Investigating the physical processes driving the evolution of gas, metals and dust in local and high-redshift low-metallicity galaxies

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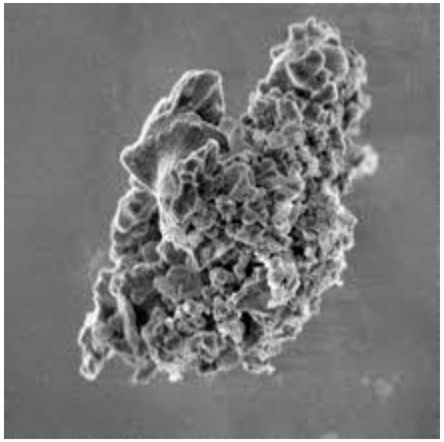
Why we study dust evolution?

Dust is composed by small solid particles (few hundredths of a μm up to few μm) of **variable composition formed from the METALS ejected by stars**.
Dust is a small fraction of the baryonic matter:
Mass fraction of the element in the solar neighborhood:
H= 70%
He= 28%
Z (all the other elements=metals) = 2%
A fraction of the metals is condensed into **dust (30–50% in mass)= 1%** or less of the **total mass of the baryons**!

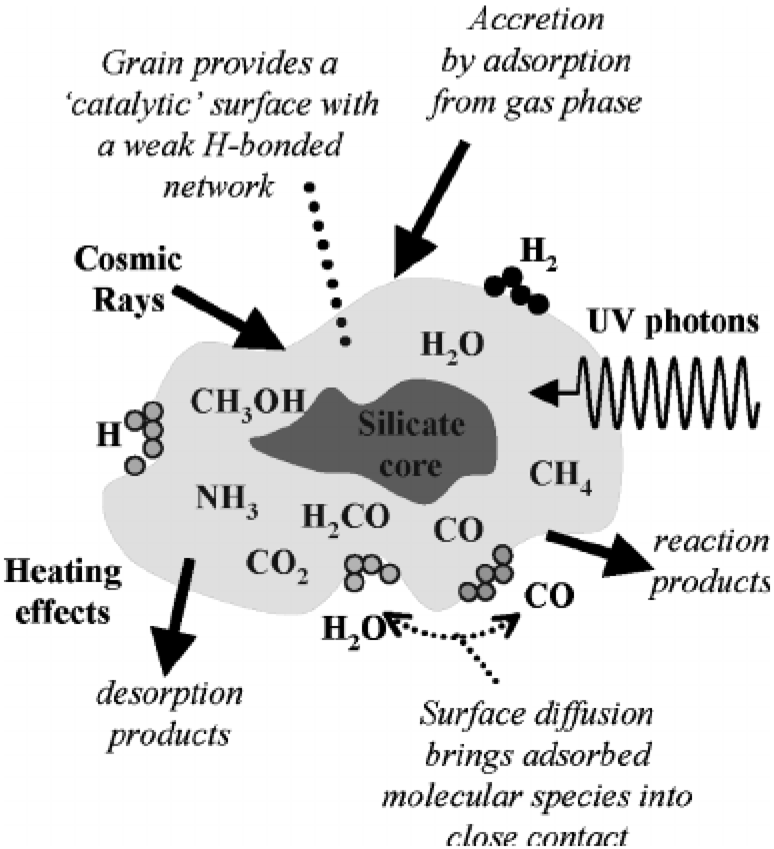
…but it is important for several reasons:

- Important in the process of star formation (gas cooling)
- Important for molecule formation
- It changes the light coming from stars
- Important in the process of planets formation
- Relevant for understanding the origins of our Solar System

A closer look to grains in the ISM



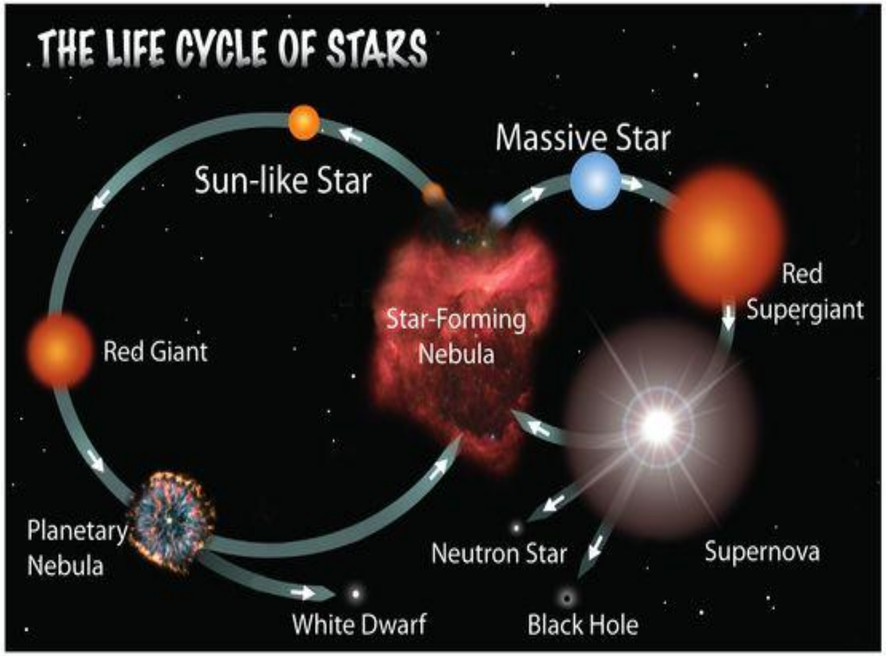
Interplanetary dust particles
(IDP) collected on Earth

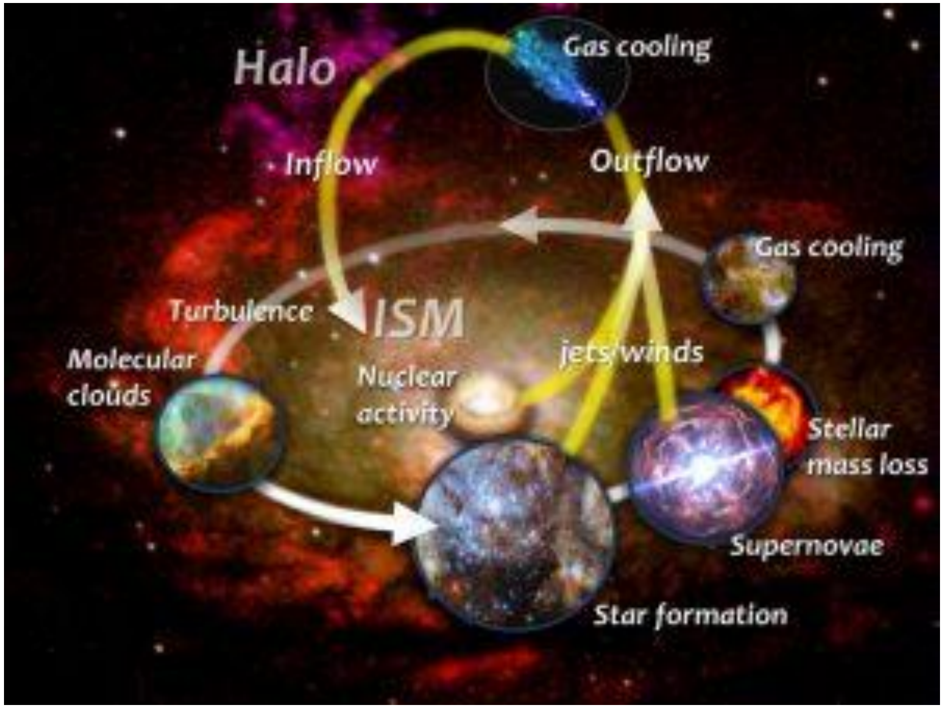


Representation of a dust grain in the ISM
(coated by ice)

- **Dust is mainly composed by silicates (Mg_2SiO_4) with some iron inclusions, amorphous carbon, metal oxides, silicon carbide (pre-solar grains)**
- **Where the ISM is cold (20 K), grains are coated with icy mantles**
- **If the temperature increases (e.g. star forming regions) the icy mantles evaporates**

Where metals come from?





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

->8-10 $M_\odot$ → evolve in less than 30 Myrs; explode as Type II supernovae (SNII)

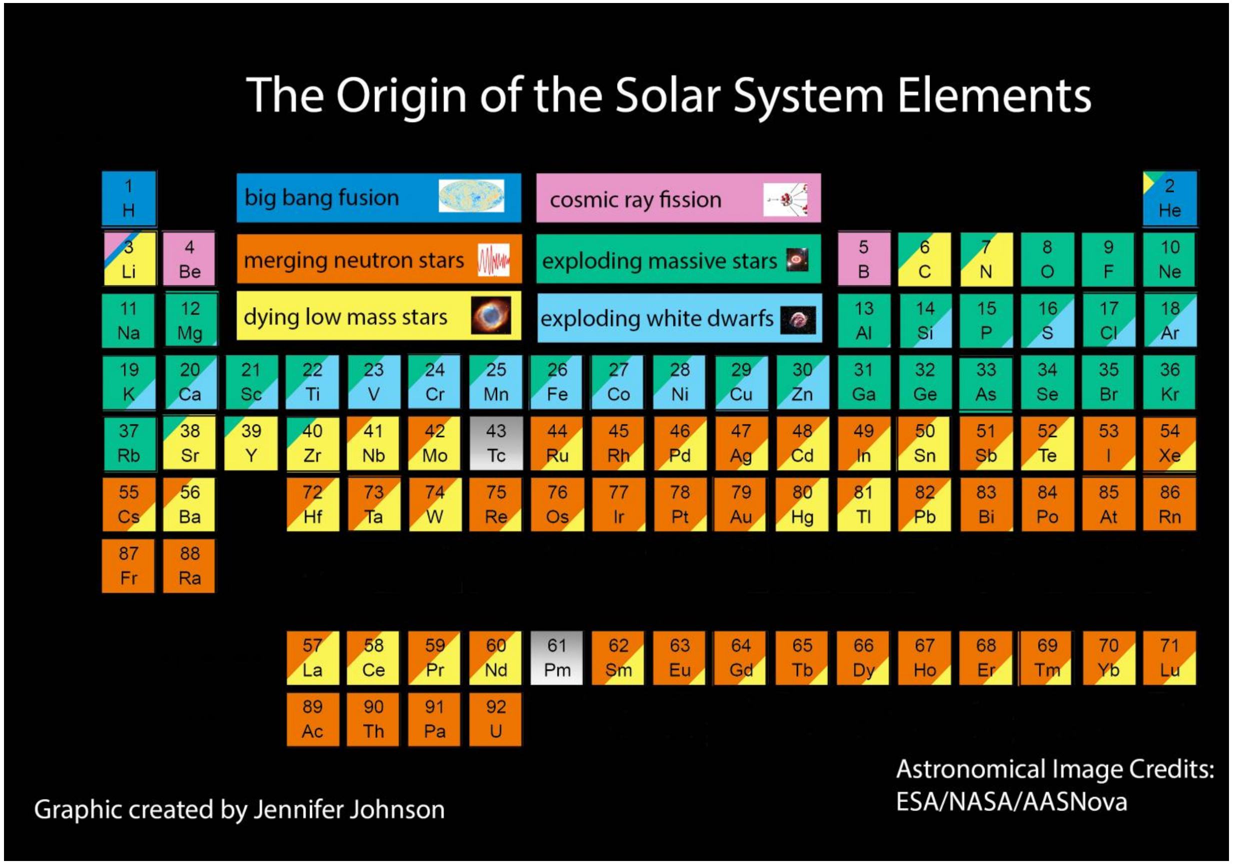
-~<6-8 $M_\odot$ → evolve in more than 100 Myrs; they gradually lose their external envelope (mass-loss) during the thermally pulsing asymptotic giant branch (TP-AGB)

- **Gas, metal and dust in galaxies change because of different physical processes:**

-star formation and evolution (metal enrichment)

-galactic inflows and outflows of gas

Where metals come from?



The Origin of the Solar System Elements

big bang fusion

cosmic ray fission

merging neutron stars

exploding massive stars

dying low mass stars

exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Graphic created by Jennifer Johnson

Astronomical Image Credits:
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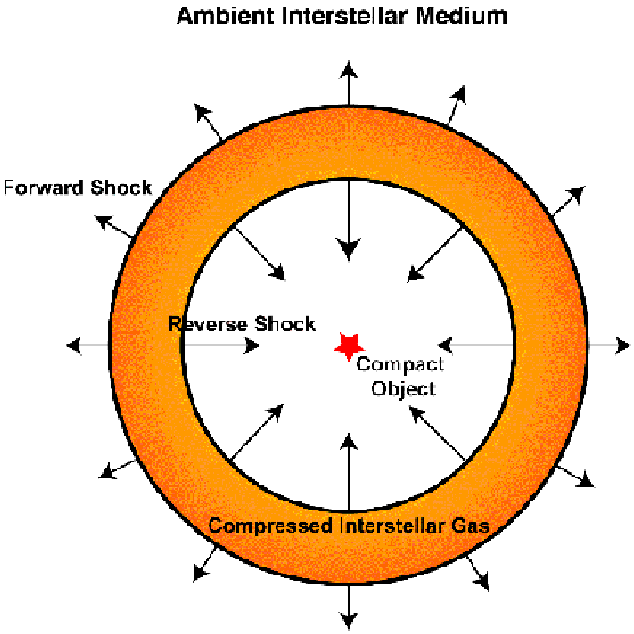
- **Silicates (e.g. Mg_2SiO_4, $MgSiO_3$):** the elements come from massive stars exploding in short time-scale
- **Carbon dust:** some carbon from massive stars, but most of them from low-mass stars (longer time-scale); Their evolution is likely to be link to the appearance of PAHs feature (Galliano+08).
- **Iron:** Type Ia supernovae (from white dwarfs in binary systems)
- **Other heavy elements**: low mass stars and neutron star mergers
- **The chemical composition of dust changes during the cosmic epochs. Different assumptions of the dust chemistry can change our estimate of the dust budget up to a factor of ~10.**

Dust evolution and uncertainties: SNe

- **Uncertain by a factor of ~5 due to different theoretical of metal yields**
- **Type II SNe**: **dust production/destruction by shocks**: **uncertain dust yields**
  - -0.1-1 $M_\odot$ of dust formed in each SN.
  - -Not clear how much dust can survive the reverse shock:
    - •maybe only 2-20% (Bianchi& Schneider07; Bocchio+16);
    - •a larger fraction if grains are big (Gall+14).
  - -Dust might be reformed in the forward shock after being destroyed (SN1987A, Matsuura+19)
- **Type Ia SNe: uncertain dust yields as well, almost completely destroyed? (Nosawa+11)**

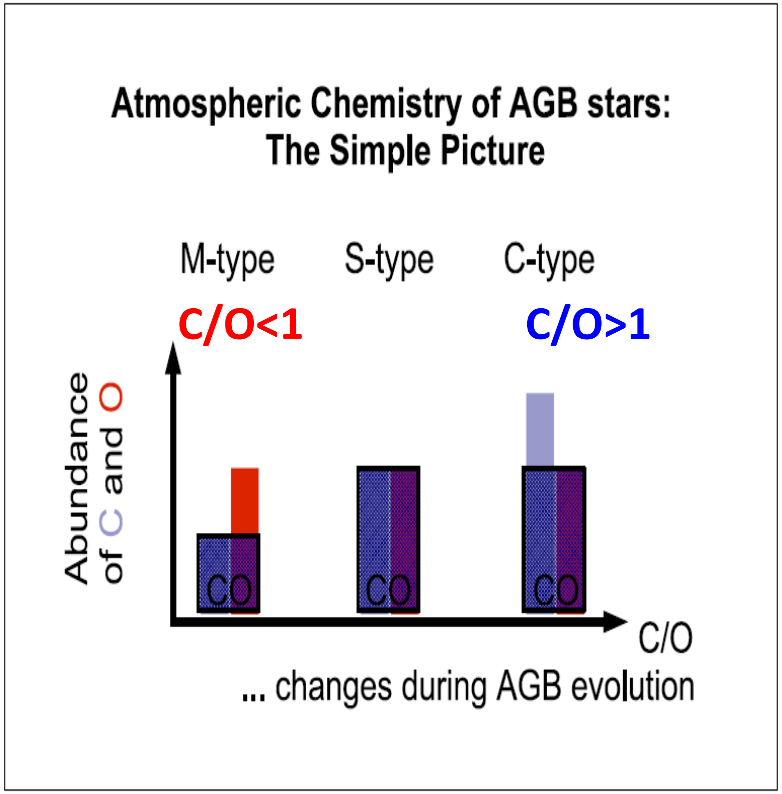


Dust evolution and uncertainties: low and intermediate-mass stars (the thermally pulsing asymptotic giant branch, TP-AGB, phase)

R Sculptoris (ALMA)
Maercker et al.

TP-AGB stars: properties and classification

Evolved star with M≤ 6-8 M⊙



Atmospheric Chemistry of AGB stars:
The Simple Picture

... changes during AGB evolution

Hoefner 2009

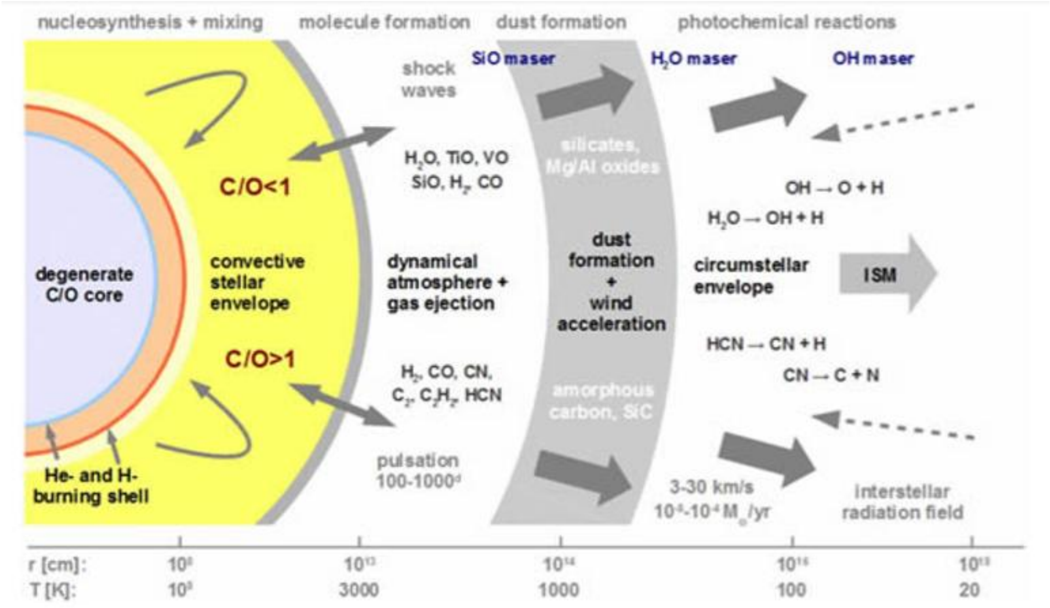
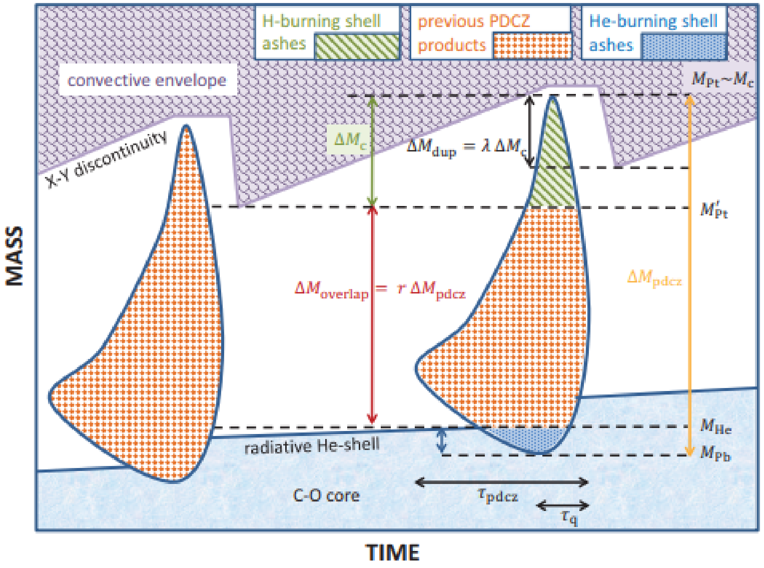


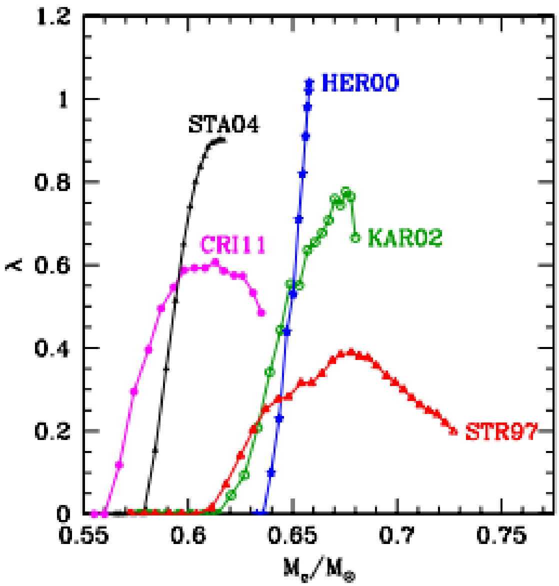
Figure 2: Schematic representation of the CSE of a TP-AGB star and of the main physical processes ongoing.

“dust-driven wind”, high mass-loss rates
(10^{-7} - 10^{-5} M⊙/yr)
Mass-loss of Sun ≈10^{-14} M⊙/yr

C/O<1 → oxygen based chemistry (mainly silicates and metal oxides)
C/O>1 → carbon based chemistry (amorphous carbon and silicon carbide)

The TP-AGB phase





Marigo et al. 2013

- **H-** and **He-burning** shells
- Several **thermal pulses**
- **Third dredge-up** for M ≥ 2 M⊙

C/O<1→ C/O>1

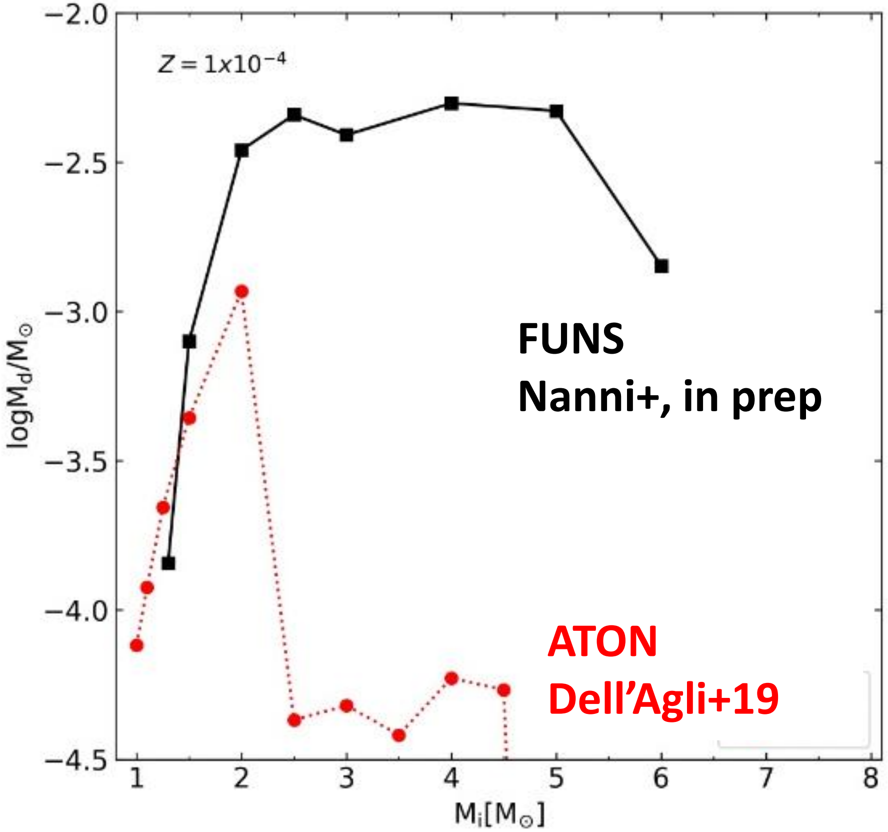
- **Hot Bottom burning** (HBB): H-burning through CNO cycle (M ≥ 4 M⊙)

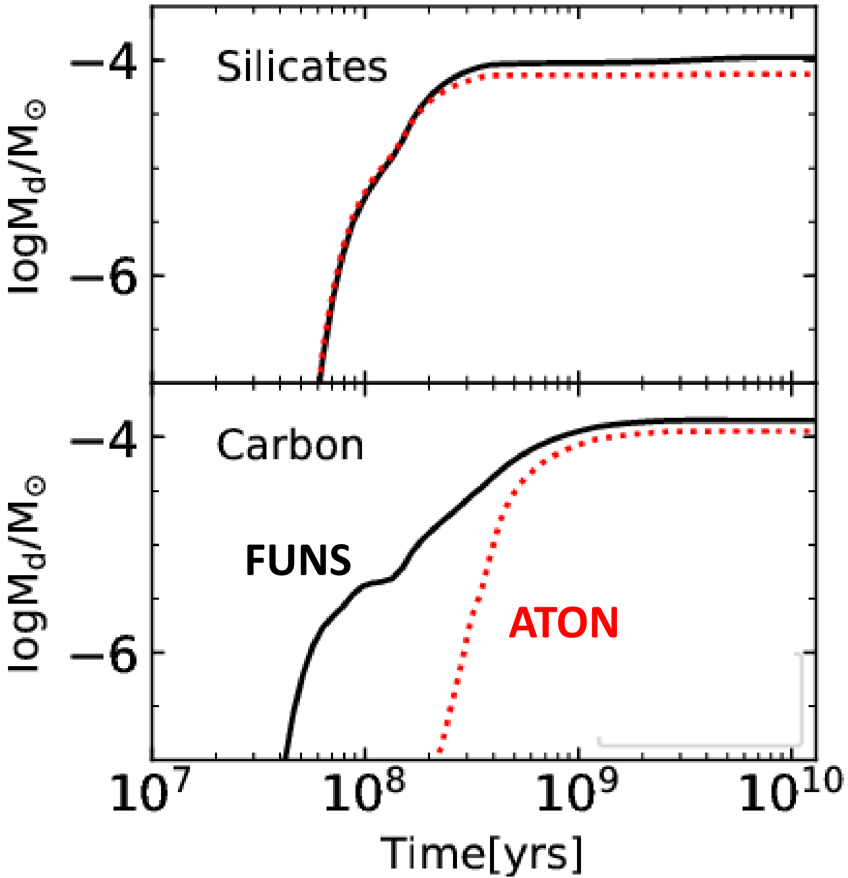
Decreases C (CN cycle):

C/O>1→ C/O<1

- **Many uncertainties** in the prescriptions adopted to model this phase: **mass-loss, efficiency of the third dredge-up, HBB**

Dust evolution and uncertainties: yields from TP-AGB stars

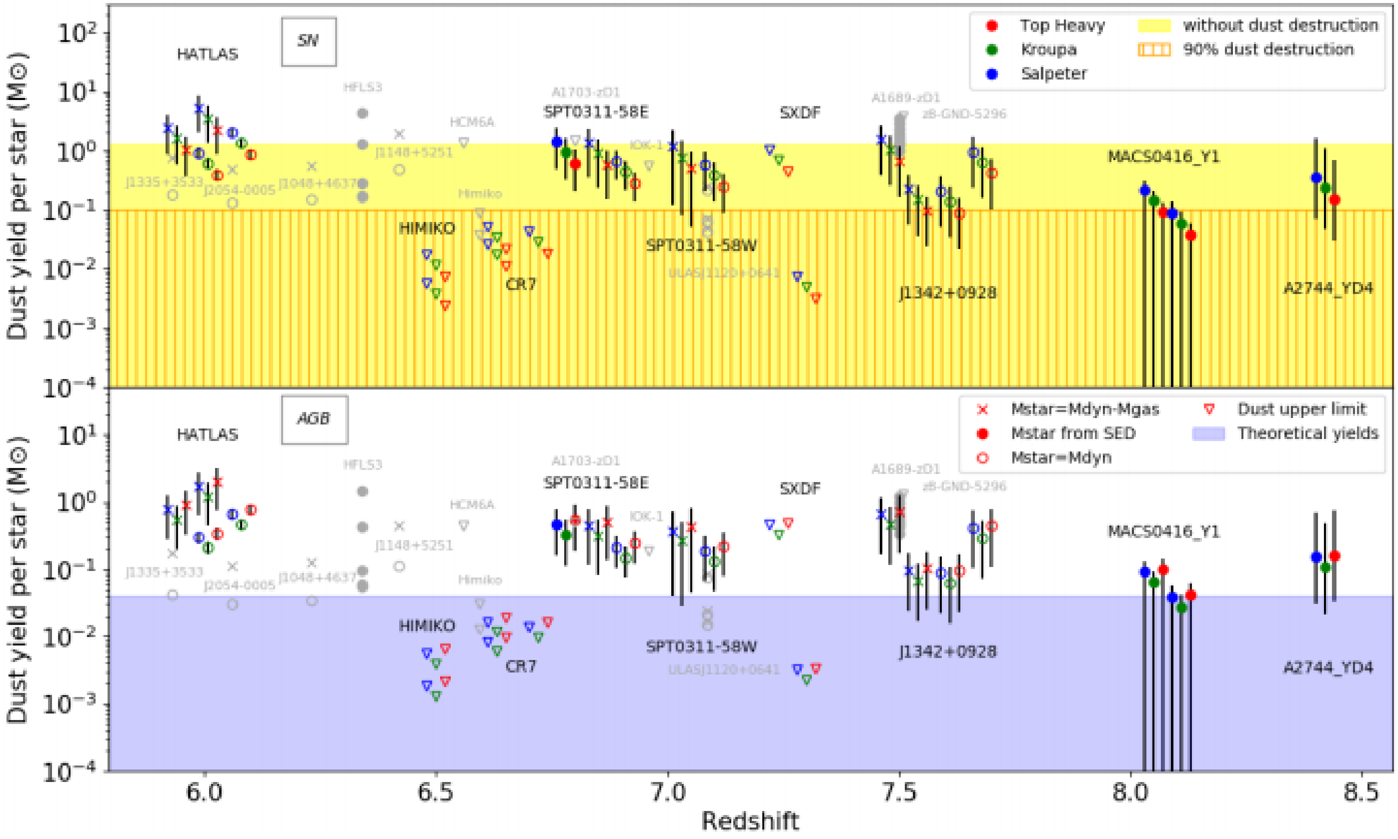




Nanni et al., in prep: dust yields will be publicly available on the FRUITY database (in collaboration with Dr. Sergio Cristallo, Osservatorio Astronomico dell'Abruzzo)

Dust yields vary among the different stellar evolutionary codes and this might affect our results of the chemical enrichment of galaxies (Nanni+13; Nanni+14)

Dust evolution and uncertainties: dust growth in the ISM?



Leśniewska & Michałowski 2019

Unless little dust is destroyed in SN reverse shock, dust growth in the ISM seems to be required to in order to explain the amount of dust observed in galaxies.

Dust growth in the ISM: a closer look to theory and experiments

The efficiency of grain accretion in the ISM is very debated

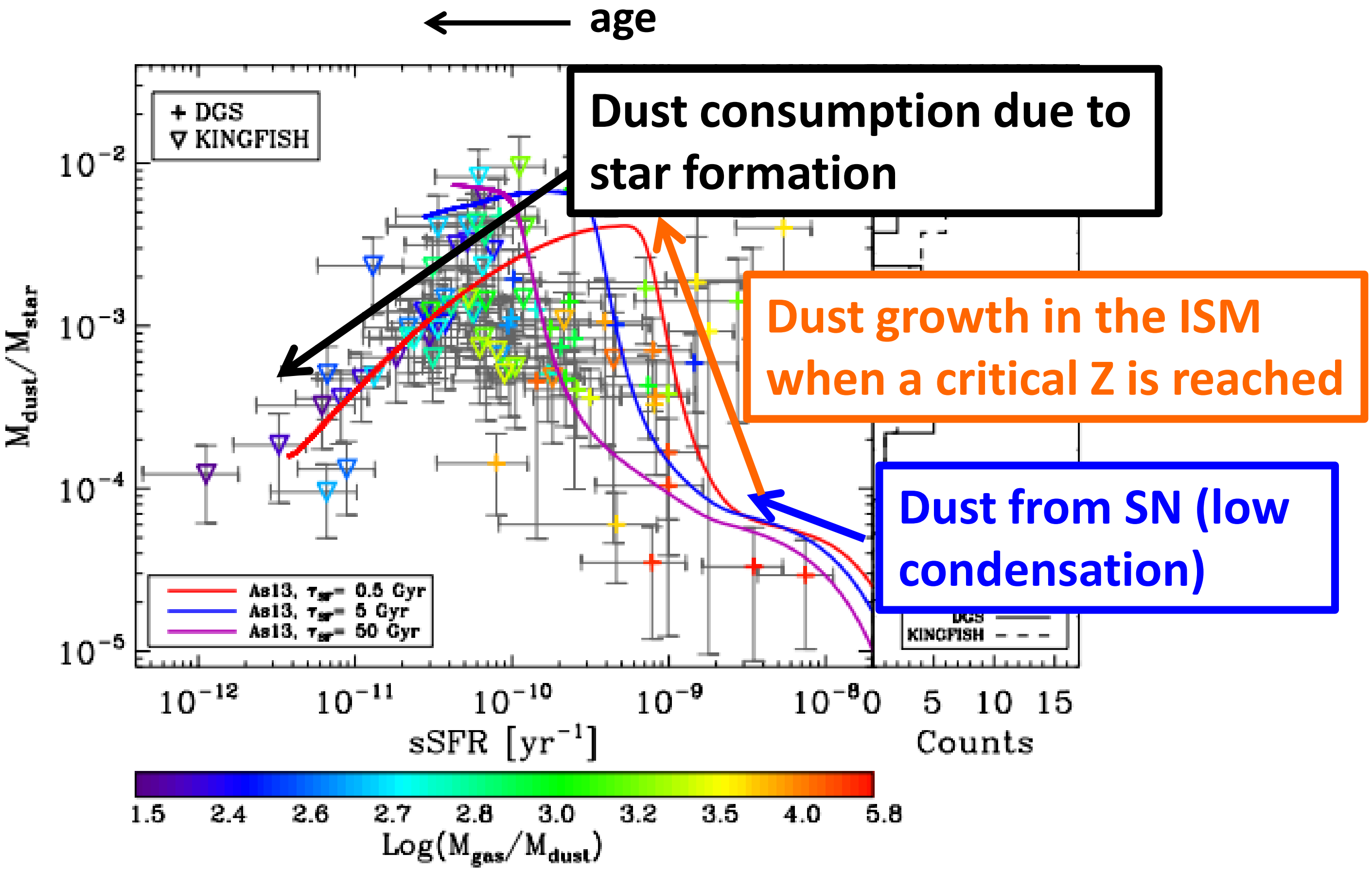
Where can dust form in the ISM?

- **Diffuse medium (cold neutral medium) -> 30 cm^{-3} , T~ 100 K**
  - no energy barrier between atoms that form silicate dust (Rouillé+15)
  - the typical low density implies slow accretion (Ferrara+16)

- **Molecular clouds -> lower temperatures (~10-20 K), higher densities (10$^{3-4}$ cm^{-3}) -> icy mantles**
  - Icy mantles can evaporate due to UV photons if the star formation rate is large (Ferrara+16)
  - Inside icy mantles it is difficult for two SiO molecules to encounter and form dust monomers (Ceccarelli+18).

- **Experiments and theory suggest that dust growth in the ISM might be efficient in low temperature plasmas** (e.g. Bleecker+06; Hollenstein 2000; Zhukovska+16). More investigations are needed.

Models vs observations



Dust consumption due to star formation

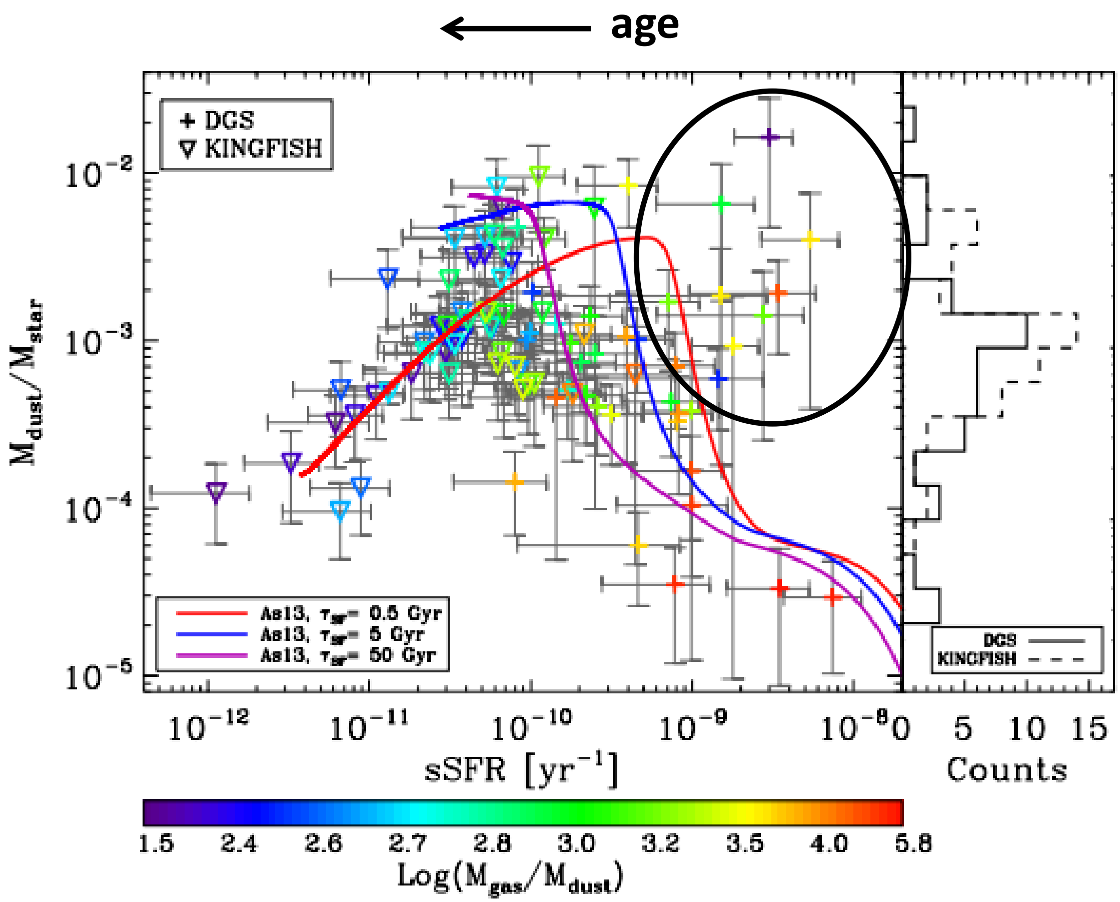
Dust growth in the ISM when a critical Z is reached

Dust from SN (low condensation)

Remy-Ruyer+15 (models from Asano+13); see also De Vis+17, +19

Models are “simple”: dust growth in the ISM is mainly related to the metallicity

Dust evolution and uncertainties: dust growth in the ISM?



Remy-Ruyer+15 (models from Asano+13); see also De Vis+17; +19

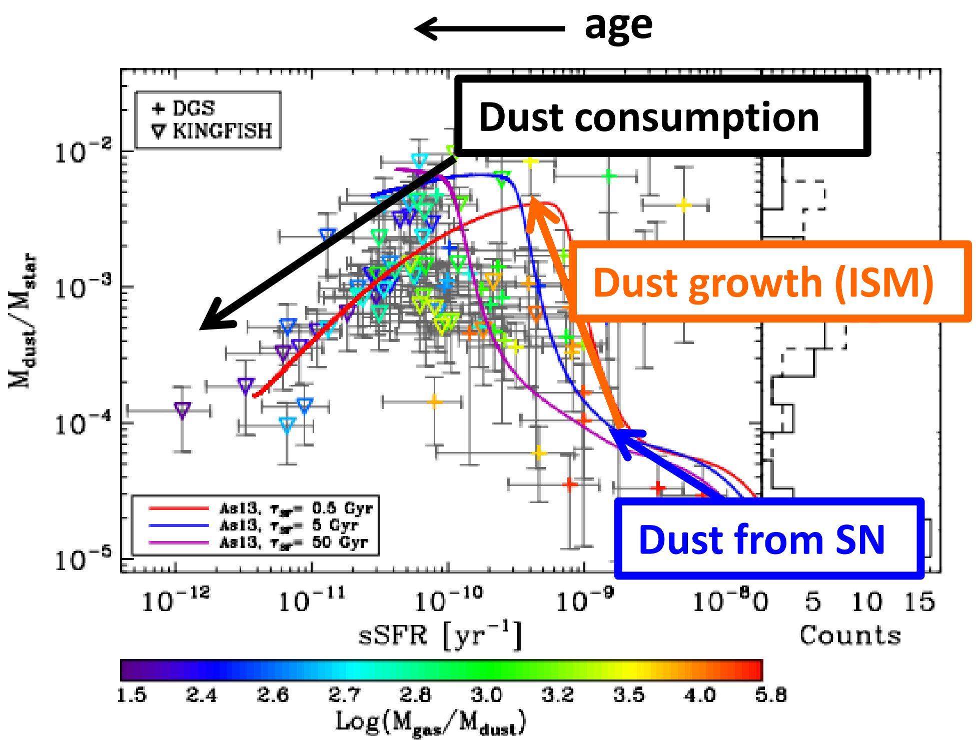
Models are “simple”: dust growth in the ISM is mainly related to the metallicity

The largest values of M_{dust}/M_{star} vs SFR/M_{star} are not reproduced!

General trends for local dwarf galaxies & Lyman Break Galaxies (5< z <10)

We want to explain:

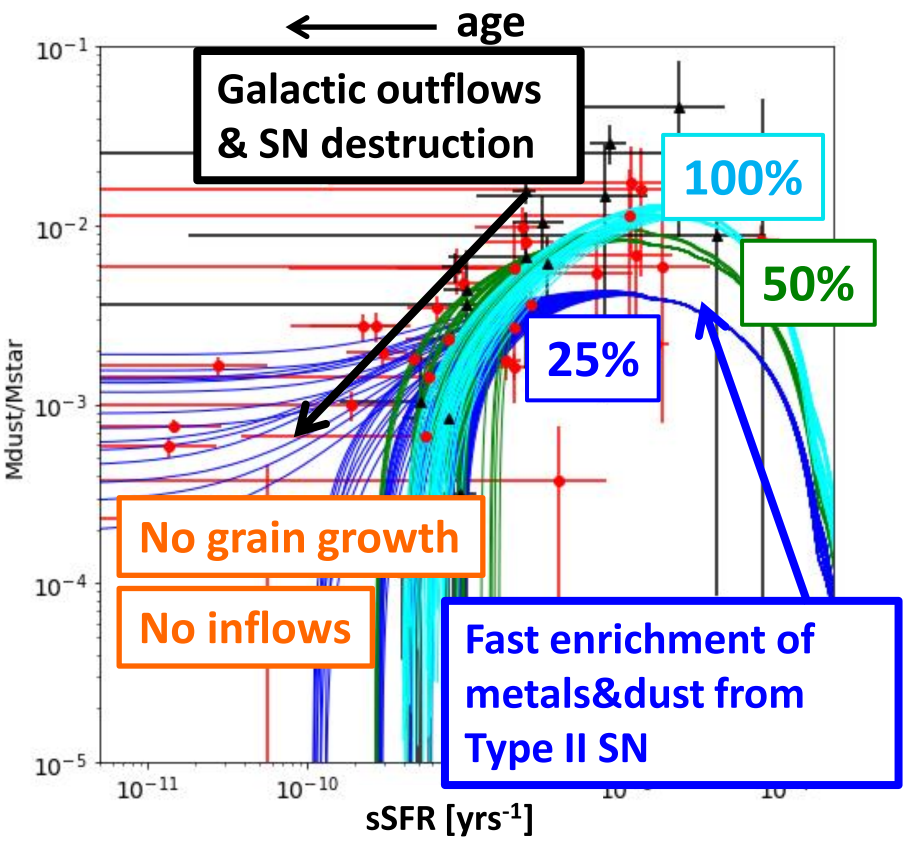
- **Dwarf galaxies** (Dwarf Galaxy Survey, Madden+13)**:** M_{dust}/M_{star}, age, SFR/M_{star}, (from CIGALE); Z, gas fraction (from Remy-Ruyer 2013); circum galactic dust (McCormick+18)
- **Lyman Break Galaxies**: M_{dust}/M_{star}, age, SFR/M_{star} (from CIGALE)



Dust consumption

Dust growth (ISM)

Dust from SN



Galactic outflows & SN destruction

100%

50%

25%

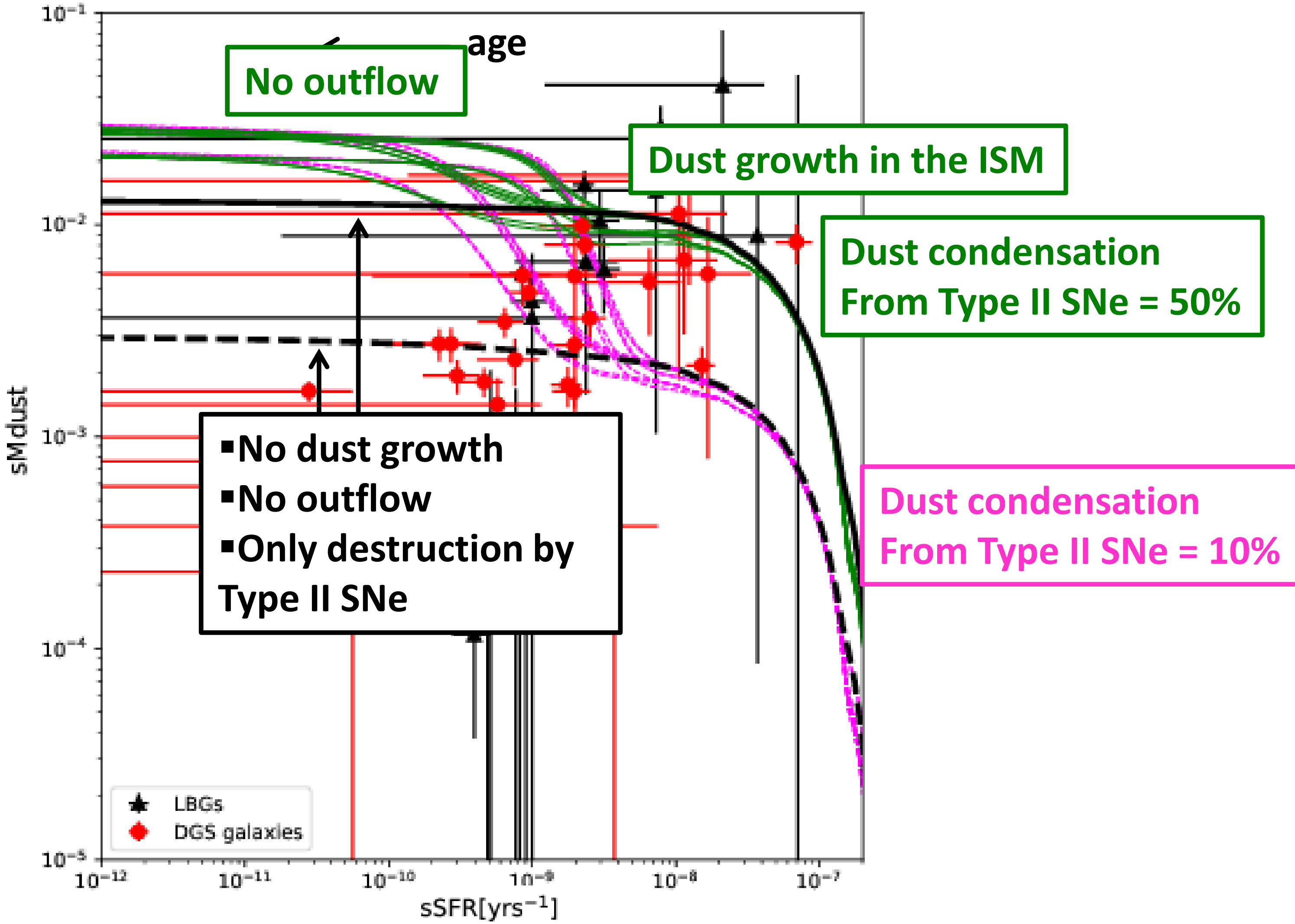
No grain growth

No inflows

Fast enrichment of metals&dust from Type II SN

Fast enrichment from Type II SNe: large condensation fraction and "top-heavy" IMF (Gall+ 2011a,b; Dabringhausen+12; Geha +13; McWilliam +13; Marks+12)→ **low contribution from TP-AGB stars (Burgarella, Nanni+20; Nanni et al., submitted)**

The role of grain growth in the ISM for low metallicity galaxies



No outflow

Dust growth in the ISM

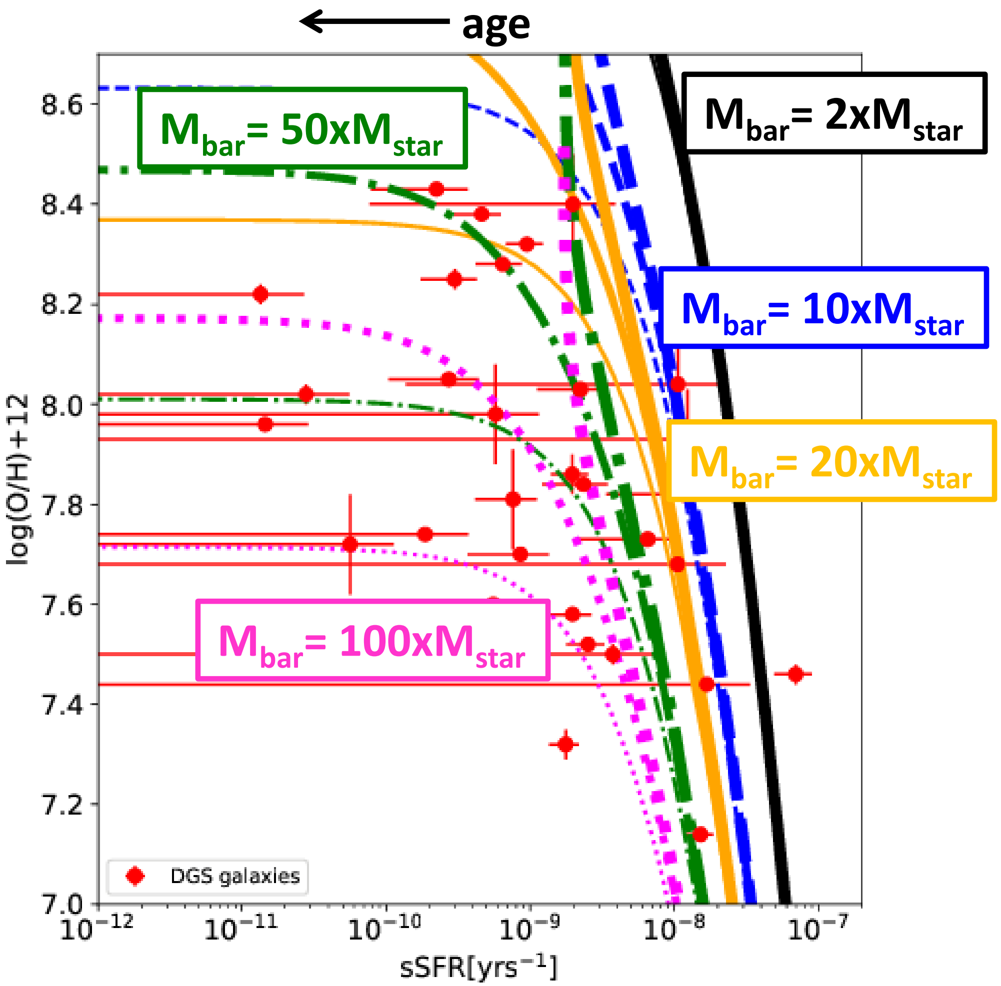
Dust condensation
From Type II SNe = 50%

Dust condensation
From Type II SNe = 10%

- **No dust growth**
- **No outflow**
- **Only destruction by Type II SNe**

- **We need a lot of dust at the beginning from Type II SNe.**
- **Dust accretion in the ISM starts to increase the specific mass of dust when the observed values is decreasing.**

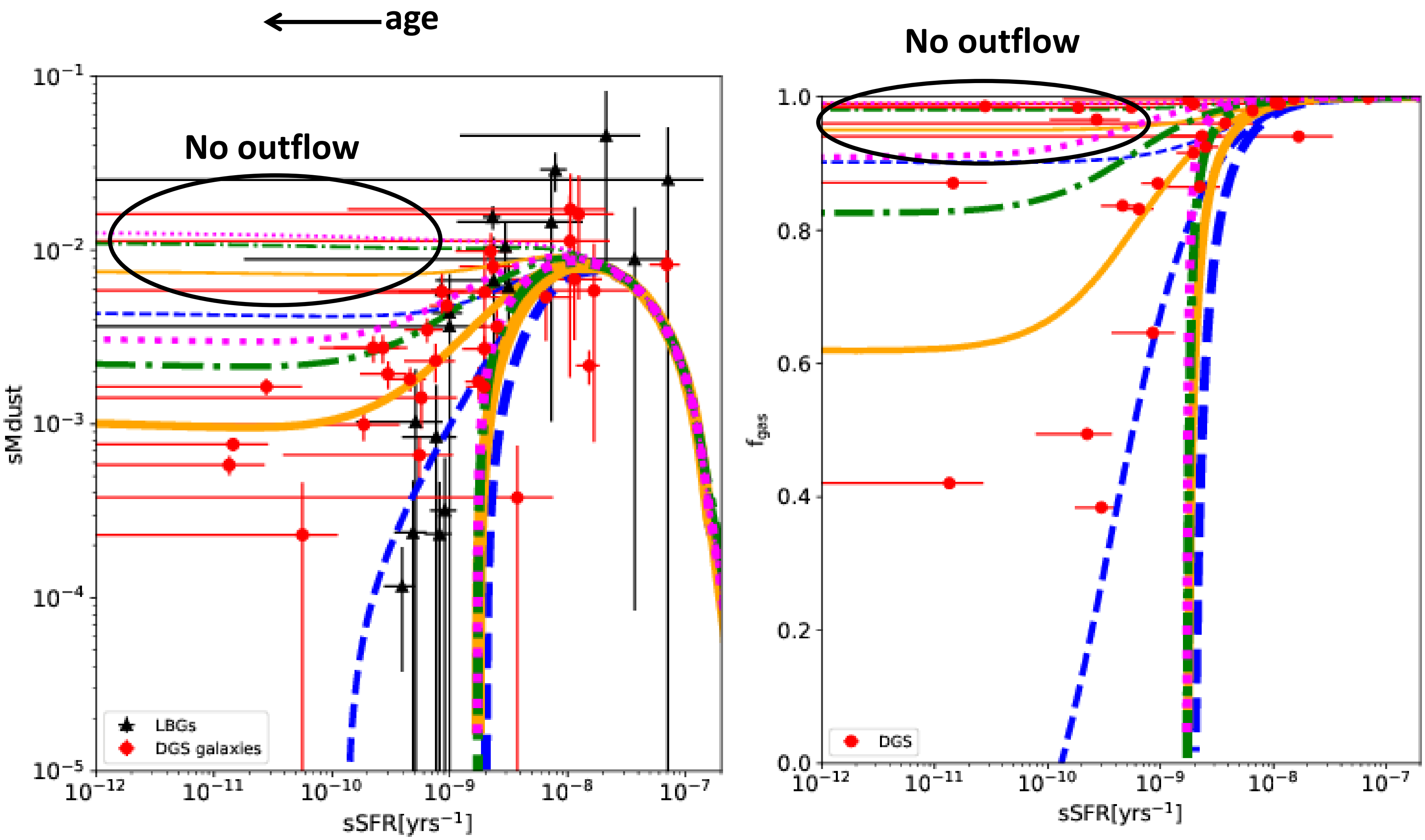
Constraints for local dwarf galaxies: metallicity



Nanni et al., submitted

Metallicity: typical star formation efficiency of just few per cents

Constraints for local dwarf galaxies: dust and gas fraction



Nanni et al., submitted

sMdust, Gas fraction: gas is later removed by outflows

Conclusions

- The origin of dust is still debated, in particular in relation to:
  - Dust condensation in SN remnants
  - Dust ejecta from low and intermediate mass stars
  - The efficiency of grain growth in the ISM
- In the standard scenario a low condensation efficiency for SN is assumed (efficient dust destruction in the reverse shock)
- The standard scenario does not reproduce the largest M_{dust}/M_{star}

In order to reproduce different observations one needs to assume:

- An initial mass function for stars favouring the production of Type II SN producing a fast enrichment from metals.
- An high condensation fraction of dust in type II SN (25-50%).
- A low star formation efficiency (~few%).
- An efficient outflow to reproduce the decrease of the dust content and of the gas fraction.
- Dust growth in the ISM is not required and, if present, its effect would not be evident due to the effect of the outflow.