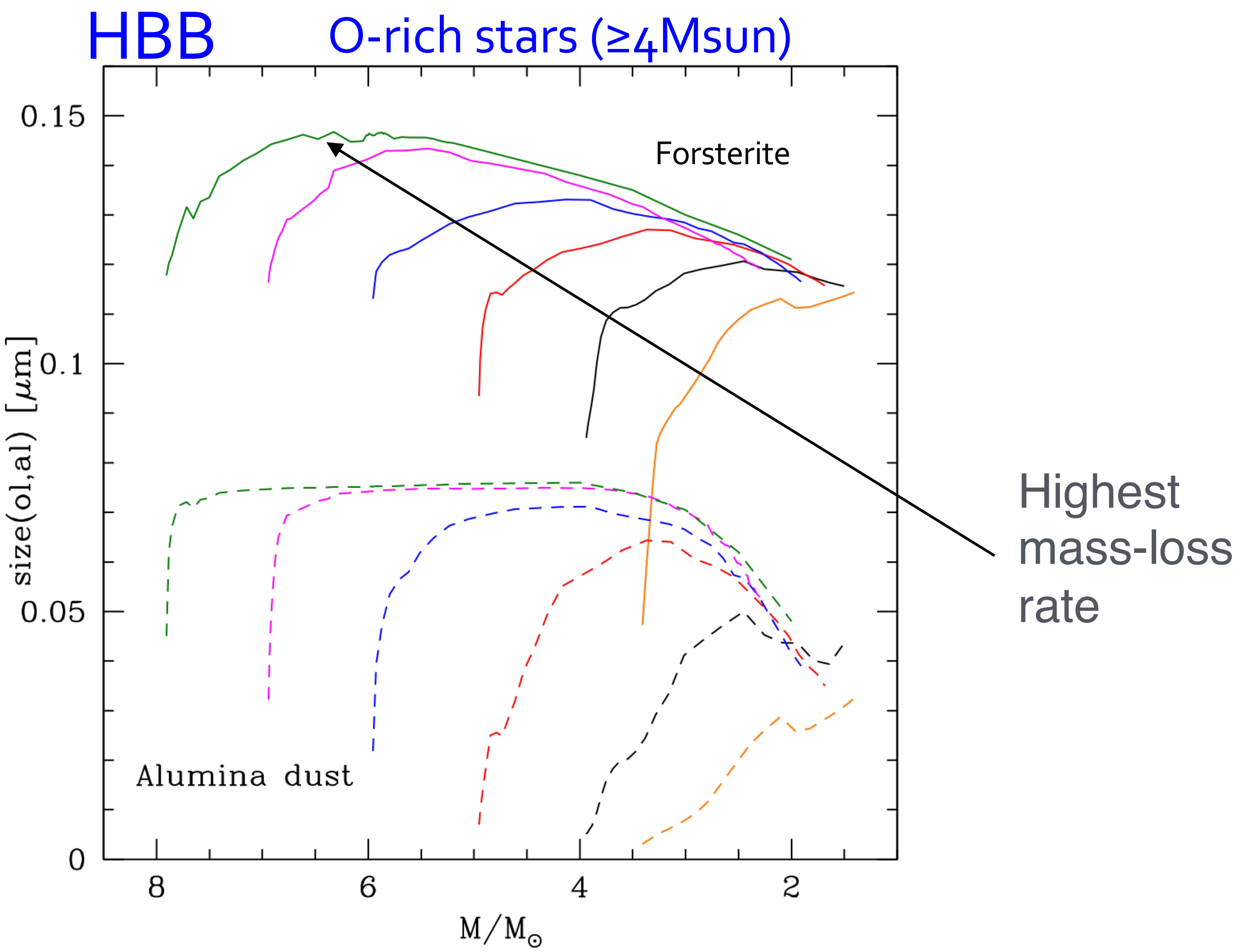
DUST GROWTH EVOLUTION DURING THE AGB PHASE



Alumina dust saturates the aluminum available in more massive stars

DUST GROWTH EVOLUTION DURING THE AGB PHASE

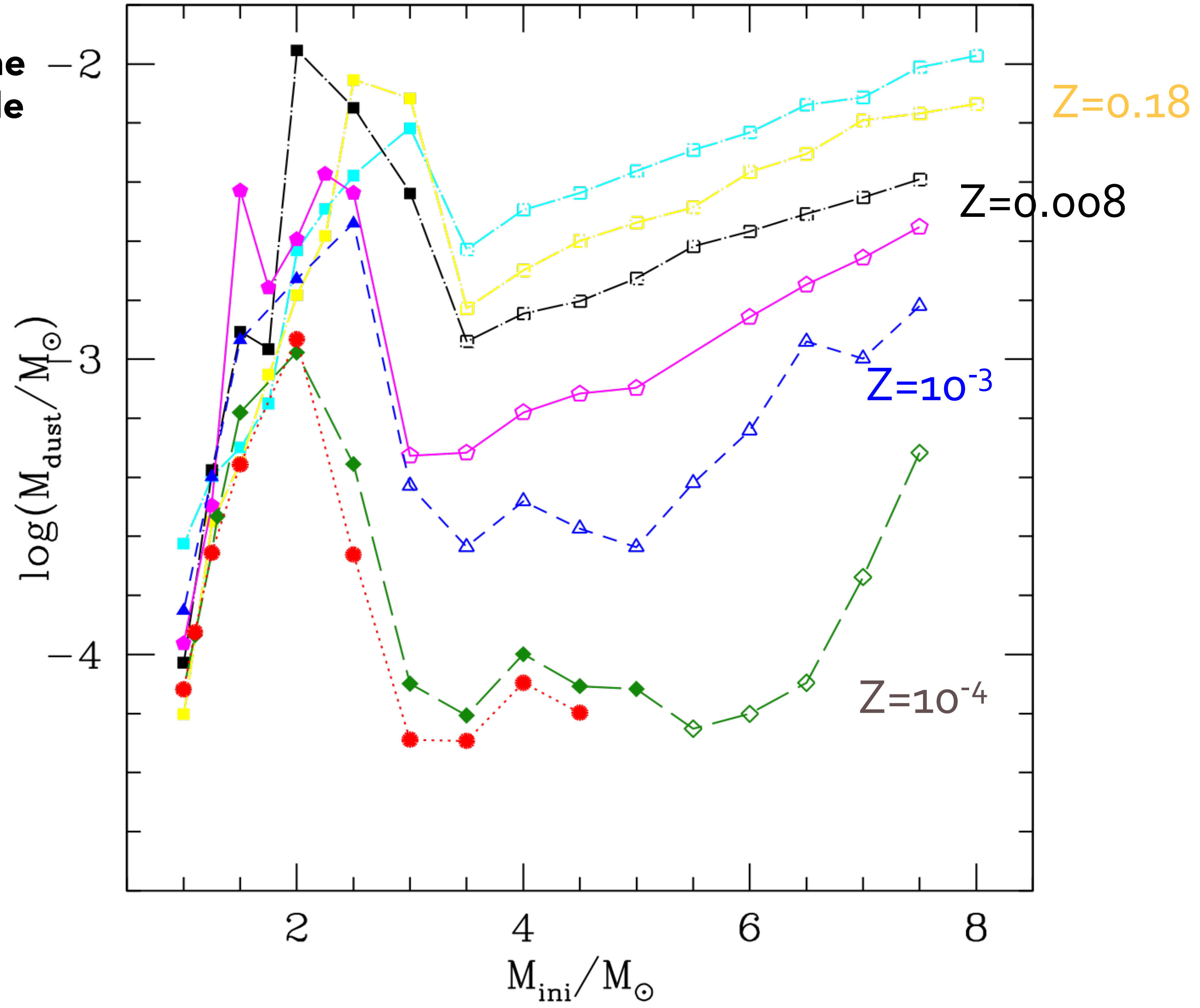




DUST YIELDS:

the total amount of dust produced during the entire AGB phase

AGB+DUST models from the ATON stellar evolution code perspective
(see e.g. Ventura + 2014; Dell'Agli+ 2018)



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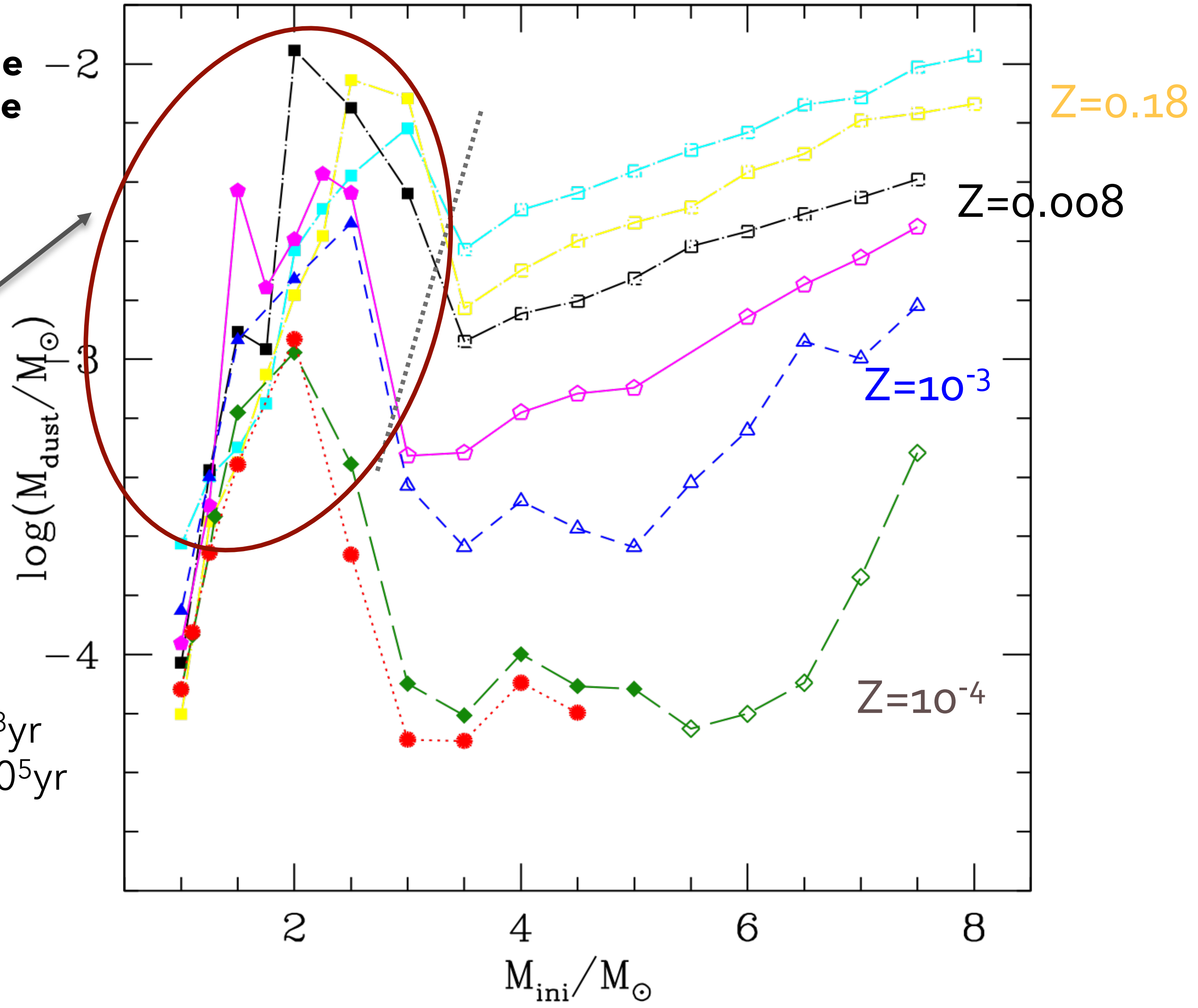
TDU
Solid carbon & SiC



1Msun≤ M_{in} < 3.5Msun:
Time MS ~ $8x10^9$ - $2x10^8$yr
Time AGB ~ $5x10^6$ - $5x10^5$yr

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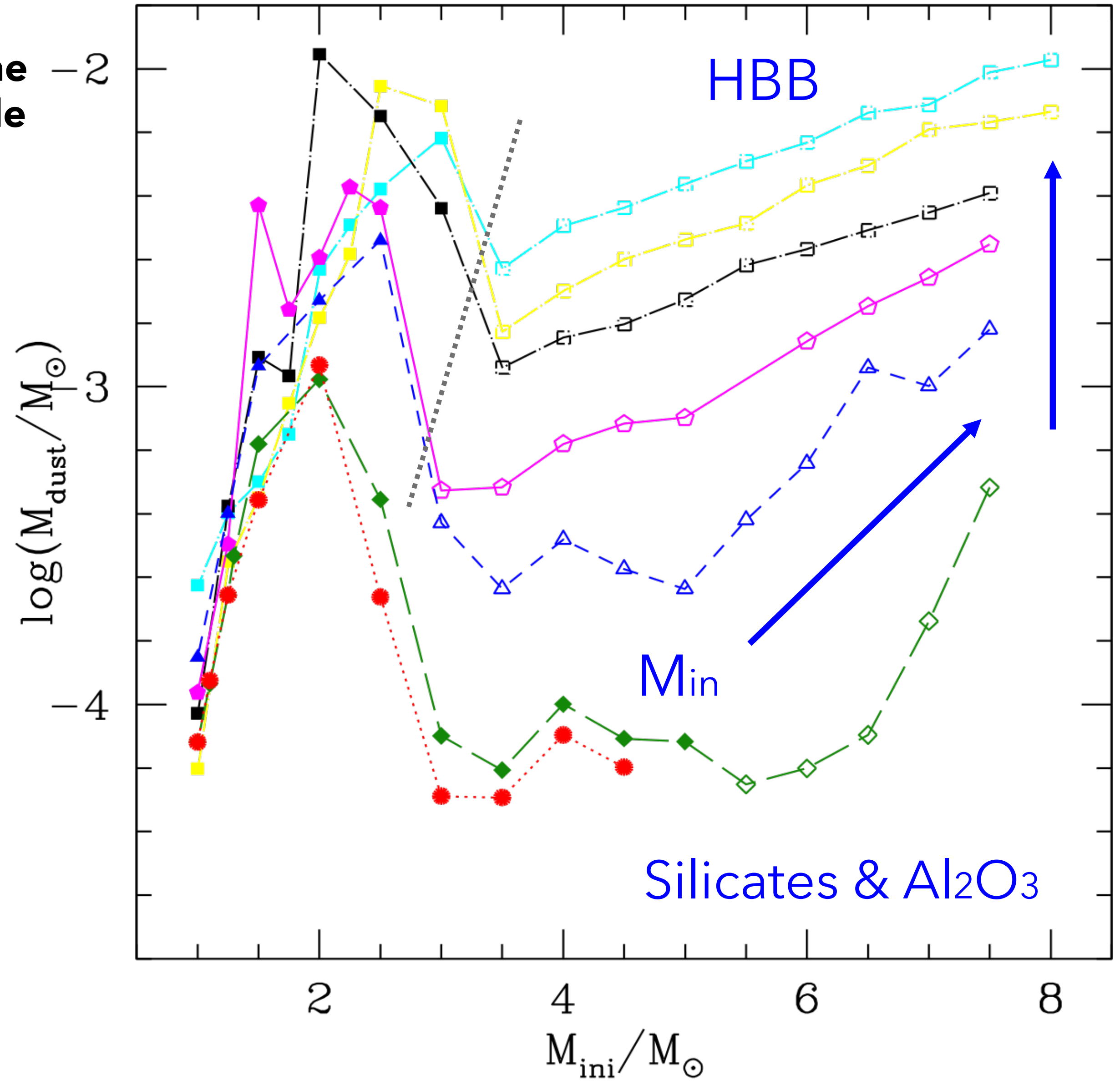

$3.5 M_{sun} \leq M_{in} \leq 8 M_{sun}$:
Time MS ~ 2×10^8 - 4×10^7yr
Time AGB ~ 4×10^6 - 10^4yr

DUST YIELDS:

the total amount of dust produced during the entire AGB phase

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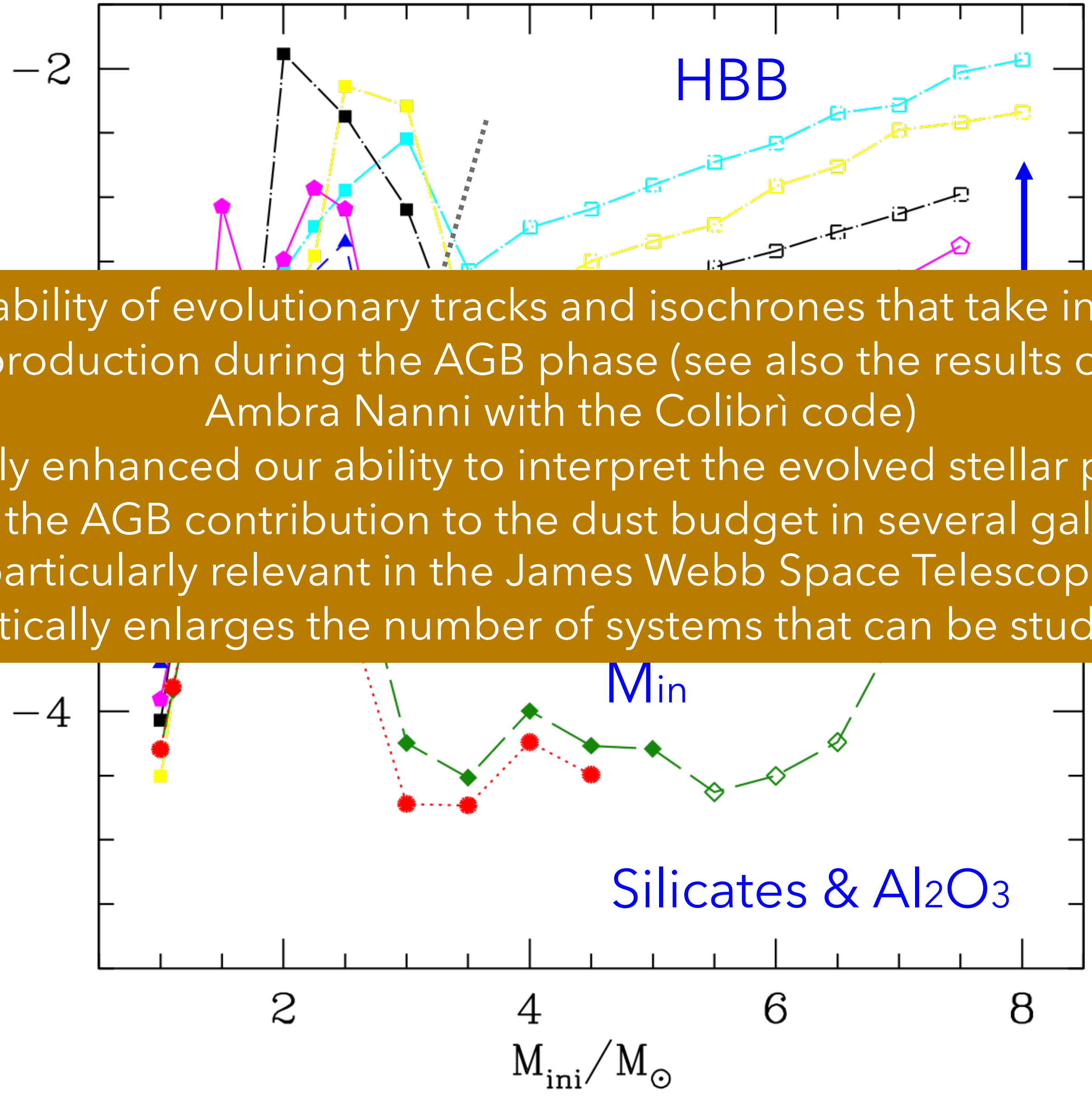

The availability of evolutionary tracks and isochrones that take into account the dust production during the AGB phase (see also the results obtained by Ambra Nanni with the Colibrì code)
has greatly enhanced our ability to interpret the evolved stellar populations and the AGB contribution to the dust budget in several galaxies.
This is particularly relevant in the James Webb Space Telescope era that critically enlarges the number of systems that can be studied.

$3.5M_{sun} \le M_{in} \le 8M_{sun}$:
Time MS ~ 2×10^8 - 4×10^7yr
Time AGB ~ 4×10^6 -10^4yr

UNCERTAINTIES at solar metallicity:

Ventura, Karakas et al. 2018

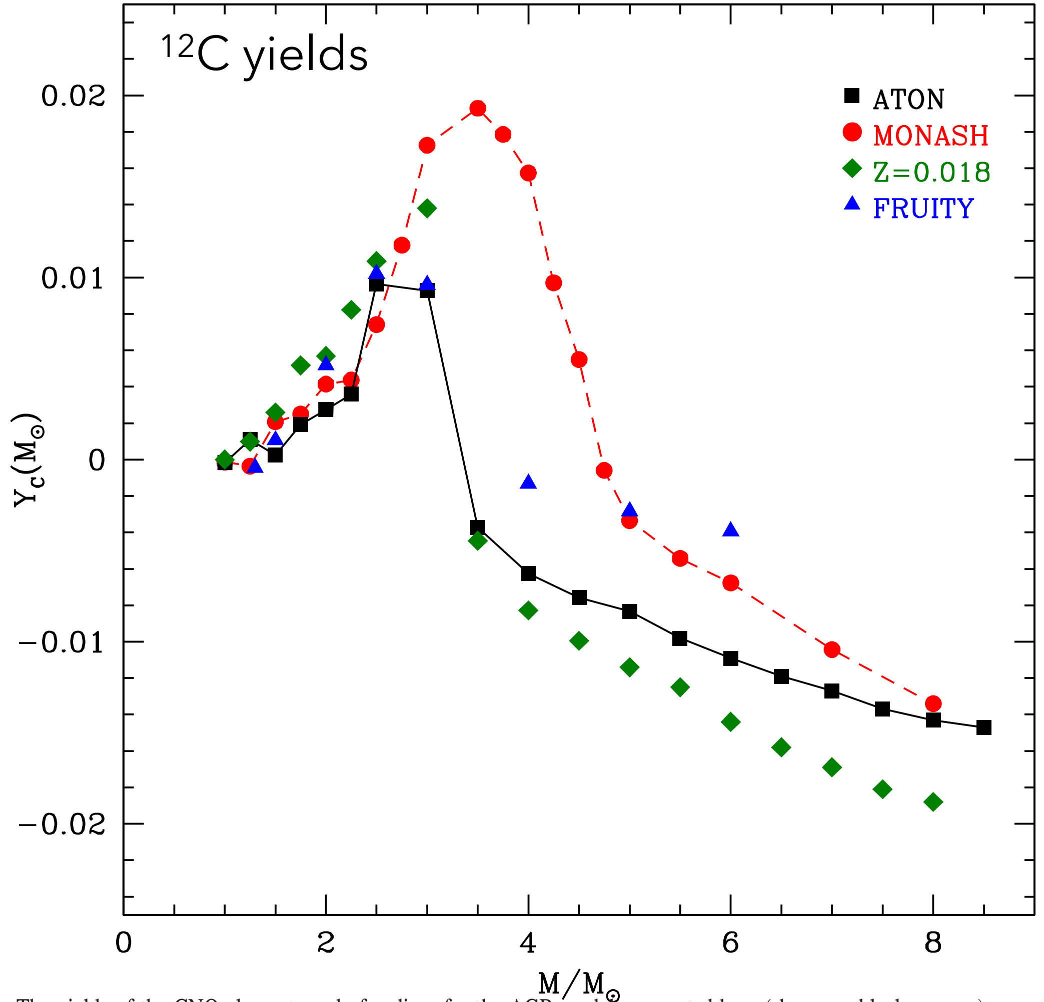

Figure 16. The yields of the CNO elements and of sodium for the AGB models presented here (shown as black squares), compared with the results from Karakas & Lugaro (2016) (red points), Cristallo, Straniero & Piersanti (2015) (blue triangles) and Di Criscienzo et al. (2016) (green diamonds). The four panels report the yields of ^{12}C (top left-hand panel), ^{14}N (top right-hand panel), ^{16}O (bottom left-hand panel) and sodium (bottom right-hand panel).

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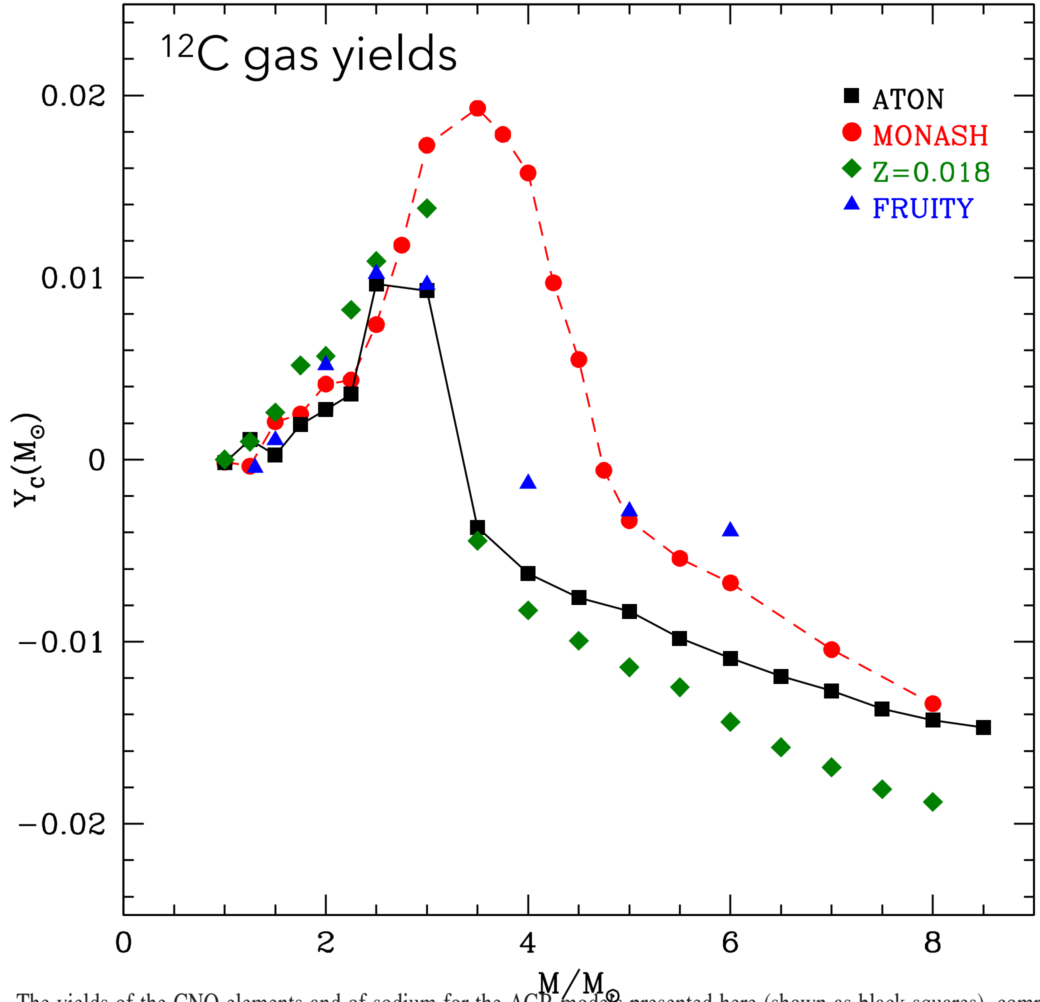

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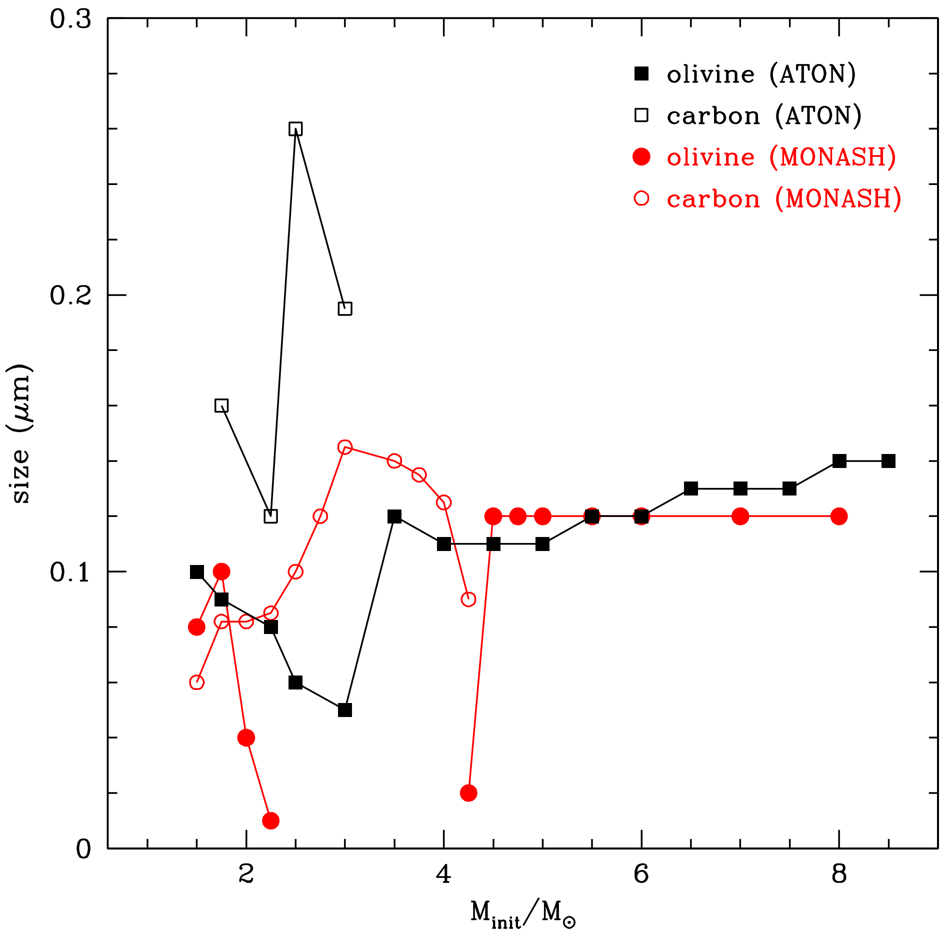


Figure 20. The size of solid carbon (open squares) and olivine (full squares) particles formed in the wind of the AGB models discussed here. Open red circles and full red points indicate, respectively, the dimension of solid carbon and olivine grains formed when the MONASH results for the description of the AGB phase are used.

UNCERTAINTIES

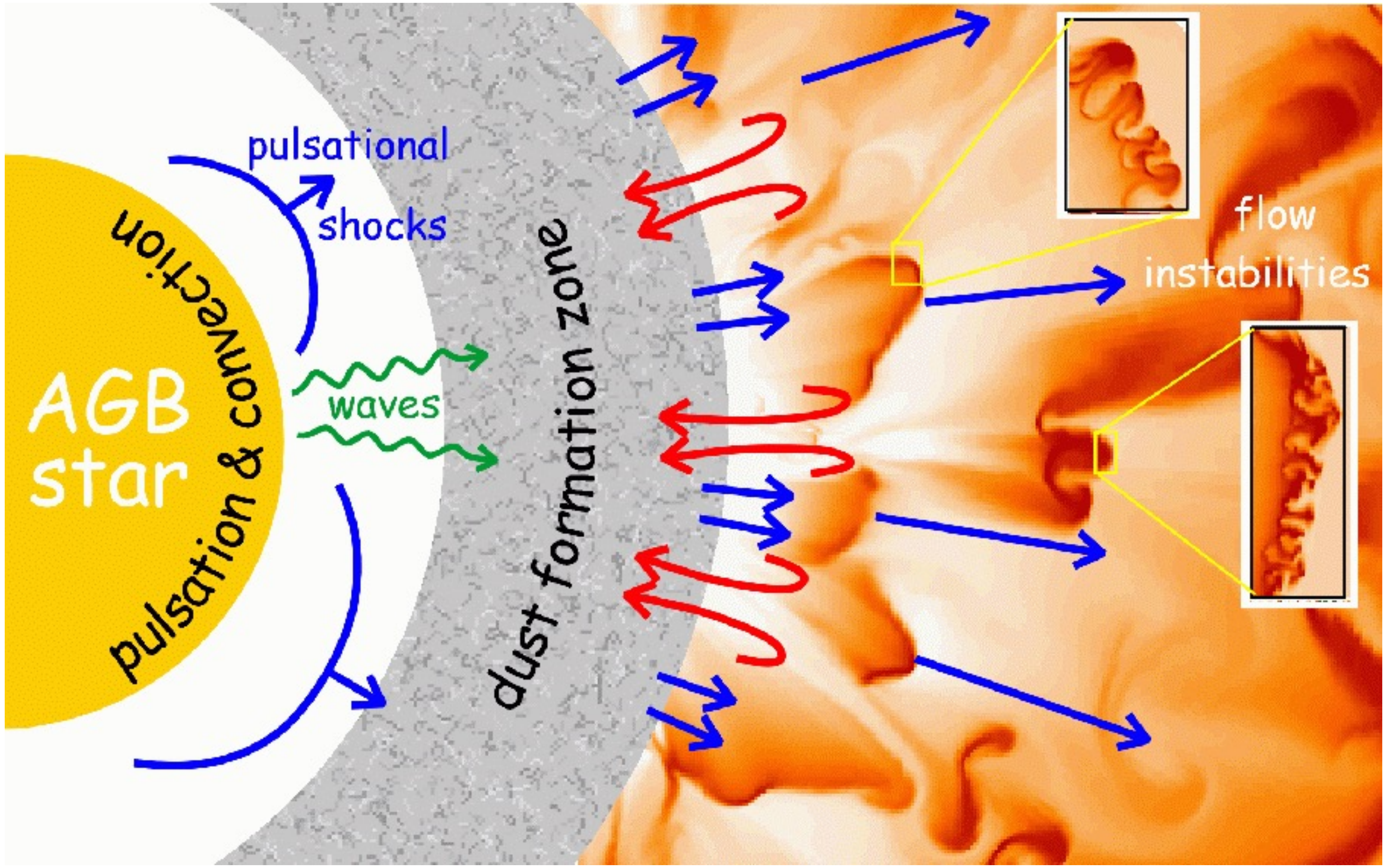
1. Stellar evolution models uncertainties

UNCERTAINTIES

1. Stellar evolution models uncertainties
2. Shocks and pulsations are not taken into account
3. The mass loss rate is assumed as an input of the model

Dynamic of the wind?

atmospheric levitation by pulsation-induced
shock waves followed by radiative acceleration of dust grains, which transfer momentum to the surrounding gas through collisions.



Peter Woikte webpage: http://www-star.st-and.ac.uk/~pw31/AGB_popular.html

What we have learnt from hydrodinamical models:

see e.g. Hofner & Olofsson 2018 (review), Hofner & Freytag 2021 (conference proceeding)

Carbon stars:
-- Slow/weak winds:
presence of dust support atmosphere structure but the outflow is generated by pulsation and thermal gas pressure (Mattsson 2016)
-- Dusty driven winds:
carbon dust driver of the wind
study of Mloss (Wachter 2002 2008, Mattsson+2009, 2011) that depends on C abundance and pulsation amplitudes (Mattsson+2009, 2011)
-- Effect of the drift? (Sandin & Mattsson 2020)

O-rich stars:
-- Wind driver? A long debate..
by photon scattering of Iron free Silicates 0.1-1micron (e.g. Hofner+2008,2021; Bladh+2019)
-- Al_2O3 at 2 stellar radii (Hofner+2016)

UNCERTAINTIES

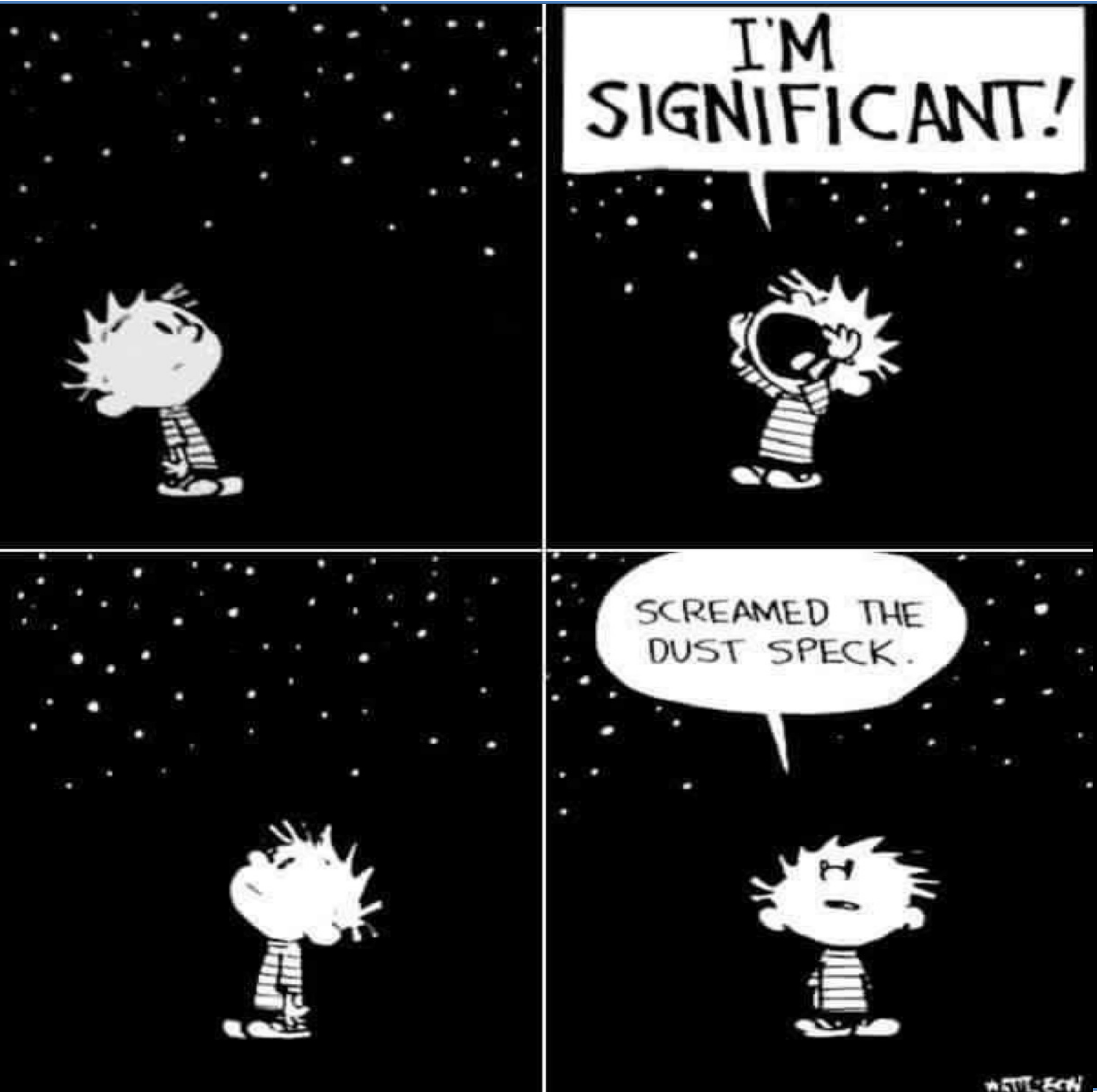
1. Stellar evolution models uncertainties

2. Shocks and pulsations are not taken into account

3. The mass loss rate is assumed as an input of the model

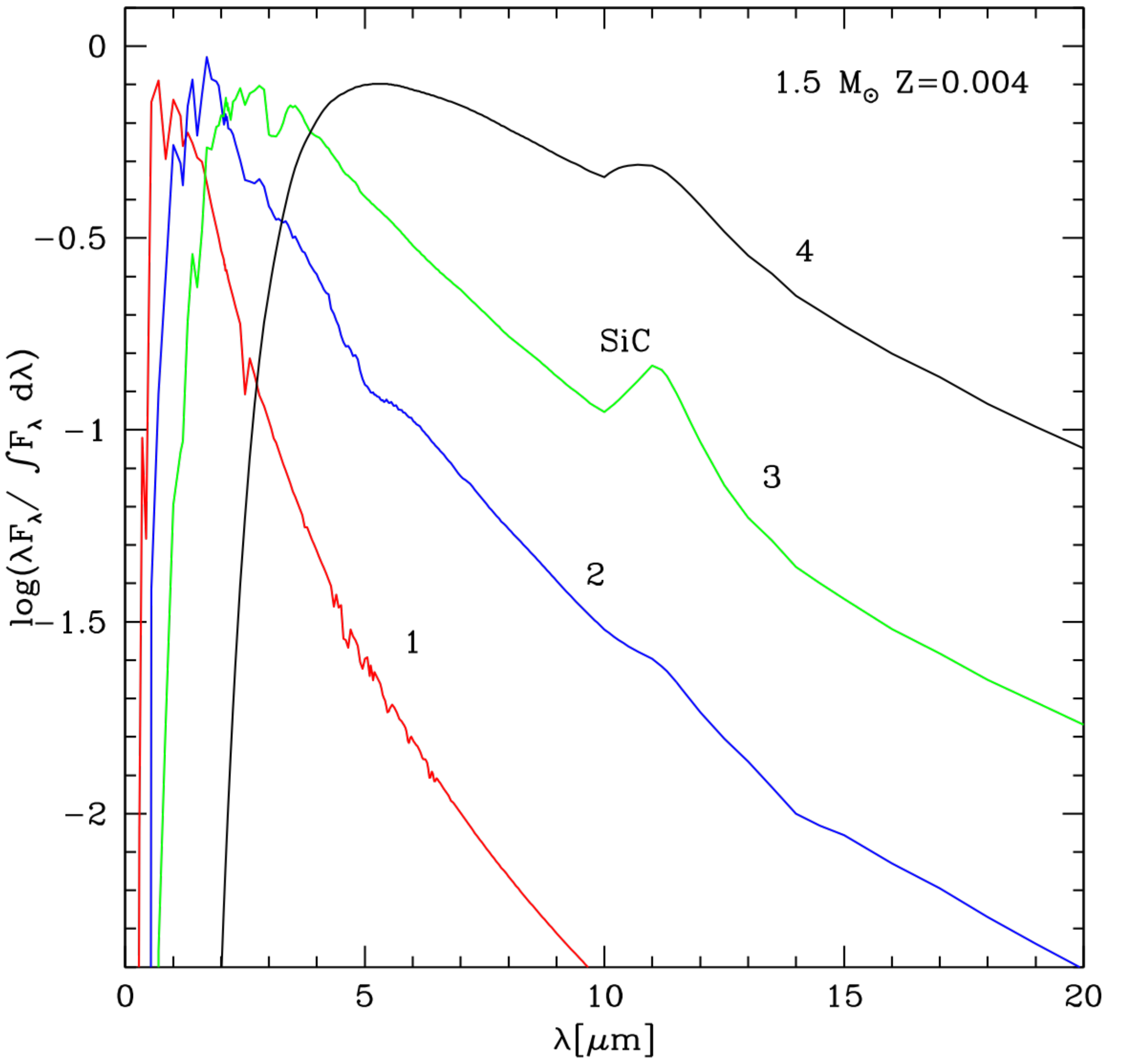
4. The density of the seeds on which the grains grow are assumed a priori

Works in progress…
on nucleation processes look at works by David Gobrecht
The Vulcan code (Cristallo et al. 2021)



Thank you!

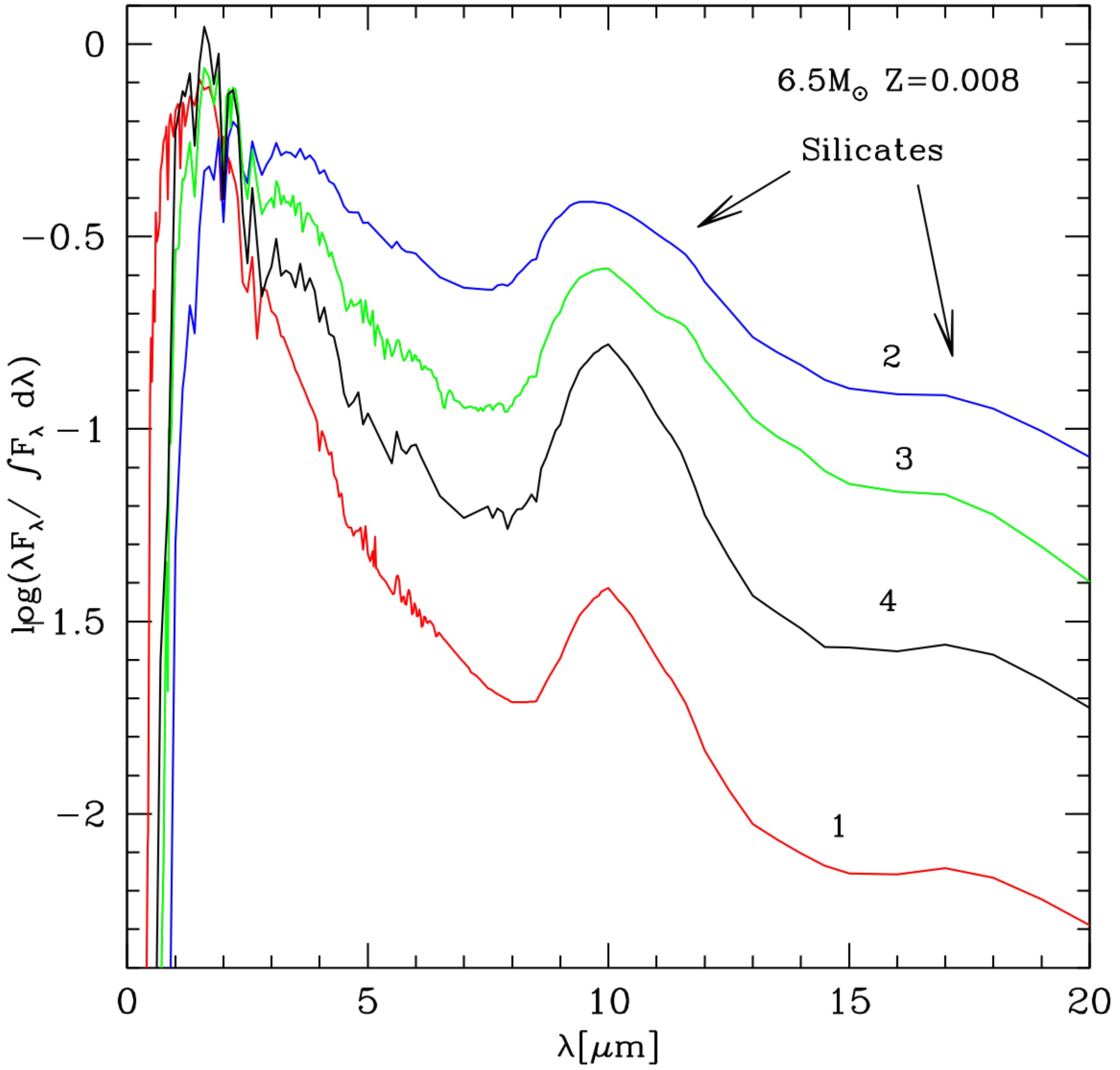
The EVOLUTION of the AGB SPECTRAL ENERGY DISTRIBUTION



Carbon rich star

$1.5\ M_\odot$	$Z= 4 \times 10^{-3}$						
n°	t_{AGB}	$M/M_\odot$	$L/L_\odot$	$\dot{M}$	T_{eff}	τ_{10}	a_{Sil}/a_C
1	8.5240D+06	1.50	3.51D+02	5.84D-11	4466.89	4.01D-10	0.001
2	1.3632D+06	1.44	5.76D+03	4.12D-07	3244.80	1.12D-02	0.092
3	1.7278D+06	1.07	6.37D+03	3.88D-06	2736.83	7.32D-02	0.141
4	1.7635D+06	0.70	6.75D+03	3.20D-05	2454.62	6.64D-01	0.207

The EVOLUTION of the AGB SPECTRAL ENERGY DISTRIBUTION

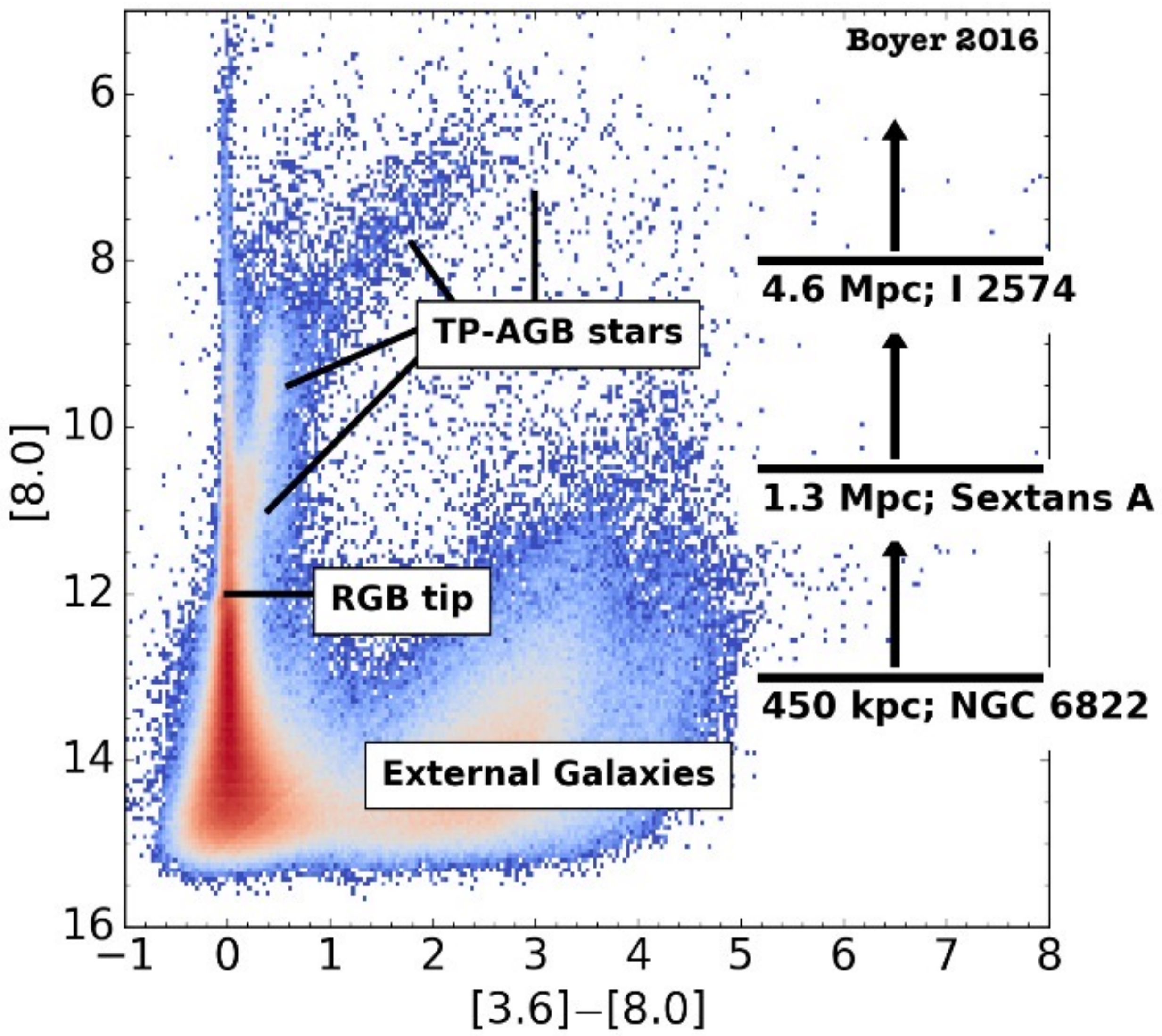


Oxygen rich star

$6.5\ M_\odot$ Z= 8×10^{-3}

n°	t_{AGB}	M/M$_\odot$	L/L$_\odot$	$\dot{M}$	T$_{eff}$	τ_{10}	a$_{sil}$
1	1.5000D+01	6.48	3.23D+04	2.57D-06	3662.05	2.97D-02	0.059
2	1.1767D+04	5.14	8.69D+04	3.07D-04	2984.91	1.82D+00	0.120
3	3.0096D+04	2.39	4.73D+04	5.99D-05	2772.24	6.87D-01	0.103
4	4.5611D+04	1.82	3.57D+04	2.35D-05	2807.08	3.51D-01	0.095

JWST era



LMC CMD at various distances as seen by JWST