Dust formation around carbon-rich (red giant) stars

The role of metallicity & Implications for dust-driven winds

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(DINGLE project)

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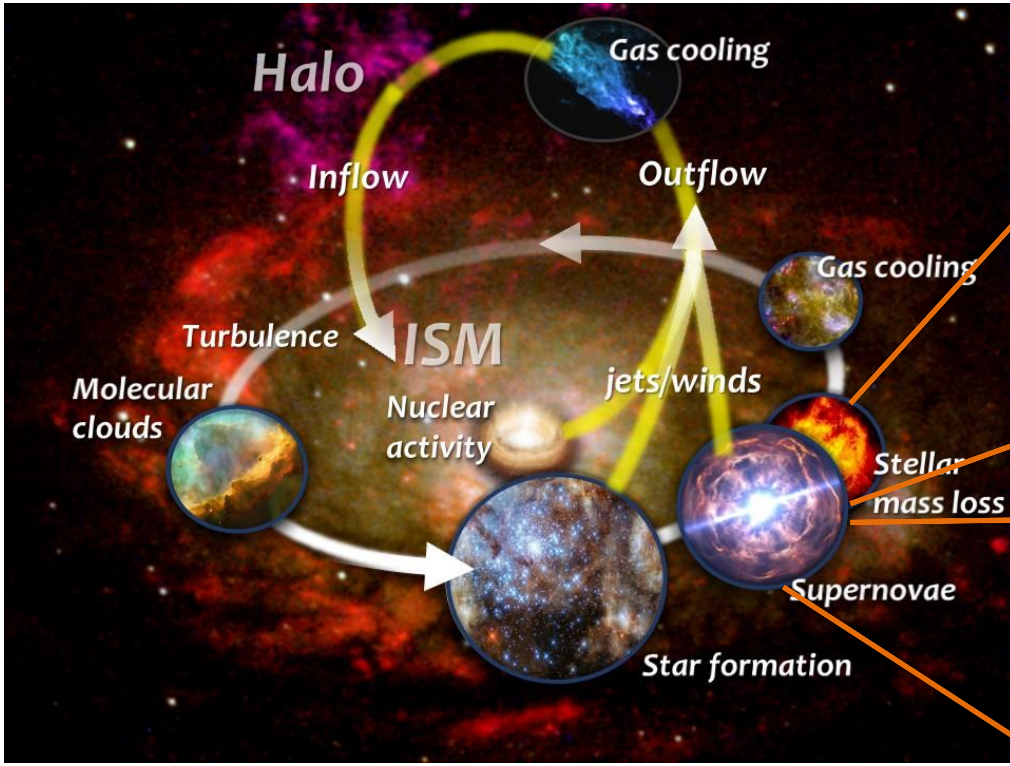
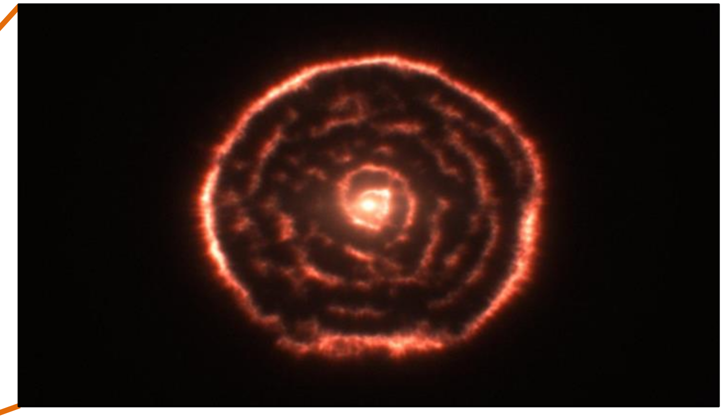
NARODOWE CENTRUM NAUKI

Why red giants are important to study?

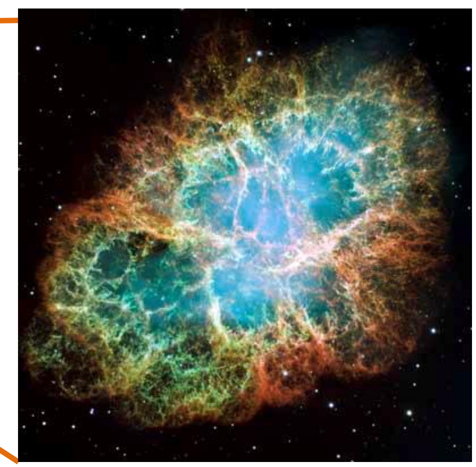


Dust in the interstellar medium of galaxies



Maercker et al.

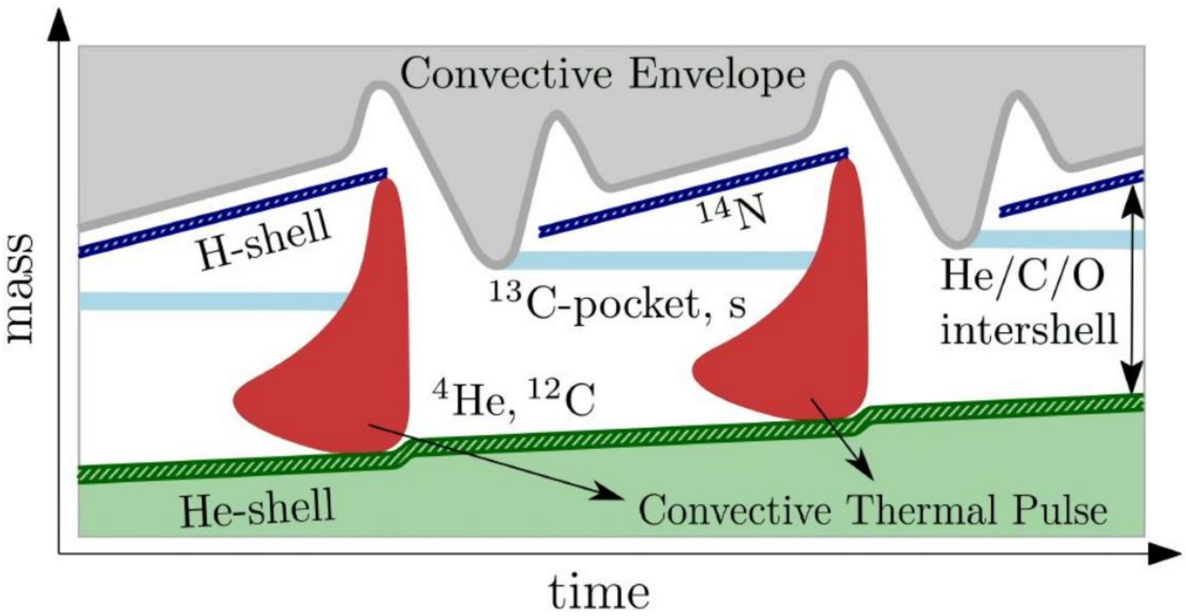
Dust around evolved stars & SN remnants



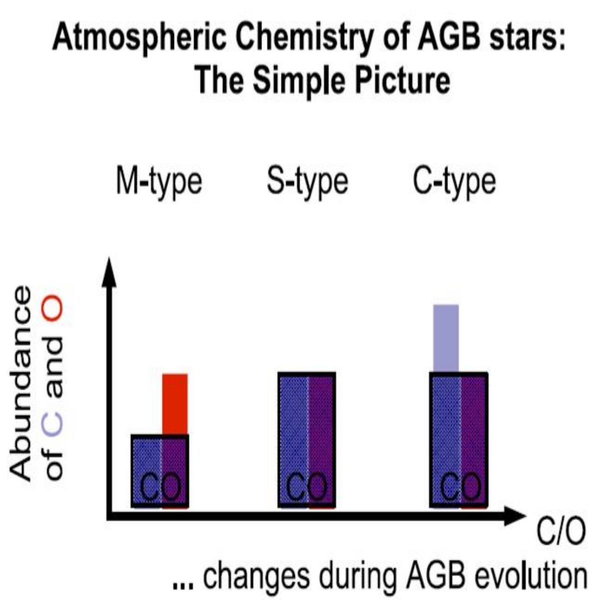
Different evolutionary time-scale according to the initial stellar mass:

- >8-10 $M_\odot$ → evolve in <30 Myrs; explode as Type II supernovae (SNe II).
- ~<6-8 $M_\odot$ → evolve in >100 Myrs; lose their envelope (mass-loss) during the red giant phase (thermally pulsing asymptotic giant branch -TP-AGB- phase).

Physical processes



Credits: Diego Vescovi (PhD thesis)



Hoefner 2009

- **H-** and **He-burning** shells
- **Thermal pulses**
- **3rd dredge-up** for M ≥ 2 M⊙

C/O<1→ C/O>1

M-star→ C-star

- **High mass-loss** rates

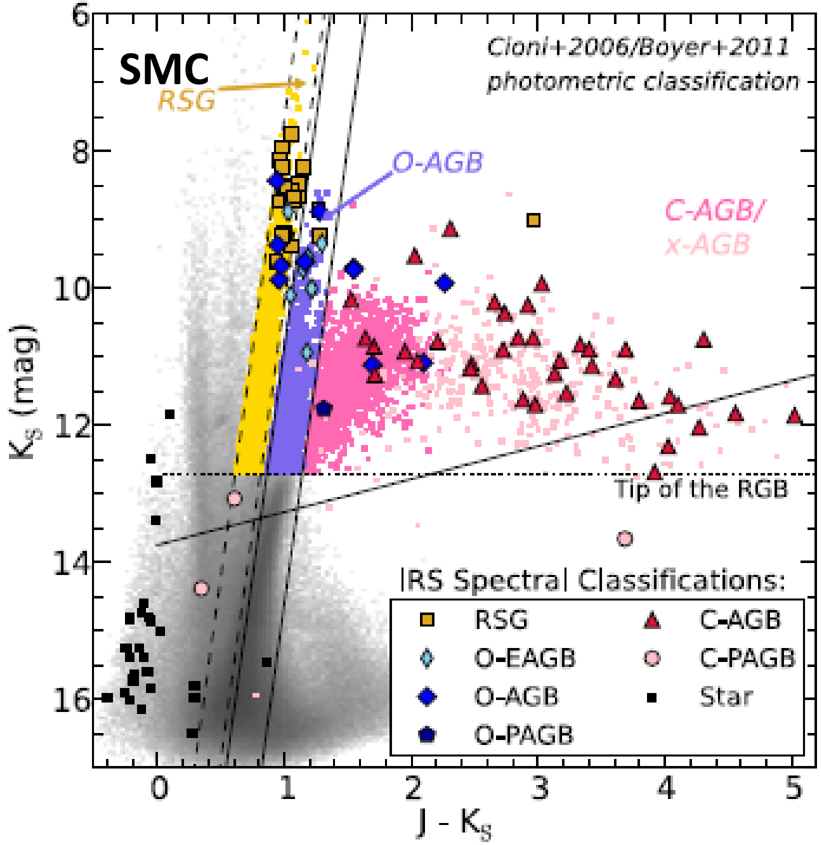
10^{-7} - 10^{-5} M⊙/yr

Mass-loss of Sun ≈10^{-14} M⊙/yr

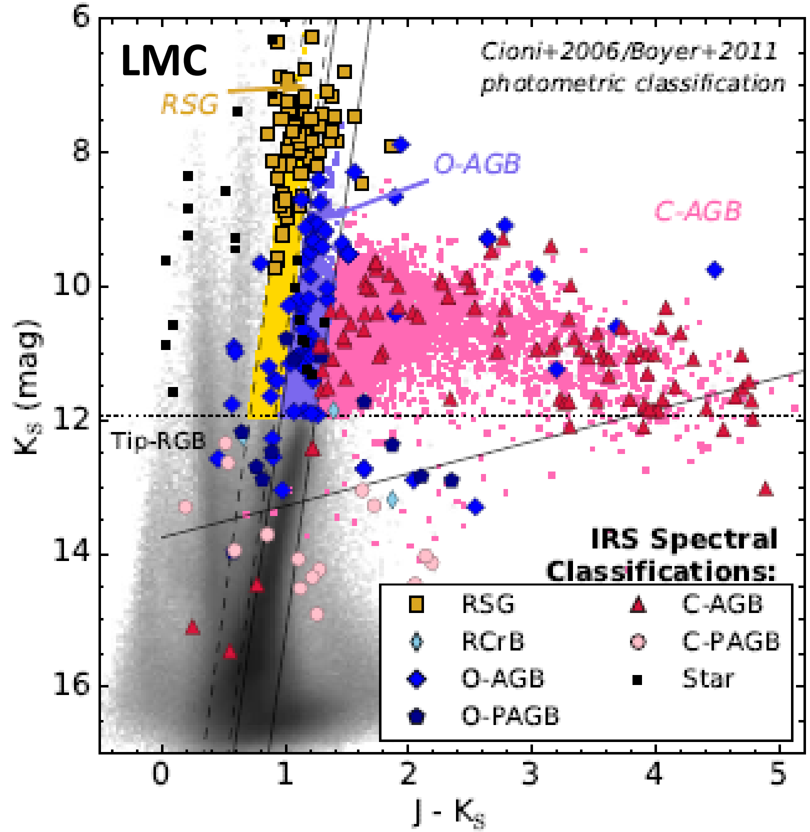
- **Hot Bottom burning** (HBB) for M ≥ 4 M⊙

Magellanic Clouds (MCs)-Observations

SAGE + *Spitzer* IRS



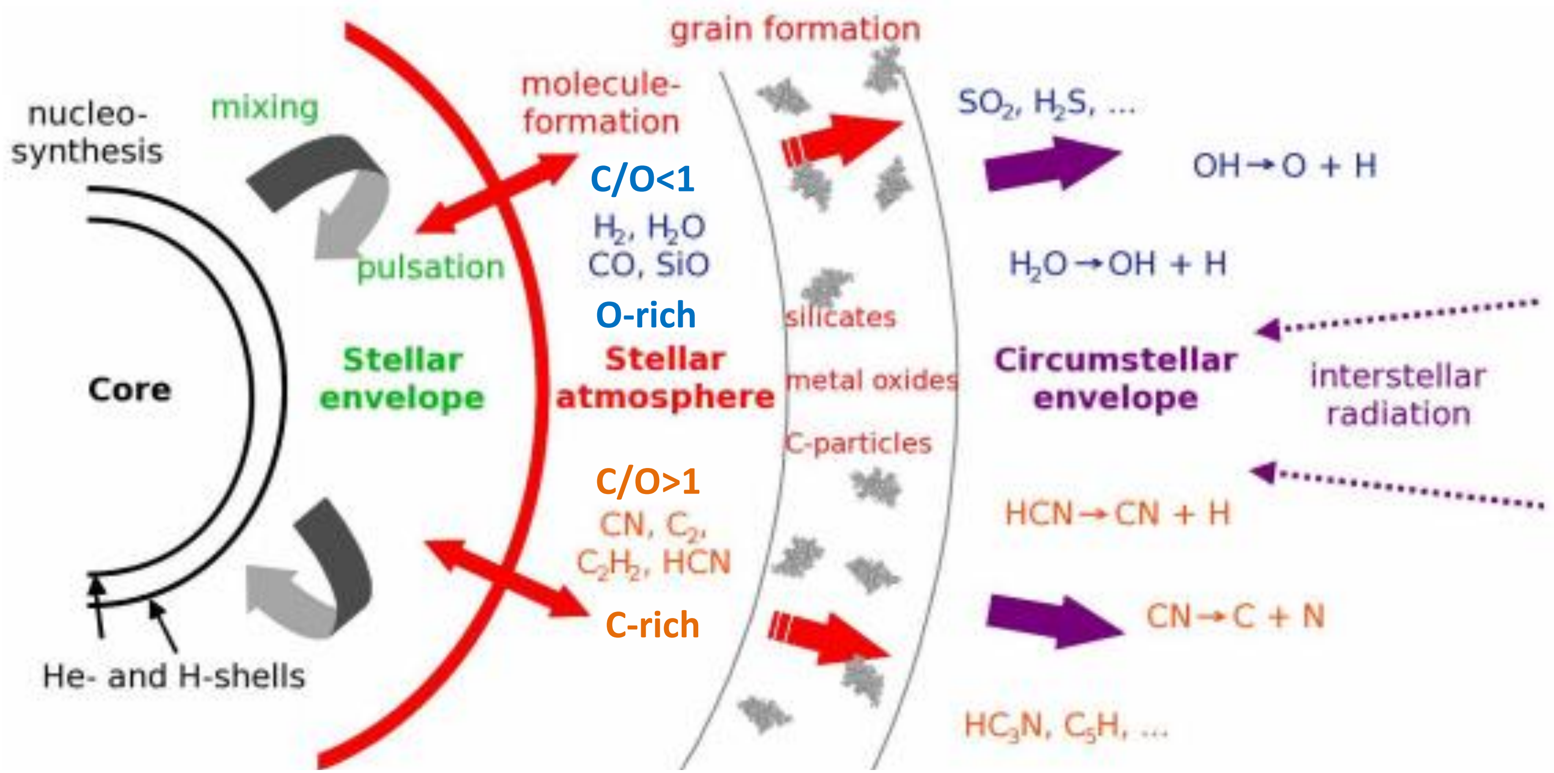
Boyer et al 2011; Ruffle et al. 2015



Boyer et al. 2011; Jones et al . 2017

Plenty of C-stars in the MCs: extreme stars have been confirmed to be predominantly carbon rich from spectral classification

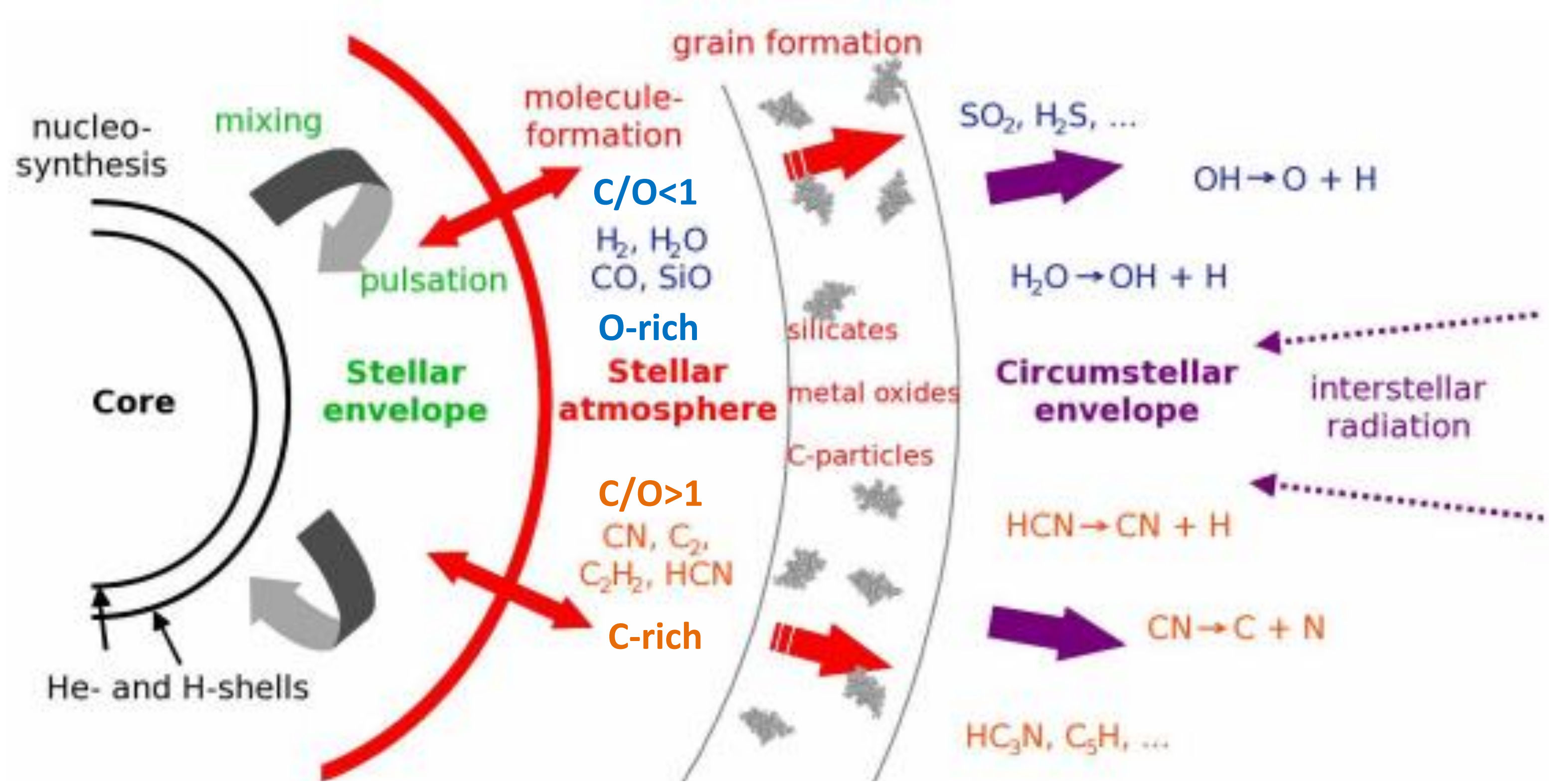
Circumstellar envelopes



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 respectively, Eriksson et al. 2014; Bladh et al. 2015);**
- **Expansion velocity: measured, i.e. CO lines, OH maser emission (Ramstedt & Olofsson 2014; Danilovich et al. 2015; Groenewegen et al. 2016; Goldman et al. 2017).**

Circumstellar envelopes



Maercker PhD thesis (adapted from Habing & Olofsson 03)

C-stars

- **Acetylene molecules (C_2H_2)**
- **Amorphous carbon**

Proportional to the carbon-excess due to 3rd dredge-up processes

Carbon dust production & dust-driven wind

The 3rd dredge-up efficiency increases if Z decreases

- **More carbon dust is produced for lower Z**
- **Higher wind speed may be expected for lower Z since more carbon is produced**

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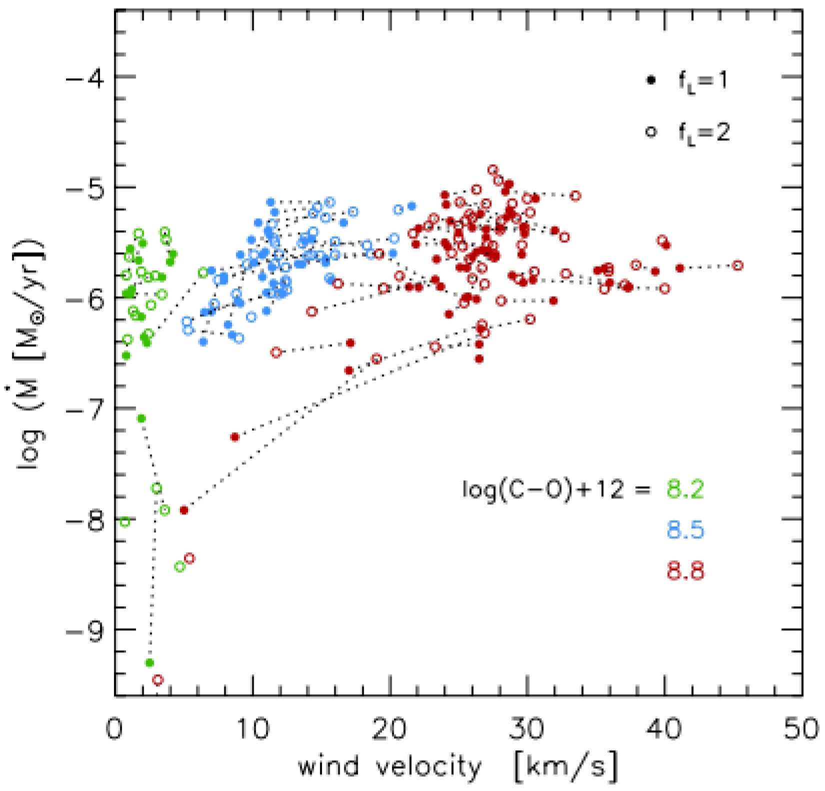
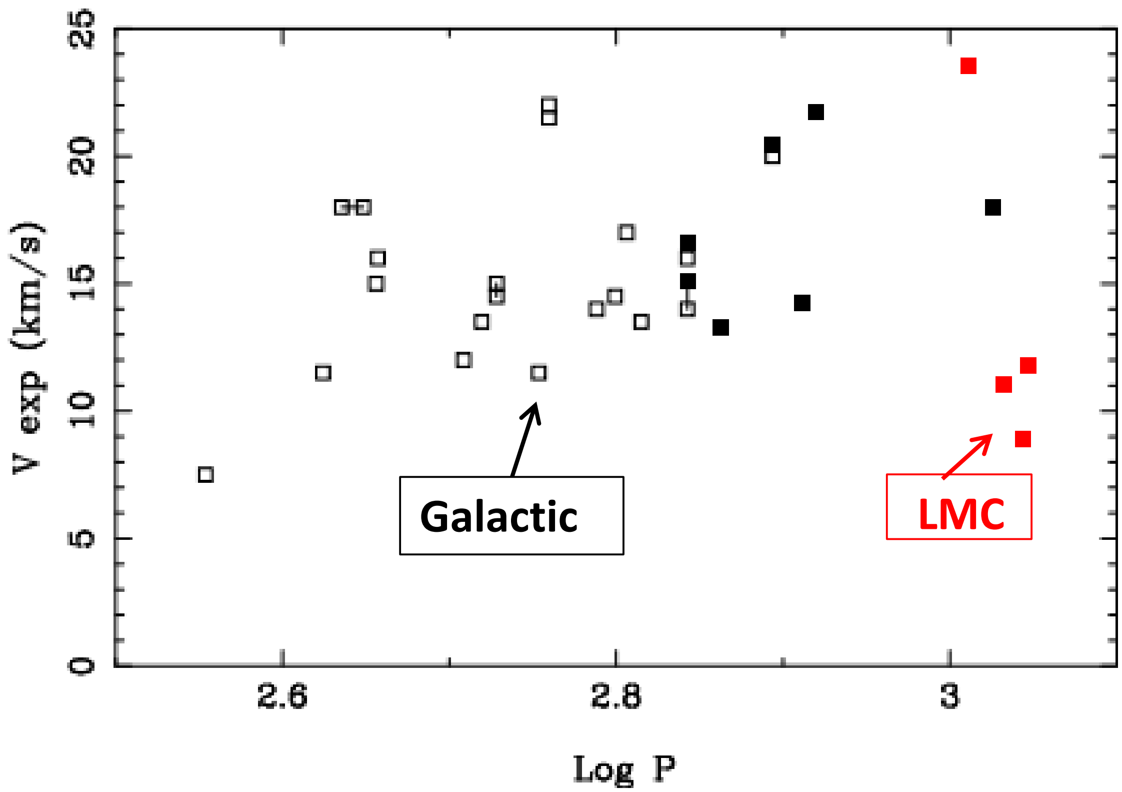


Eriksson et al. 2014

Observed expansion velocities



Ramsted&olofsson 2014; Danilovich et al. 2015, Groenewegen et al. 2016

- C-stars in the LMC seem to have lower V_{exp} than C-stars in the Milky Way in agreement with observations in the Galactic halo (e.g. Lagadec et al. 2010);
- ALMA proposal: CO(2-1) observations of 41 carbon-rich stars in the LMC and SMC (PI: Dr. Groenewegen).

Problem

The wind speed does not depend only on one parameter (e.g. C-O) but on the variation of all the parameters during the red giant phase (stellar models)

Objective

Explaining the wind speed as a function of metallicity by employing models of dust growth (Nanni et al. 2013) coupled with stellar evolutionary tracks (FRUITY, Cristallo et al. 2009).

Model & constraints

Model

- **Dust growth for several dust species coupled with dust-driven wind, see Nanni et al. 2013 (Ferrarotti&Gail 2006; Ventura et al. 2012)**
- **Time-averaged effect of shocks, see Cristallo et al. 2020 (Cherchneff et al. 1992)**
- **Coupled with Radiative transfer code "More of DUSTY", see e.g. Nanni et al. 2019 (Groenewegen 2012; Ivezic&Elitzur 1997)**

Input:

- **stellar parameters: L, dM/dt, M, T_{eff}, C/O;**
- **dust optical properties;**
- **seed particle abundance (affects the grain size).**

Nanni et al. 2016; Nanni 2019

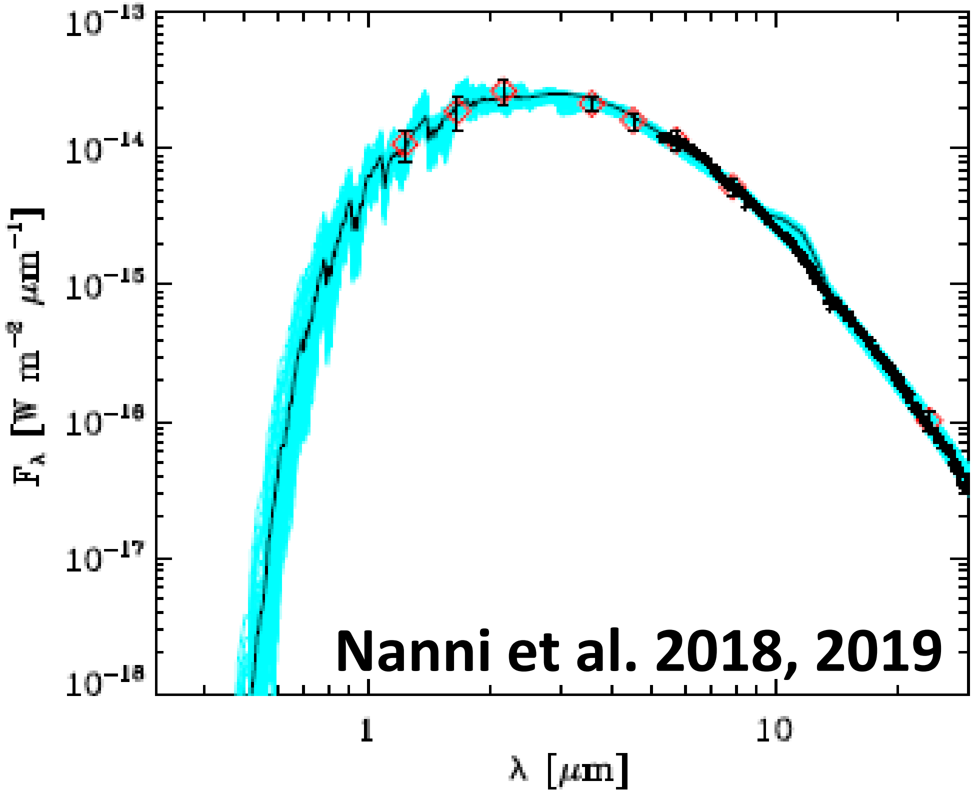
→

Output: circumstellar envelope:

- **dust composition;**
- **dust production rate;**
- **wind speed (v_{exp});**
- **spectra.**

Our assumptions have been tested against different observations.

Constraints: SED fitting



We employed the combinations of optical constants and grain sizes that simultaneously reproduce the infrared and Gaia DR2 photometry (Nanni al. 2016; Nanni 2019).

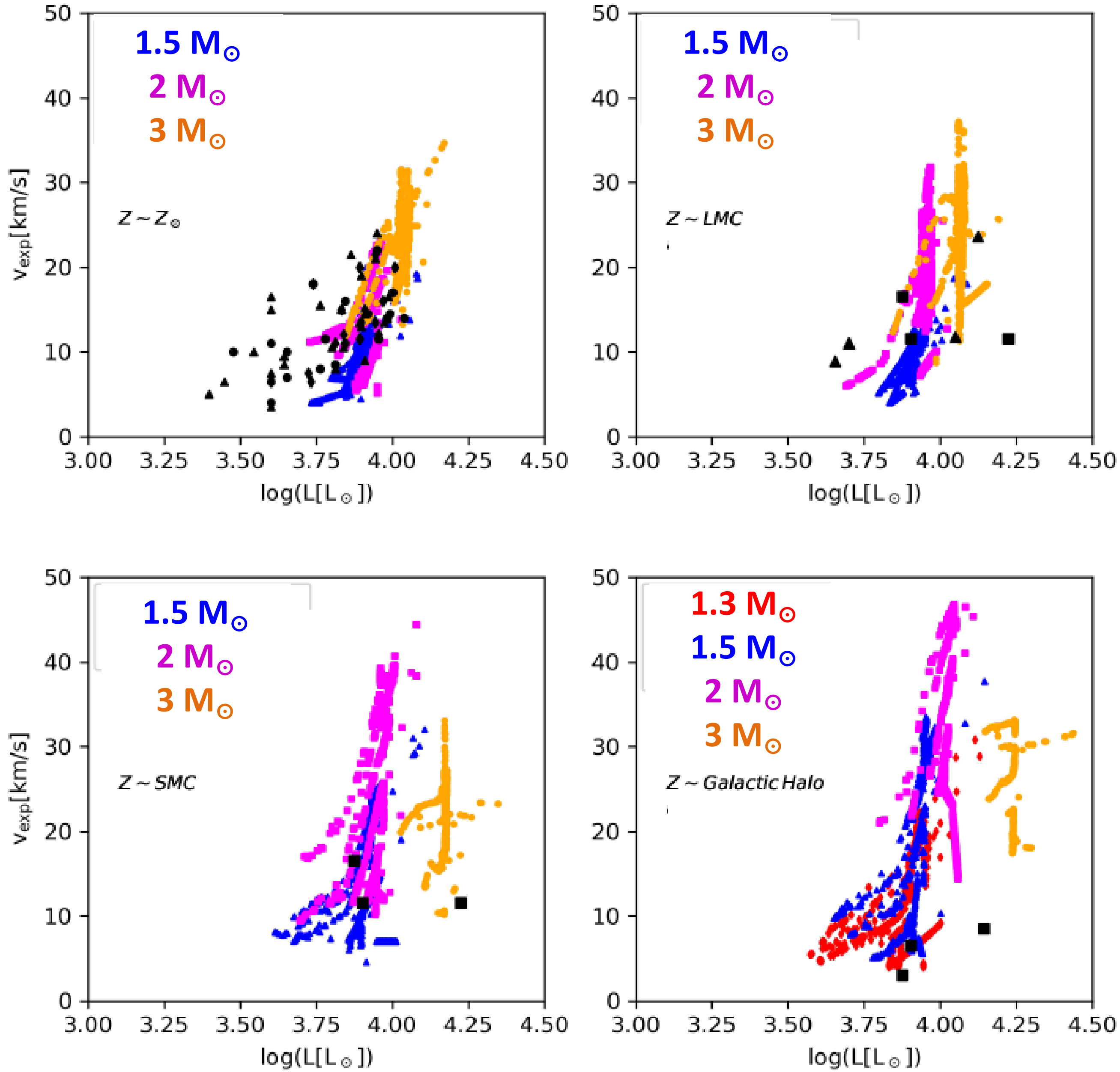
- **~3000 C-stars in the SMC**
- **~8000 C-stars in the LMC**

→

- **Mass-loss rate**
- **Dust production rates**
- **Gas-to-dust ratio (ψ)**

Results

Results: wind speed



Nanni et al., 2021

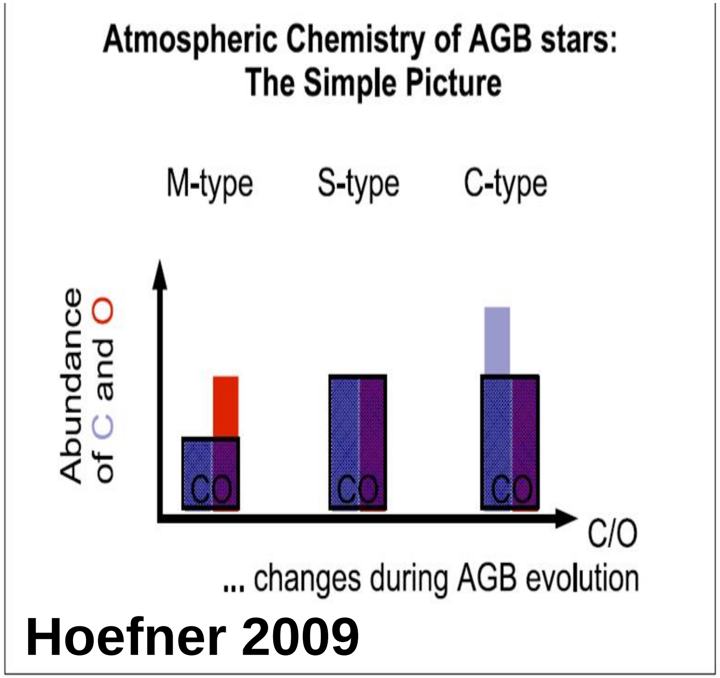
- Observations are fairly well reproduced by our predictions.
- If confirmed, **the observed trend V_{exp}↓ Z↓ is obtained in the 3 $M_\odot$ model rather than in the 1.5-2 $M_\odot$.**

Take home message

- Our dust prescriptions couple with FRUITY stellar tracks qualitatively well reproduce the observed trends as a function of the metallicity for the wind speed.
- In particular, the trend with metallicity is reproduced for $M=3\ M_{sun}$ because of their higher effective temperatures at low-Z which inhibits dust production (→ lower wind speed).
- For lower initial stellar masses the effective temperature does not change much but the carbon-excess becomes larger for decreasing Z (→ larger wind speed).

Thank you!

Dust composition around C-stars



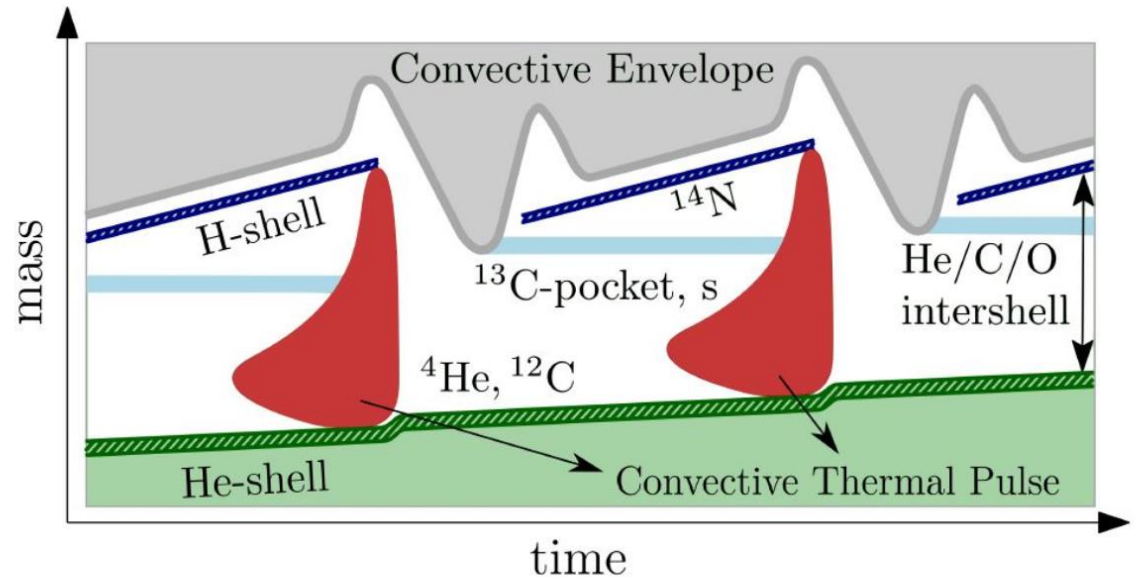


Figure 1.1: Schematic sketch of the mixing episodes during thermal pulses.

Credits: Diego Vescovi (PhD thesis)

C-stars

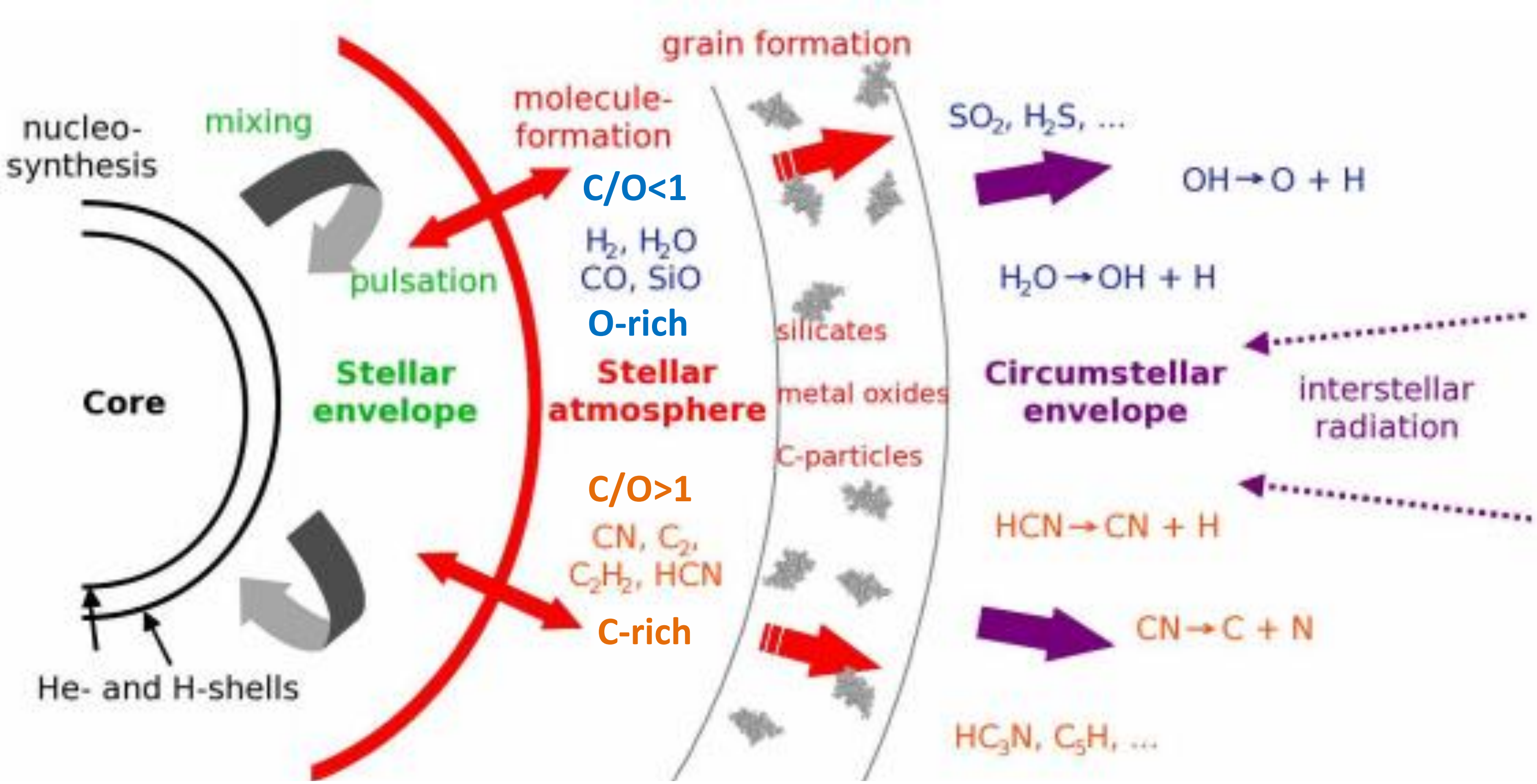
- **Acetylene molecules (C_2H_2)**
- **Amorphous carbon**

} **Proportional to the carbon-excess** due to 3rd dredge-up processes

- **Silicon Carbide (SiC)** → Feature at 11.3 μm
- **Magnesium Sulfide (MgS)** → Bump at 30 μm
- **Iron (?)** → Featureless

} **Proportional to Z**

Circumstellar envelopes

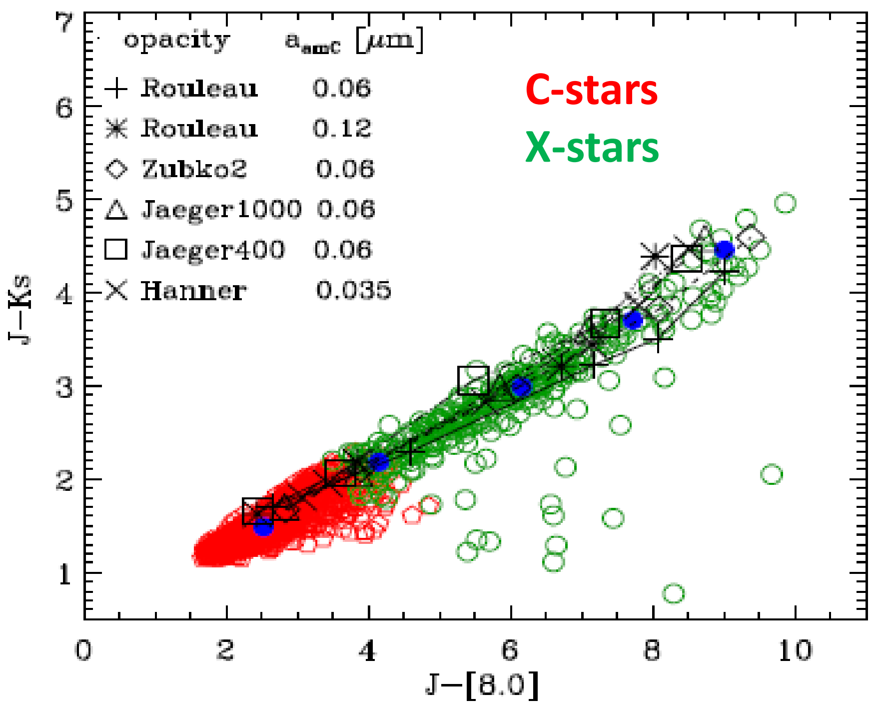


Maercker PhD thesis (adapted from Habing & Olofsson 03)

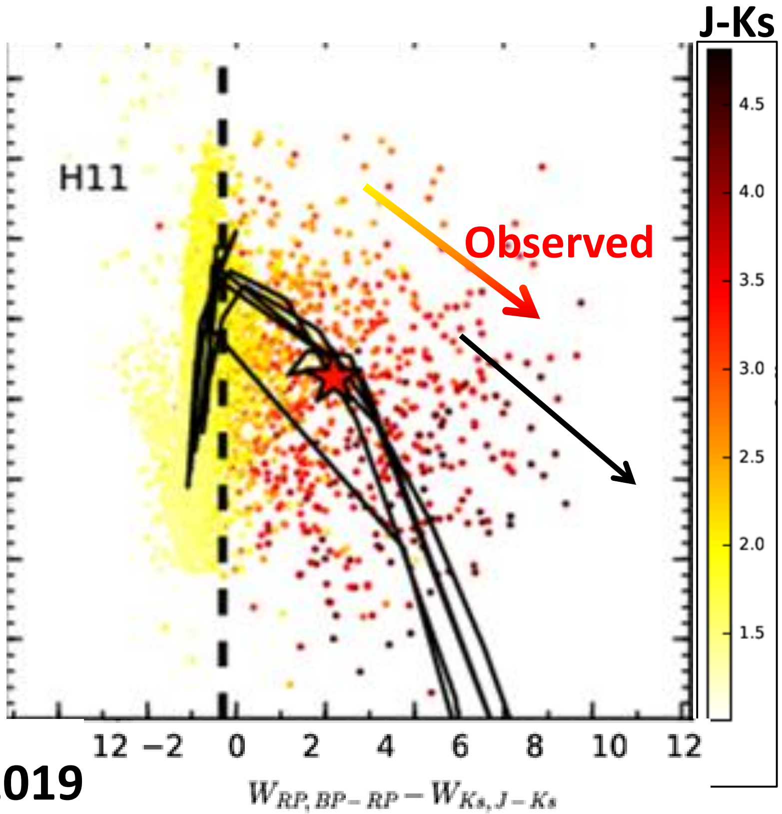
$$v\frac{dv}{dr} = -\frac{GM_*}{r^2}(1-\Gamma)$$

$$\Gamma = \frac{L_*}{4\pi c G M_*}\kappa \qquad \kappa = \Sigma_i f_i k_i$$

Constraints: dust optical properties



Nanni et al. 2016

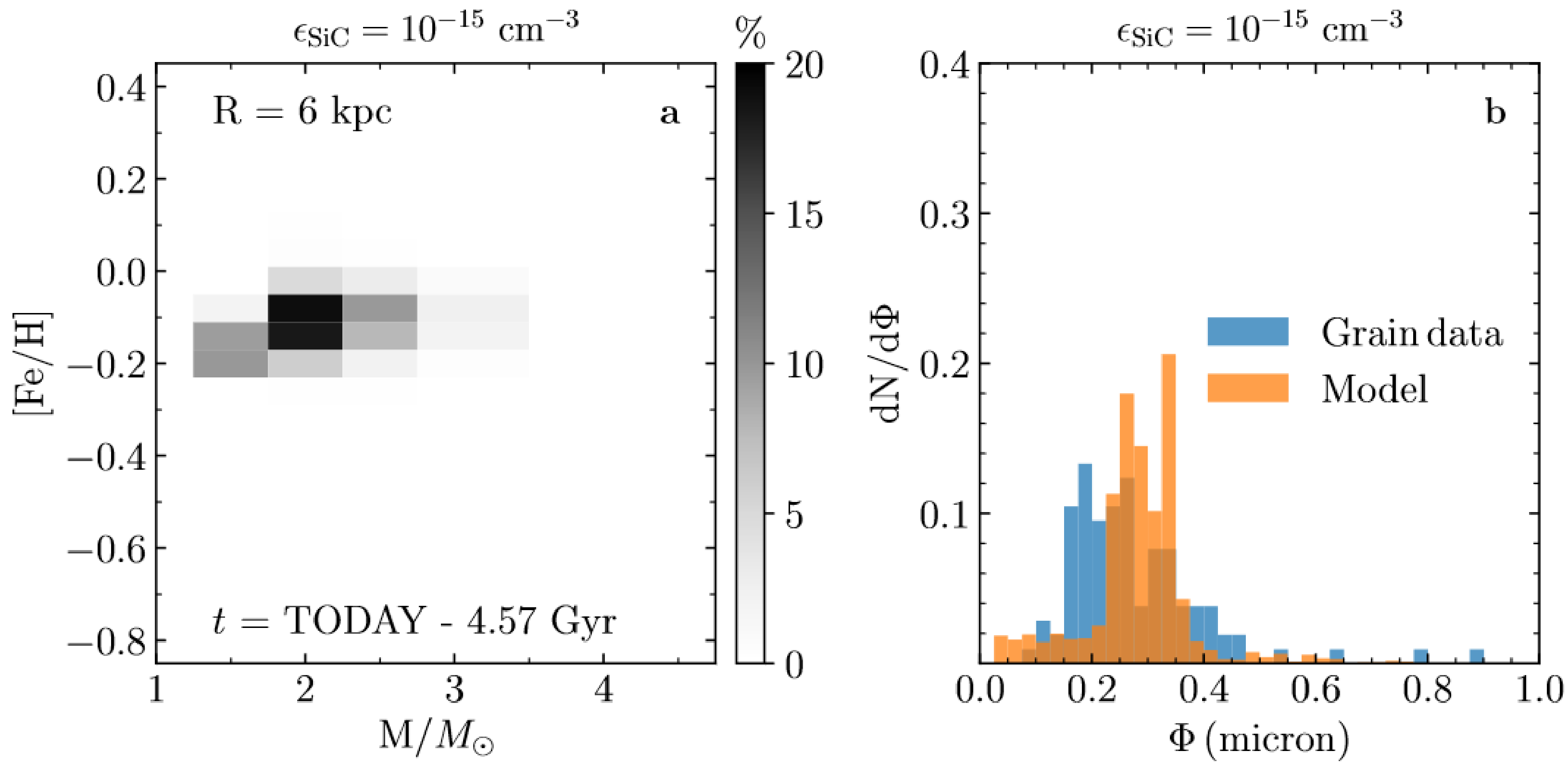


Nanni 2019

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

- **Only 2 combinations out of 50: simultaneously reproduces the infrared observations as well as the trends obtained by combining 2MASS and Gaia DR2 photometry (Lebzelter et al. 2018).**
- **Small (spherical) grains (0.04-0.1 μm) + optical data sets from Hanner 88; Jaeger+98 (1000°C)**

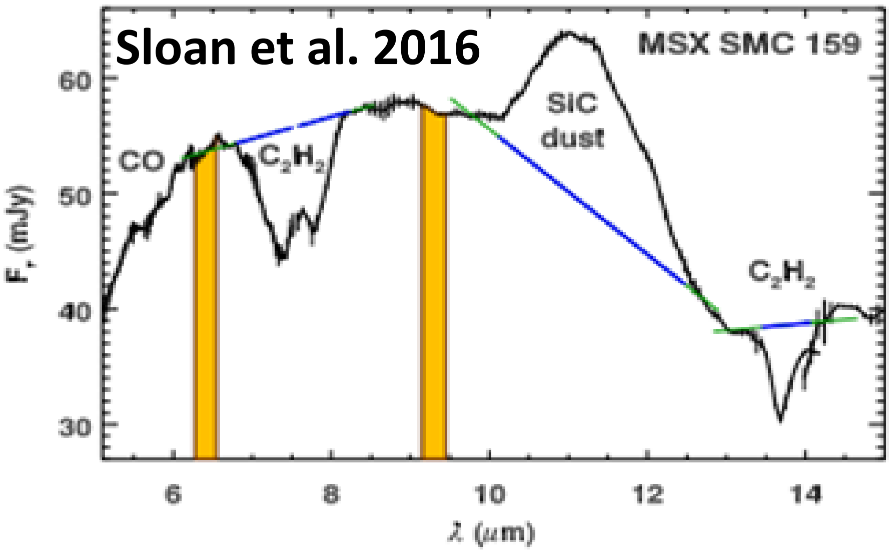
Constraints: pre-solar grains



Cristallo et al. 2020

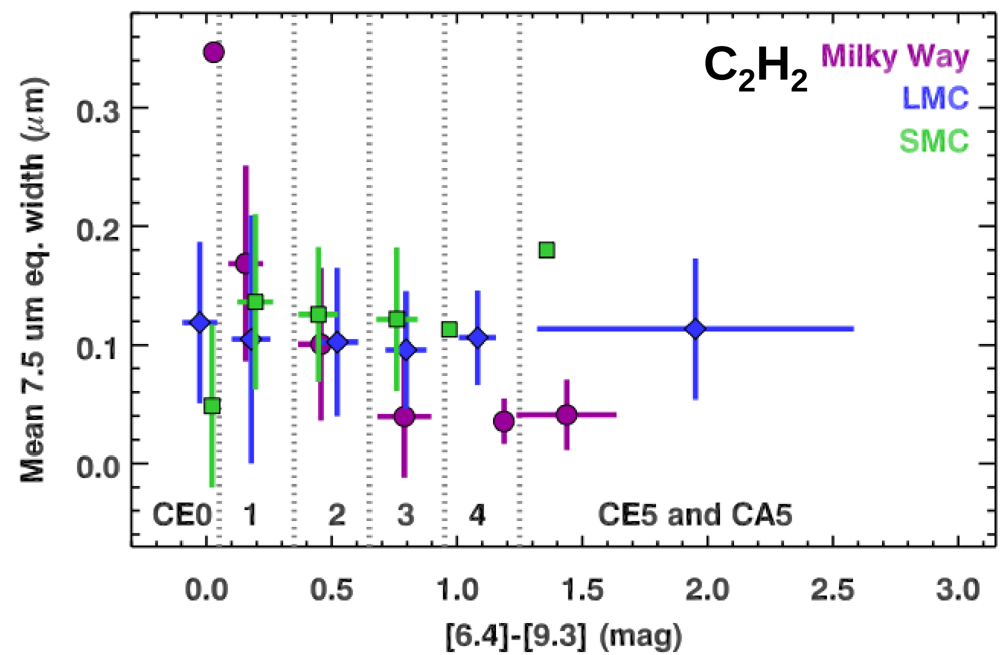
- **The prescriptions for dust growth and wind dynamics have been coupled with FRUITY evolutionary tracks (Cristallo et al. 2009).**
- **By including the time-average effect of pulsation (and suitable seed particle abundance), the size distribution of SiC grains is fairly well reproduced by stars of M ~ 2 $M_\odot$ and Z ~ $Z_\odot$(Cristallo et al. 2020).**

Observations: acetylene feature



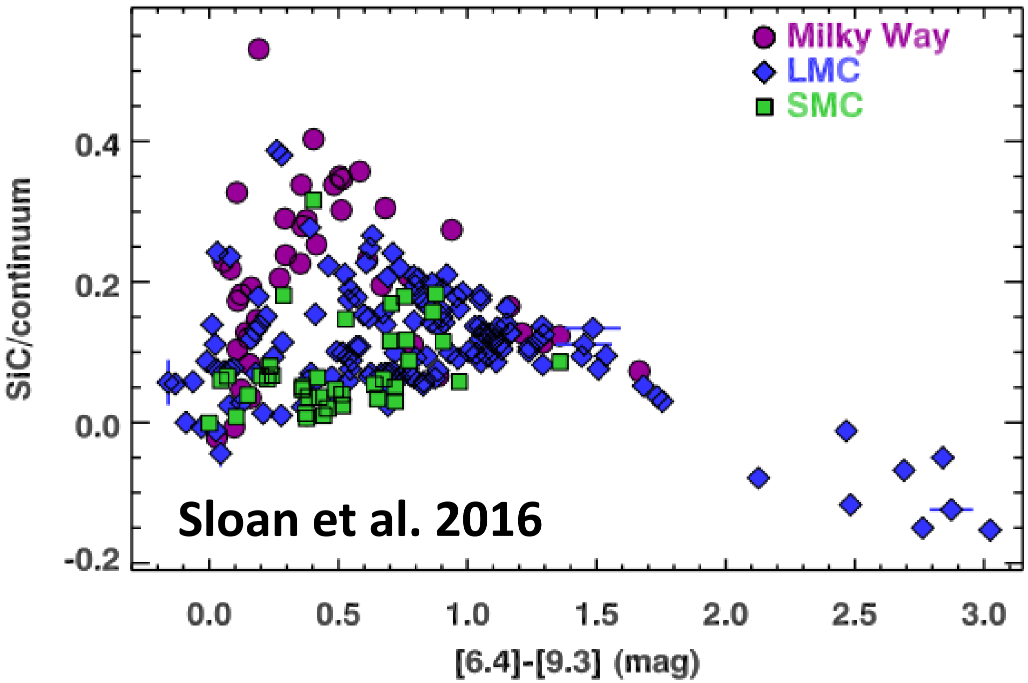
Manchester method

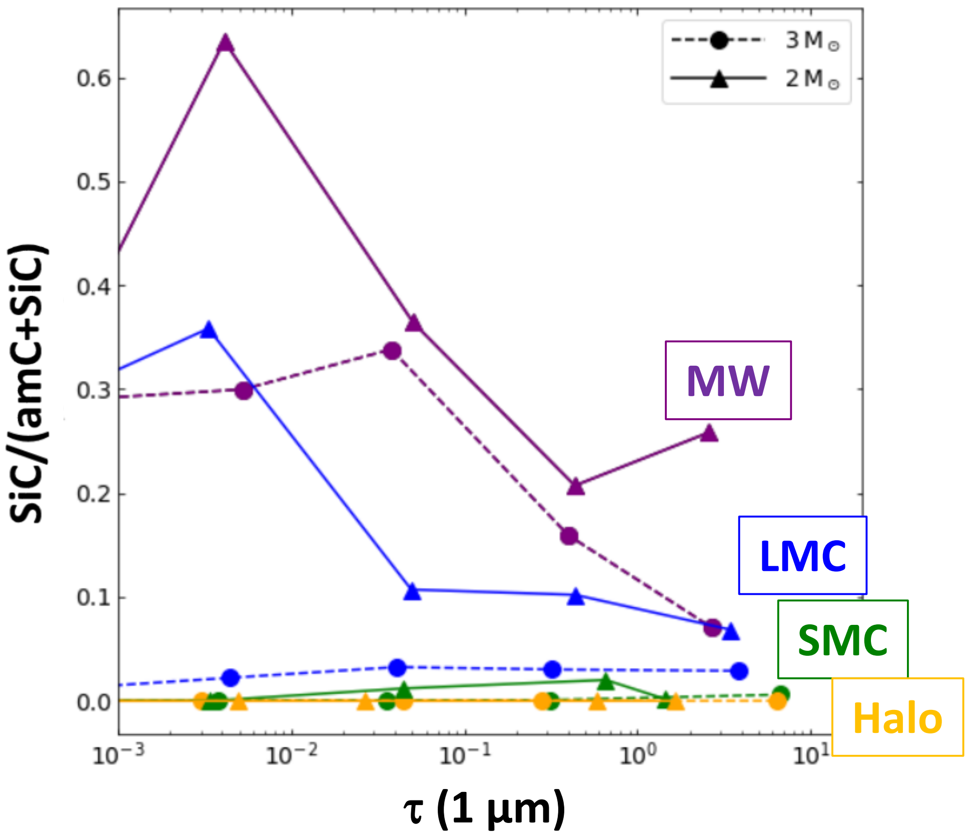
IRS on *Spitzer* 5.2 -38 μm



The equivalent width of acetylene feature & SiC feature strength change as a function of the metallicity and of mass-loss rate.

Constraints: SiC content

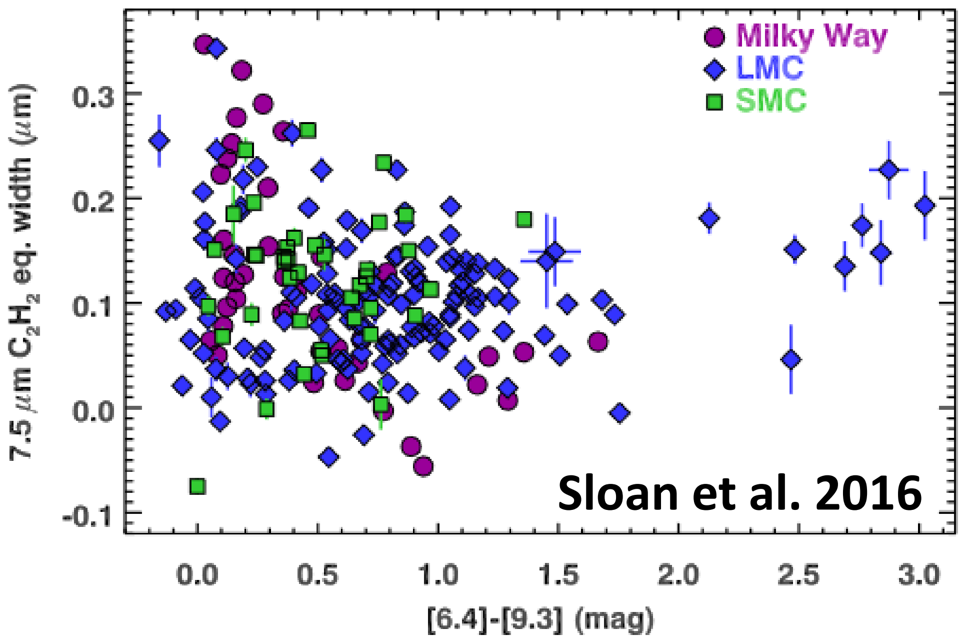


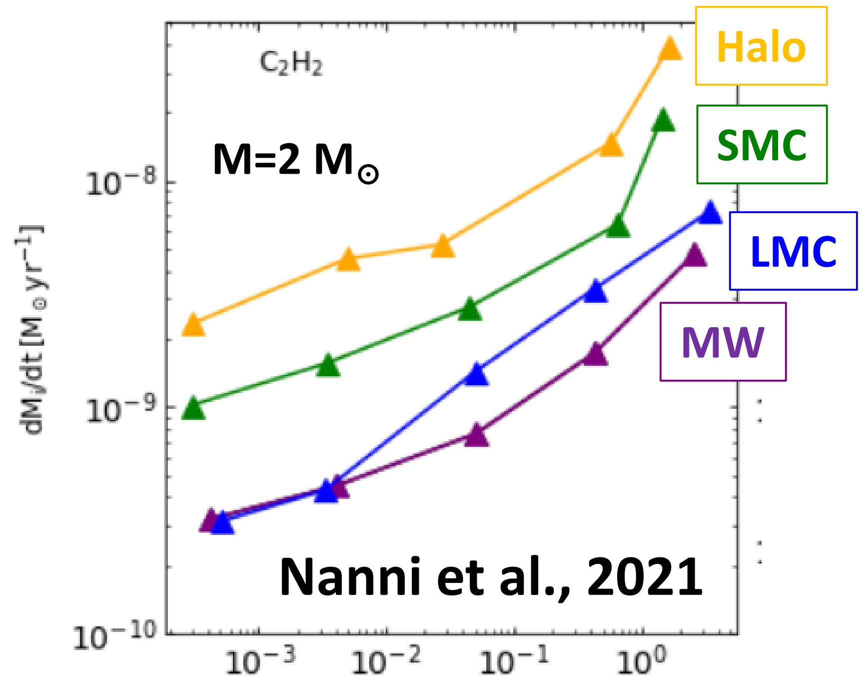


Nanni et al., sub

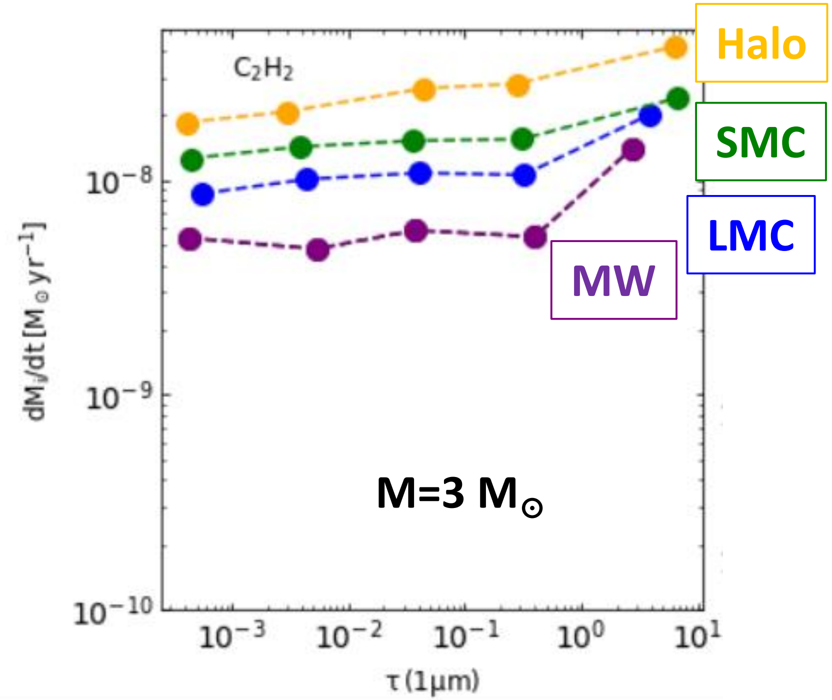
- The SiC mass fraction is Z-dependent (Si↑).
- Similar trends are found when similar dust growth models are applied to different stellar tracks (e.g. Nanni et al. 2013; Ventura et al. 2016).

Constraints: acetylene abundance

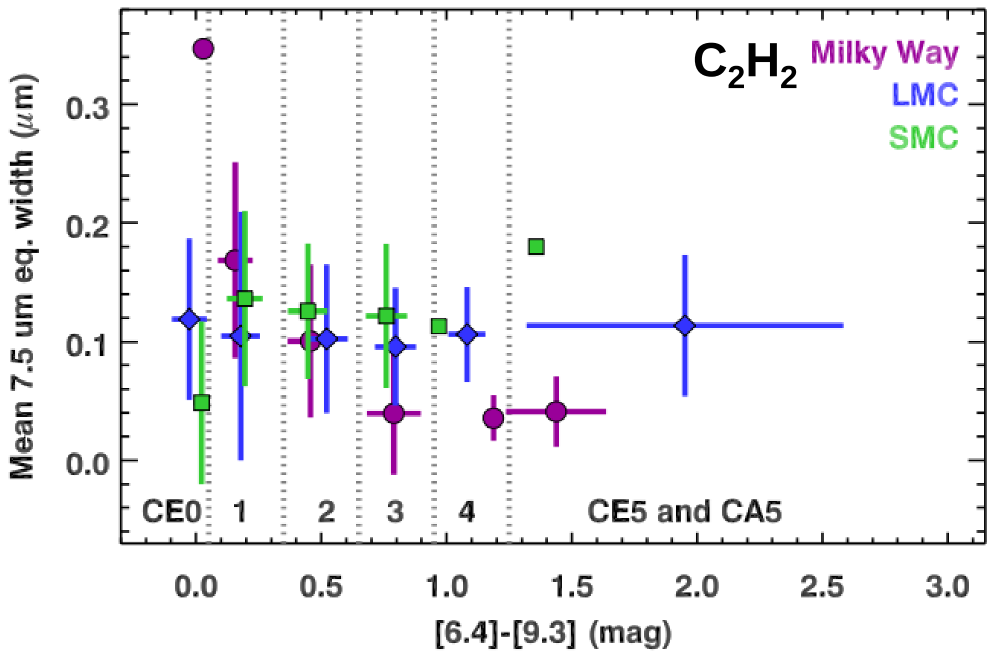


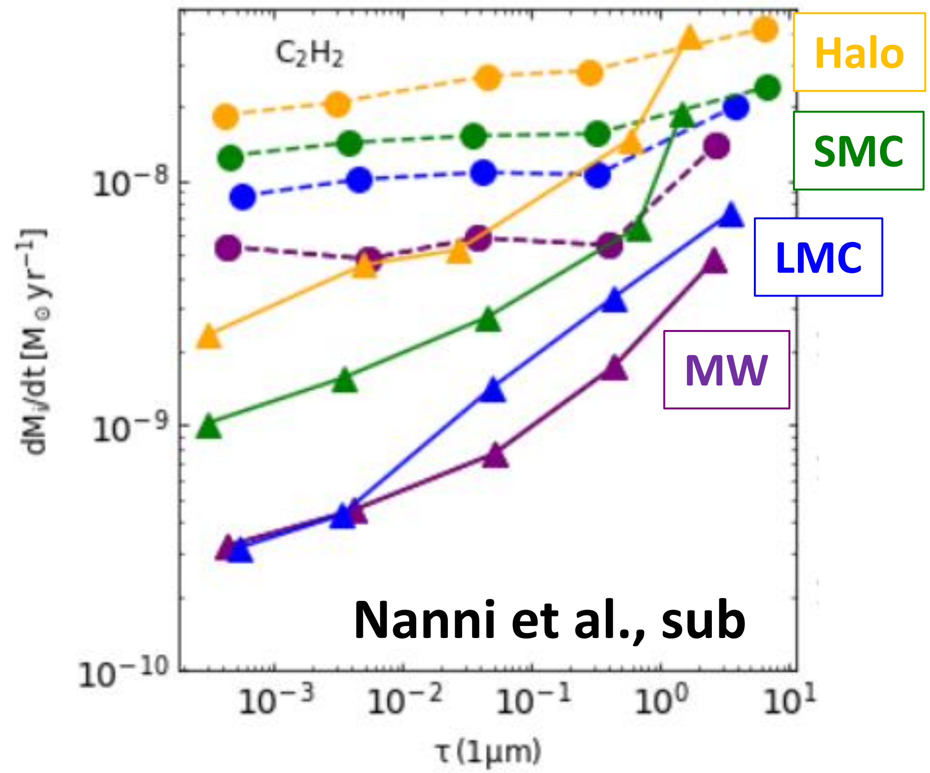


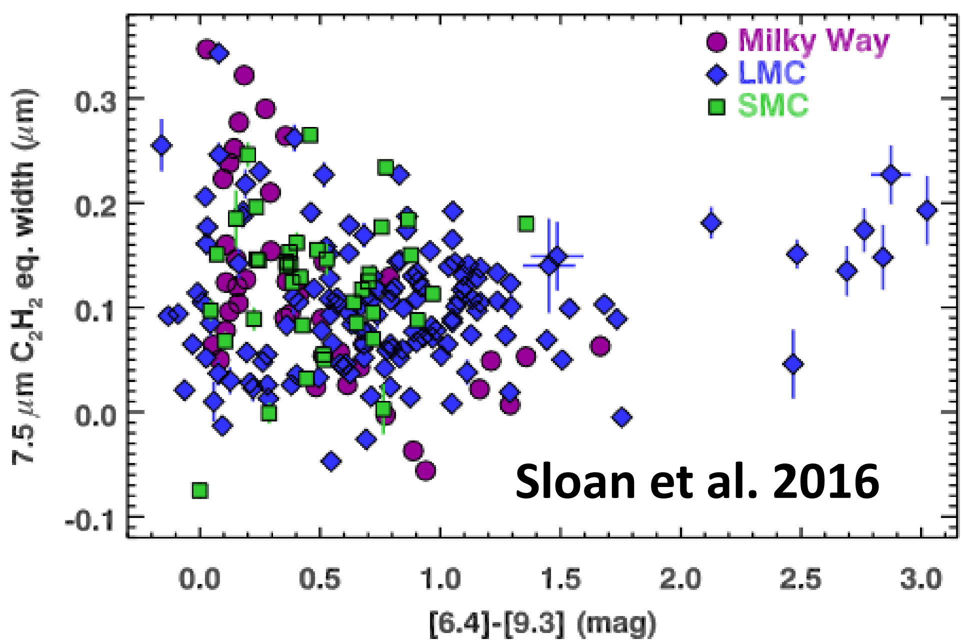
- **C_2H_2 & carbon dust ↑ if Z ↓**: due to the increase of free carbon (more efficient 3rd dredge-up).
- **More carbon dust @ low-Z**, but it remains low enough to allow **C_2H_2 ↑ if Z ↓ (dust-driven wind)**.



Acetylene content: scatter







The observed scatter may be explained by the presence of different initial stellar masses.