Oxygen-rich dust production in evolved stars and supernovae

Lars Mattsson
(in collaboration with Anja C. Andersen)
Dark Cosmology Centre
http://www.dark-cosmology.dk/

Outline

- Dust formation in general
- Dust around AGB stars: oxygen vs. carbon
- Supernovae as dust producers: significant or not?
- The high-z dust mystery: how can there be so much dust so early on?
- Interstellar dust growth

General dust facts

- Grain **nucleation** – requires supersaturation pressure.
  - Only in stellar environments

$$S = \frac{P_{mon}}{P_{sat}(T_d)}$$

- Grain **growth** - both in stellar environment and in the ISM.

- **Important elements**: C, O, Mg, Si, S and Fe

Example of oxide grain growth

Olivine:

$$2xMg + 2(1\text{-}x)Fe + SiO + 3H_2O \rightarrow Mg_{2x}Fe_{2(1-x)}SiO_4(s) + 3H_2$$

Pyroxene:

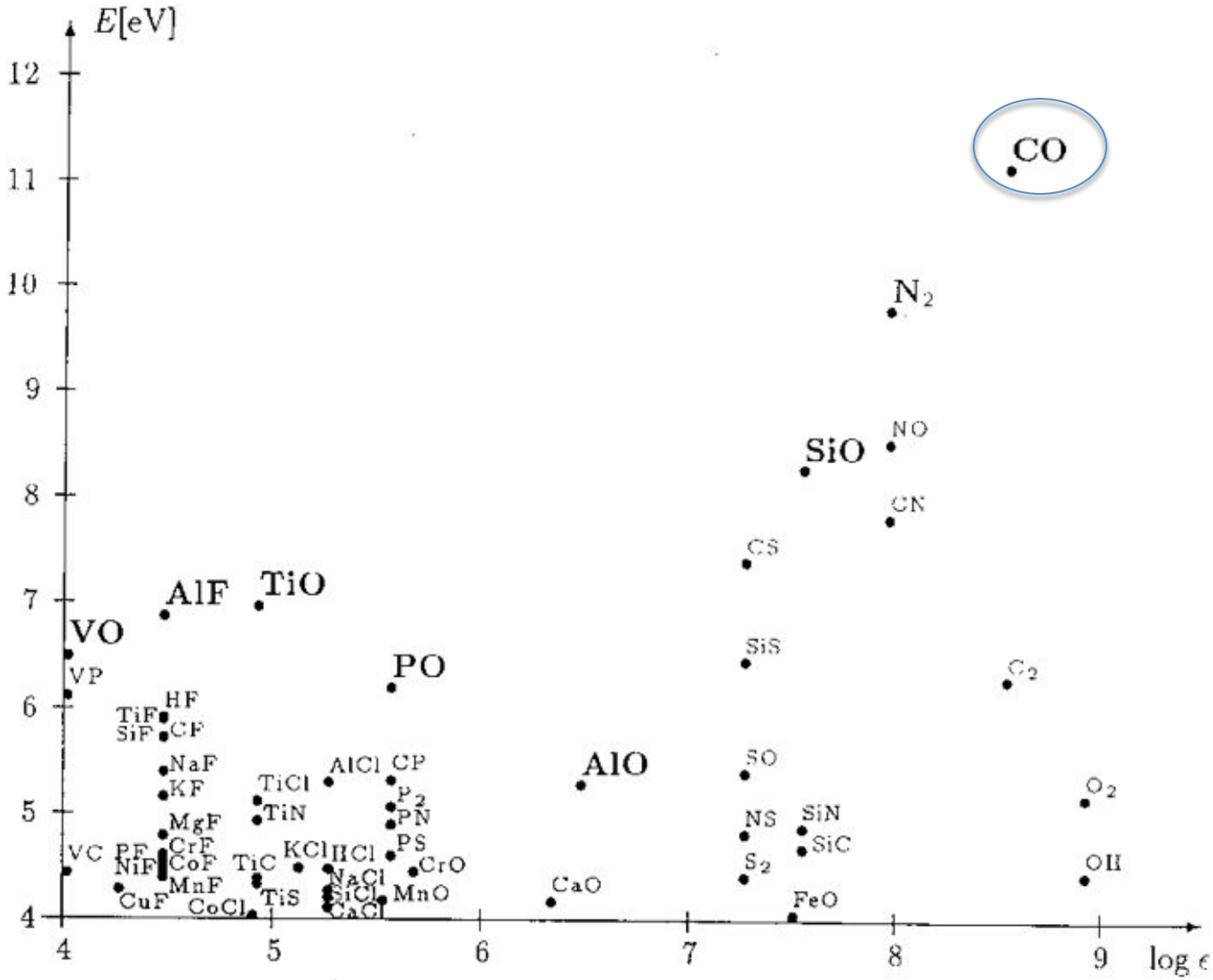
$$xMg + (1\text{-}x)Fe + SiO + 2H_2O \rightarrow Mg_xFe_{(1-x)}SiO_3(s) + 2H_2$$

It is even more complicated since:

$$Fe_2SiO_4(s) + 2Mg(g) \rightarrow Mg_2SiO_4(s) + 2Fe(g)$$

Forsterite

Oxygen vs. Carbon



Sedlmayr (1994, LNP 428, 163)

CO divides dust nucleation and growth into two different chemical paths

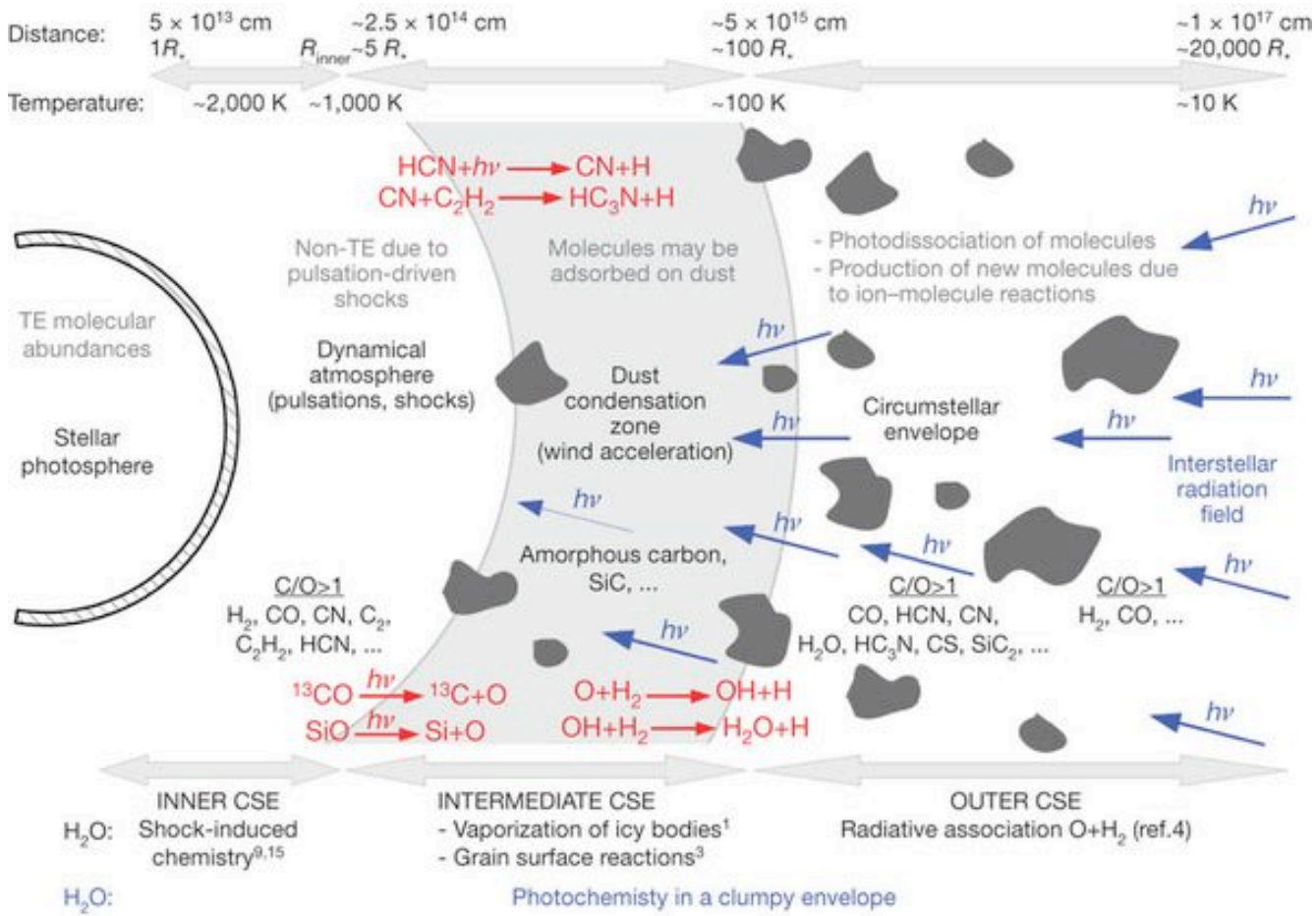
- **C/O > 1** Carbon chemistry
  - *Molecules:* C_2, CN, CH, C_2H_2, C_3, HCN).
  - *Possible **dust** types:* graphite (C), amorphous carbon (C), diamond (C), silicon carbide (SiC),…

- **C/O < 1** Oxygen chemistry
  - *Molecules:* OH, SiO, TiO, H_2O, TiO_2, VO, ZrO, ScO, YO, LaO).
  - *Possible **dust** types:* enstatite ($MgSiO_3$), olivine ($MgFeSiO_3$), ferrosilite ($FeSiO_3$), pyroxene ($MgFeSiO_4$), forsterite (Mg_2SiO_4), fayalite (Fe_2SiO_4),…

The dust formation window in AGB stars

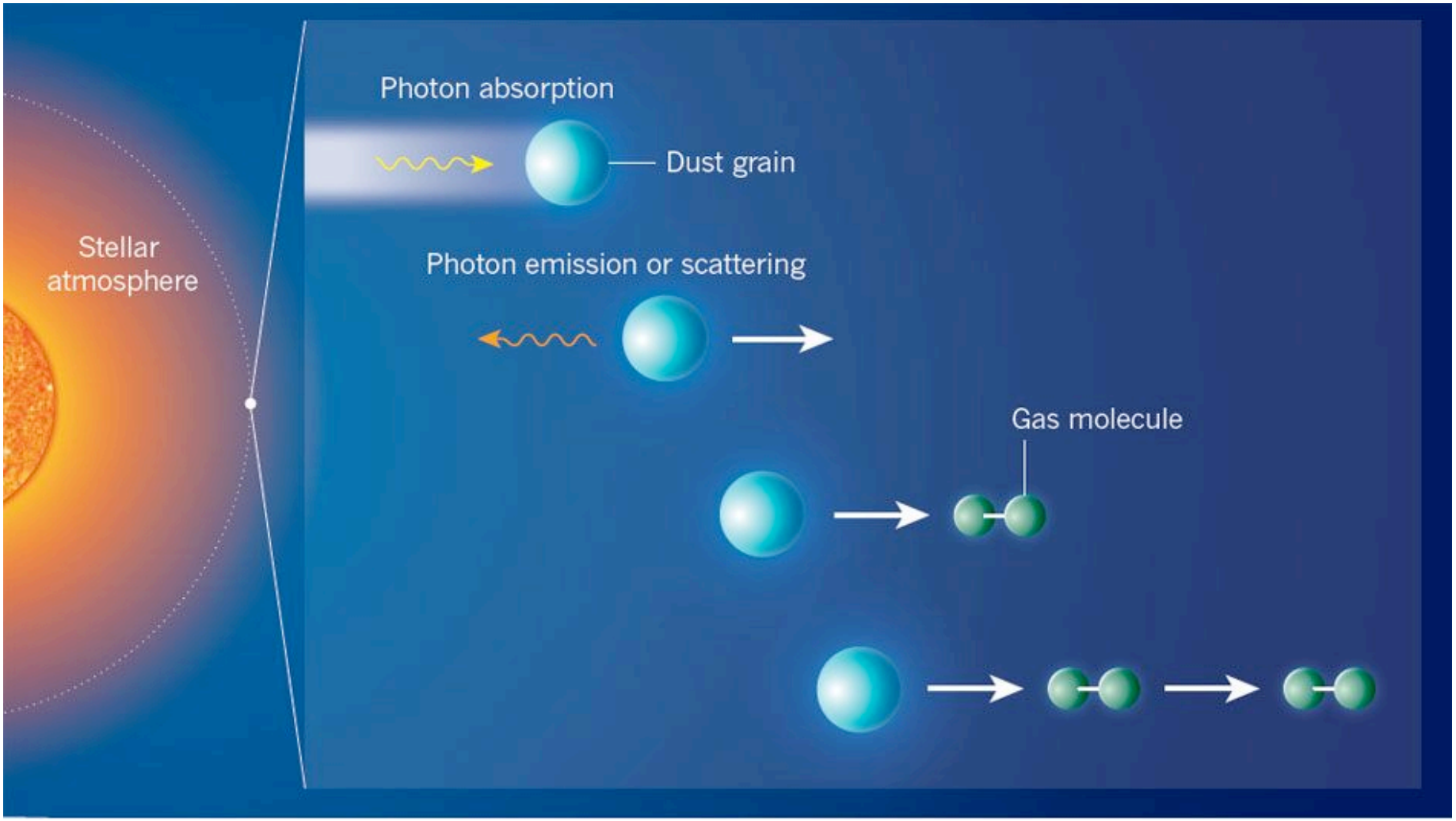
Grain nucleation – difficult!

Grain growth – easier!



Decin et al. (2010, Nature, 467, 64)

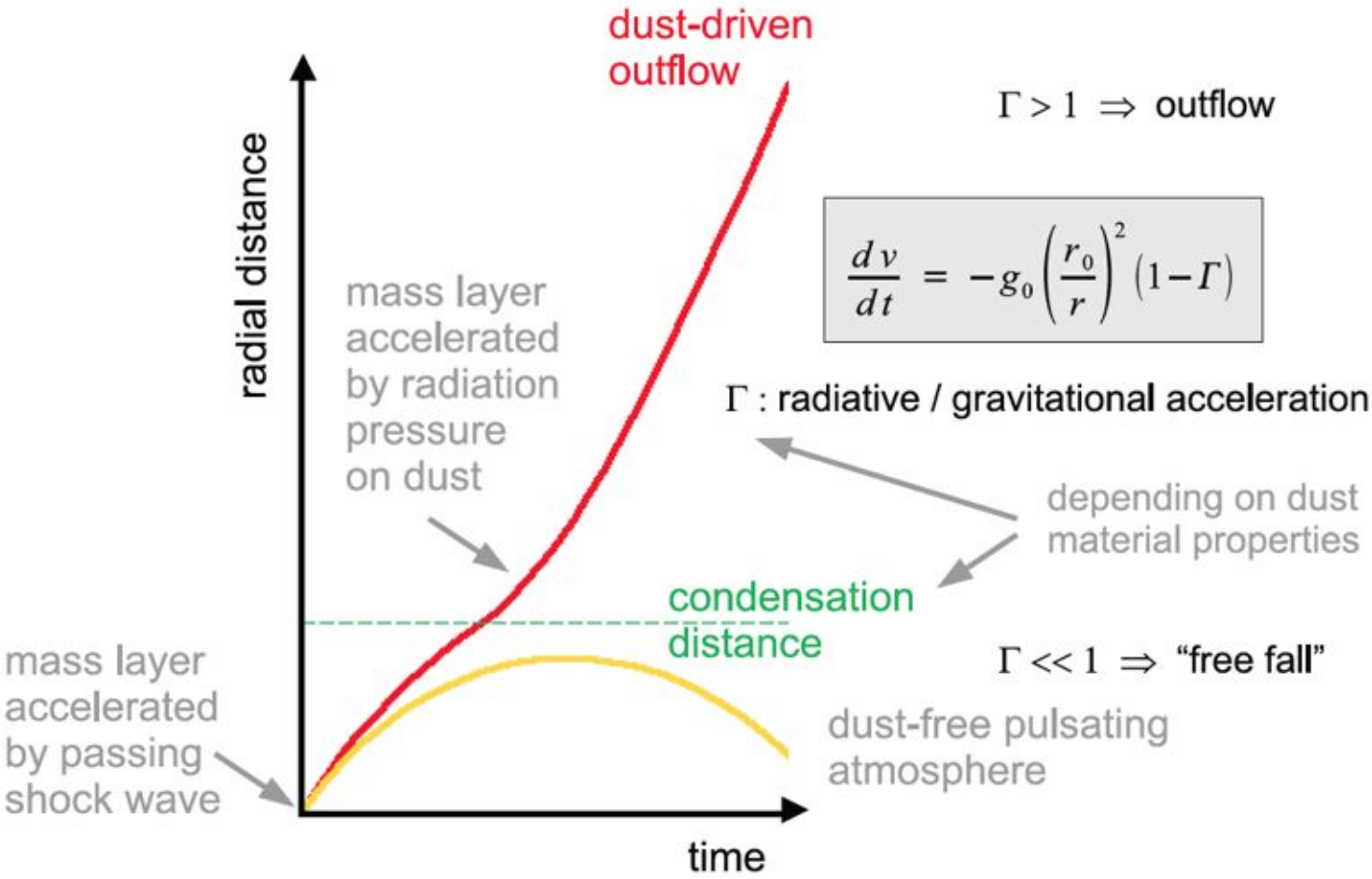
Microphysics of dust-driven winds



Dust grains acquire momentum from stellar photons and transfer it to the surrounding gas via collisions.

Höfner (2012, Nature, 484, 172)

Macrophysics of dust-driven winds



$\Gamma > 1 \Rightarrow$ outflow

$$\frac{dv}{dt} = -g_0 \left(\frac{r_0}{r}\right)^2 (1-\Gamma)$$

Γ : radiative / gravitational acceleration

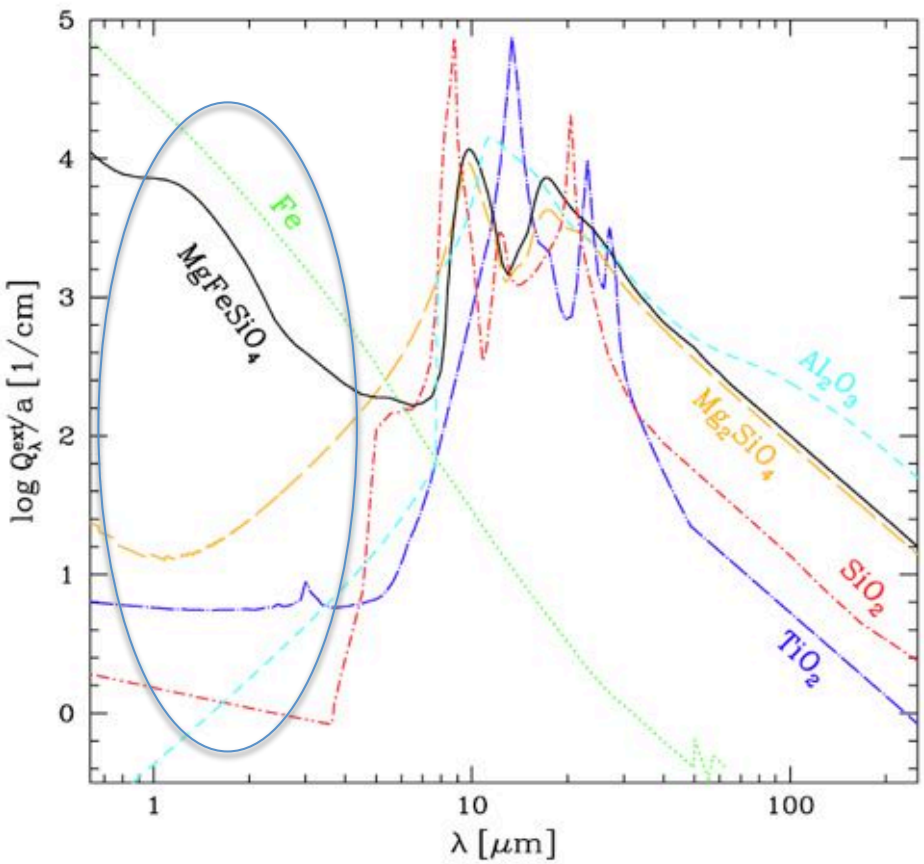
depending on dust
material properties

$\Gamma << 1 \Rightarrow$ "free fall"

There is a critical condensation radius!

Höfner (2011, ASPC, 445, 193)

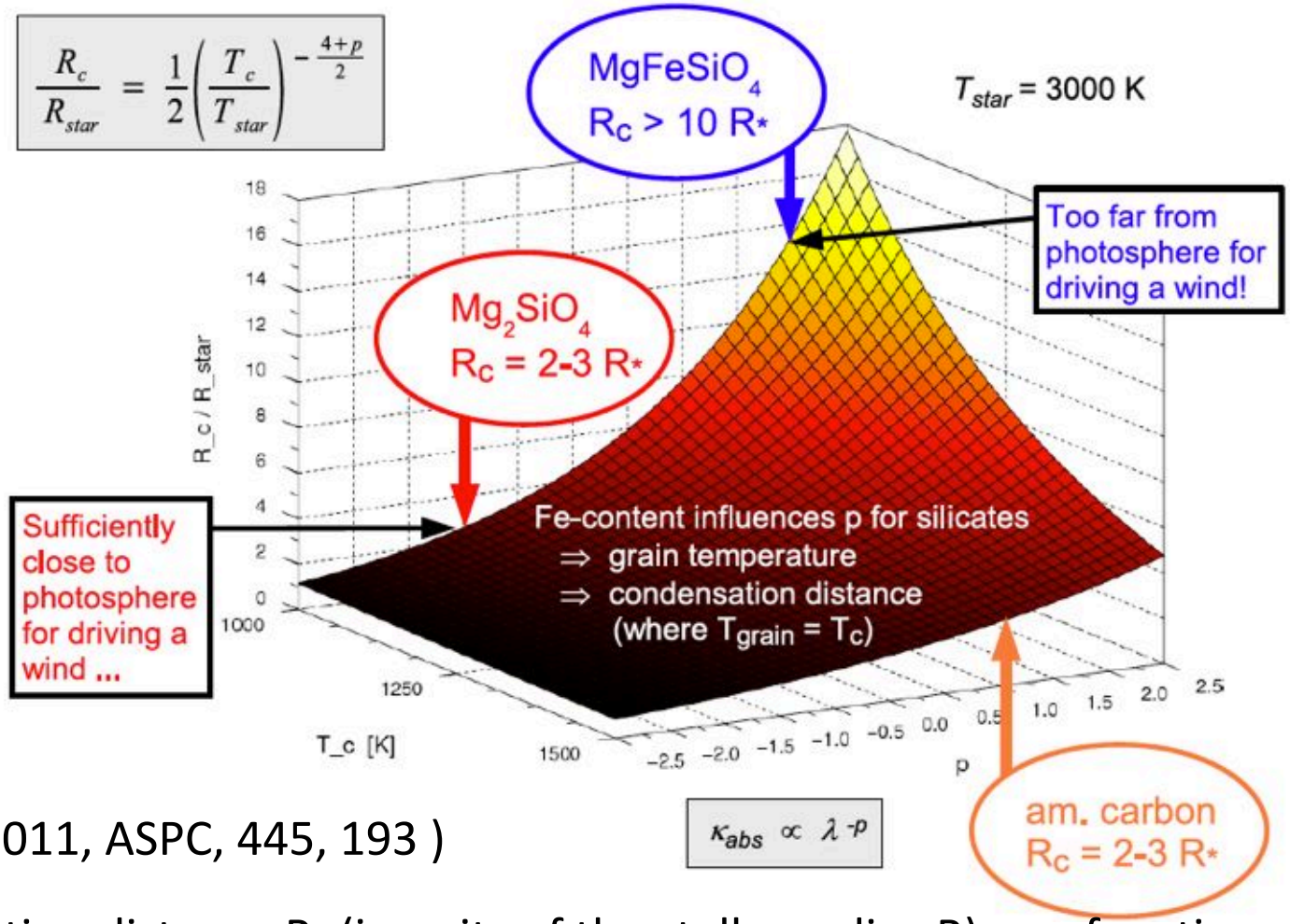
Dust extinction efficiencies



Extinction efficiencies over particle radius Q_{ext}/a in the Rayleigh-limit of Mie theory.

Woitke (2006, A&A, 460, L9)

Dust condensation distances in AGB stars

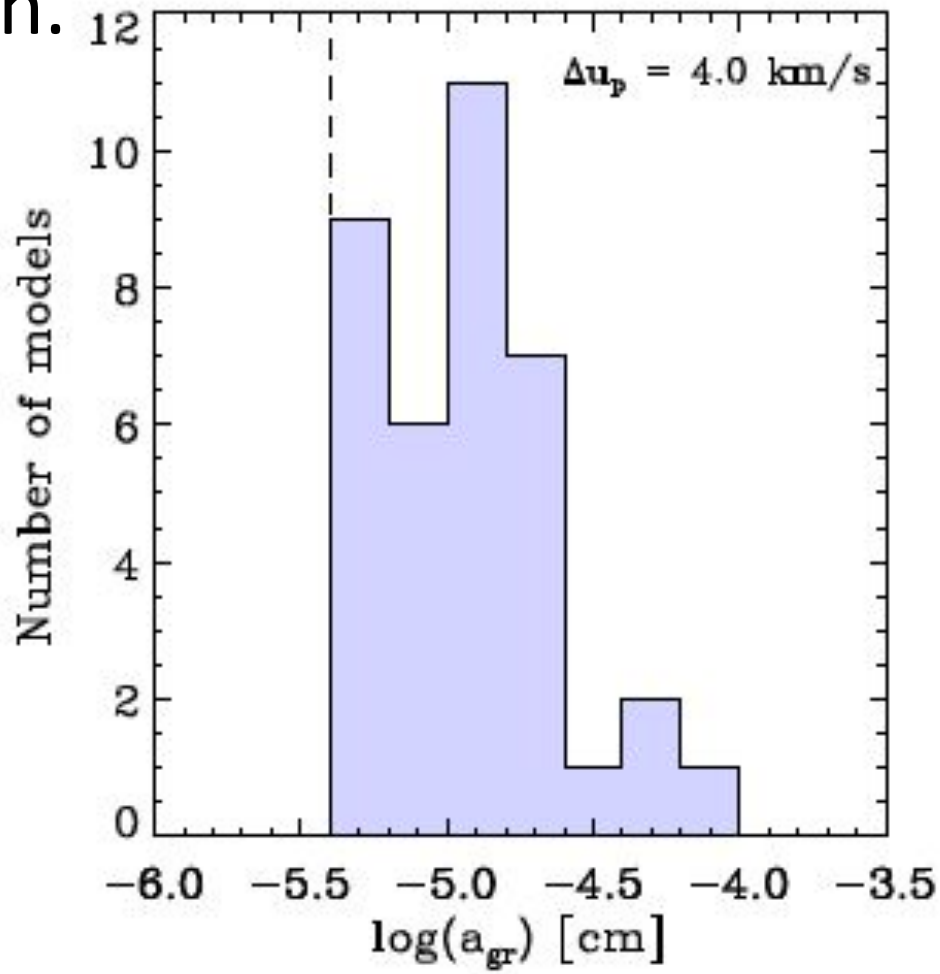


Höfner (2011, ASPC, 445, 193)

Condensation distance R_c (in units of the stellar radius R) as a function of the power law index of the absorption coefficient p for a range of condensation temperatures T_c (assuming a stellar temperature of T= 3000 K.

Models of dust formation in AGB stars

- Small particle limit: grains much smaller than the relevant wavelength.
- Grain size distribution
  - C-rich stars >0.1 μm
  - O-rich stars ~0.3 μm is optimal.



Very large grains!

Mattsson & Höfner (2011, A&A, 533, A42)

Observed dust properties

From

A close halo of large transparent grains around extreme red giant stars

Barnaby R. M. Norris, Peter G. Tuthill, Michael J. Ireland, Sylvestre Lacour, Albert A. Zijlstra, Foteini Lykou, Thomas M. Evans, Paul Stewart & Timothy R. Bedding

Nature **484**, 220–222 (12 April 2012) | doi:10.1038/nature10935

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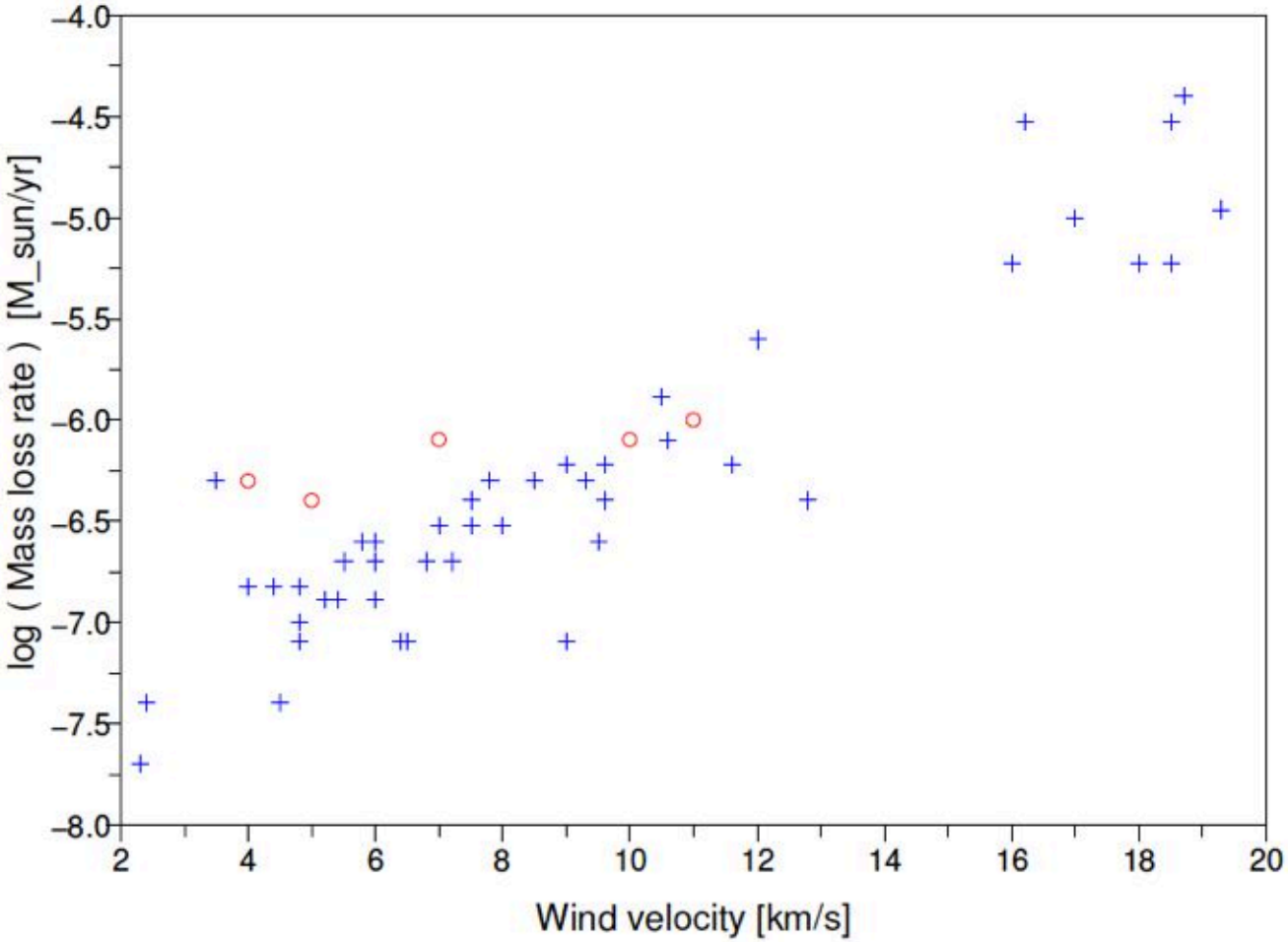
Table 1: Summary of fitted model parameters

Star	Φ	λ (μm)	R_{star} (mas)	R_{shell} (mas)	Scattered fraction	Grain radius (nm)	Scattering-shell mass
RDor	0.7	1.04	27.2±0.2	43.3±0.3	0.124±0.003	299±39	$(2.7\pm0.2)\times10^{-10}\,M_\odot$
		2.06	27.7±1.4	43.6±3.2	0.014±0.002		
WHya	0.2	1.04	18.7±0.4	37.9±0.2	0.176±0.002	316±4	$(1.04\pm0.02)\times10^{-9}\,M_\odot$
		1.24	18.9±0.5	37.0±0.3	0.110±0.003		
		2.06	18.9 (fixed)	37.0 (fixed)	0.022±0.004		
RLeo	0.4	1.04	18.3±0.3	29.9±0.4	0.120±0.003	~300*	$\sim2\times10^{-10}\,M_\odot$

Norris et al. (2012, Nature, 484, 220)

Observed dust properties



Mass loss rate vs. wind velocity for M-type AGB stars.

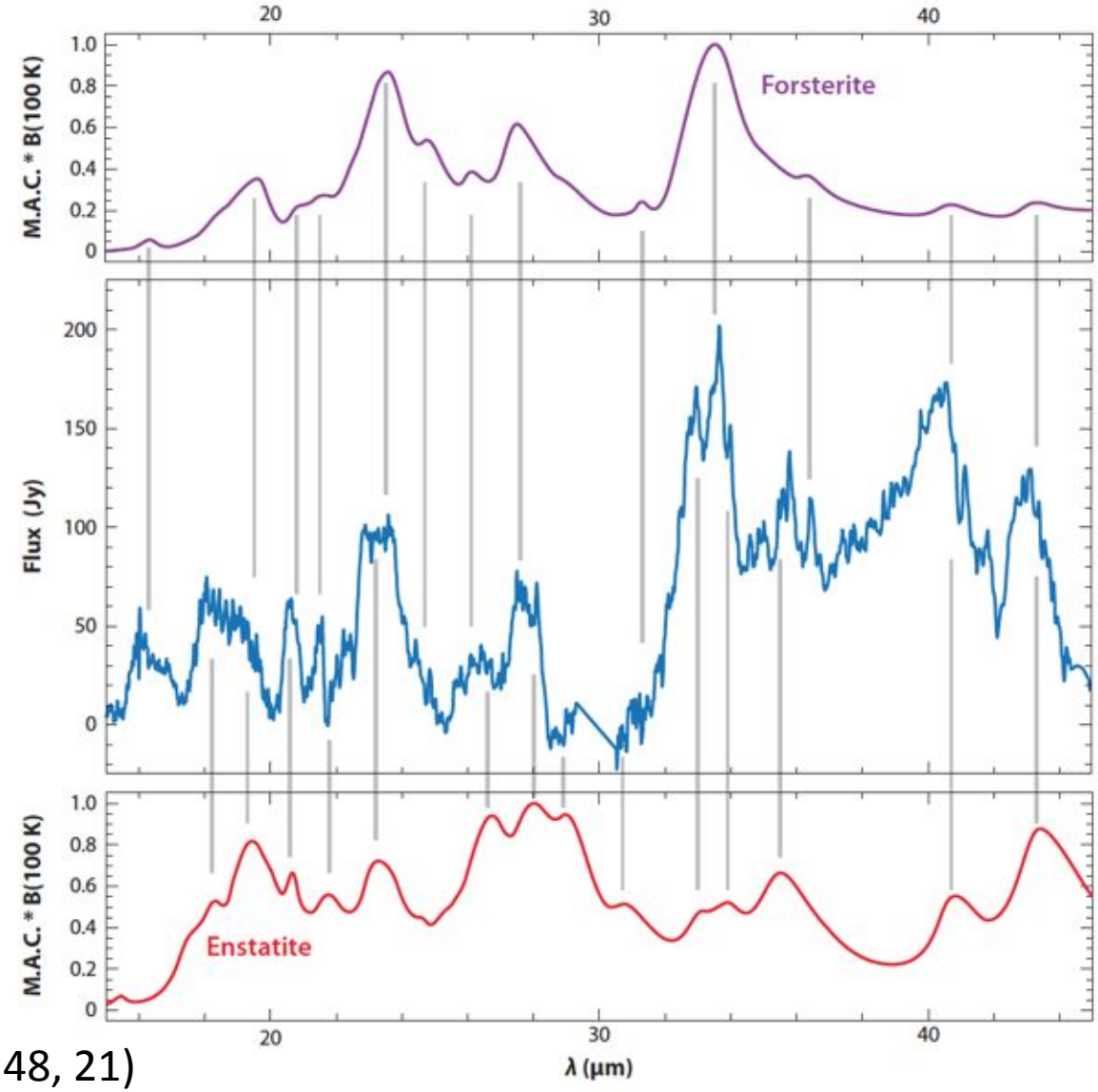
Crosses observations by Olofsson et al. (2002, A&A, 391, 1053), González Delgado et al. (2003. A&A, 411, 123)

Circles models by Höfner (2008, A&A, 491, L1); winds driven by micron-sized Fe-free silicate grains.

Observed dust properties

Figure 6

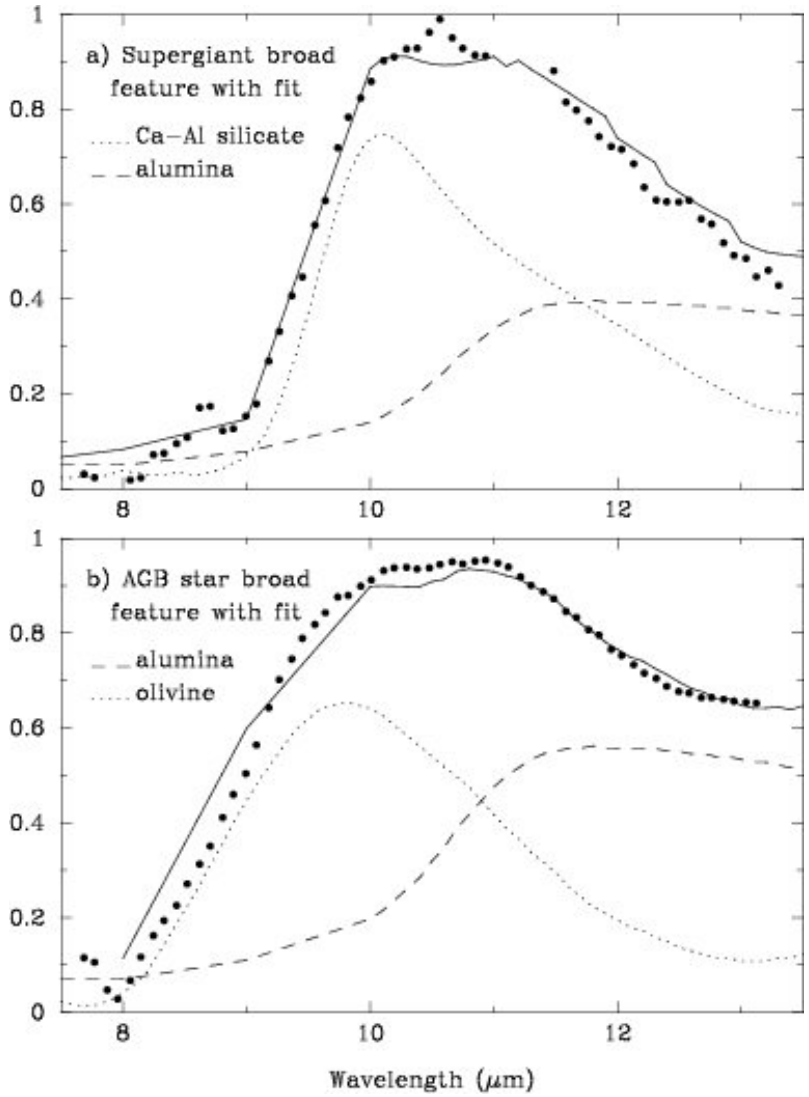
Comparison of the continuum-subtracted spectrum of the object AFGL 4106 with the mass absorption coefficient of forsterite (*purple line*) and enstatite grains (*red line*) multiplied by a Planck curve of 100 K and normalized to 1. AFGL 4106 is a double-line spectroscopic binary; the warmer component is likely a post-Red-Supergiant. After Jäger et al. (1998).



Henning (2010, ARA&A, 48, 21)

Observed dust properties

- Older observations suggested olivine and porous amorphous Al_2O_3.
- Probably an incorrect conclusion drawn from limited data.
- But shows how difficult this is!



Speck et al. (2000, A&AS,146, 437)

Implication on dust from AGB stars observations and theory

- AGB stars - **intense (dust-driven) mass loss**.
- O-rich AGB winds are driven by micron-sized **Fe-free silicates**.

Supernova dust production efficiency

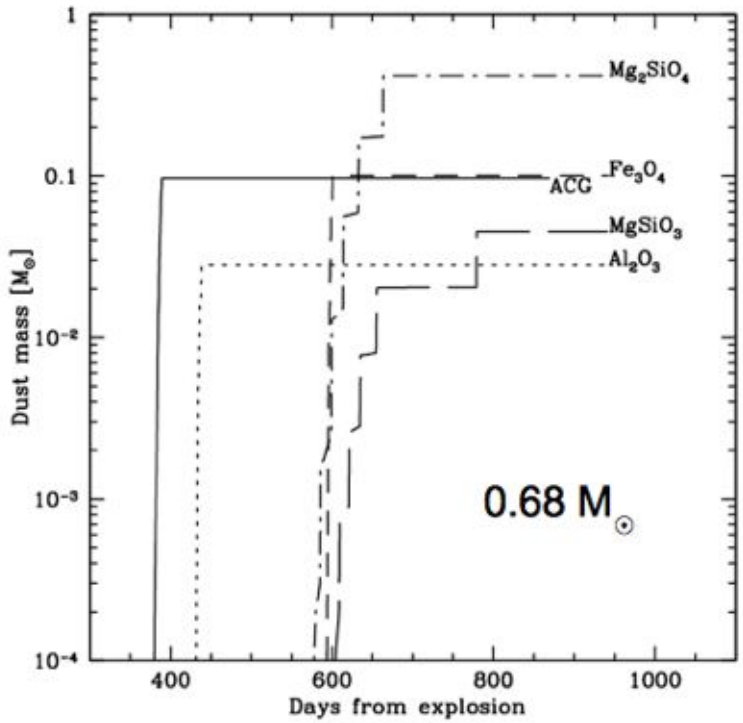


Figure 1. Dust formation as a function of time elapsed since explosion in SN1987A.

Todini & Ferrara (2001, MNRAS, 325, 726)

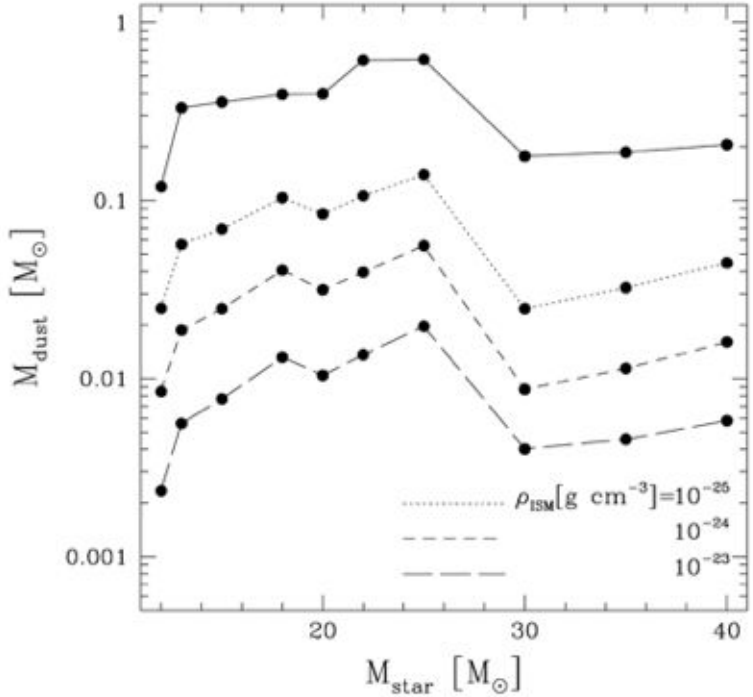


Figure 5. Mass of dust that survives the passage of the reverse shock in the ejecta, as a function of the mass of the progenitor star and of the density of the surrounding ISM. The solid line shows the initial dust mass (same as the solid line in Fig. 2).

Bianchi & Schneider (2007, MNRAS, 378, 973)

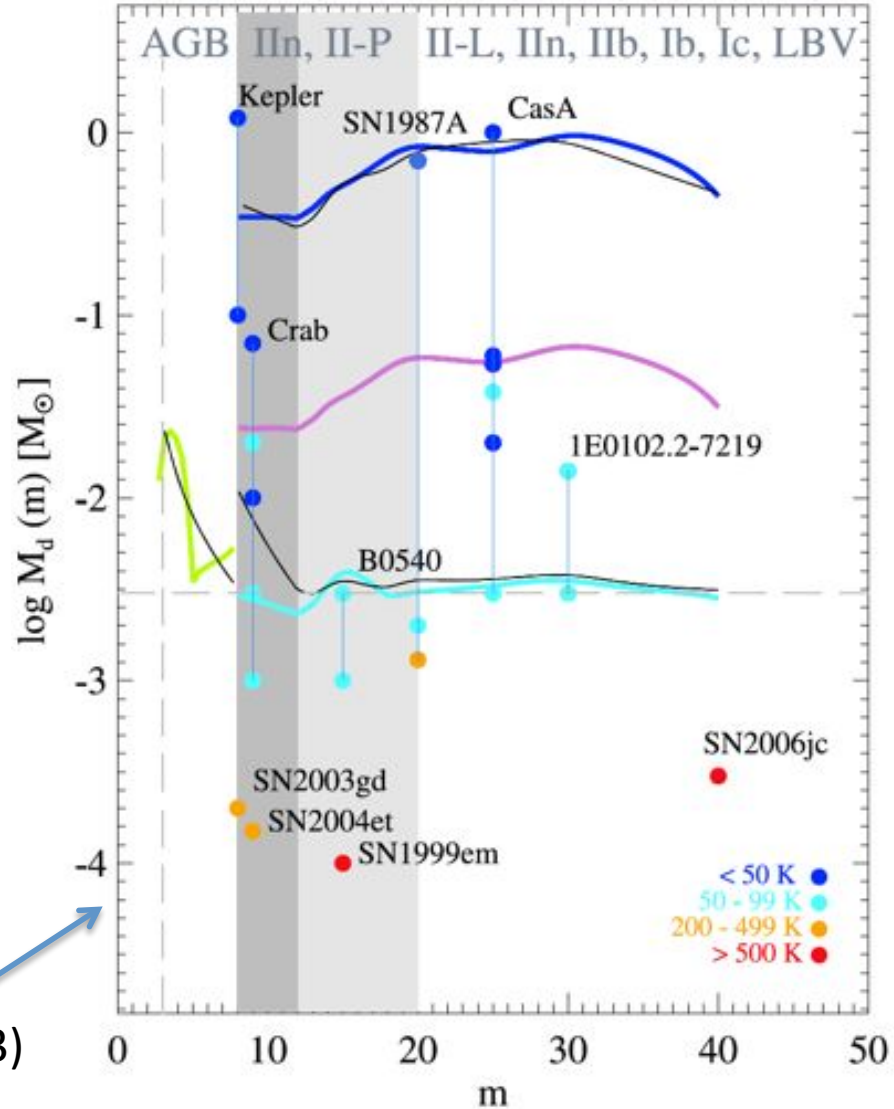
Similar findings by Fallest et al. (2011, MNRAS 418, 571), Nosawa et al. (2007, ApJ, 666, 955)

Mass of dust that **survives** the passage of **the reverse shock** in the ejecta, as a function of the **mass of the progenitor** star and of the **density of the surrounding ISM**.

Observational limits on SN dust

Very little warm dust observed in SNe, < 10^{-2} M_O
(e.g. Wooden et al. 1993, ApJS, 88, 477; Elmhamdi et al. 2003, A&A, 426, 963; Kotak et al. 2009, ApJ, 704, 306; Meikle et al. 2011)

But controversy over large cold dust mass in SNRs
(see Dunne et al. 2009, MNRAS, 394, 1307 and related papers on Cas A)



Gall et al. (2011, A&AR, 19, 43)

Observational limits on SN dust

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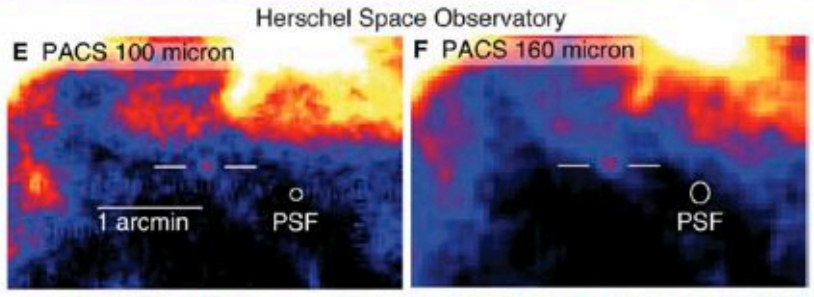


Matsuura et al. (2011, Science, 333, 1258)

SN1987A

- A 100% dust efficiency.
- **All** metals are locked up in dust – no free metals to enter the ISM?

SN 1987 A

- Progenitor: 15 – 20 M_{sun}
- Matsuura et al. 2011 – cold dust
  - If C-dust + silicates: 0.5 – 0.7 M_{sun}
  - If only silicates: 2.4 M_{sun}

- 18 M_{sun} produces 0.13 M_{sun} of silicon.
- $A_{silicates} = 121.41 \rightarrow M_{silicates} < 0.56\ M_{sun}$
- $M_C = 0.22\ M_{sun} \rightarrow M_{C\text{-}dust} < 0.22\ M_{sun}$

SN 1987 A

- More elaborate: upper limit ~0.2 M_{sun}.
- The reason is **dust chemistry**.
- 1.2 M_{sun} of molecules – have Matsuura et al. detected molecular gas?

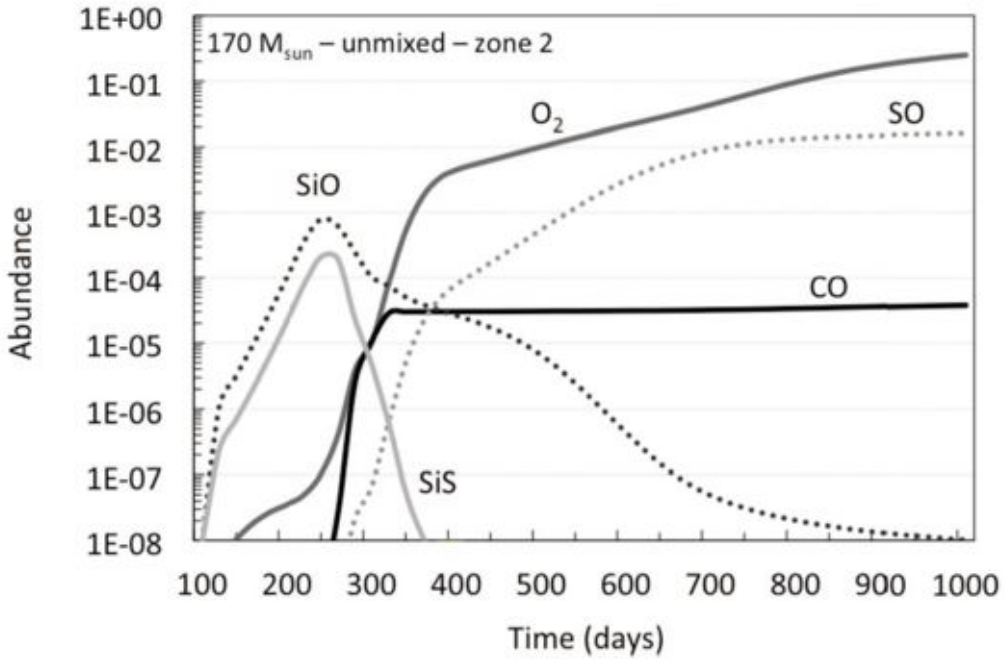


Figure 3. Molecular abundances as a function of total gas number density for Zone 2 of the unmixed PISN ejecta with a 170 $M_\odot$ progenitor (Cherchneff & Dwek 2009).

Table 1. Molecular and Dust Masses Ejected at 1000 Days Post-explosion for the Unmixed 170 $M_\odot$ and 20 $M_\odot$ Progenitors.

Progenitor Mass	170 $M_\odot$	20 $M_\odot$
Molecules	37.1 $M_\odot$	1.2 $M_\odot$
% of Progenitor Mass	21.8	6.0
Dust upper limit	5.5 $M_\odot$	0.2 $M_\odot$
% of Progenitor Mass	3.2	1.0

Cherchneff (2010, APSC, 425, 237)
Cherchneff & Dwek (2009, ApJ, 703, 642)

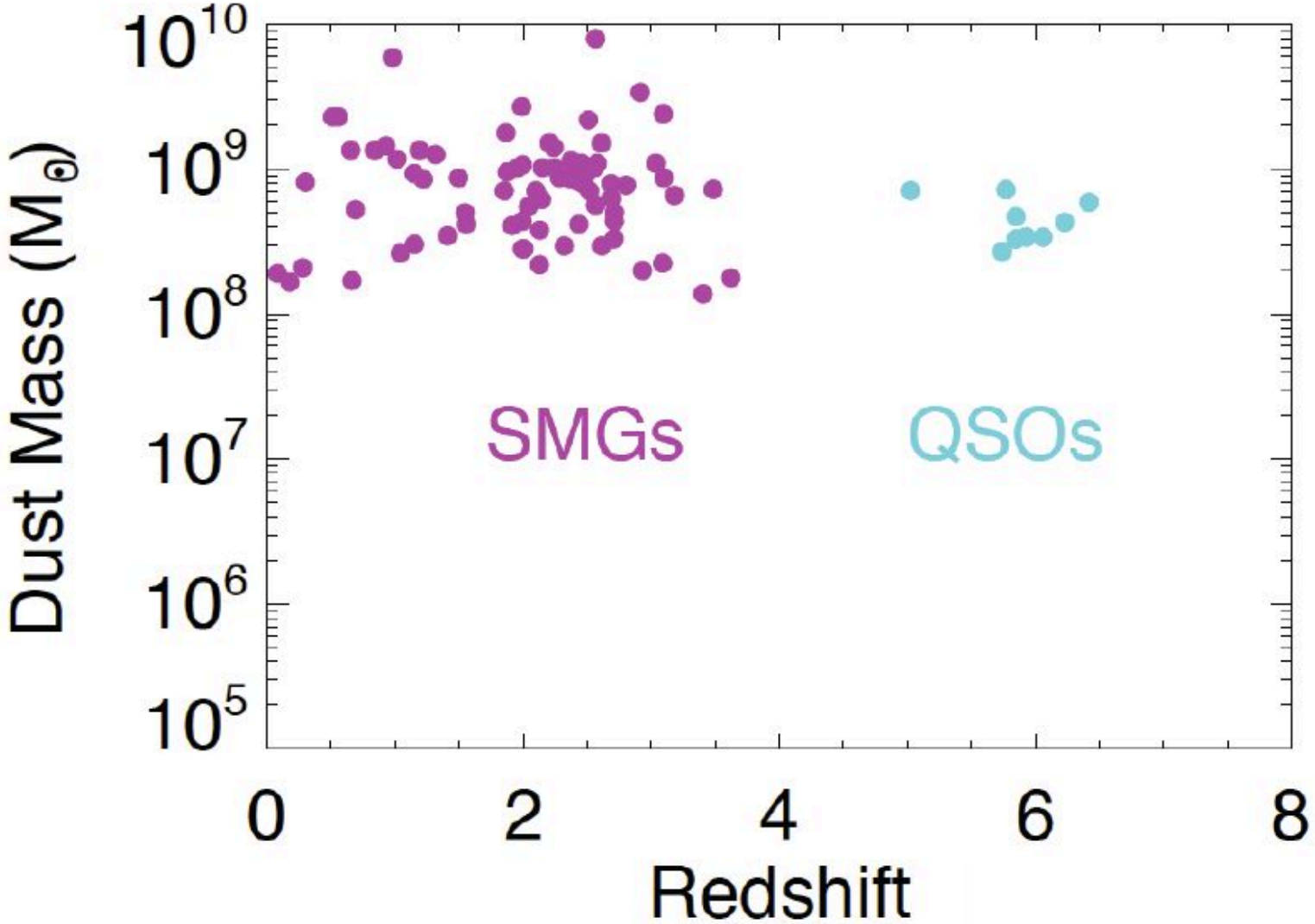
SN 1987 A

- If dust evenly distributed, then $A_V > 12$… eh?
- So dust must be in clumps?
- Is the supernova environment O-rich or C-rich or both?
- Dust types? (Iron free again?)

Implication on dust from SN theory and observations

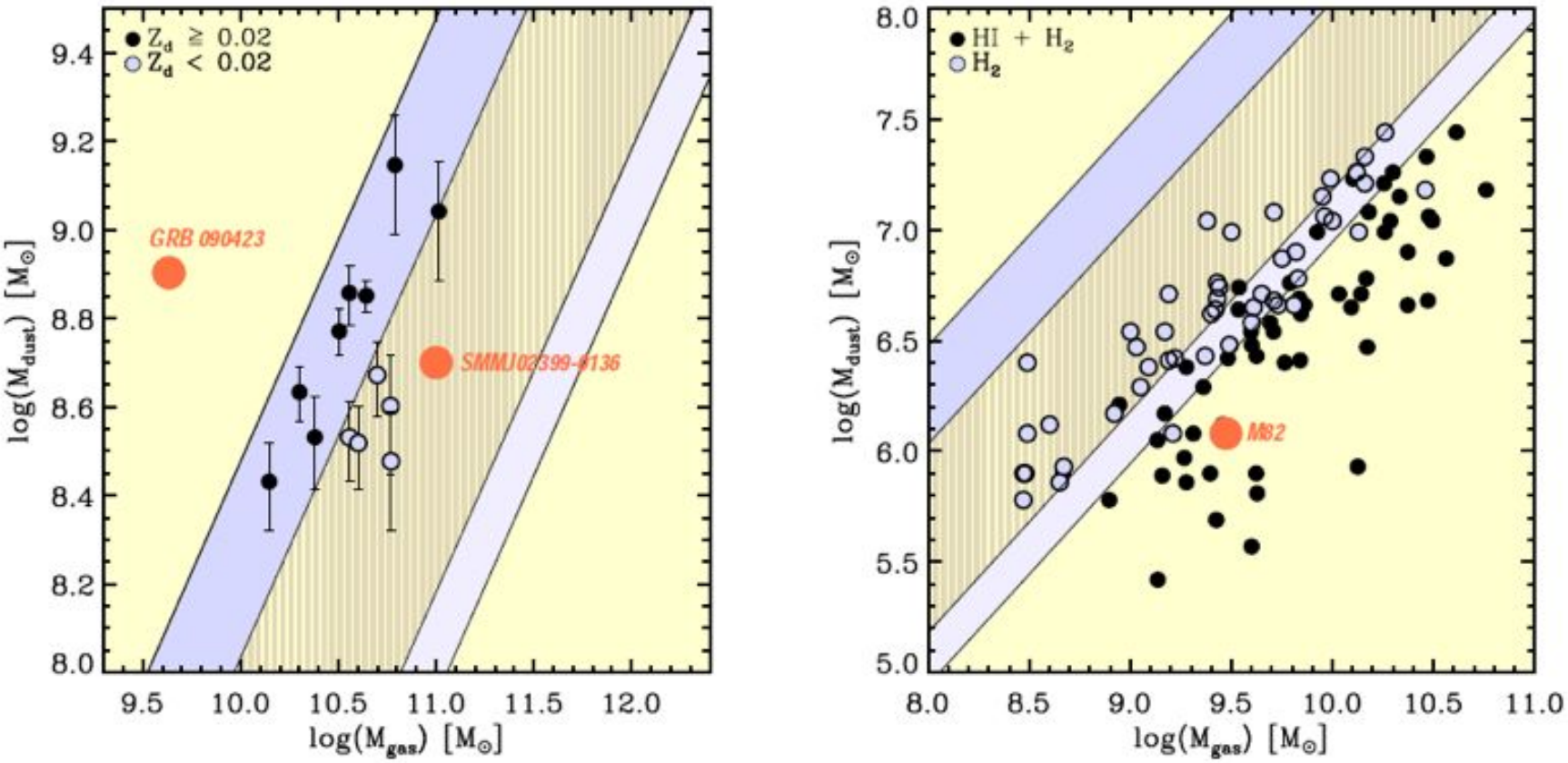
- SNe forms most of the elements.
- Theoretical models predict (significant) dust formation to occur in the remnant.
- Grain sizes are small and distributed in clumps?
- **Dust efficiency unclear** as it depends on the harsh environment, reverse shock, clumps.

Large amounts of dust at high redshift



Bertoldi et al. (2003, A&A, 406, L55), Michalowski et al. (2011) and others….

Large amounts of dust at high redshift



Mattsson (2011, MNRAS, 414, 781)

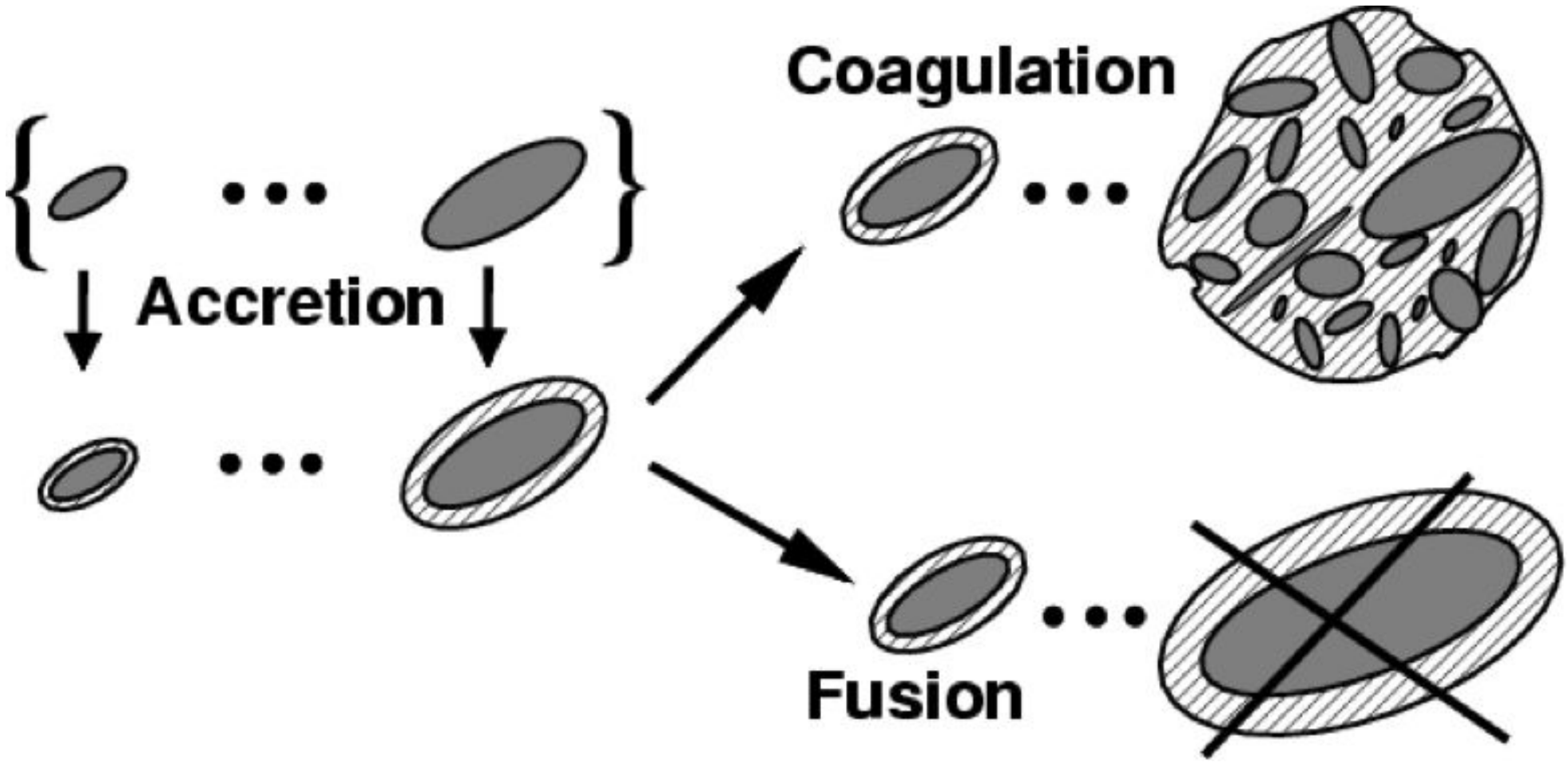
Implications of the observations

- Maximum time to build large dust masses: <400–500 Myr.
- SNe can produce dust radidly, but also destroy dust – A catch 22!
- The universe have been at least as dusty and possibly even more dusty at earlier epochs. But how?

Grain growth in the ISM

- Silicate dust in meteorites: ~20% crystalline (Keller 2008).
- Interstellar silicates: < 2% crystalline (Kemper et al. 2005).
- Indicates ≤ 10% of interstellar silicates is stardust, while ≥90% is grown in the ISM, since (≤ 10%) × 20% → ≤ 2% (Bruce Draine).

Grain growth in the ISM



Dartois 2006, A&A 445, 959

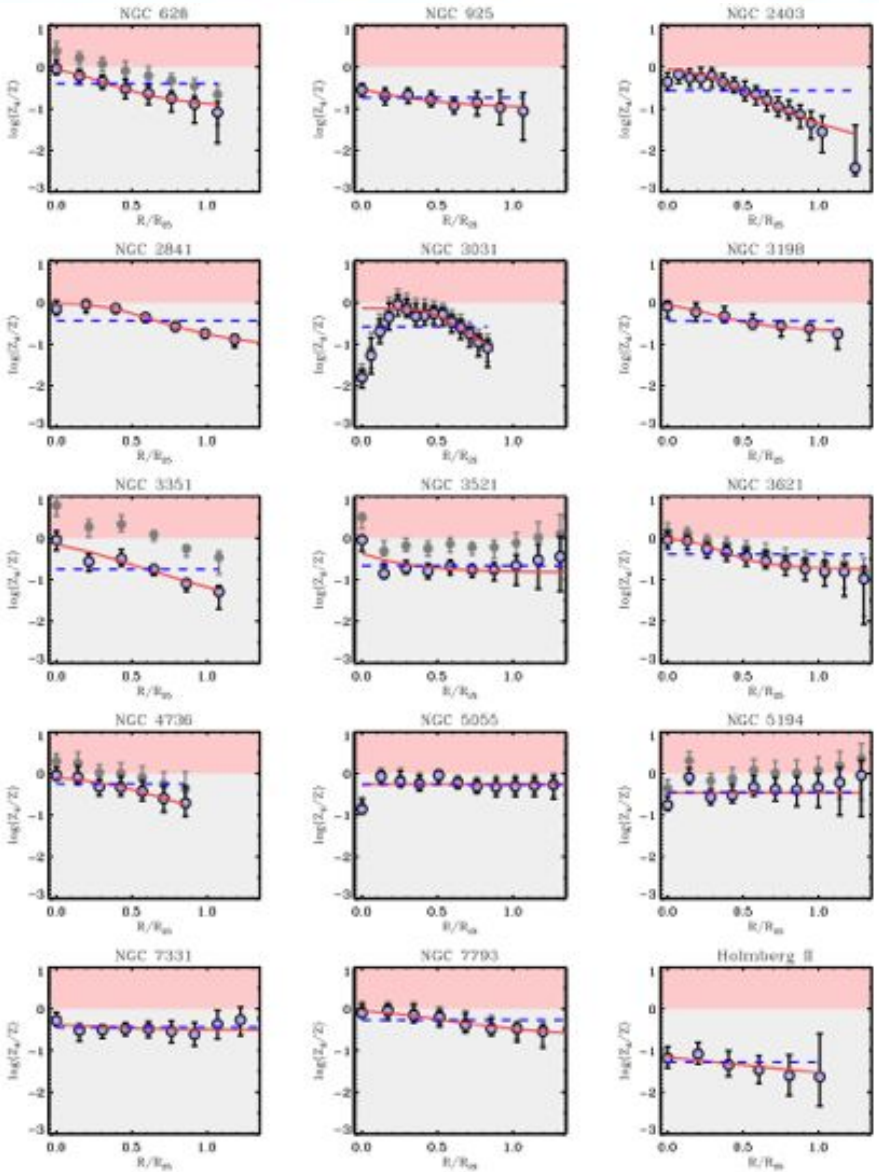
Can we distinguish between the SN vs. ISM scenario?

- High-SN dust efficiency – SNe produce all dust
  - Crystalline dust?
  - Both C-dust and silicates?
  - Grain size distribution?

- High ISM growth efficiency – SNe provides seeds and metals, but dust grown in the ISM
  - Amorphous dust?
  - Dirty silicates?
  - Grain size distribution?

Can we distinguish between the SN vs. ISM scenario?

- ”THEOREM”: *If the dust gradient is steeper than the metallicity gradient, dust must be grown in the ISM unless the stellar dust yield has a very steep dependence on metallicity.*
- Extreme radial flows with ”drift” may in principle also work, but there is no observational evidence…



Mattsson et al. (2012, MNRAS, online), Mattsson & Andersen (2012, MNRAS, online)

Conclusions

- Oxygen rich AGB stars expel mainly large iron-free silicates.
- Supernovae may, or may not, be significant dust producers. Probably iron-free silicates.
- Dust sources at high-z still not clear, but SN seems a likely source while AGB stars are minor contributions at best.
- Interstellar dust growth is also an option, but stars still need to provide the seeds.