COSMIC FACTORIES
of
METALS & DUST

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OUTLINE

Revised Metals Yields based on new

- evolutionary tracks of intermediate mass stars (calibrated AGB)
- evolutionary tracks of massive stars (new mass-loss rates)
- SN explosion recipes

Dust formation model + updated stellar AGB tracks

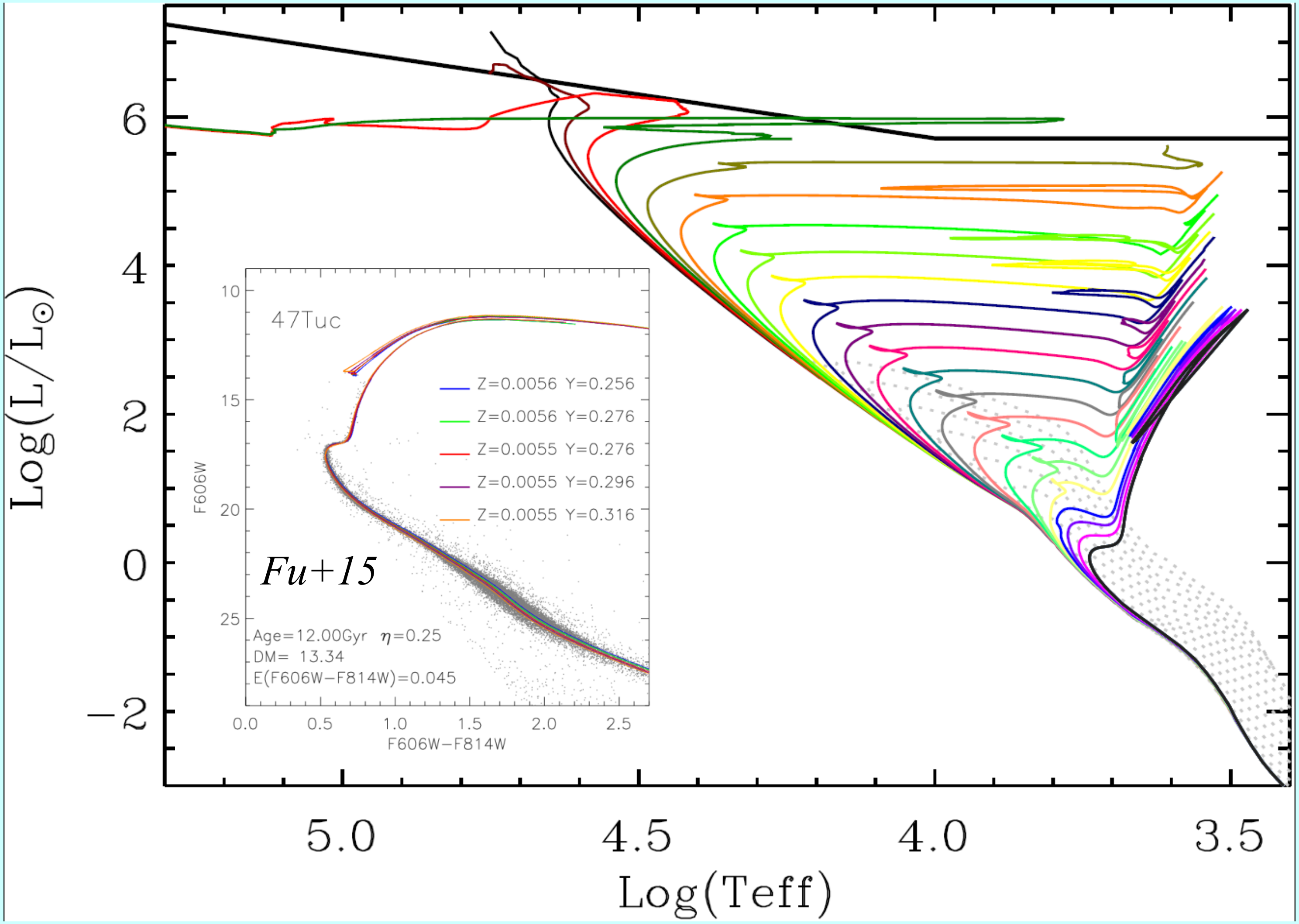
- contribution of AGB stars to the dusty ISM

Dust formation in MCs collapse

- how efficient is dust formation ?

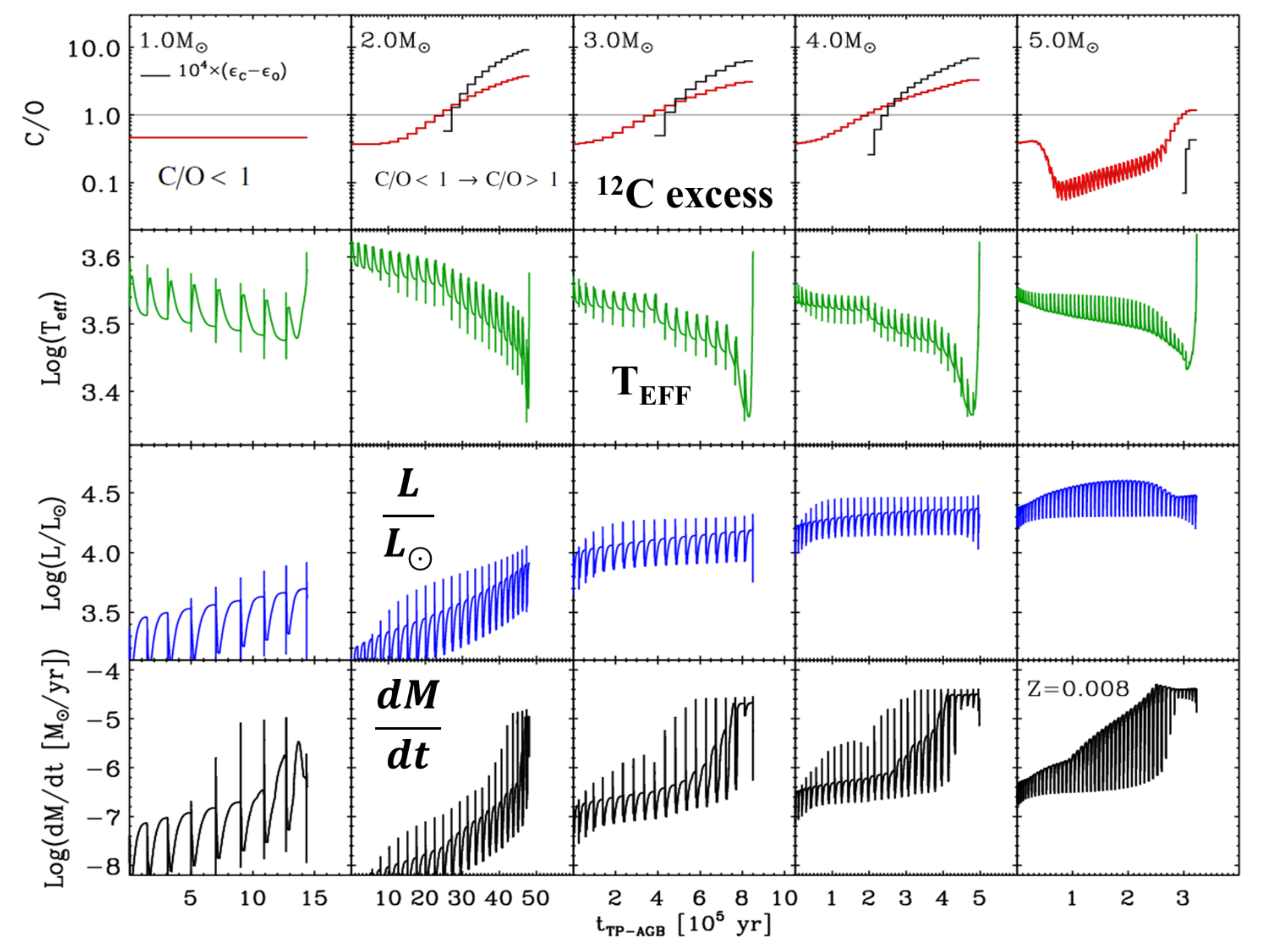
NEW DATABASE OF STELLAR EVOLUTIONARY TRACKS BASED ON *PARSEC* CODE (*Bressan+12; Tang+14,15; Chen+14,15)*

- **INITIAL MASS: 0.1M$_\odot$ - 350M$_\odot$ METALLICITY: 0.0001≤Z≤0.06**
- **FROM THE PRE-MAIN SEQUENCE TO CARBON IGNITION OR <u>E-AGB</u>**



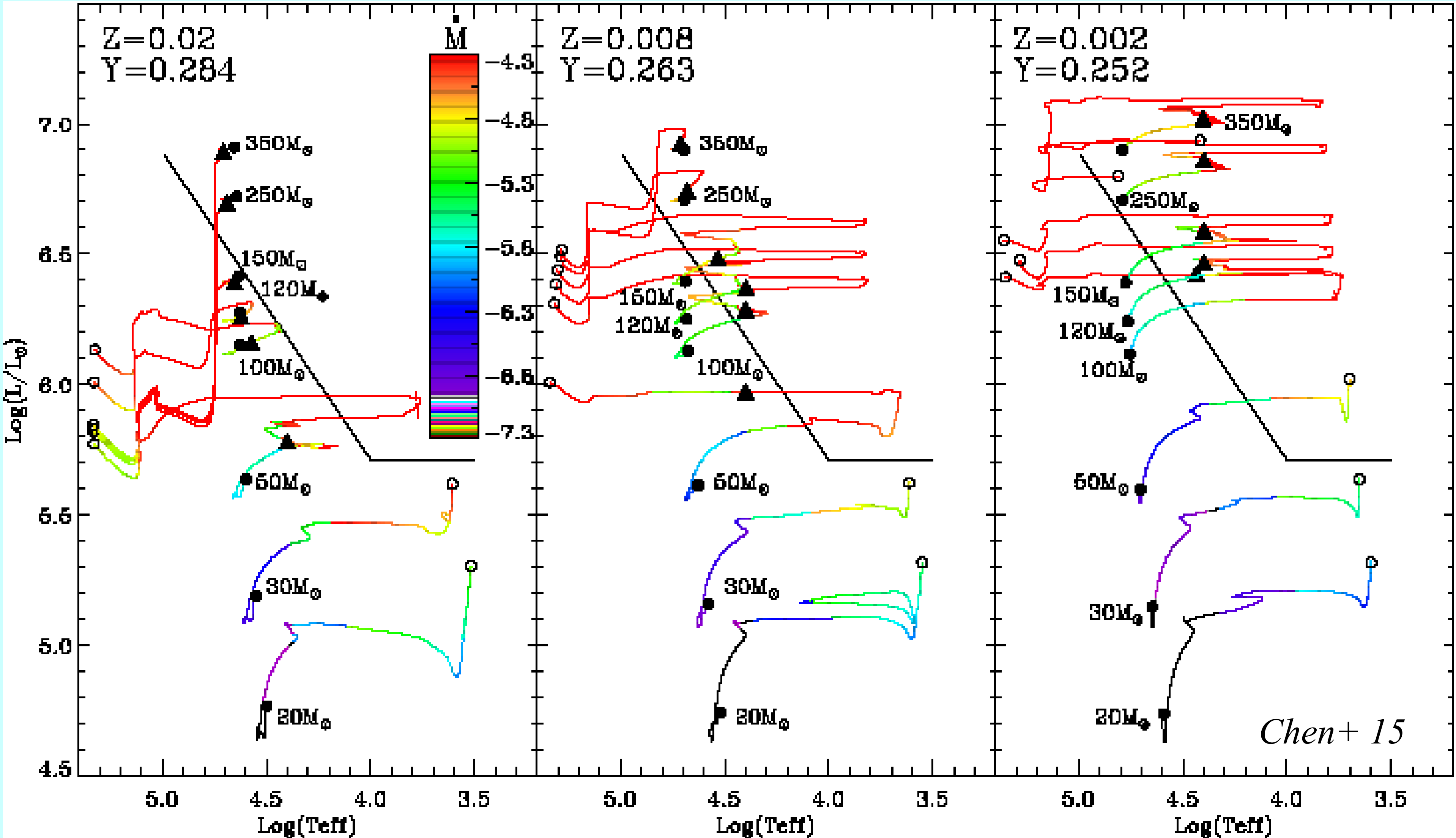
ASYMPTOTIC GIANT BRANCH: *COLIBRI Marigo+13*

(Nanni, Bressan, Marigo, Girardi 13, 14; Marigo+ 15)



MASSIVE STARS

(Tang, Bressan, Marigo, Girardi 14, 15; Chen, Bressan, Marigo, Girardi, Lanza 15)



CORE COLLAPSE SUPERNOVAE

DO ALL DYING MASSIVE STARS CONTRIBUTE TO ENRICHMENT ?

Stars with H-exhausted core mass **2.25M$_\odot$ <M$_{HE}$ <40M$_\odot$** evolve into core collapse supernovae (CCSN), leaving a **Neutron Star** (**Successful SN**) or a **Black Hole** (**Failed SN**). The He-core range corresponds to initial mass **8M$_\odot$<M <100M$_\odot$**

To find the incidence of '*Failed SN*' we take into account the bi-parametric criterion for explosion (e.g. Ertl et. 2015).

We evolve a set of models with MESA (Paxton et al., 2013) up to near core collapse with the mass-loss prescriptions of PARSEC.

*We separate between SNe and Failed-SNe adopting w20 calibration by Ertl +15, between **M4** (the mass enclosed at the dimensionless entropy s=4) and **μ4** (the mass gradient at the same location).*

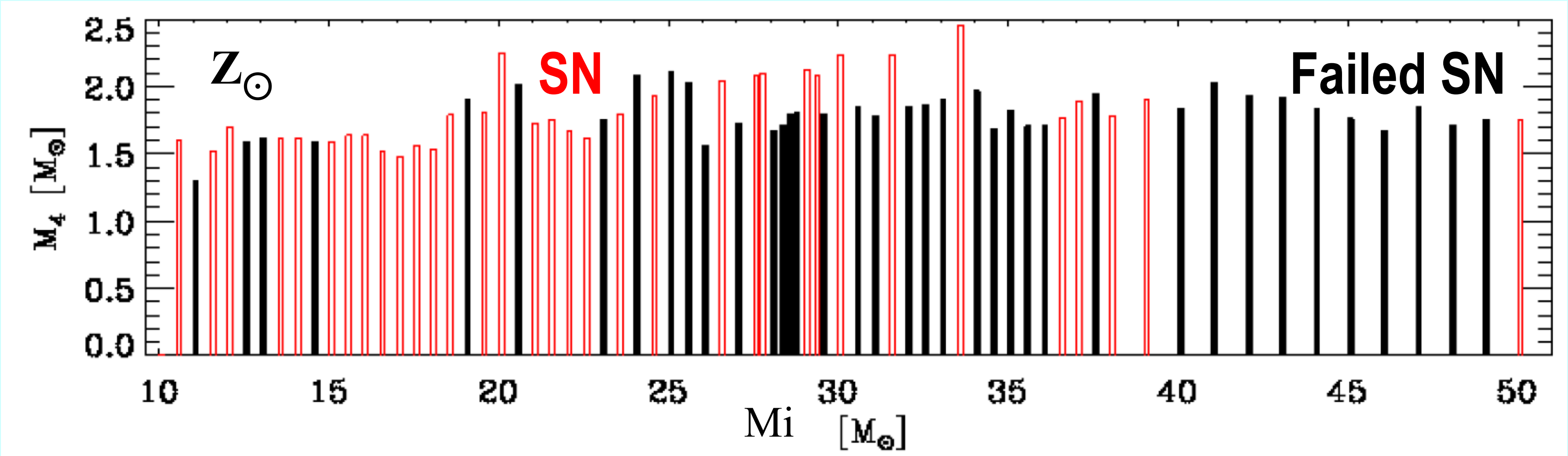
$$\mu_4 = 0.284\ M4\ \mu_4 + 0.0393$$ *(Slemer+15 in preparation)*

Core Collapse Supernovae

Do all dying massive stars contribute to enrichment ?

Massive stars with initial mass $M>28$ - $30\ M_\odot$ collapse to a BH and do not contribute to metal production by SN explosion.
However they may contribute through stellar winds !!

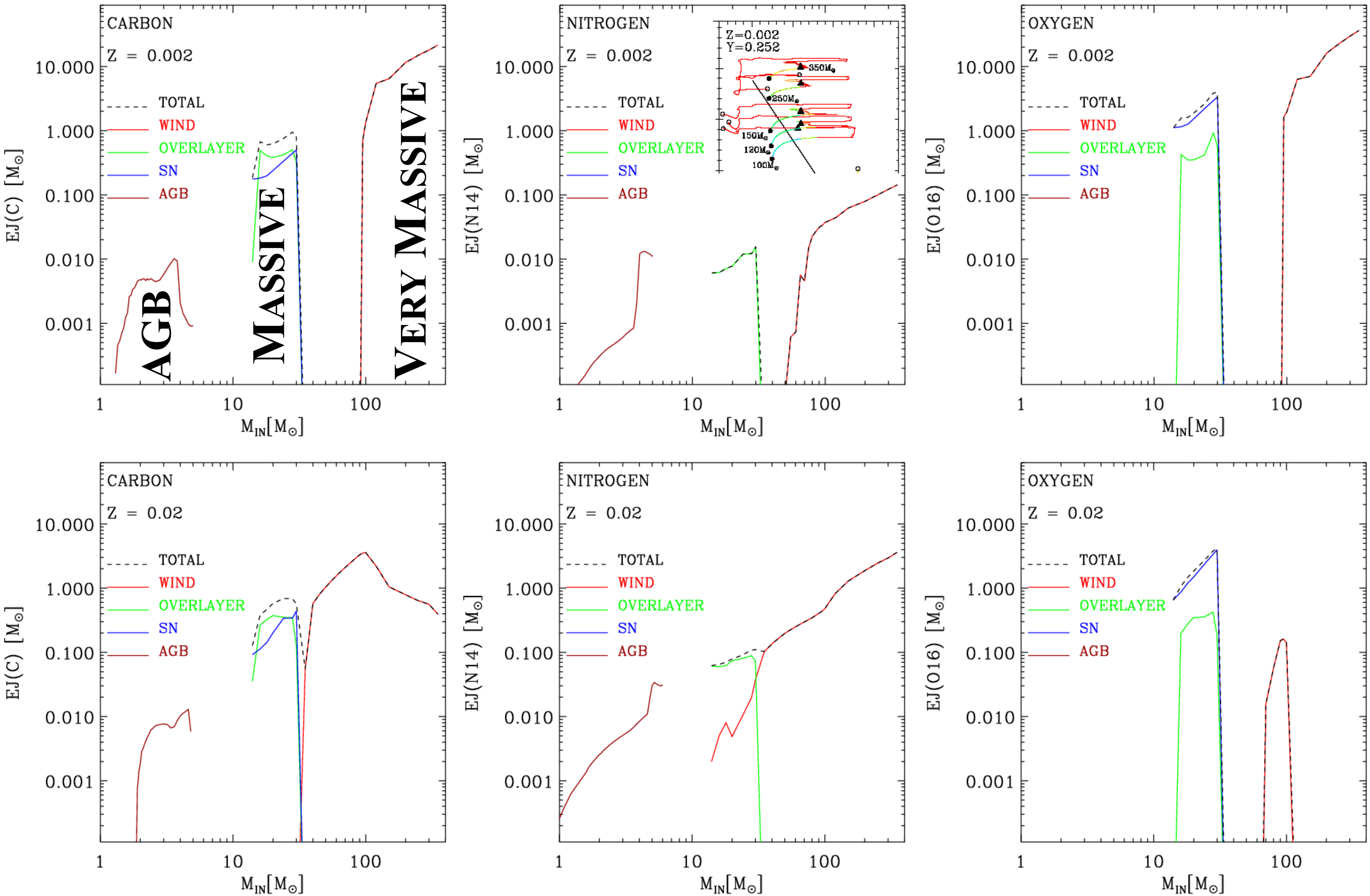
- ***Adopt a separation mass of $M = 30\ M_\odot$ (see also Spera et al. 2015) at all metallicities.***
- ***Explosive ejecta from Chieffi & Limongi 2004***
- ***At the moment do not consider possible contribution from Pair-Instability SNe***



$\mu_4 = 0.284\ M4\ \mu_4 + 0.0393$ *(Slemer+15 in preparation)*

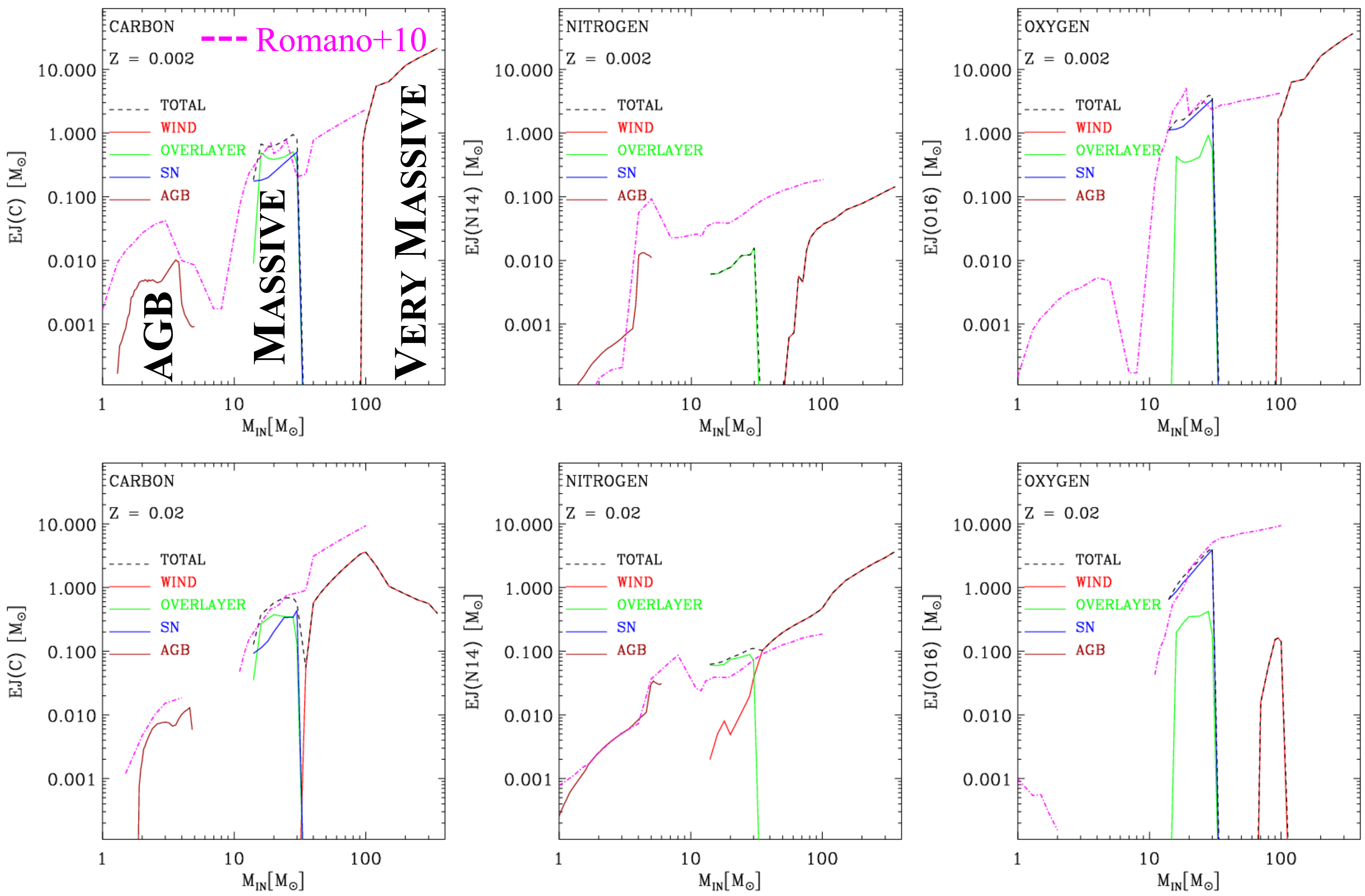
Ejecta of Newly Produced Metals

Slemer + 15



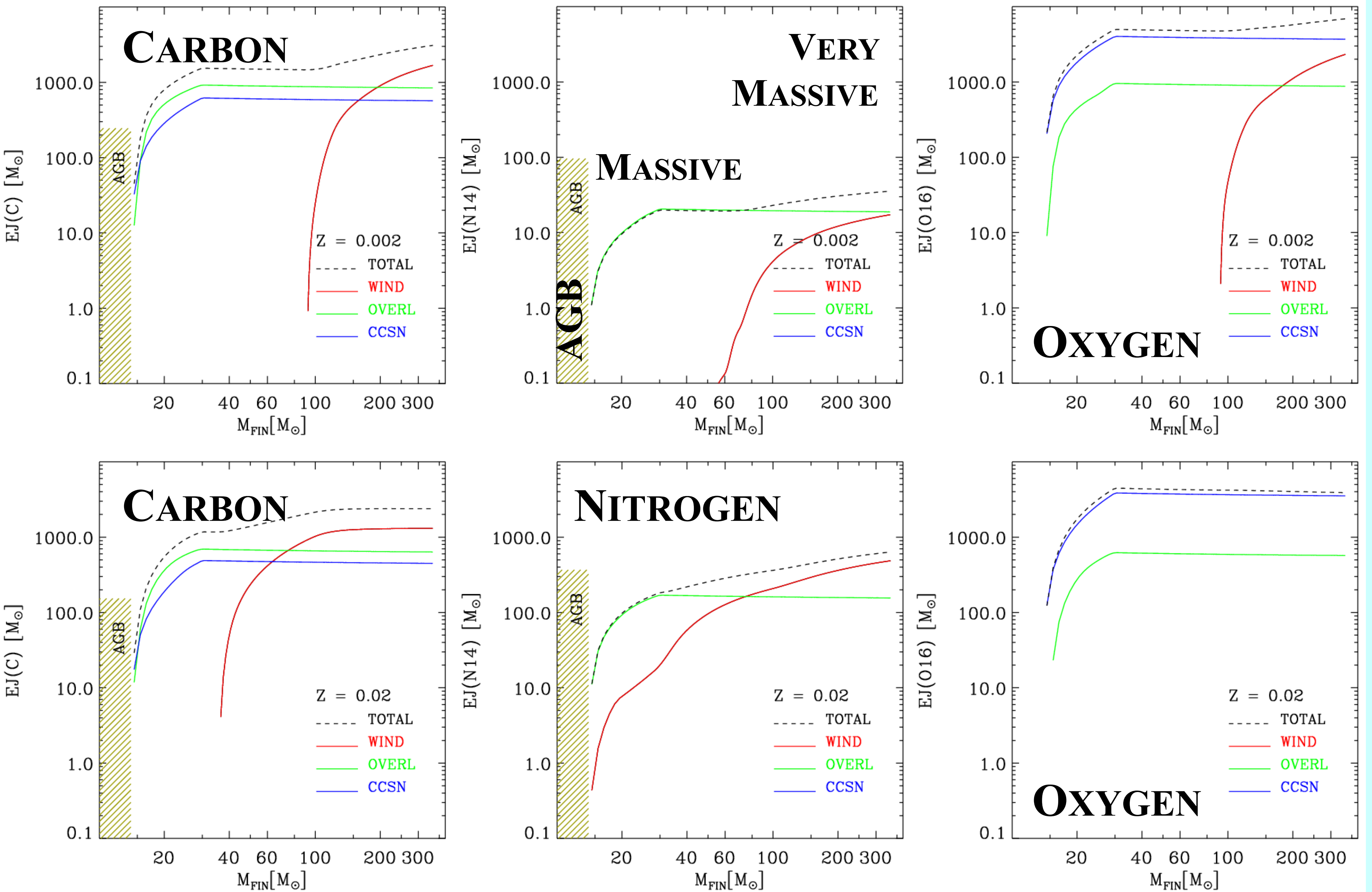
EJECTA OF NEWLY PRODUCED METALS

Slemer + 15



IMF WEIGHTED EJECTA (*for a cluster of* $10^6\,M_\odot$)

Integrated over Salpeter Initial Mass Function from $\mathbf{0.1M_\odot}$ **to** $\mathbf{M_{FIN}}$



DUST FACTORIES

CLUES FROM HIGH-REDSHIFT GALAXIES: **~4 × 10^8M$_\odot$** of dust observed in the high-redshift quasar J1148+5251; z = 6.4: **t < 1Gyr** (*Dwek+11)*

DUST FORMS QUICKLY !

- **Core Collapse SN (CCSN) 0.1 M$_\odot$/SN (t ~ 10 Myr, 20M$_\odot$)**
  (Cas A: *Rho+08; Barlow+10, Nozawa+10*)
- **Wolf Rayet (WC) stars 0.2M$_\odot$ but #WC only 0.1 x #CCSN**

➢ **Asymptotic Giant Branch (AGB)**

t > 50 Myr *(Ferrarotti & Gail 06, Nanni+13,14)*

most efficient: 3M$_\odot$; t ~300 Myr; 0.01-0.04 M$_\odot$; Z dependent

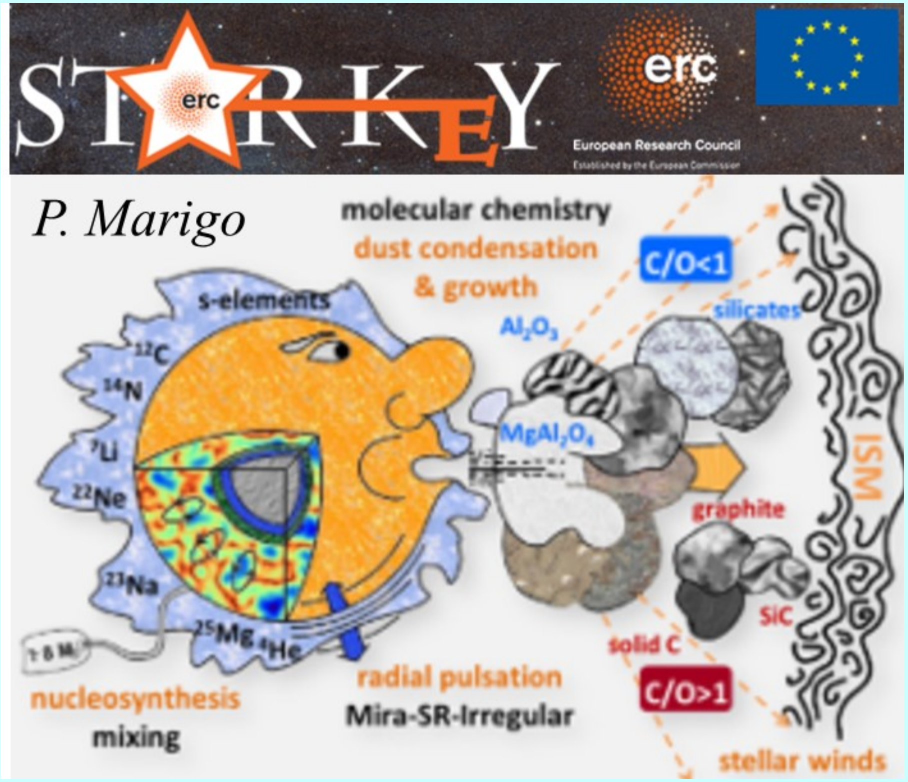
- **In steady state (needs 1 Gyr *Galliano+08*)**

  CCSN:WR:AGB 1.0 : 0.11 : 4.6 (*Dwek+11*)

❑ **Dust formation within MCs *(Ripamonti+15 in prep.)***

Dust in AGBs

Nanni, Bressan, Marigo, Girardi (2013, 2014)



- **pulsations generate shocks that levitate matter to outer regions**
- **dust forms**
- **radiation pressure on dust grains accelerate matter outwards**

• complex models solve coupled hydrodynamics and radiation transfer equations
• initial velocity set by shocks (pulsations or convection)
(Hoefner +09,12,14;Winters+03; Elitzur & Ivezic 01; Willson 00; Bowen & Willson 91; Marigo+15)

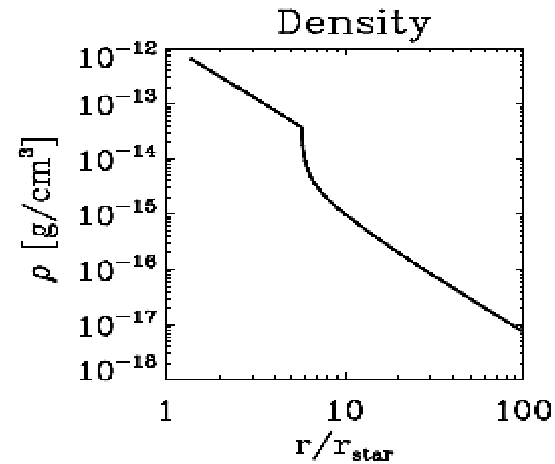
Dust mineralogy depends on C/O ratio (*e.g. Ferrarotti & Gail 06, Ventura+ 12*)

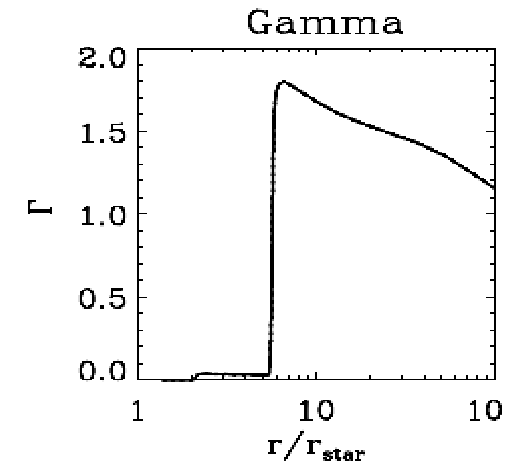
O rich AGB: silicates (olivine- and pyroxene-type materials)

C- stars : amorphous carbon, SiC

GRAIN GROWTH IN AN EXPANDING ATMOSPHERE (Gail & Sedlmayr 99)

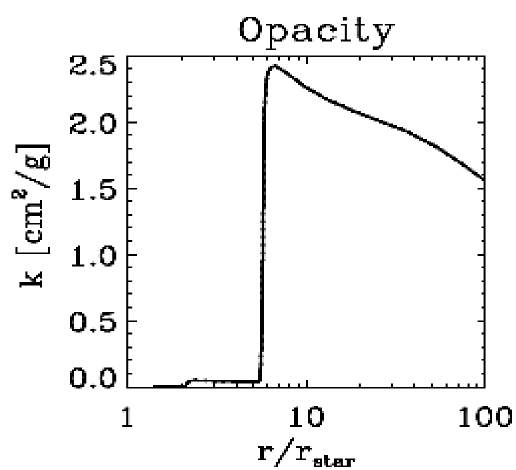
$$\begin{cases} v\dfrac{dv}{dr} = -\dfrac{GM_*}{r^2}(1-\Gamma) \\ \dfrac{d\tau}{dr} = -\rho\kappa\dfrac{R_*^2}{r^2}, \\ \dfrac{da_i}{dt} = \dfrac{da_i}{dt}^{gr} - \dfrac{da_i}{dt}^{dec} = V_{0,i}(J_i^{gr} - J_i^{dec}) \end{cases}$$

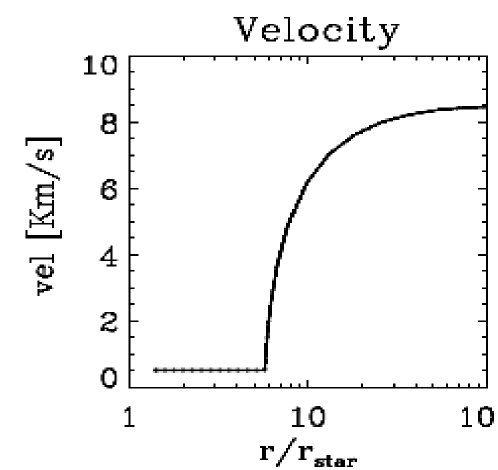




Nanni +2013, 2014

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v} \qquad \Gamma = \frac{L_*}{4\pi c G M_*}k$$



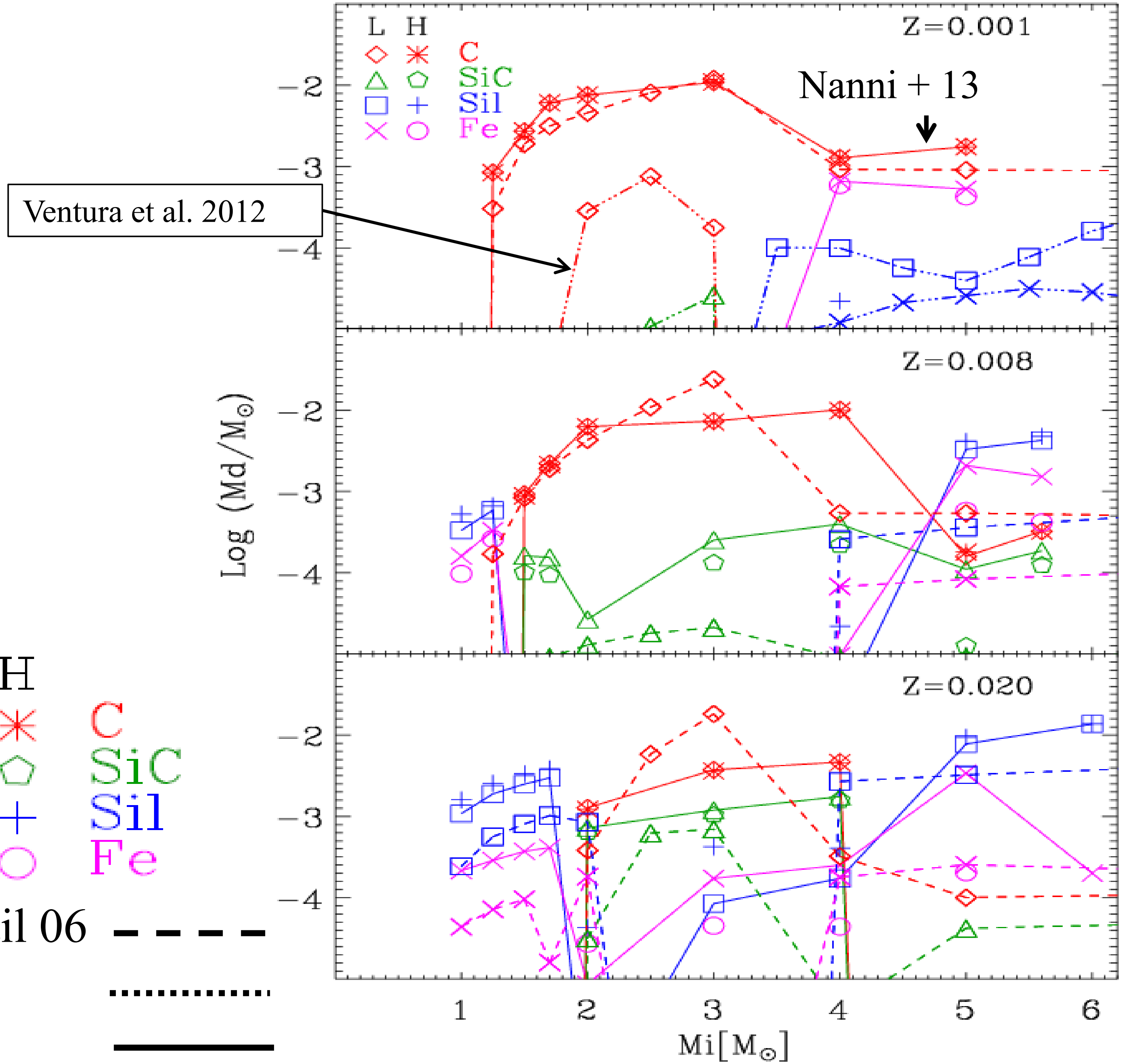


$$T(r)^4 = T_{\rm eff}{}^4\left[W(r) + \frac{3}{4}\tau\right]$$

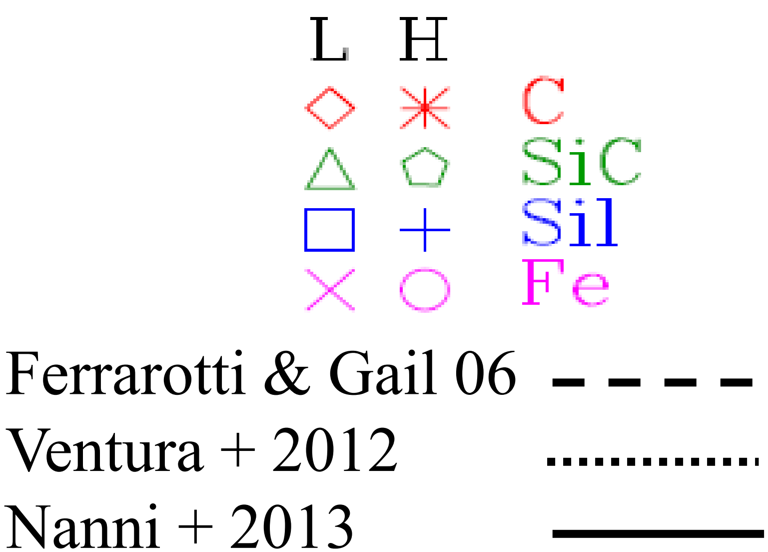
$$W(r) = \frac{1}{2}\left[1 - \sqrt{1 - \left(\frac{R_*}{r}\right)^2}\right]$$

$$\kappa = \kappa_{gas} + \sum_i f_i\kappa_i \qquad \kappa_{gas} = 10^{-8}\rho^{2/3}T^3 \qquad f_i = n_{k,i}\frac{4\pi(a_i^3 - a_0^3)\rho_{d,i}}{3m_{d,i}\epsilon_{k,i}}\epsilon_s$$

Dust Ejecta

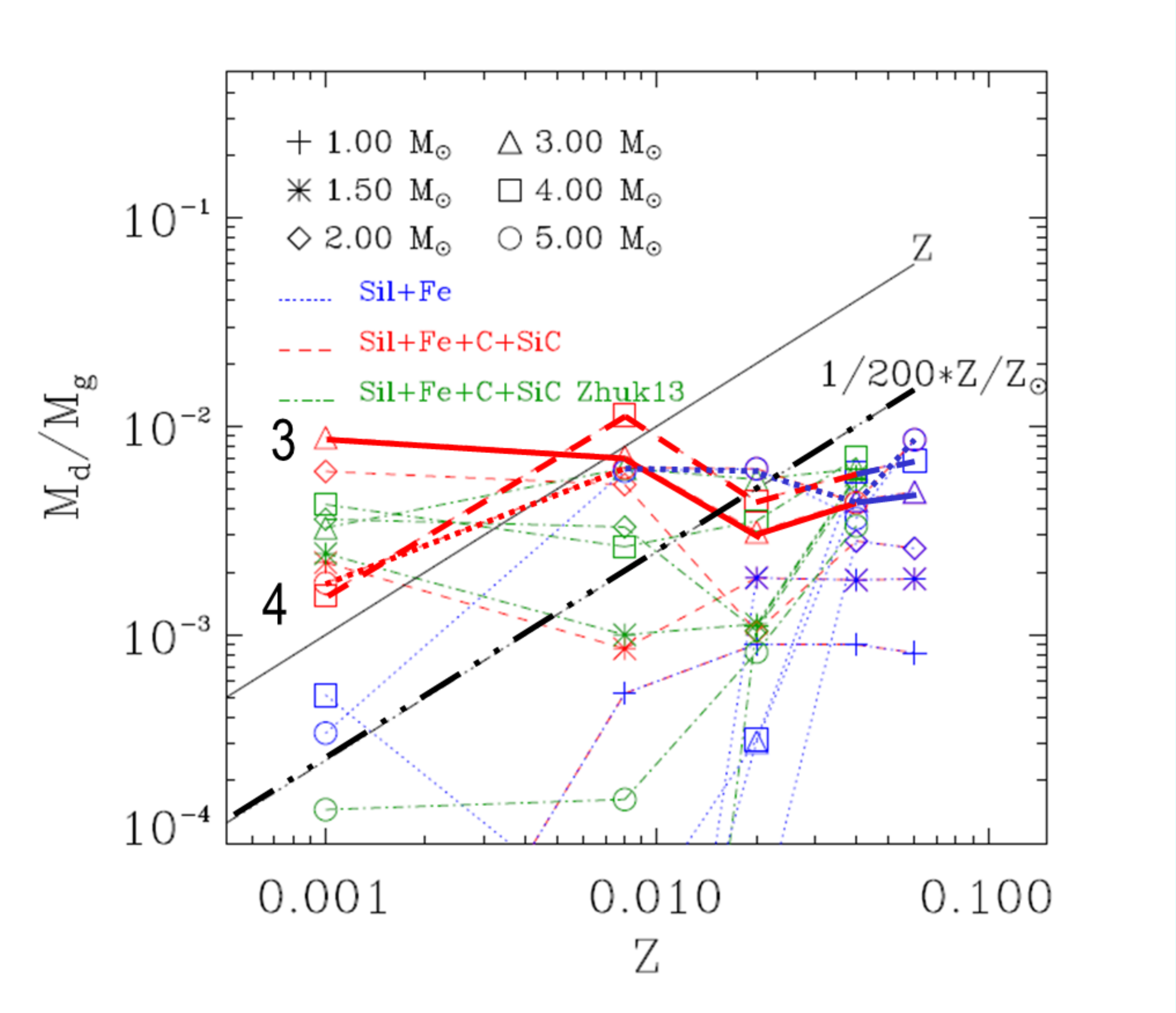


Ventura et al. 2012
Nanni + 13
Z=0.001
Z=0.008
Z=0.020
L H
C
SiC
Sil
Fe
Log (Md/M⊙)
Mi[M⊙]
-2
-3
-4
1
2
3
4
5
6



L H
C
SiC
Sil
Fe
Ferrarotti & Gail 06
Ventura + 2012
Nanni + 2013

AGB Dust Production at varying metallicity (Nanni+14)



- **At low Z, contribution may <u>exceed initial metallicity</u> due to strong IIIDredge-UP**
- **At high Z, dust production inhibited by fast acceleration**

MOLECULAR CLOUDS AS DUST FACTORIES

While MCs collapse & fragment during SF process, conditions for dust growth are easily reached *(Ripamonti+15 in prep.)*

- 1D Hydrodynamic code for MC collapse *(Ripamonti+10)*
- Evolution of gas chemistry with KROME *(Grassi et al. 2014)*
- Dust growth (~ as in AGB)

Initial seeds ($\varepsilon = N_S/N_H$)

$$2Mg + SiO + 3H_2O \rightarrow Mg_2SiO_4(s) + 3H_2$$

RESULTS

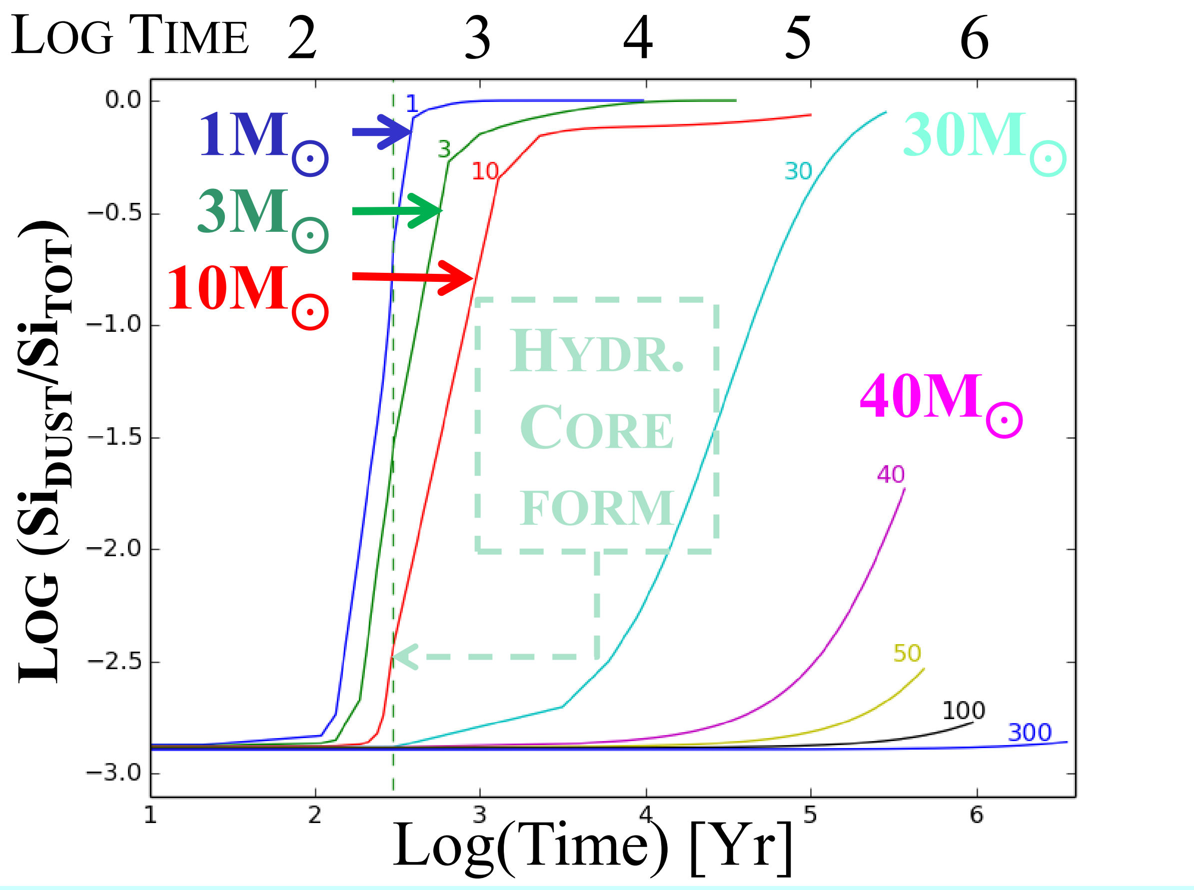
Figure: integrated contribution on fragment size =10 x M*

➢ **RAPID DUST CONDENSATION DURING FORMATION OF LOW–INTERMEDIATE STARS**

➢ **UP TO ~ 5 TIMES MORE DUST THAN CORRESPONDING AGBs**

➢ **EFFICIENT FOR $Z > \frac{1}{10} Z_\odot$**

➢ **FASTER THAN MASSIVE STARS**



Conclusions

Revised Metals Yields based on new

- evolutionary tracks of intermediate mass stars (calibrated AGB)
- evolutionary tracks of massive stars (new mass-loss rates)
- SN explosion recipes (both ejecta and remnant nature)
  - Fair agreement with previous calculations at $Z_{\odot}$
  - Lower ejecta at lower Z, likely shorter AGB lifetimes
  - Winds from very massive stars important (~ / > SN)

Dust formation model + updated stellar AGB tracks

- contribution of **AGB stars** to the **dusty ISM**
  - Confirm significant contribution at $Z_{\odot}$
  - At low Z contribution may exceed initial metallicity due to strong III Dredge-UP

Dust formation in MCs collapse

- Seems the most rapid/efficient vehicle for dust formation at $\mathbf{Z} > \frac{\mathbf{1}}{\mathbf{10}}\mathbf{Z}_{\odot}$