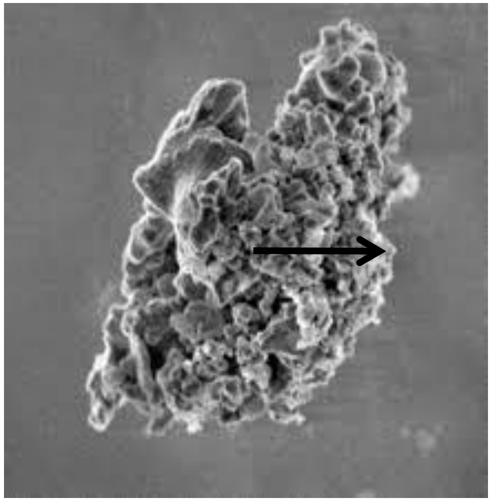
What is dust and why we study it?



few hundredths of a µm up to few µm

Silicates (Mg_2SiO_4,$MgSiO_3$)

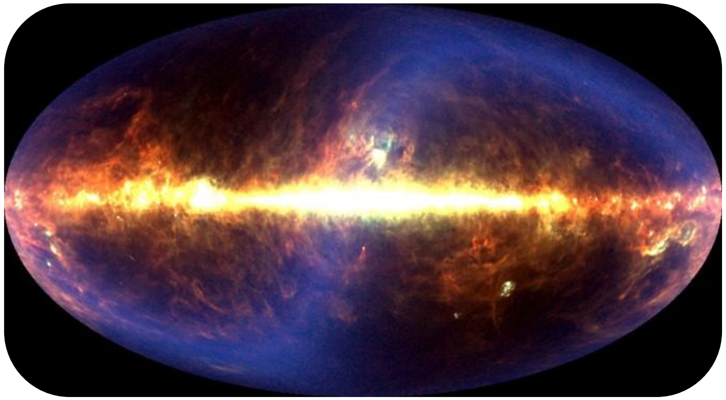
Carbon

Dust is formed from metals, it is ~1% of the total mass of the baryons!
…but it is important in several astrophysical contexts:

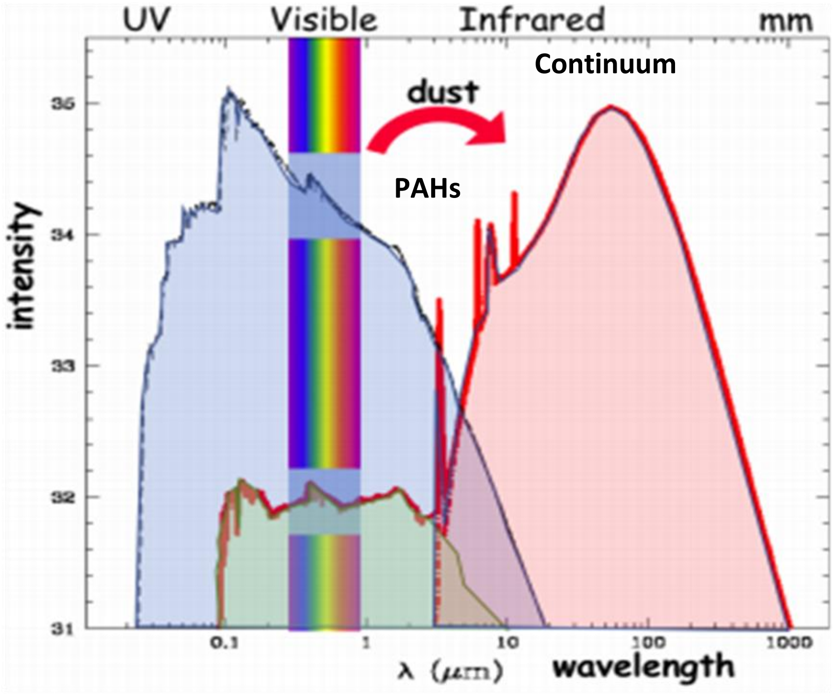
- star formation (gas cooling)
- molecule formation ("mechanical" catalyst)
- planets formation
- for studying the Solar System (pre-solar grains)
- stellar evolution (mass-loss in low-mass stars)
- baryon cycle in galaxies

Dust absorption and re-emission

Milky Way in the optical
(credits: Axel Mellinger)

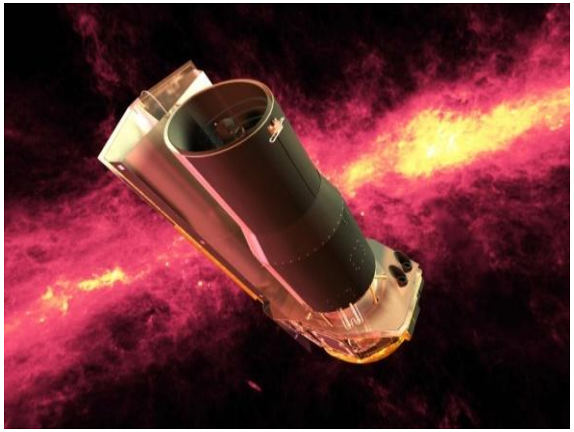


Milky Way in the infrared
(credits: COBE satellite)



Attenuation of the light from stars in the UV/optical
Re-emission in the Infrared

How do we see dust?

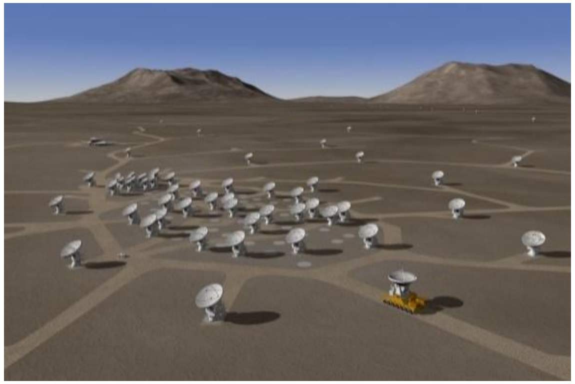


Spitzer

Mid-IR 3.6-38 µm

Herschel

Far-IR 55-672 µm



ALMA

Sub-mm/mm
0.3-3.6 mm

NOEMA

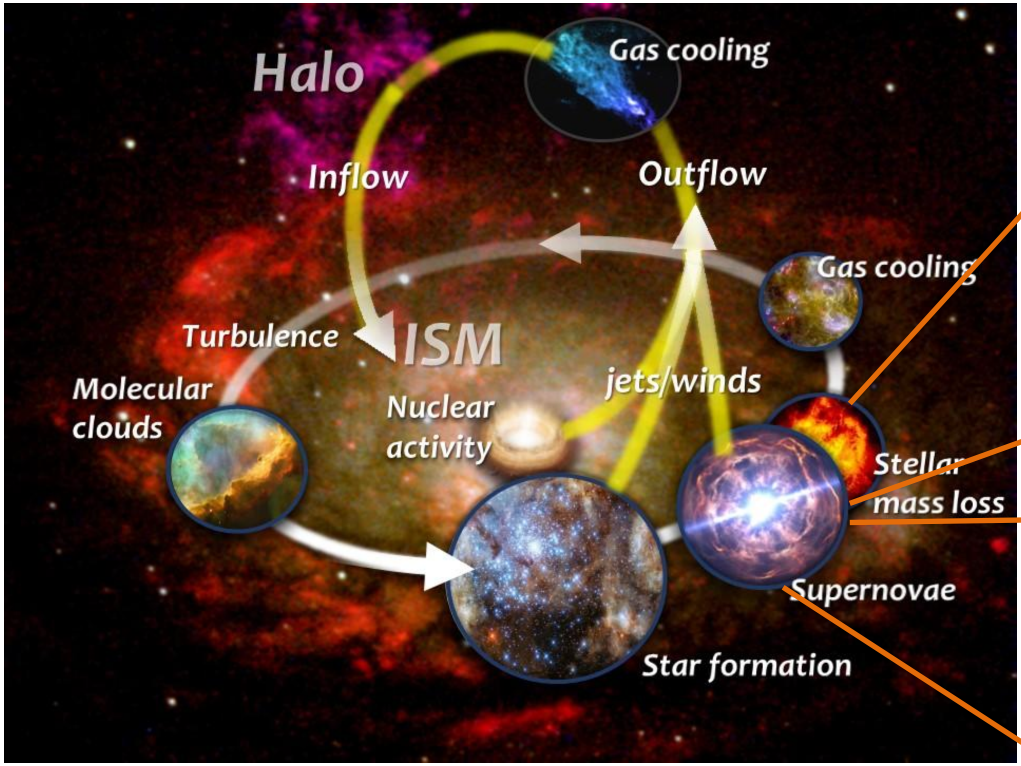
Sub-mm/mm
0.8-4.2 mm

James Webb Space Telescope (JWST), launched: December 2021

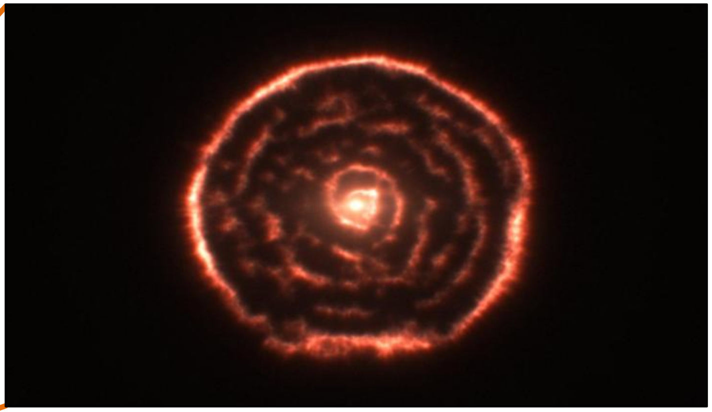
Near- to Mid-IR: 0.6-28 µm

- Dust up to 2 Gyrs after the Big Bang
- Stars in galaxies 500 Myrs after the Big Bang

Dust evolution in the interstellar medium (ISM) of galaxies

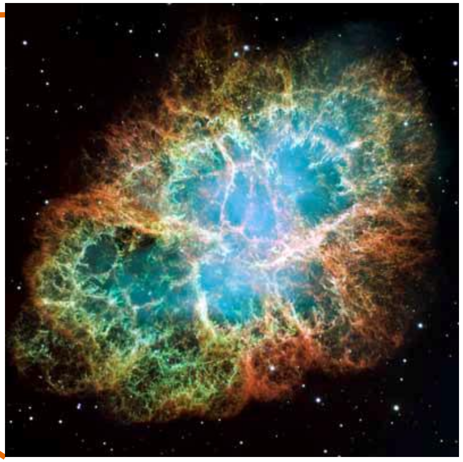


Dust in the interstellar medium of galaxies



Maercker et al.

Dust around TP-AGB stars ($M<6\text{-}8\ M_\odot$)

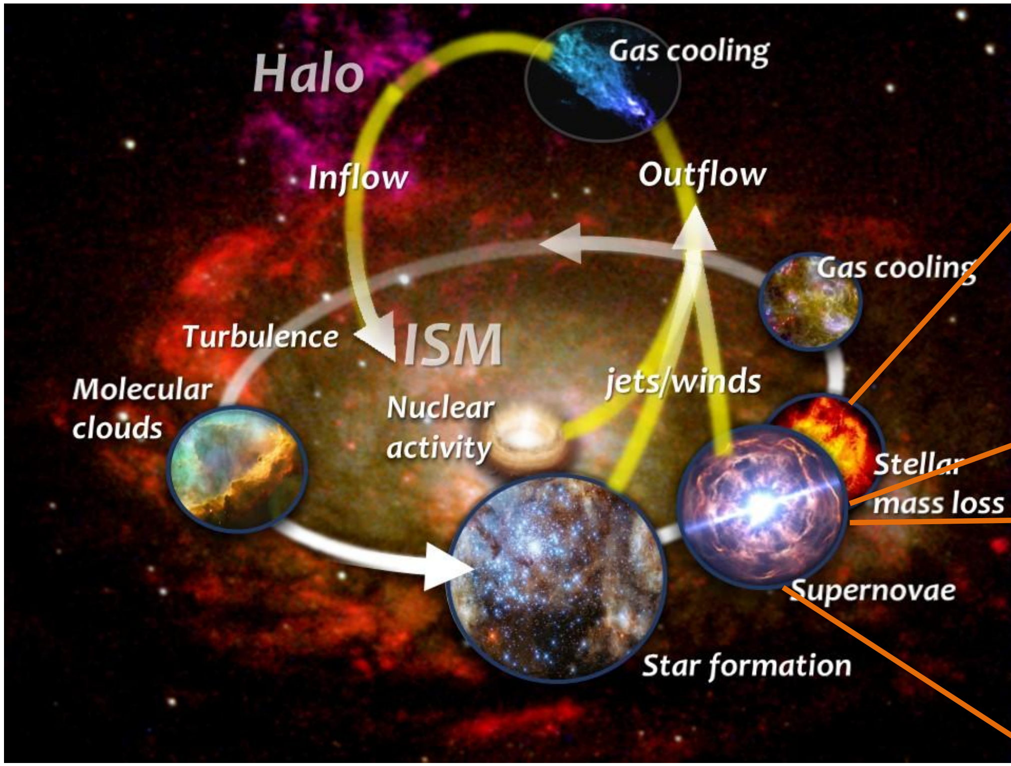


Dust around SN remnants ($M>8\ M_\odot$)

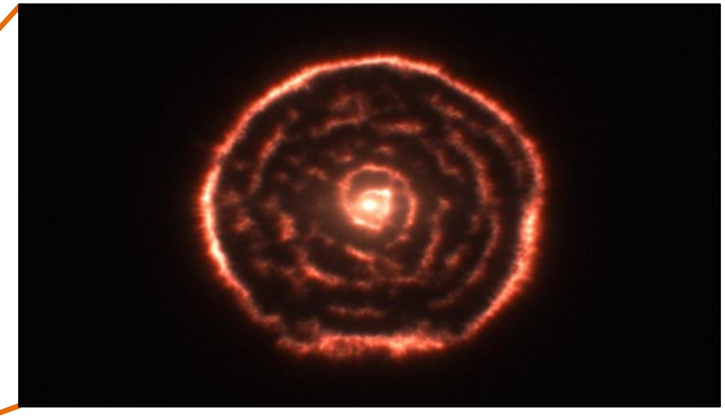
Complex interplay between:

- Stellar evolution;
- Evolution of dust grains: growth & destruction;
- Galactic inflows and outflows.

Dust evolution in the interstellar medium (ISM) of galaxies

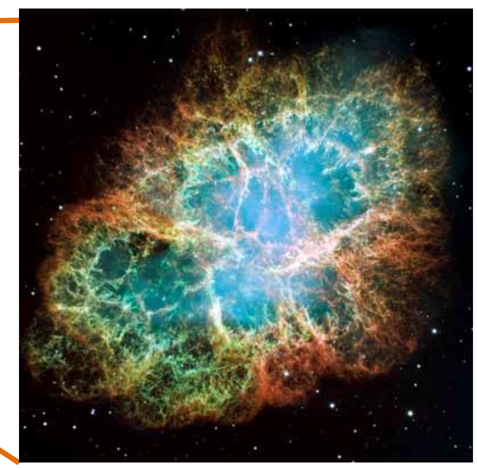


Dust in the interstellar medium of galaxies



Maercker et al.

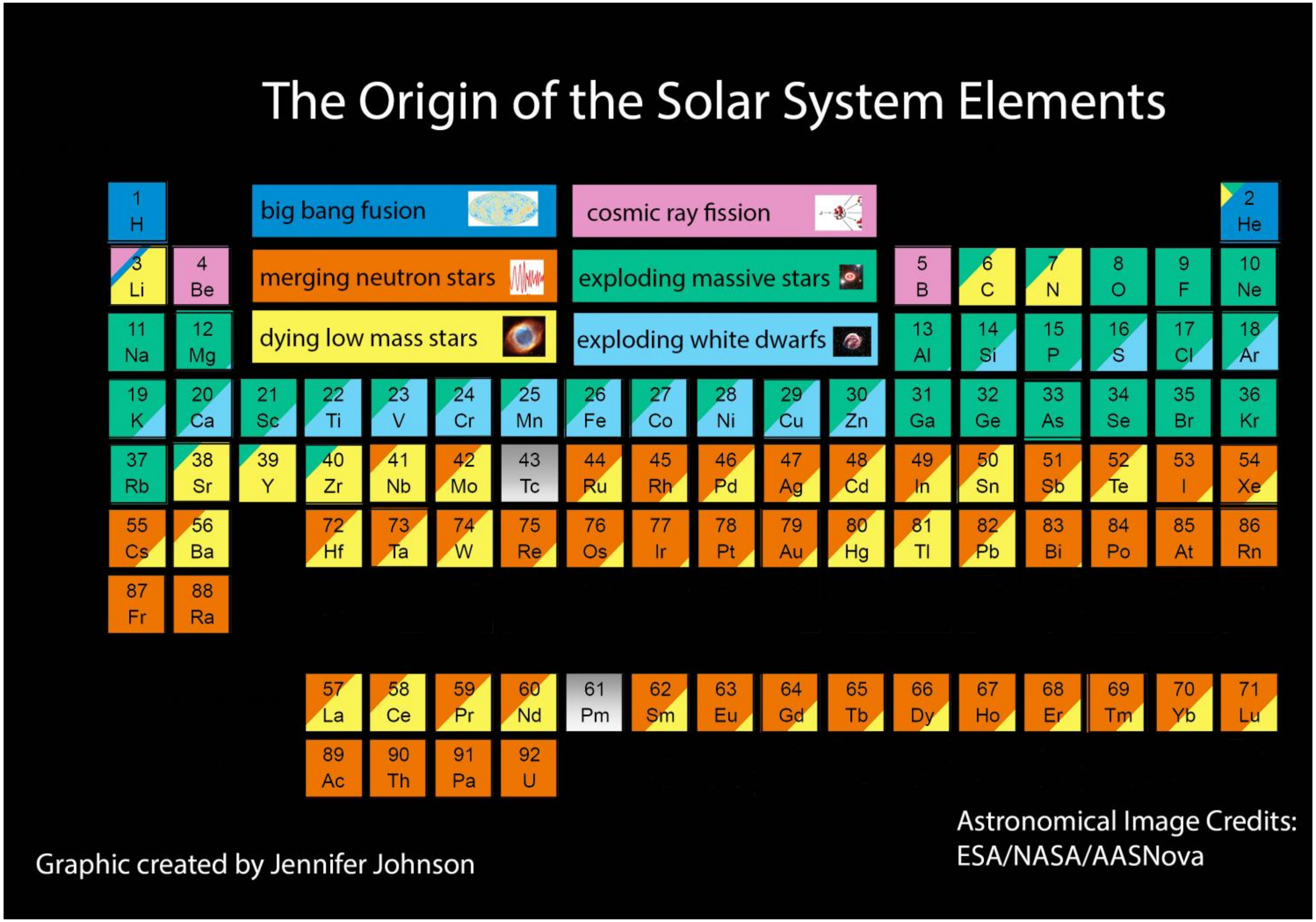
Dust around TP-AGB stars ($M<6\text{-}8\ M_\odot$)



Dust around SN remnants ($M>8\ M_\odot$)

- TP-AGB stars account for ~50-60% of dust in the Local Universe (Gehrz 89)
- May be important also at high redshifts (z>5) (e.g. Valiante+09)
- Most of the stars go through the TP-AGB phase

Where metals come from?



- **Silicates (e.g. Mg_2SiO_4, $MgSiO_3$)**: the elements come from massive stars exploding in short time-scale
- **Carbon dust**: some carbon from massive stars, but most of them from low-mass stars (longer time-scale); Their evolution is likely to be link to the appearance of PAHs feature (Galliano+08).
- **Iron**: Type Ia supernovae (from white dwarfs in binary systems)
- **Other heavy elements**: low mass stars and neutron star mergers

TP-AGB stars

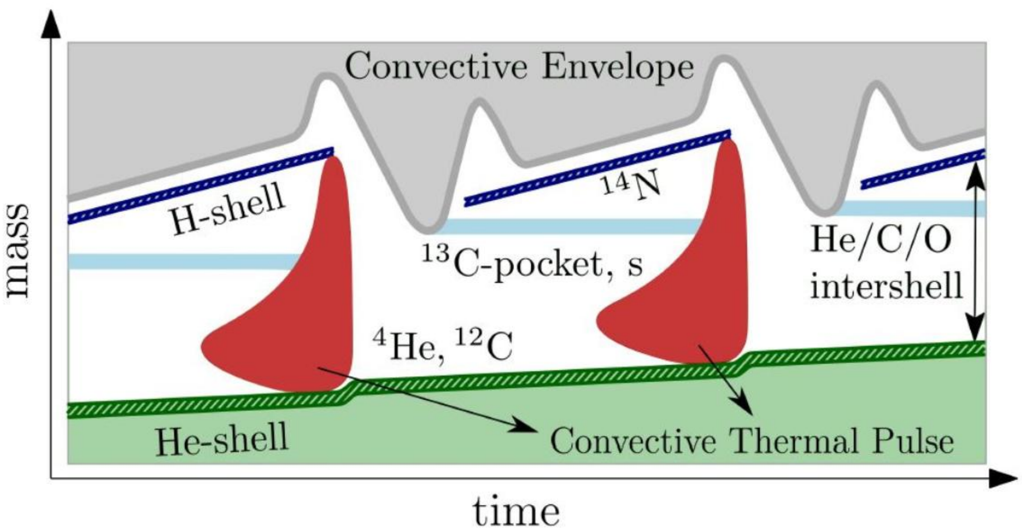
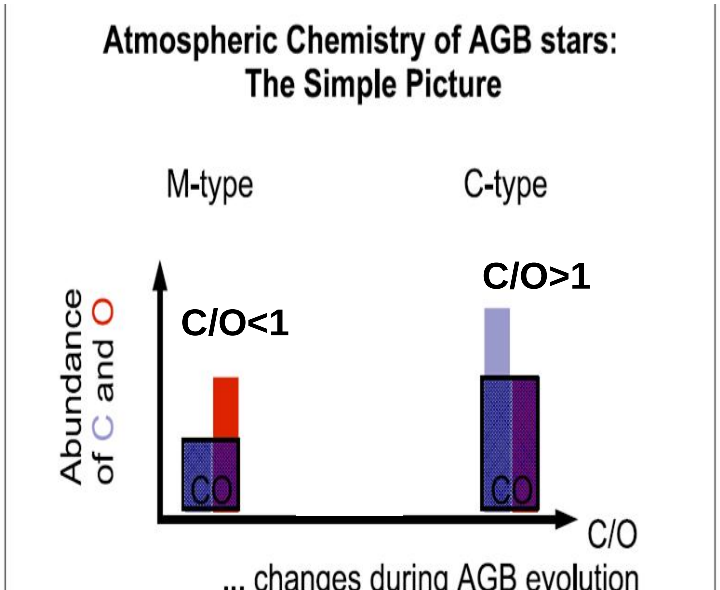


Figure 1.1: Schematic sketch of the mixing episodes during thermal pulses.

Credits: Diego Vescovi (PhD thesis)



Hoefner 09

- H- and He-burning shells
- Several thermal pulses
- Third dredge-up for $M \geq 2\ M_\odot$

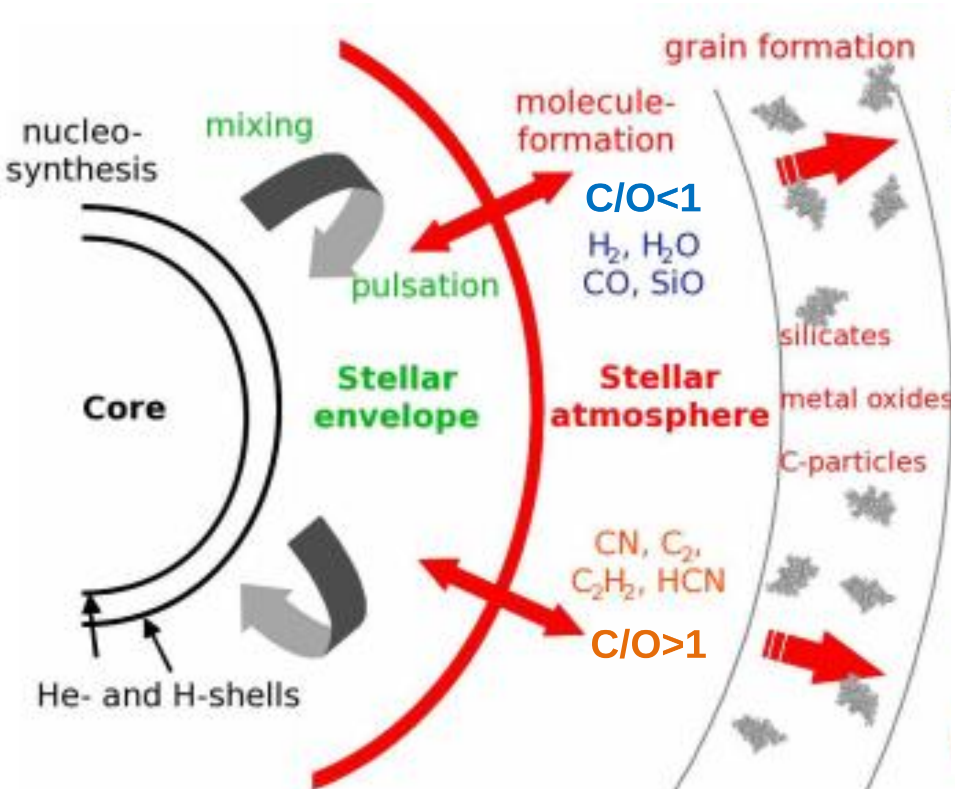
C/O<1→ C/O>1

Dredge-up more efficient at lower metallicities

- High mass-loss rates (10^{-7}-10^{-5} $M_\odot$/yr)
- Mass-loss of Sun ≈10^{-14} $M_\odot$/yr
- Hot Bottom Burning (HBB): H-burning through CNO cycle ($M \geq 4\ M_\odot$)
- Decreases C (CN cycle):

C/O>1→ C/O<1

Circumstellar envelope



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

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

$\Gamma > 1 \rightarrow$ acceleration

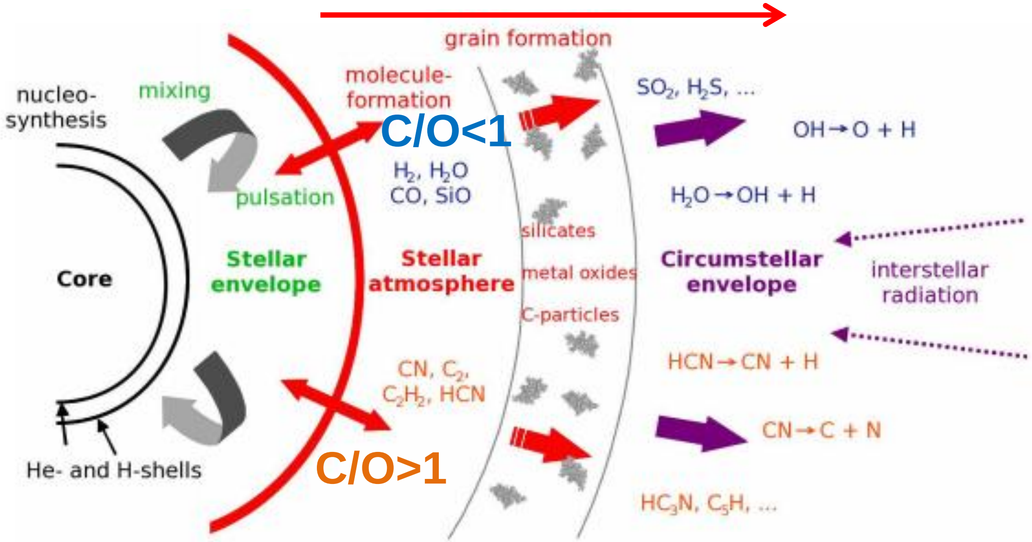
$\kappa \rightarrow$ dust opacity

Maercker PhD thesis (adapted from Habing & Olofsson 03)

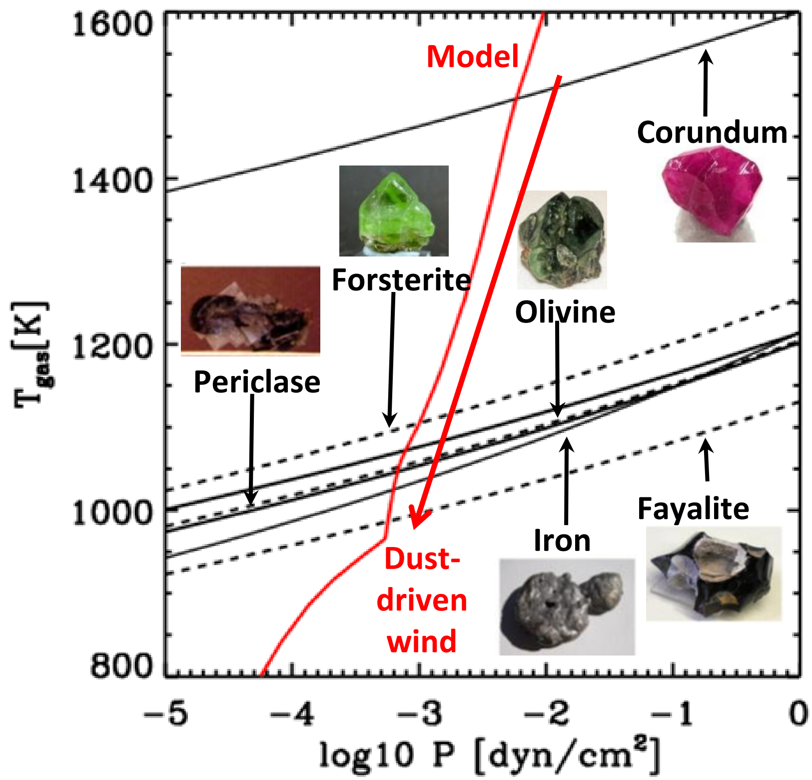
- **Dust-driven wind & mass-loss: momentum transferred to the dust grains (silicate/carbon dust for M/C stars, Eriksson+14; Bladh+15)**
- **Expansion velocity: measured, i.e. CO lines, OH maser emission** (e.g. **Marshall+04; Lagadec+10; Ramstedt & Olofsson 14; Goldman+17**)

Stationary wind model

e.g. Ferrarotti & Gail 06; Ventura+12; Nanni+13,+14; Dell'Agli+15



Maercker PhD thesis (adapted from Habing & Olofsson 03)



Input stellar parameters

- current stellar mass
- effective temperature
- stellar luminosity
- mass-loss
- elements abundances

Output

- dust mass
- dust composition
- outflow velocity
- spectra

Comparison with observation

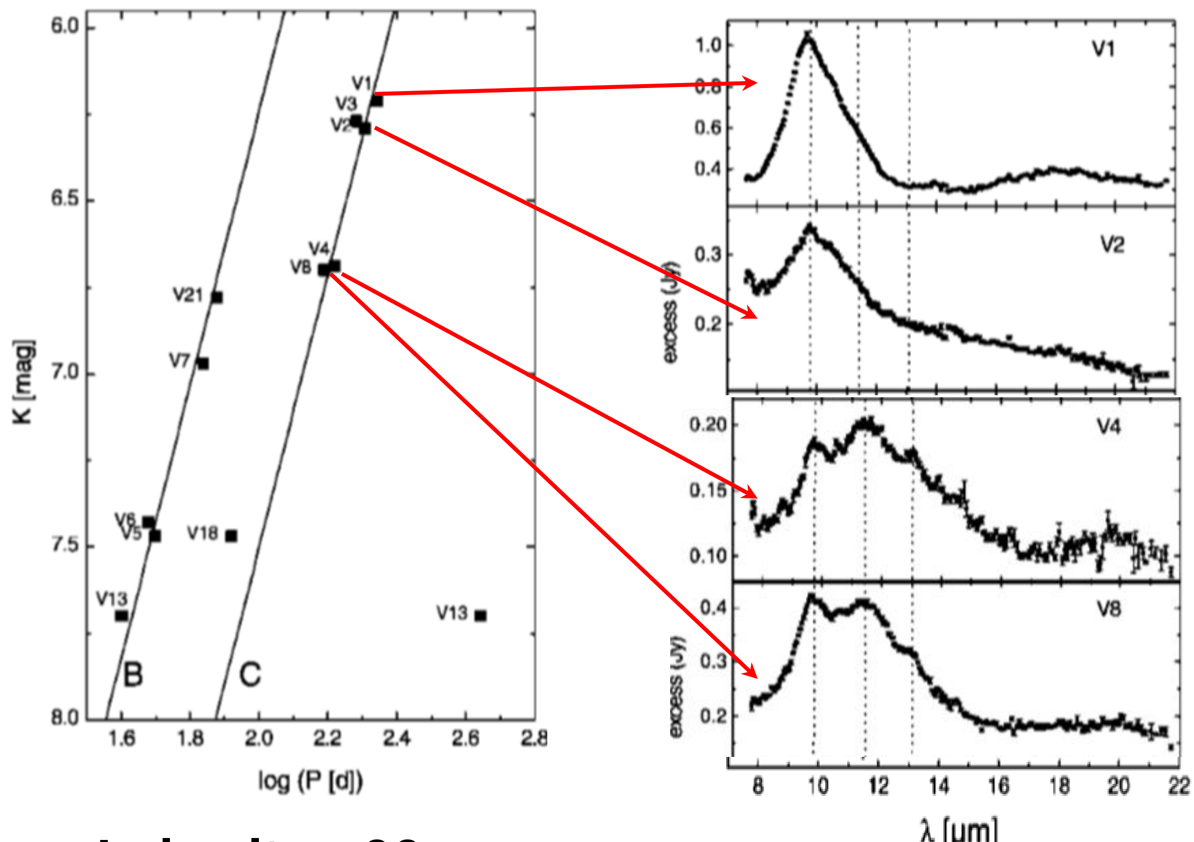
Main results

- dust yields (**Nanni+13, +14**)
- dust growth/destruction (**Nanni+13**)
- grain size and optical properties (**Nanni+16, Nanni19**)
- dust production for resolved stars (**Nanni+18,+19**)

Dust spectral feature

O-rich stars:

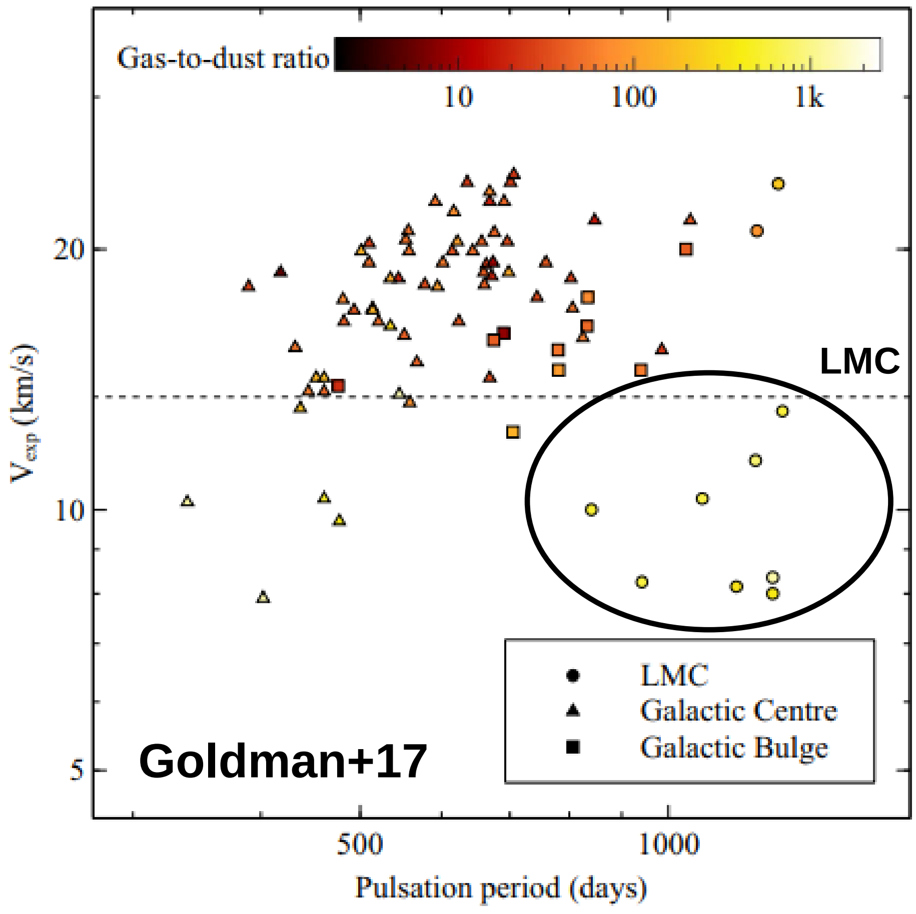
- **Silicates**: **olivine, pyroxene, quartz** → Feature at 10, 18 μm **(amorphous)**; 10, 18, 23, 28, 33, 40 and 60 μm (**crystalline,** e.g. Jones+12)
- **Aluminium oxide - corundum (Al_2O_3)** → Bump around 12 μm
- **Iron (?)** → Featureless (may condense at low Z, McDonald+11)
- **Corundum** and **silicates features**: depend on **luminosity** and **mass-loss rate** (e.g. **Lebzelter+06**).
- **Dust α Z**



Lebzelter+06

M-stars expansion velocities

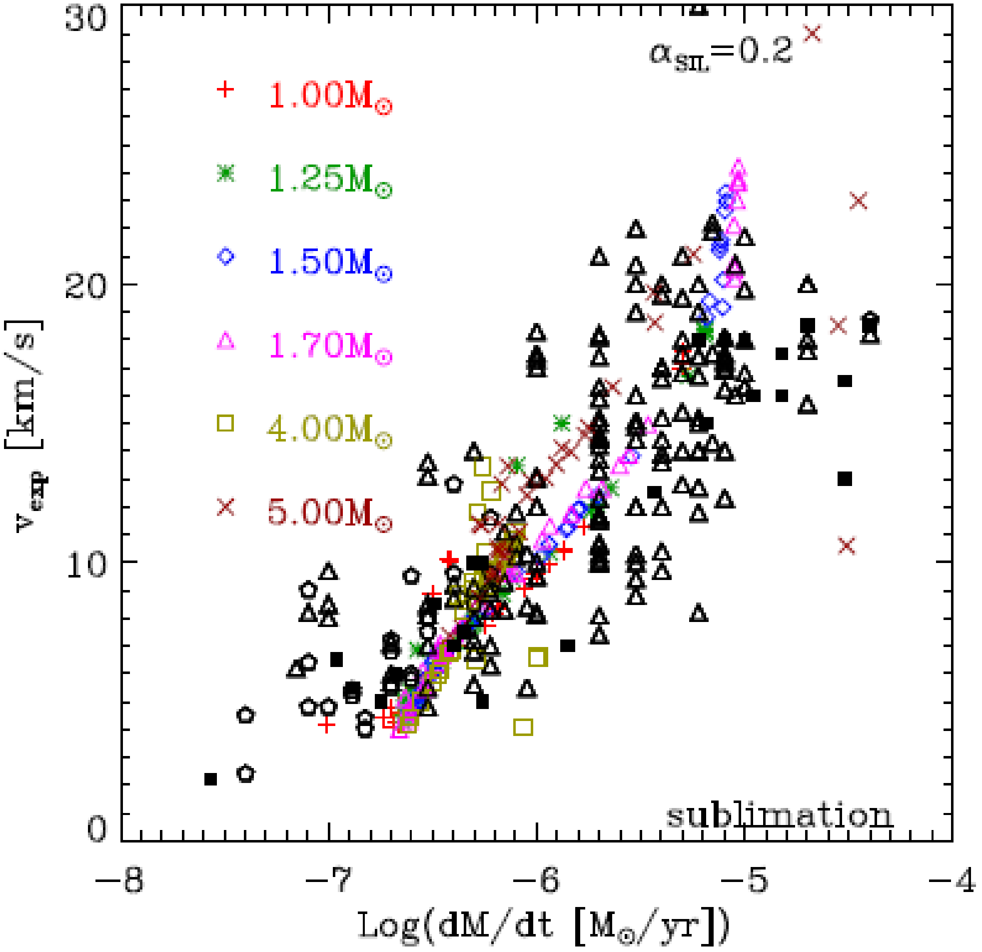
The predicted dust content and wind speed depends on the metallicity (as expected)



- **OH/IR stars in the LMC and in the Galaxy**, e.g. **Goldman+17**
- **No OH maser emission detection in the SMC (Goldman+18)**

What drives the wind in O-rich TP-AGB stars?

Nanni+13



Stationary wind models couples with stellar tracks

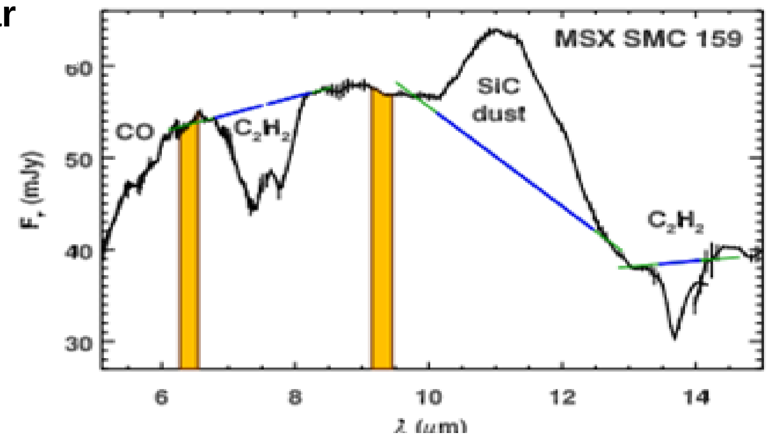
Iron-rich: scattering+absorption

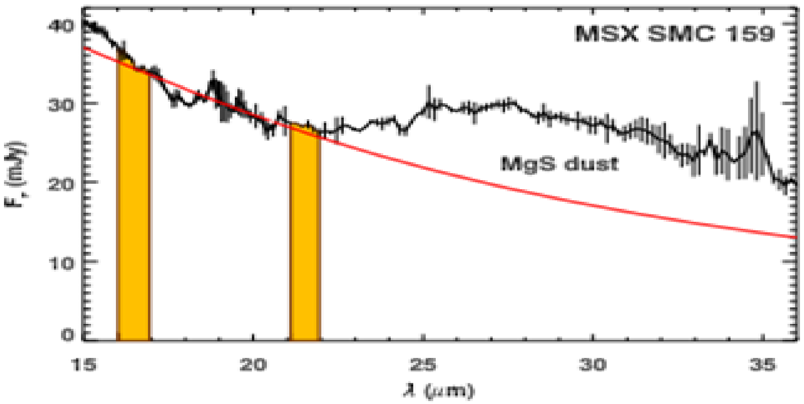
Dust spectral feature

C-rich stars:

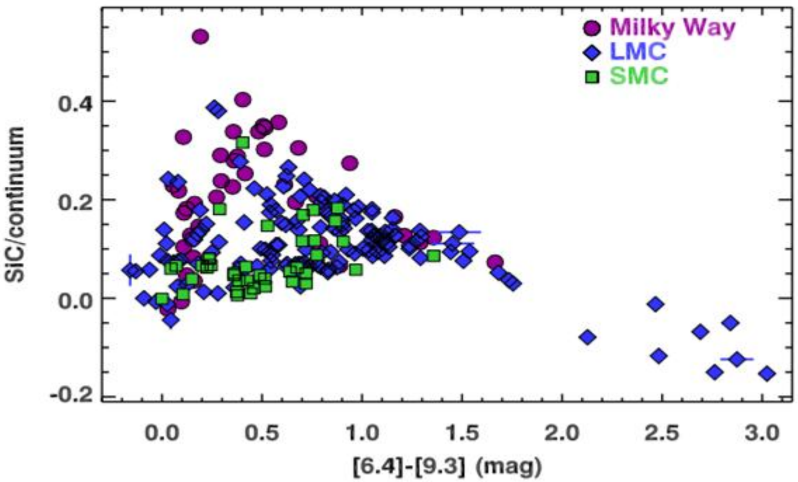
- **Amorphous carbon** → Featureless (its abundance does not depend on the initial Z)
- **Silicon Carbide (SiC)** → Feature at 11.3 μm
- **Magnesium Sulfide (MgS)** → Bump around 30 μm
- **SiC** and **MgS features:** dependent on **metallicity** and **mass-loss rate** (**Sloan+06; Zijlstra+06; Lagadec+07; Leisenring+08; Sloan+15**)

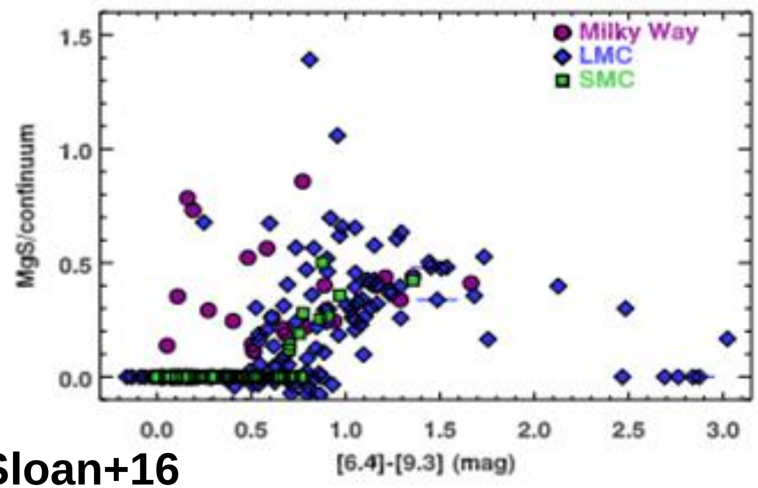
C-star





IRS on *Spitzer* 5.2 -38 μm

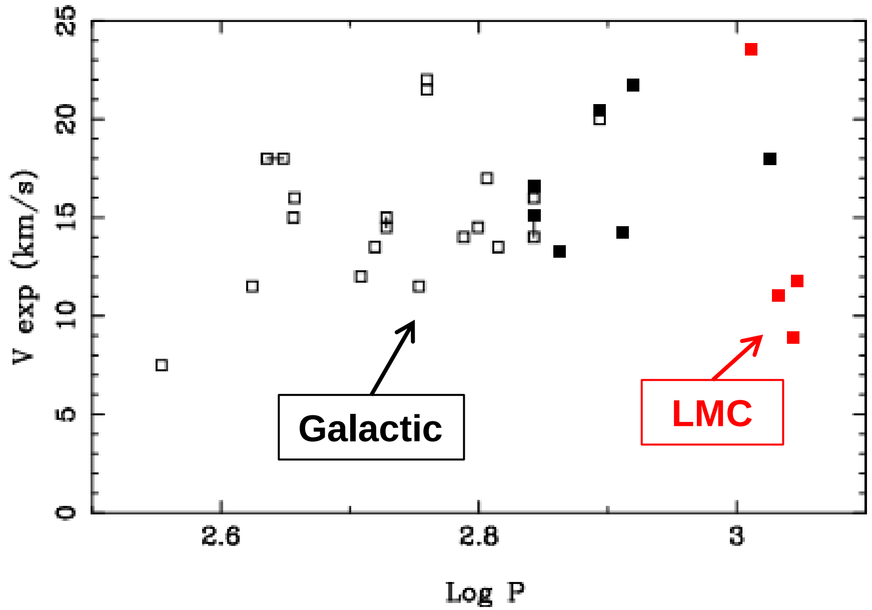


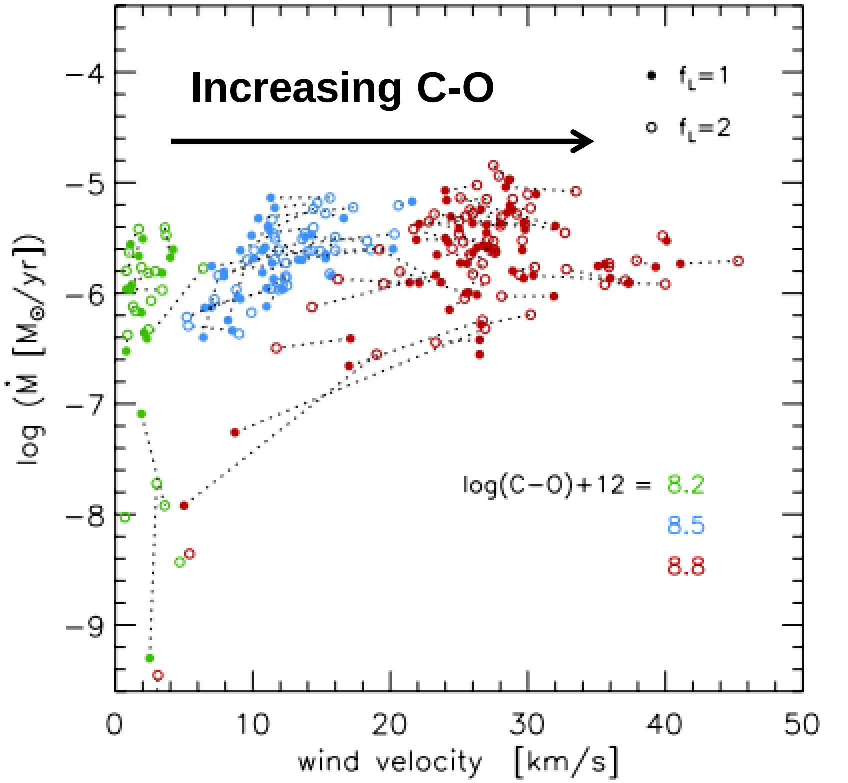


Sloan+16

C-stars: wind speed

More complex situation for C-stars



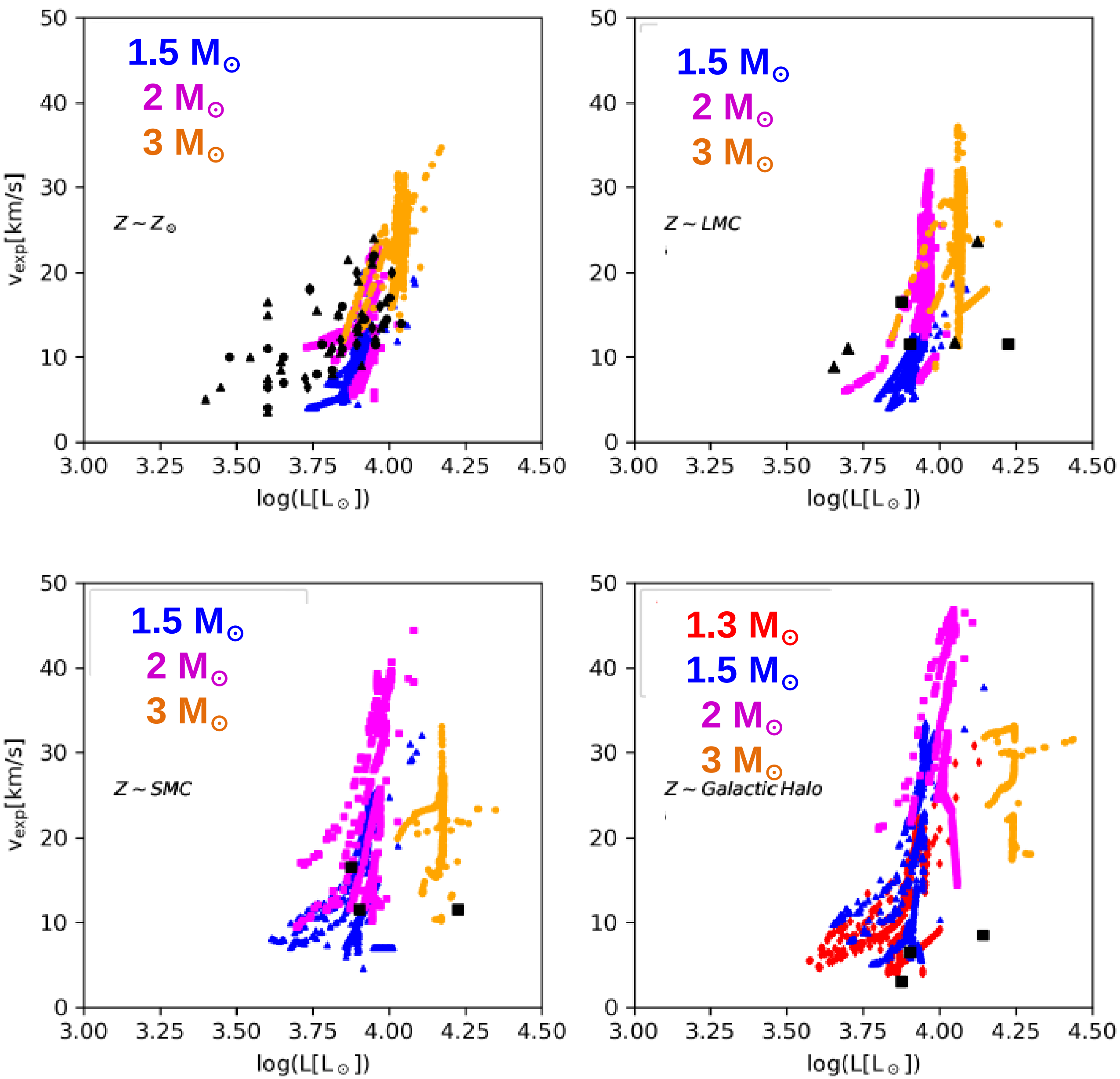


- Galactic extremes + Ramstedt&Olofsson 14; Danilovich+15
- ALMA observations for the LMC sources (Groenewegen+16)

Hydrodynamic simulations (Eriksson+14)

- V_{exp} should depend carbon-excess rather than on the metallicity (e.g. Blah+19)
- C-stars in the LMC seem to have lower V_{exp} than C-stars in the Milky Way
- Observations in a larger range of stellar parameters are needed!

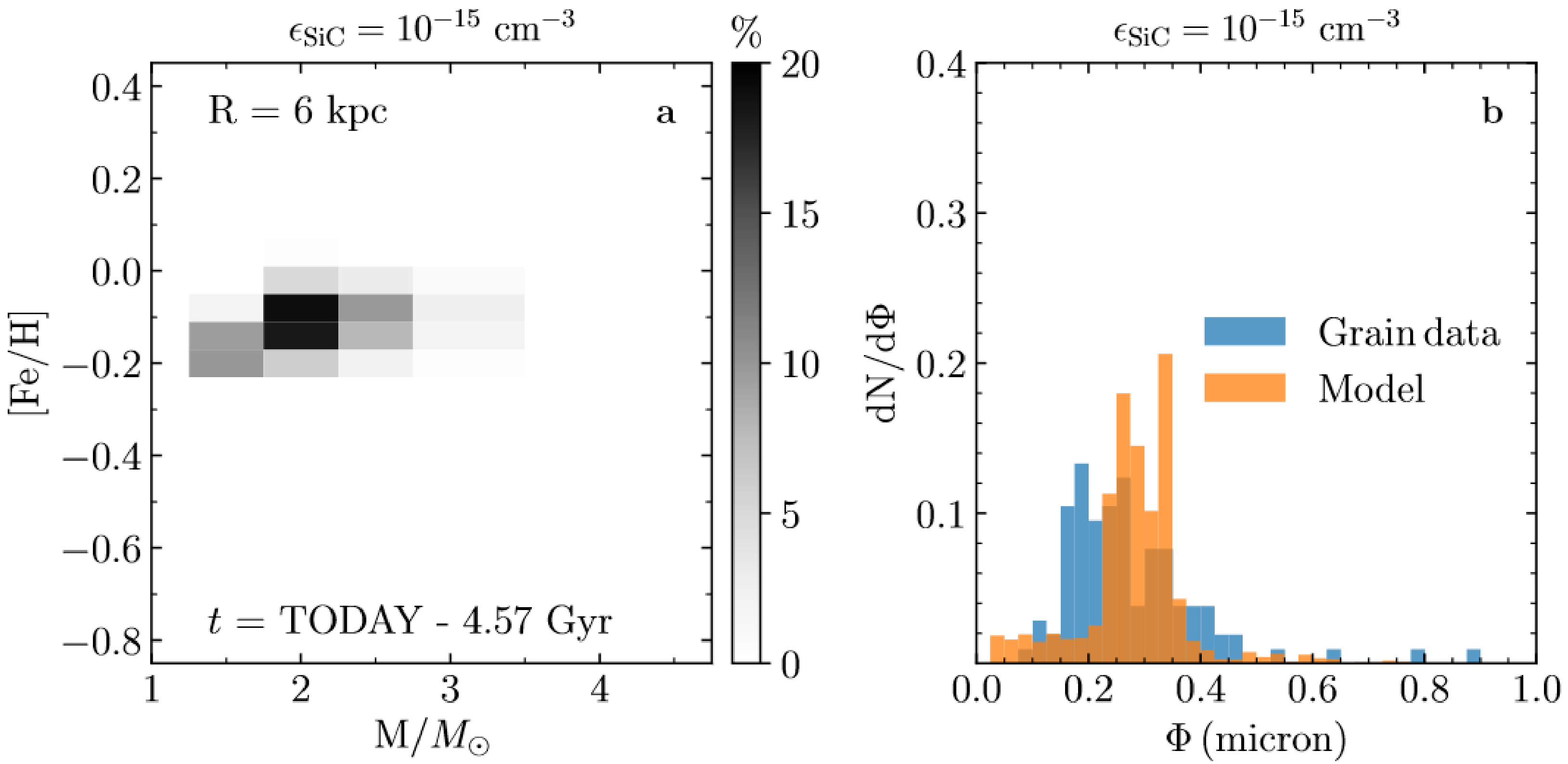
C-stars: wind speed



Nanni+21

- **Stationary wind models couples with stellar tracks (Cristallo+09)**
- **Observations are fairly well reproduced by our predictions**

Pre-solar grains

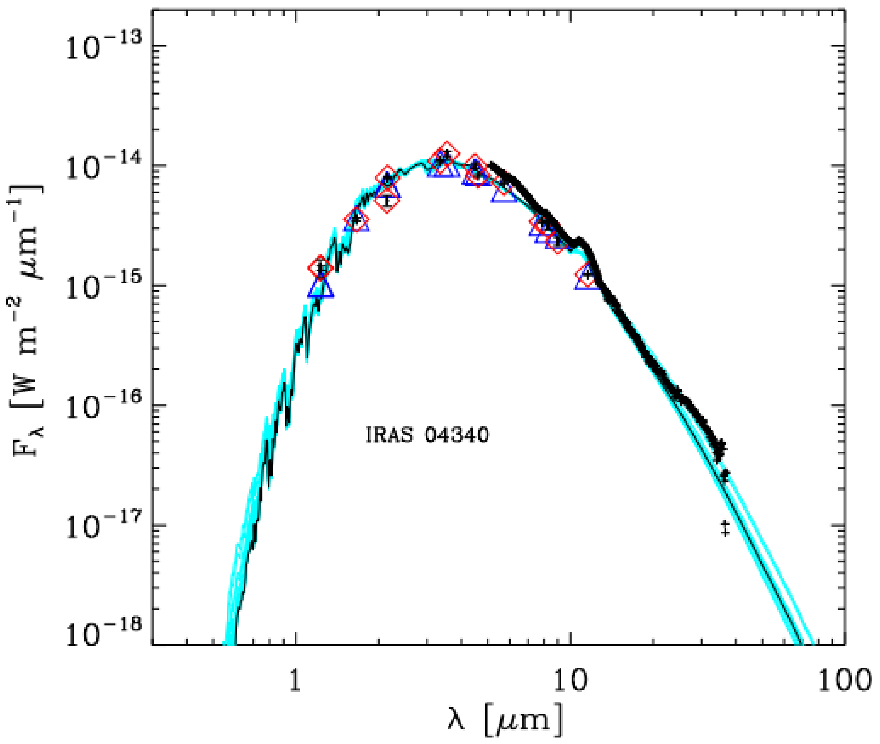


Cristallo, Nanni+20

- **The prescriptions for dust growth and wind dynamics have been coupled with FRUITY evolutionary tracks (Cristallo+09).**
- **By including the time-average effect of pulsation (and suitable seed particle abundance), the size distribution of SiC grains is fairly well reproduced by stars of M ~ 2 $M_\odot$ and Z ~ $Z_\odot$(Cristallo+20).**

Dust production from TP-AGB stars

Mass-loss & dust production rates



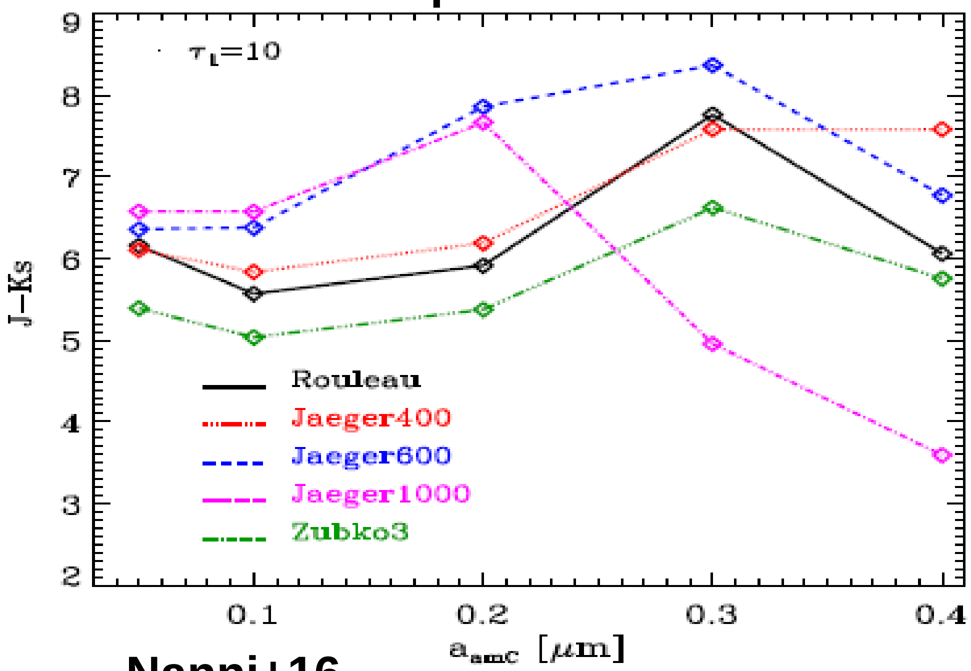
$$\tau_\lambda(\mathrm{approx}) = \frac{3\dot{M}_{\mathrm{dust}}\bar{Q}_{\mathrm{ext}}(\lambda, a)}{4aR_s v_{\mathrm{exp}}\bar{\rho}_d}$$

DPR α τ_λ V_{exp}/Q_{ext}

Mass-loss = DPR*Gas-to-dust

Which optical constants?

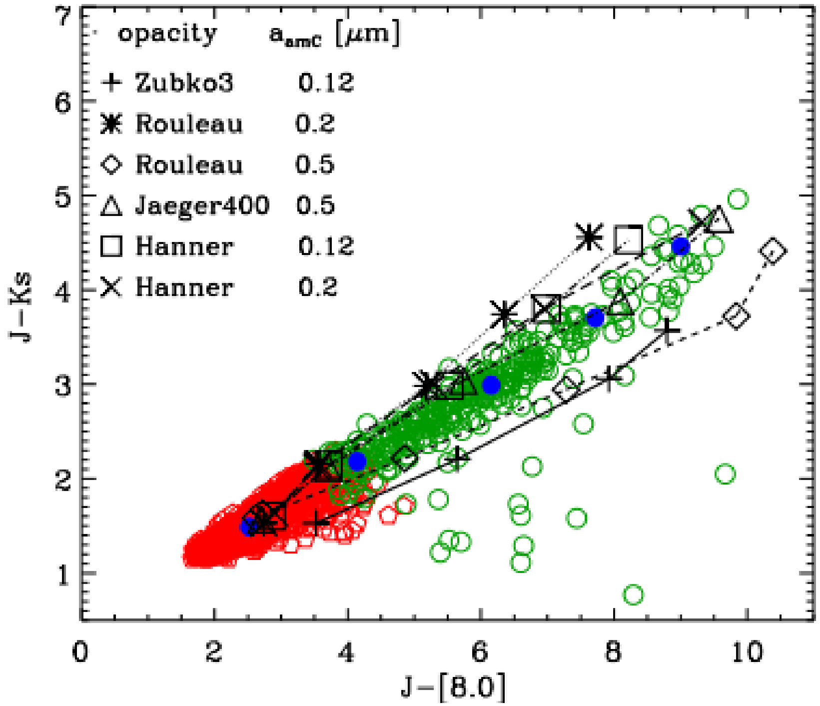
Amorphous carbon

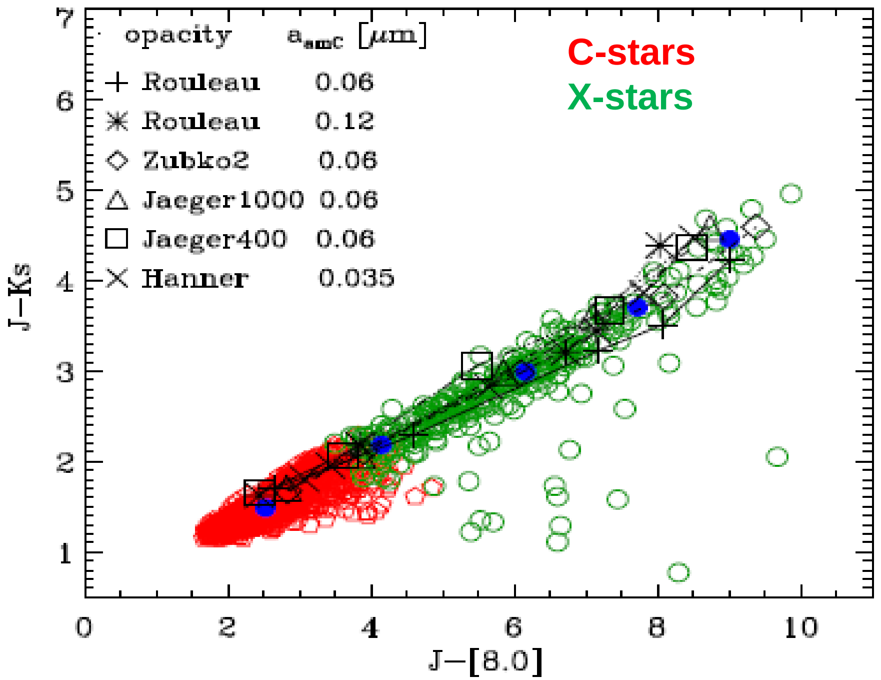


Nanni+16

- **Different optical data sets and grains sizes yield very different colours**
- **We constrained the optical constants in order to reproduce different observations in the infrared and Gaia DR2 bands (Nanni+16; Nanni 19)**

Constraining dust properties: amorphous carbon around C-stars

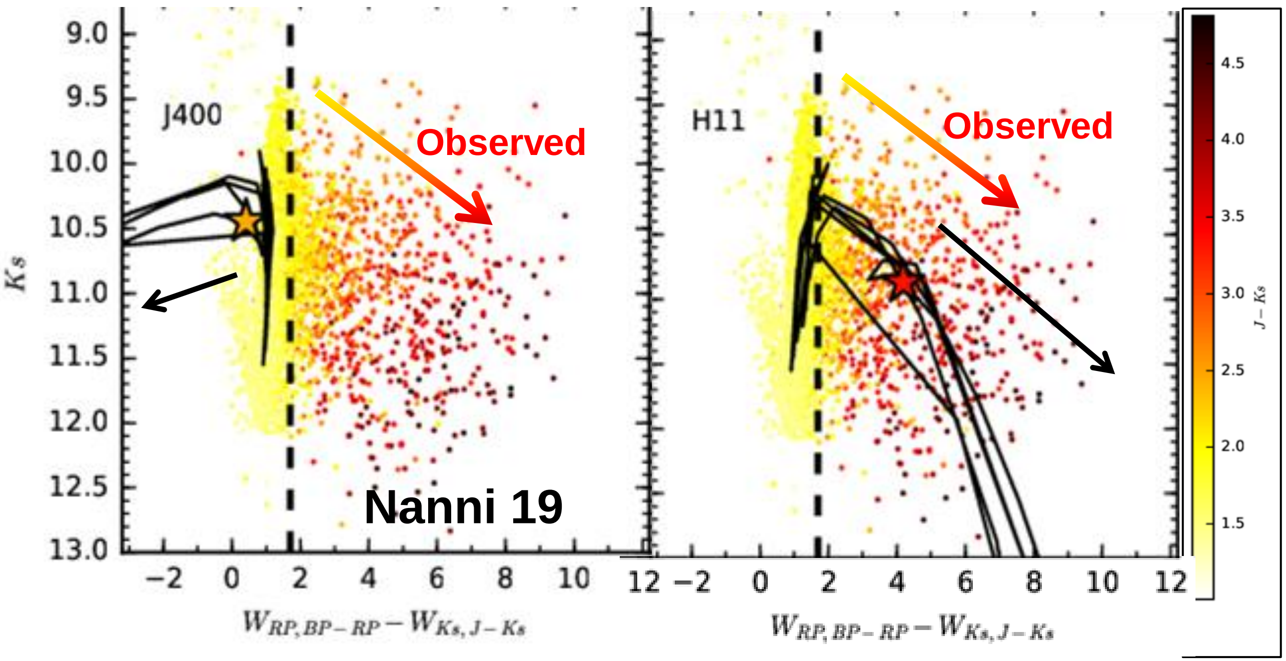




Nanni+16

Small grains (< 0.04-0.1 μm) best reproduce different CCDs in the IR

Constraining dust properties: amorphous carbon around C-stars



$$W_{RP,BP-RP} = G_{RP} - 1.3 \times (G_{BP} - G_{RP}) \quad W_{K_s,J-K_s} = K_s - 0.686 \times (J - K_s)$$

- **Only 2 combinations out of ~50 tested** **simultaneously reproduce both the infrared observations and the trends obtained by combining 2MASS and Gaia DR2 photometry from Lebzelter+18;**
- **Small grains (< 0.04-0.1 μm) + optical data sets from Hanner 88; Jaeger+98 (1000°C).**

Spectra reprocessed by dust

Dust growth coupled with a stationary wind (Nanni+13; Nanni+14)

Input: stellar parameters:
L, dM/dt, M, T_{eff}, C/O
+
Dust optical properties
(Nanni+16, Nanni 19)

→

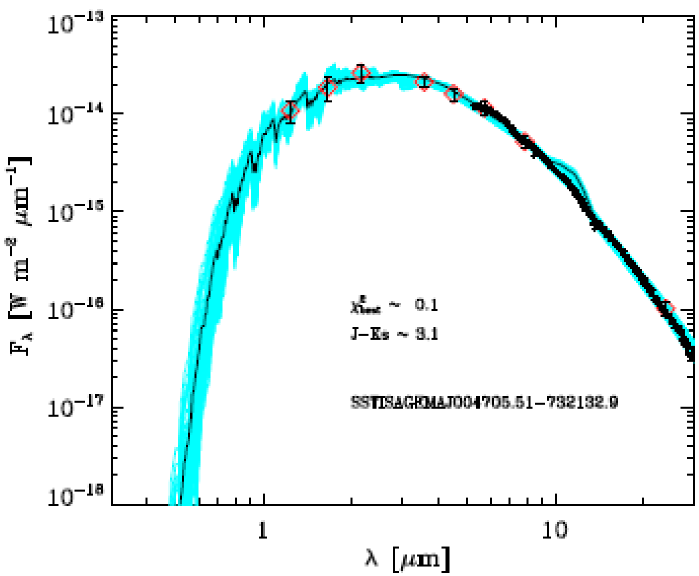
Output: circumstellar envelope
dust composition, gas-to-dust ratio, v_{exp}, spectra
(GRID of MODELS)

↓

SED fitting

↓

- **Dust production rate** and **mass-loss rate**
- **Gas-to-dust ratio**
- **Dust composition**



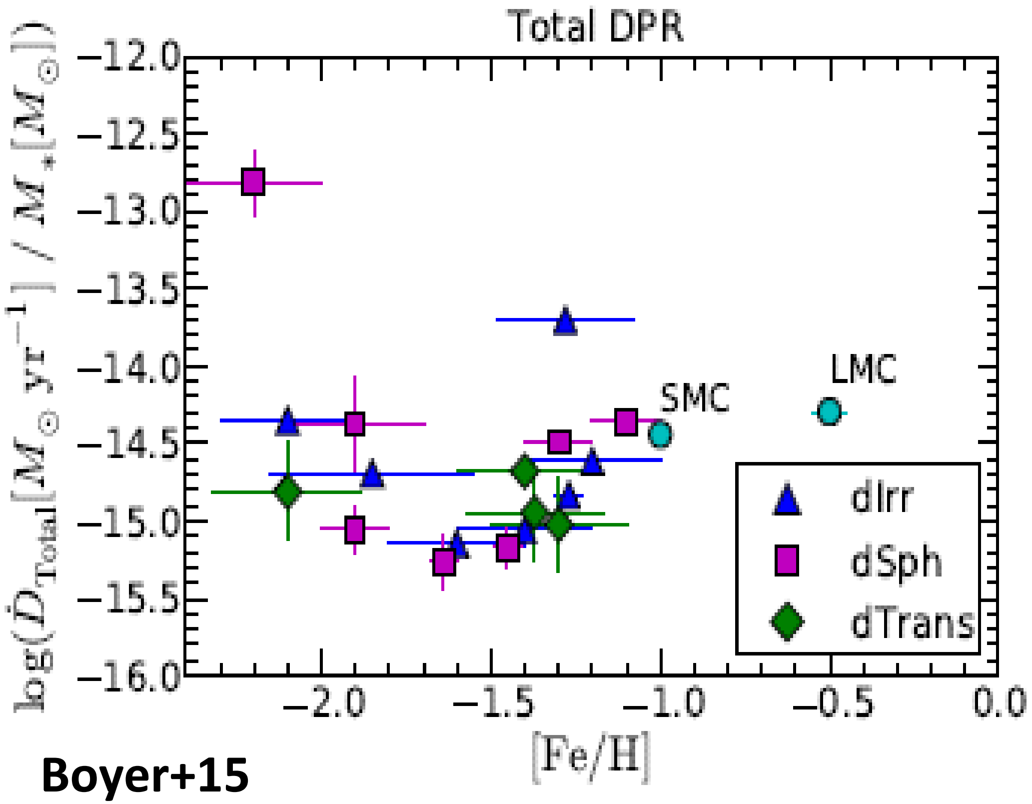
~3000 C-stars are fitted for the SMC and ~8000 in the LMC (Nanni+18, +19)

DPRs from C-stars in the Magellanic Clouds

SMC	DPR_C
Nanni+19	~25.2
Srinivasan+16	~ 8.0
Boyer+12	~ 7.5
Matsuura+13	~ 40
LMC	**DPR_C**
Nanni+19	~ 17.7
Srinivasan+16	~ 12.8
Dell'Agli+15	~ 40
Riebel+12	~ 17.0
Matsuura+09	~ 43-100

Variation of a factor ~5 and ~3 for the SMC and LMC respectively for different methods and assumptions

Dust production rates: low-Z galaxies

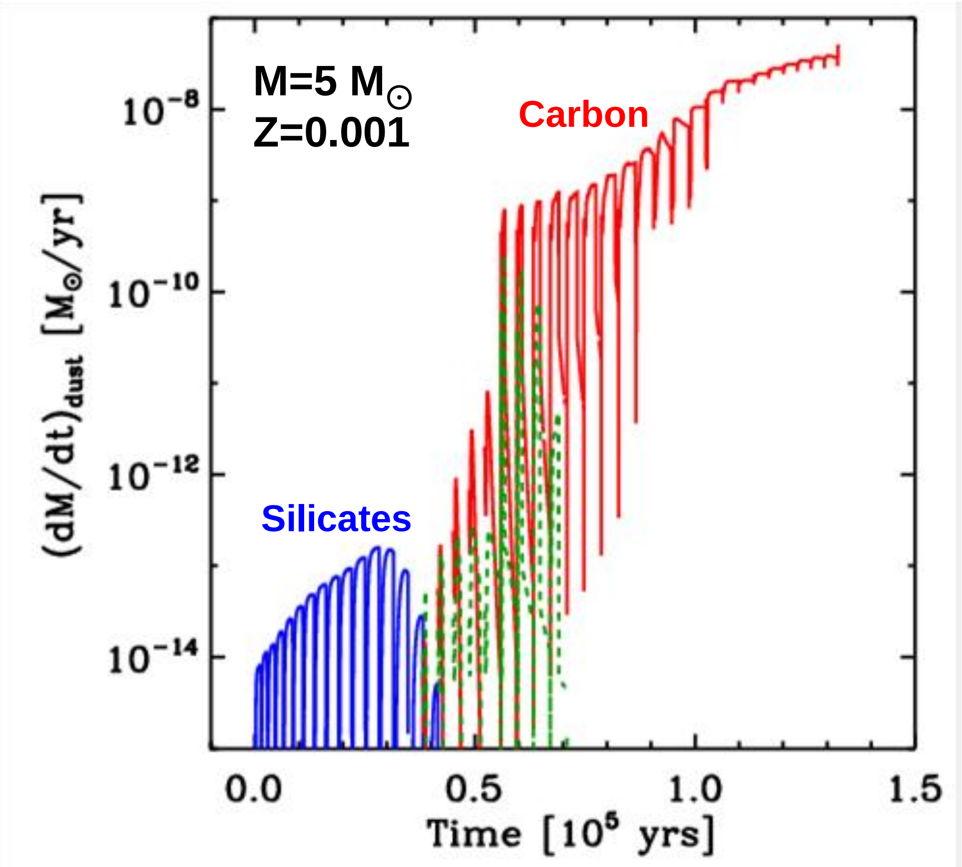


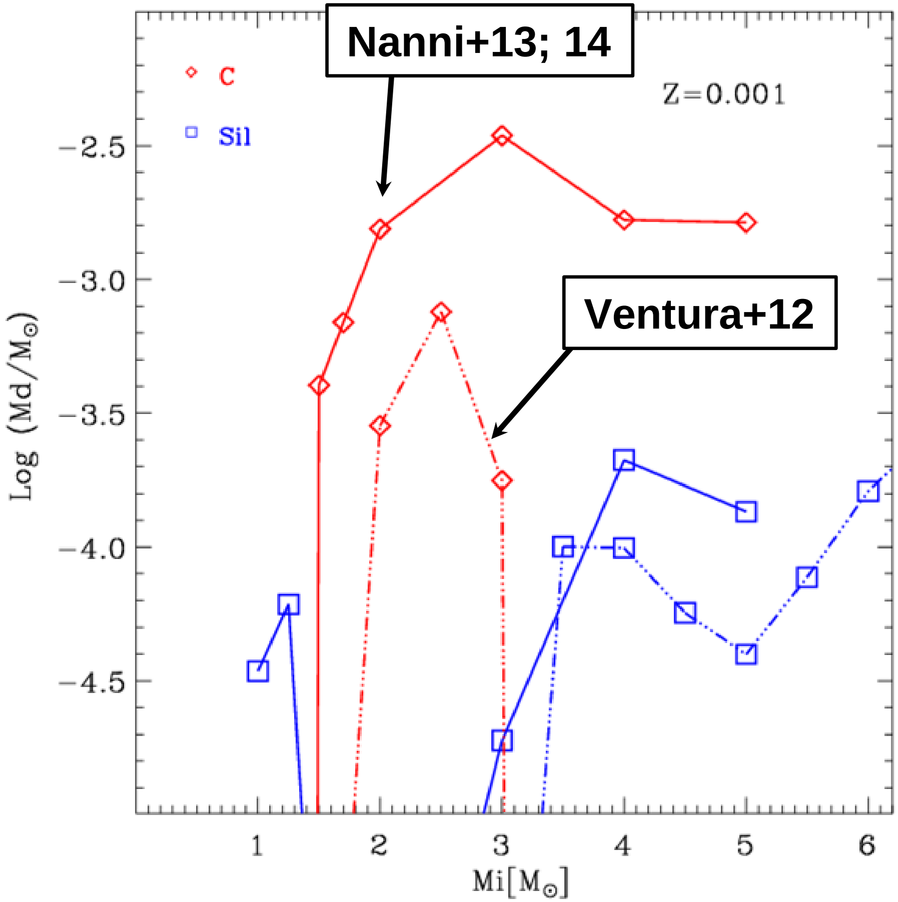
Boyer+15

- **No dependence of the DPR with the metallicity (most of the stars are C-rich)**
- **Different from Galactic Globular Clusters low-Z AGB stars, M<~1 M $_\odot$ (e.g. McDonald+11a,b)→ low dust enrichment**

TP-AGB stars and dust evolution in galaxies

Dust yields and the chemical enrichment of galaxies

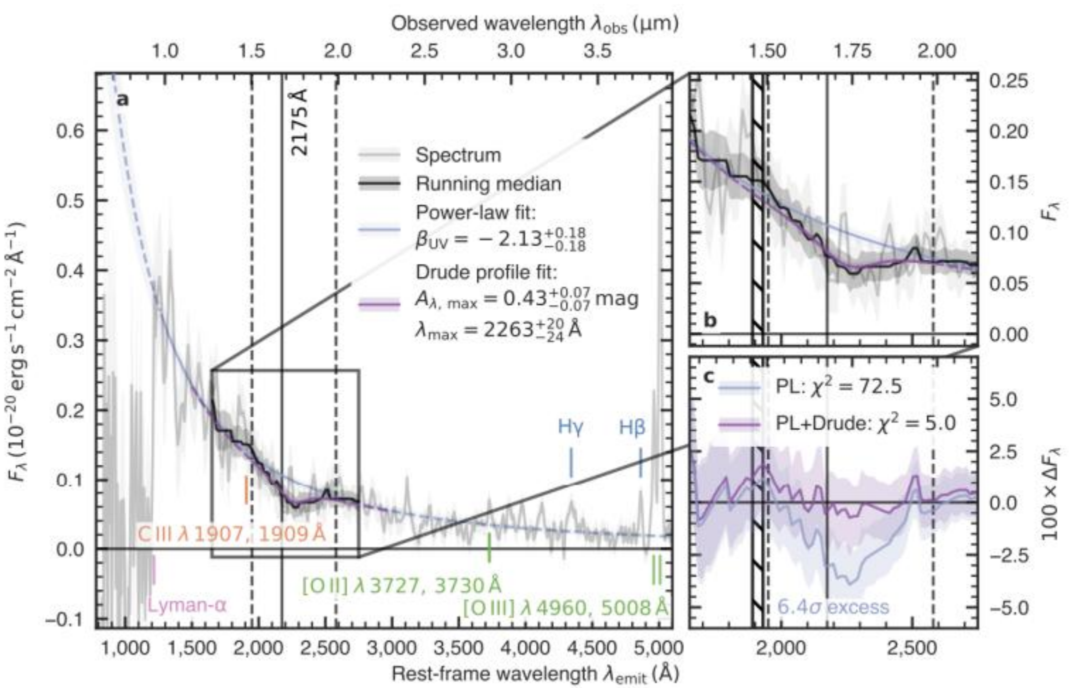


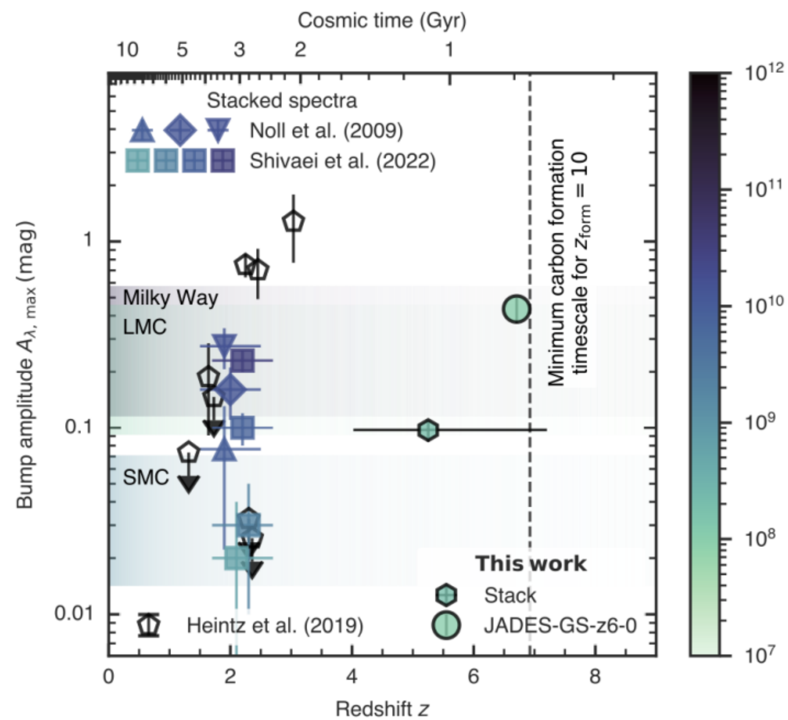


Dust ejecta as a function of mass and metallicity

Dust in the early Universe with JWST

- **NIRSpec spectroscopy in the PRISM configuration (0.6 - 5.3 μm, R ~ 100)**
- **Focus on JADES-GS+53.15138-27.81917 at z~6.71**
- **Bump at 2175 Å**

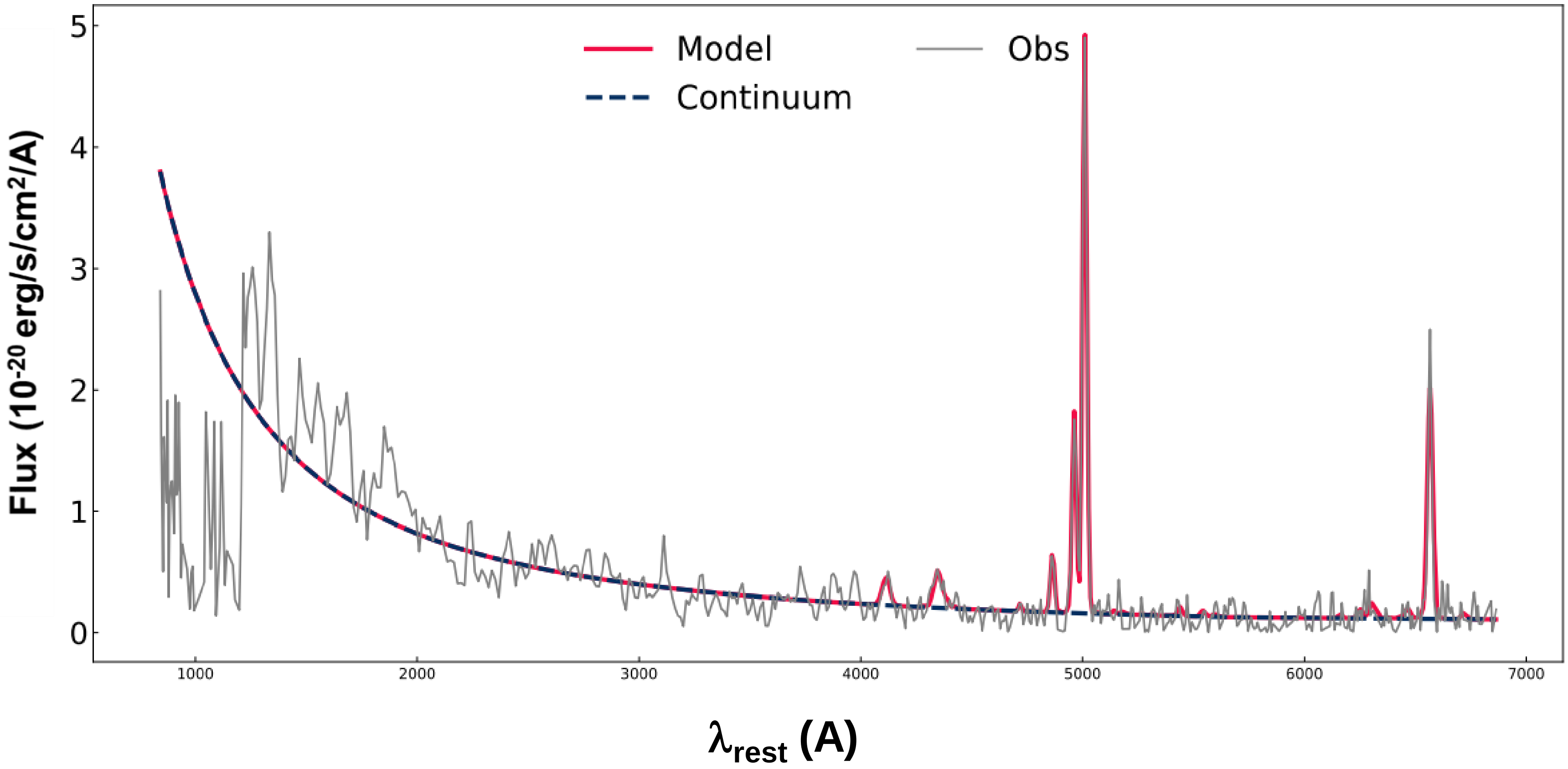




Witstok et al. 2023

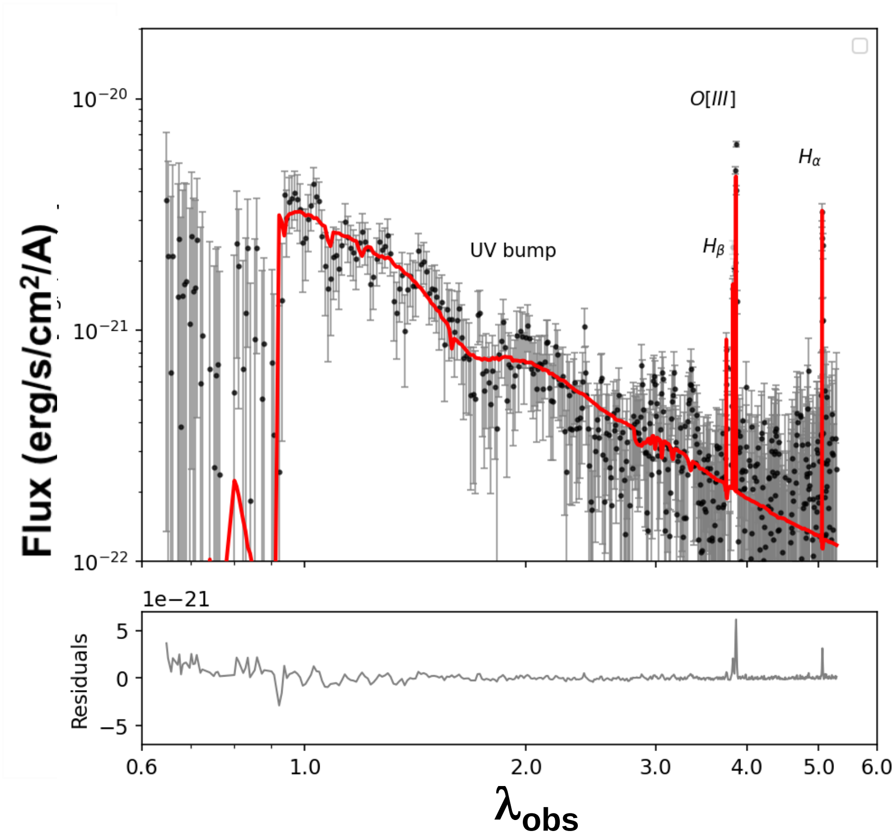
JADES
JWST ADVANCED DEEP EXTRAGALACTIC SURVEY

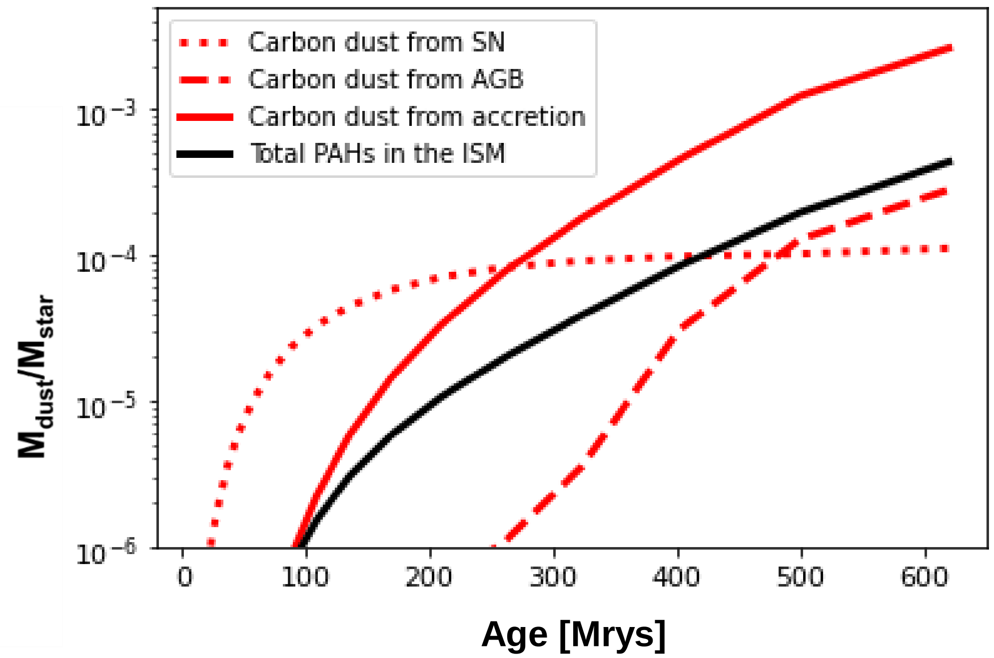
Metal in the early Universe with JWST



- H_α/H_β ~ 3.7
- Strong oxygen lines (1/5 solar; Witstok+23)

Results





Nanni+, in prep

- **Attenuation well reproduced (H_α/H_β~3.7)**
- **Young burst needed to reproduce the UV slope (30% mass of stars produced)**
- **2175 Å bump reproduced with a ~4% PAHs mass fraction**

Conclusions

- **It is possible to derive information about the dust composition around TP-AGB stars by studying their infrared spectra**
- **The wind speed of the outflow is connected the metallicity; few observations for C-stars at metallicity lower than solar are available**
- **The dust production rates of TP-AGB stars in different type of galaxies and clusters (characterized by diverse metallicity) are derived**
- **The estimate of the dust production and mass-loss rates is affected by the assumptions in radiative transfer calculations (e. g. dust optical constants)**
- **Optical properties of dust grains can be (somehow) constrained**
- **Theoretical dust ejecta depend considerably on the TP-AGB modelling. It is important to have robust constrain on the TP-AGB phase to model the metal and dust evolution in galaxies.**