Nanoparticles in space: the synthesis of cosmic dust in the universe

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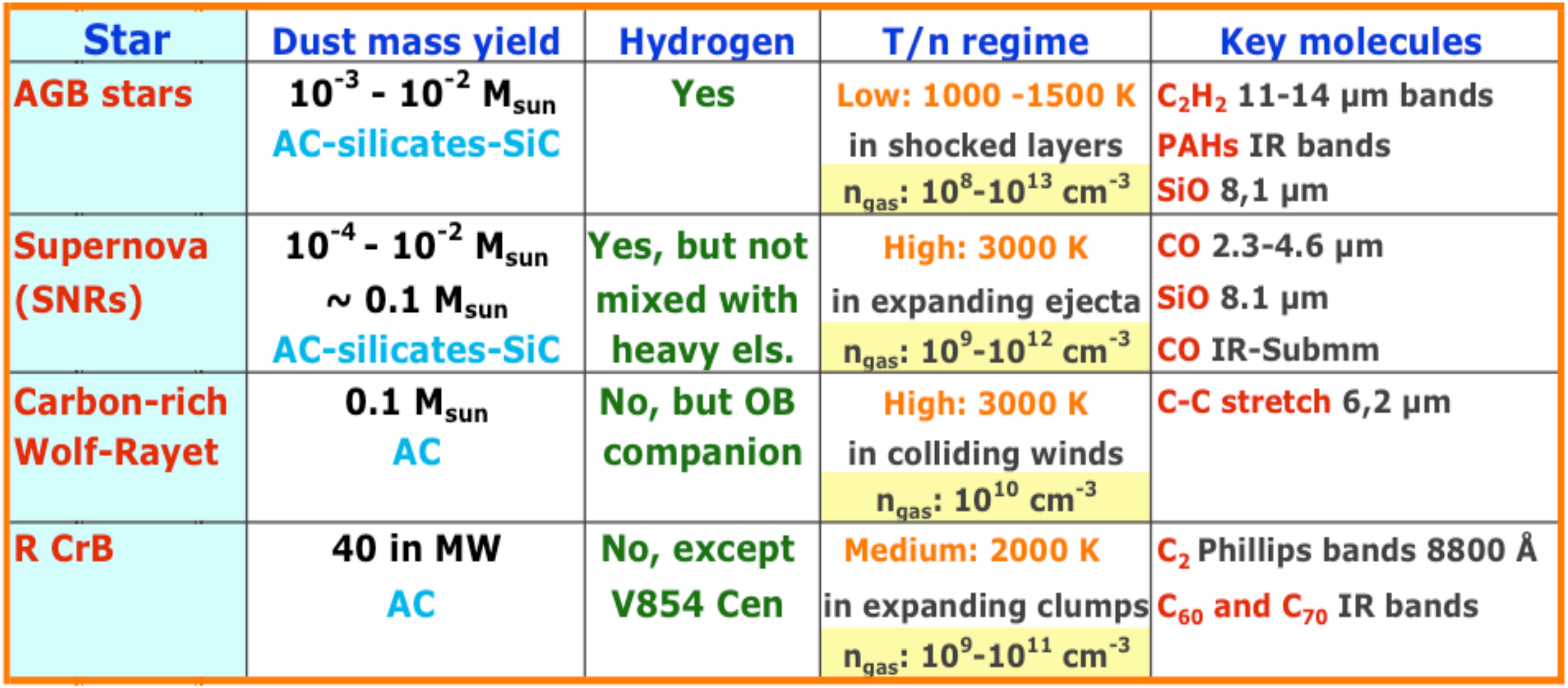
Overview

- Dust factories in galaxies
- Types of dust
- Physics & chemistry of dust formation:
  - existing models
  - chemical kinetics
- Formation pathways in stars
- A case study: Type II-P supernovae
- Conclusions

Dust factories in galaxies

Cosmic dust synthesis requires **high gas temperatures & densities, & enough time (chemical reactions and collisions)**

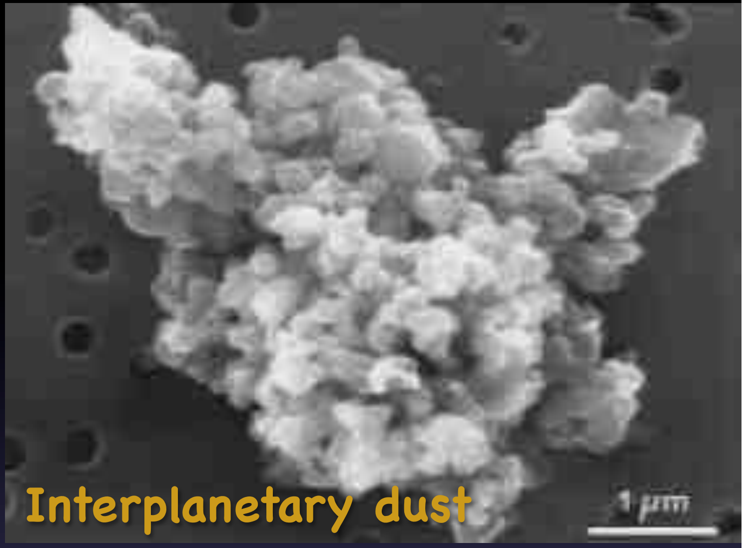
→ best loci are evolved circumstellar environments (shocks)



Star	Dust mass yield	Hydrogen	T/n regime	Key molecules
AGB stars	10^{-3} - 10^{-2} M_{sun} AC-silicates-SiC	Yes	Low: 1000 -1500 K in shocked layers n_{gas}: 10^{8}-10^{13} cm^{-3}	C_2H_2 11-14 μm bands PAHs IR bands SiO 8,1 μm
Supernova (SNRs)	10^{-4} - 10^{-2} M_{sun} ~ 0.1 M_{sun} AC-silicates-SiC	Yes, but not mixed with heavy els.	High: 3000 K in expanding ejecta n_{gas}: 10^{9}-10^{12} cm^{-3}	CO 2.3-4.6 μm SiO 8.1 μm CO IR-Submm
Carbon-rich Wolf-Rayet	0.1 M_{sun} AC	No, but OB companion	High: 3000 K in colliding winds n_{gas}: 10^{10} cm^{-3}	C-C stretch 6,2 μm
R CrB	40 in MW AC	No, except V854 Cen	Medium: 2000 K in expanding clumps n_{gas}: 10^{9}-10^{11} cm^{-3}	C_2 Phillips bands 8800 Å C_{60} and C_{70} IR bands

Origin of dust in the early universe...

Types of dust?


Interplanetary dust

Cosmic dust

- ✓ Fluffy aspect or more spherical shape for pure grains
- ✓ Size ranges from a few Å to a few µm

Silicates:

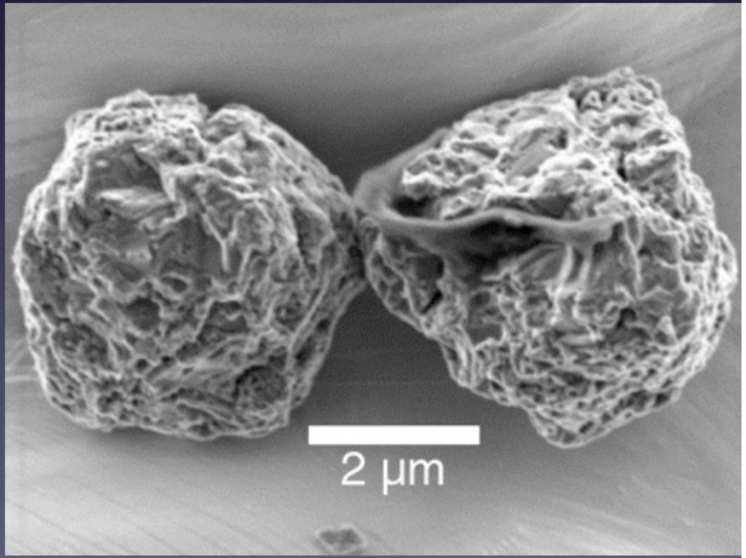
- ✓ Amorphous Fe/Mg-silicates
- ✓ Forsterite (Olivine - Mg_2SiO_4)
- ✓ Enstatite (Pyroxene - $MgSiO_3$)

Oxides:

- ✓ Alumina (Al_2O_3)
- ✓ Spinel ($MgAl_2O_4$)
- ✓ Wuestite (FeO)
- ✓ Hibonite ($CaAl_{12}O_{19}$)
- ✓ Rutile (TiO_2)

Carbides:

- ✓ Silicon carbide (SiC)
- ✓ Titanium carbide (TiC) ?



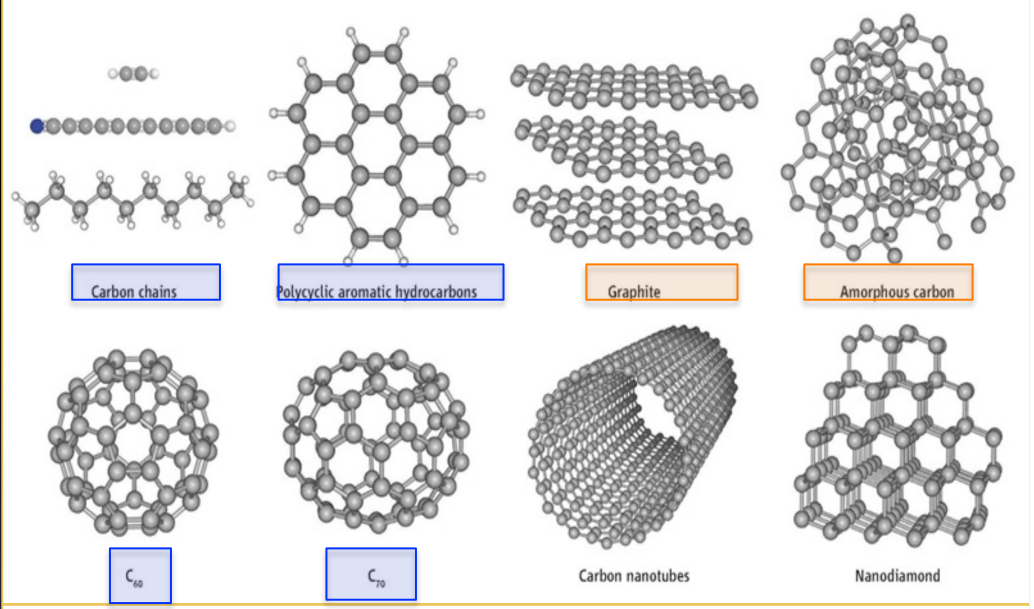
SiC stardust from Murchison meteorite

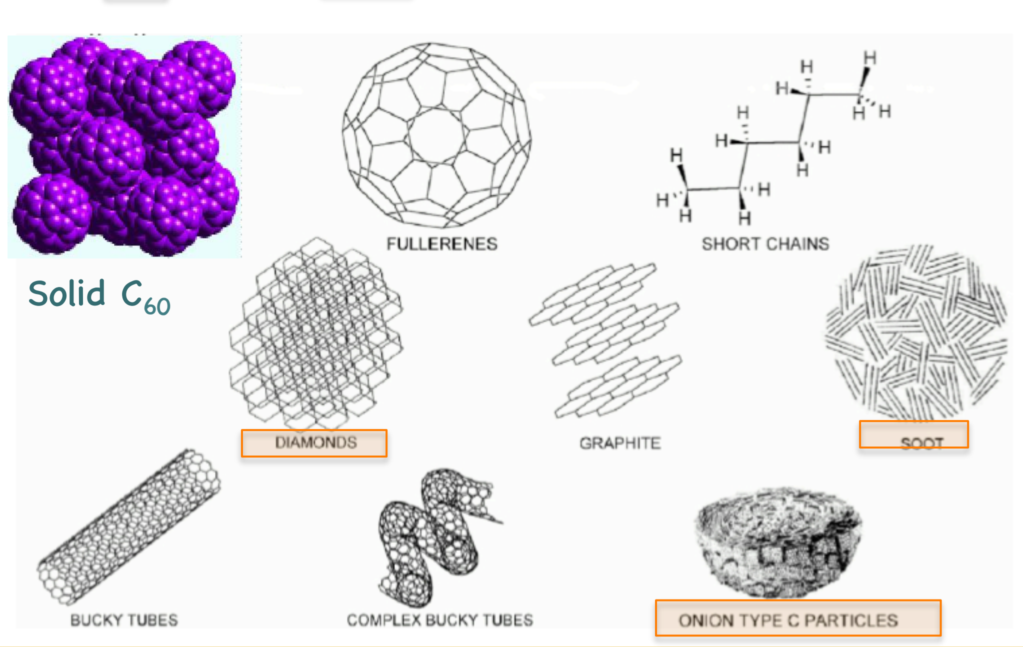
Types of dust?

Carbonaceous compounds

- ✓ Amorphous carbon & Graphite
- ✓ Diamond
- ✓ Hydrogenated Amorphous Carbon (HAC)
- ✓ Graphene (?) & Polycyclic Aromatic Hydrocarbons (PAHs)
- ✓ Fullerenes (C_{60}, C_{70}) Cami et al. 2010, solid (?) Evans et al. 2012

All these compounds are easily synthesised & well studied on Earth





Physics & chemistry of dust formation: existing models

To date, there exist no satisfactory model of dust formation in evolved circumstellar environments

- ✓ Thermodynamic equilibrium
- ✓ Classical Nucleation theory

Most promising

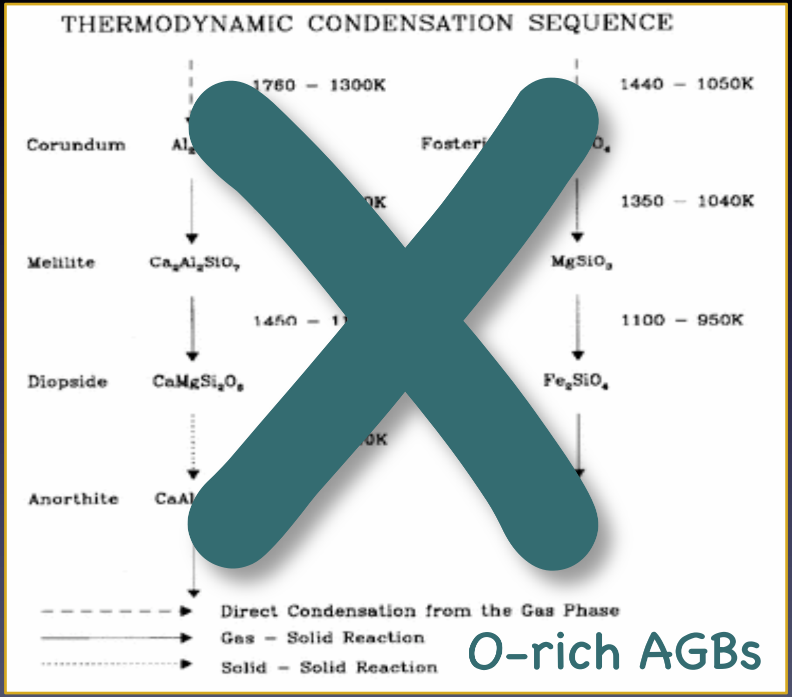
- ✓ Chemical kinetic approach

Physics & chemistry of dust formation: existing models

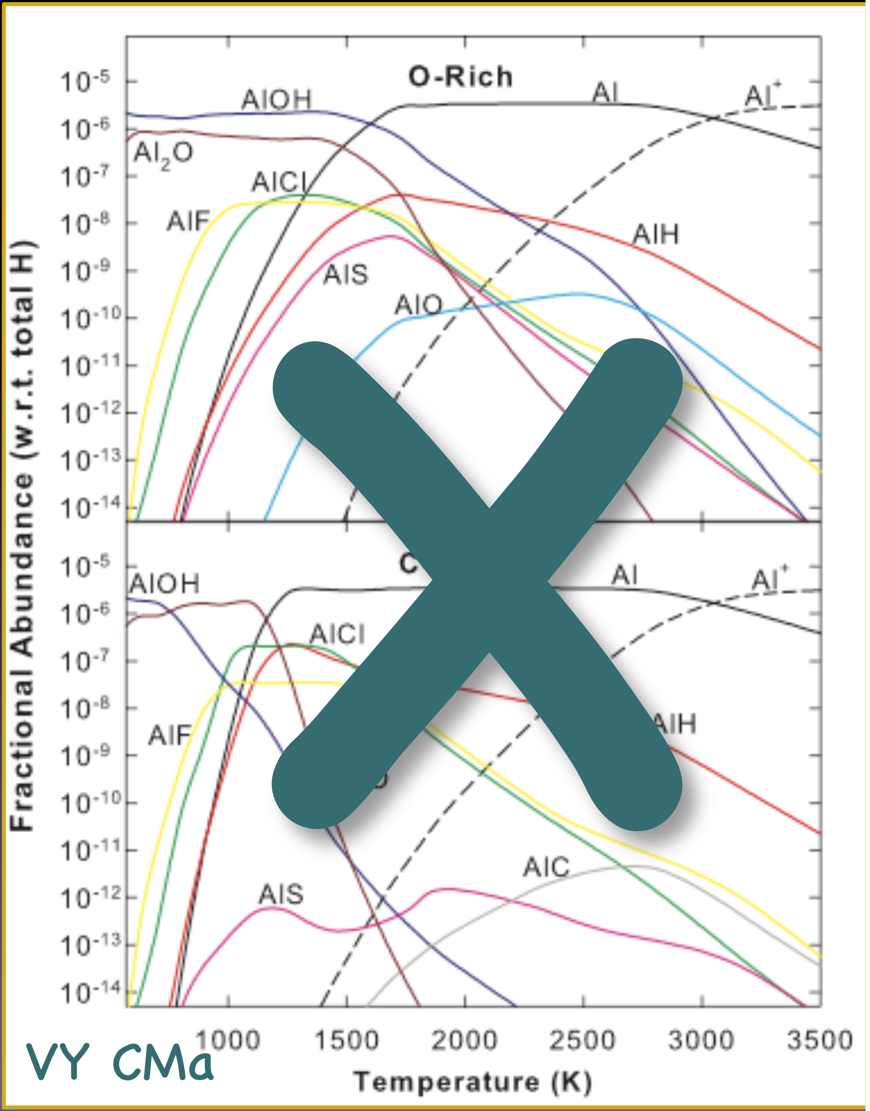
Thermodynamic equilibrium: used in meteorite studies & elsewhere!

Lodders & Feigley 1995, Tielens 1990, 1998, Ziurys et al. 2009

Tielens et al. 1998



P-T phase diagram inappropriate for dynamical outflows out of equilibrium



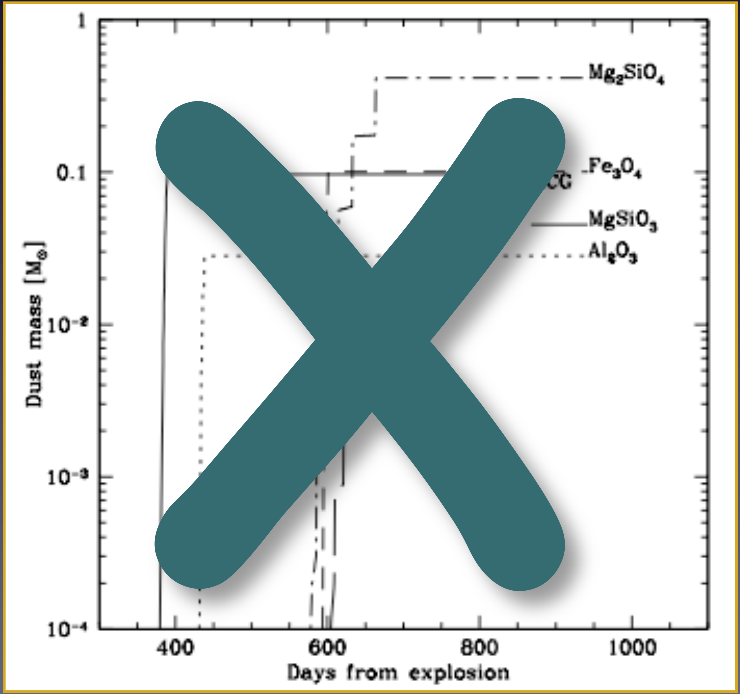
Ziurys et al. 2009

Physics & chemistry of dust formation: existing models

__Classical nucleation theory (CNT)__: **dust formation in SNe and AGB stars** (Draine 1979, Kozasa et al. 1989, Gail & Sedlmayr 1997, Todini & Ferrara 2001, Nozawa et al. 2003, 2007, 2010, Schneider et al. 2004, Ferrarotti & Gail 2006, Zhukovska et al. 2008, Fallest et al. 2011)

$$J = \alpha\Omega\left(\frac{2\sigma}{\pi m_1}\right)^{1/2} c_1^2 \exp\left[-\frac{4\mu^3}{27(\ln S)^2}\right]$$

Nucleation current J = number of monomers formed
Uses concepts like surface tension, sticking coefficient, supersaturation ratio, equilibrium distribution of critical clusters…



SN1987A

__Fully mixed ejecta__

$M_{dust} = 0.67\ M_{sun}$

Todini & Ferrara (2001)

- ✓ Often monomers do not exist – e.g. silicates
- ✓ Use elemental yields & no constraints from the gas phase on the dust composition
- ✓ CNT predicts too large amounts of any dust!

Physics & chemistry of dust formation: existing models

Ignore the chemical synthesis of molecules (e.g., SiO, PAHs) and dust precursors (small clusters) from the gas phase...

Chemical kinetic approach:

Nucleation of gas phase dust precursors + condensation (coagulation)

Couple the gas phase to the solid phase
... good for astronomy ...

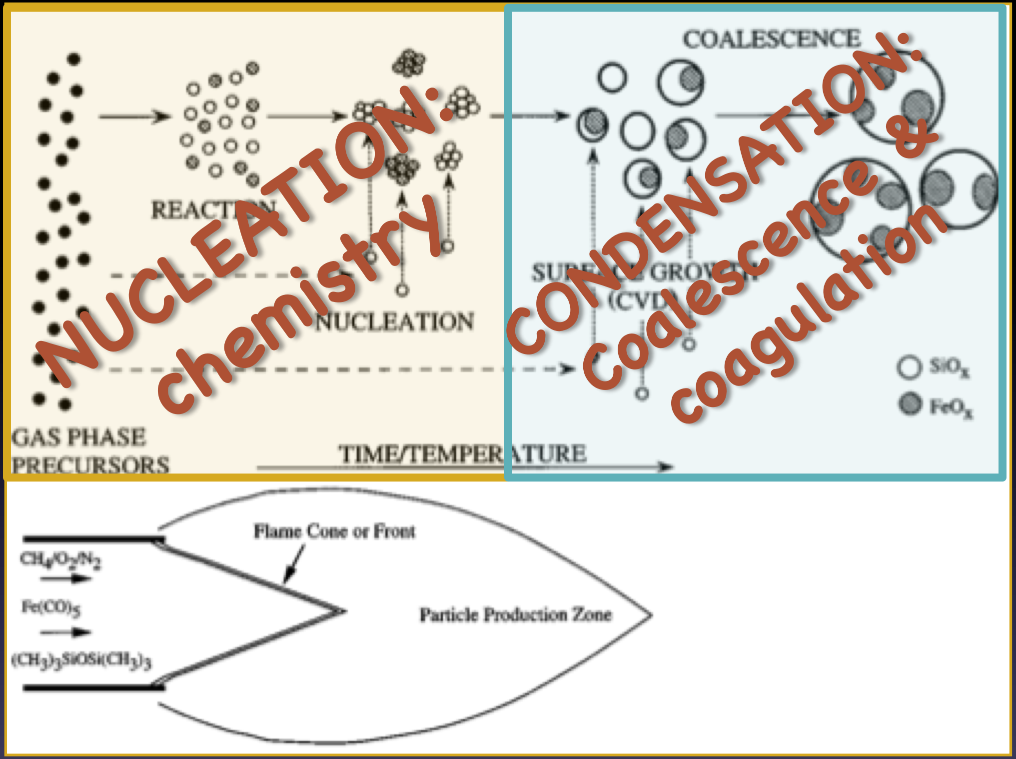
Very general and powerful approach which can be applied to any stellar outflow...
Drawback: need to characterise each chemical process

Physics & chemistry of dust formation: existing models

In the laboratory, dust forms from the gas phase using different techniques:

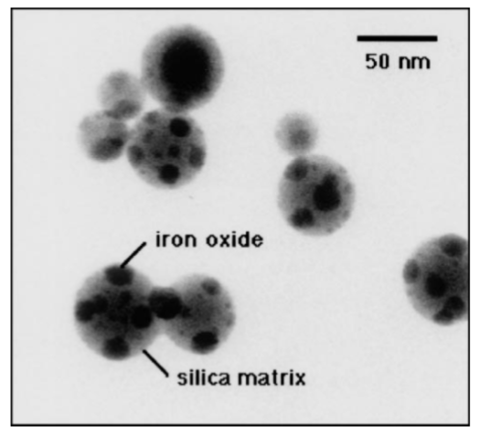
- ✓ Vaporization of solid rods
- ✓ Pyrolysis of hydrocabons
- ✓ Flame aerosol reactors

Study the synthesis of soot, metal oxides, silicate, metal carbide, pure metal dust…
(Kaito et al. 2003, Jäger et al. 2009)



(McMillin et al. (1996)

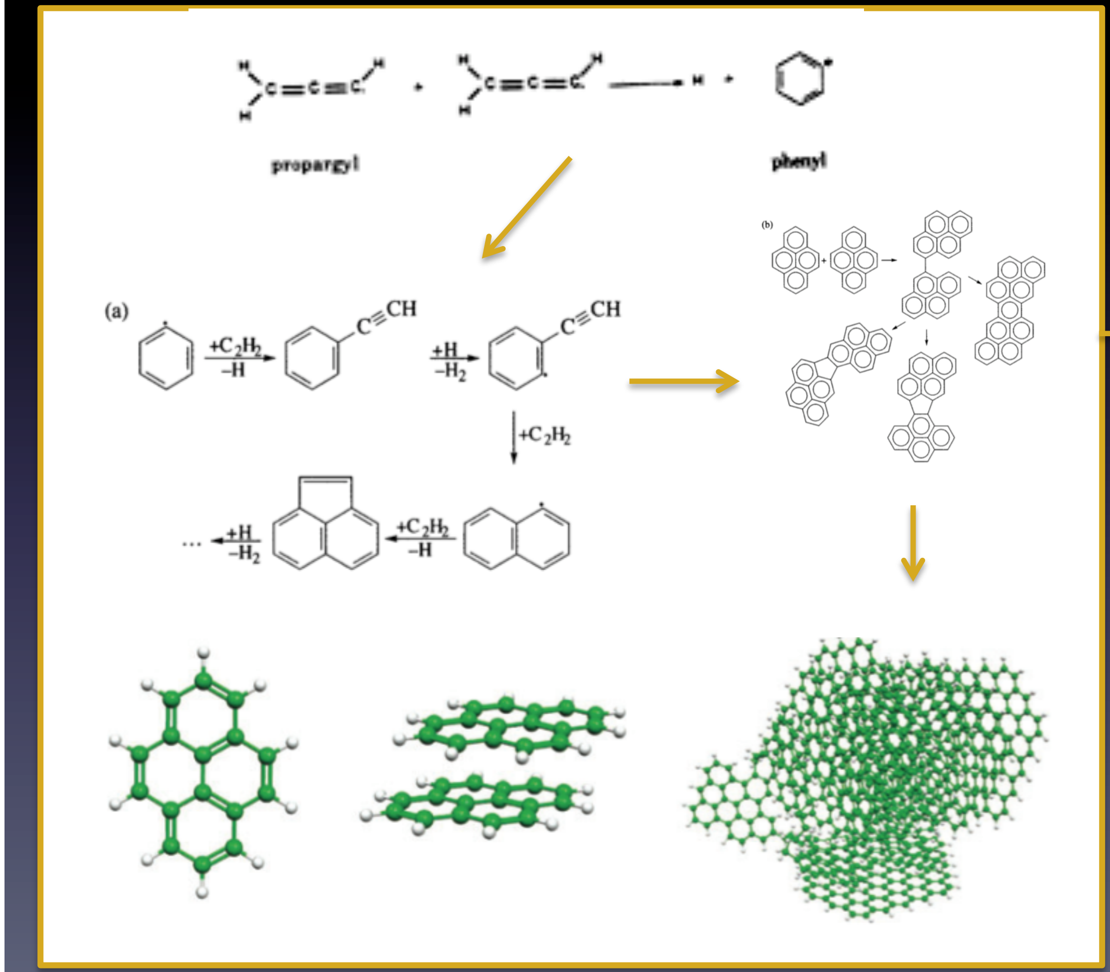
Fe_2SiO_4
Fayalite



Formation pathways

Chemical routes to Amorphous Carbon

With hydrogen: aromatic route from sooting flames



Cherchneff et al. 1992, Tielens 1998

- ✓ Neutral-neutral reactions (activation barrier) → high temperature required ~ 1000 K
- ✓ PAH coalescence to graphene sheets & amorphous carbon grains

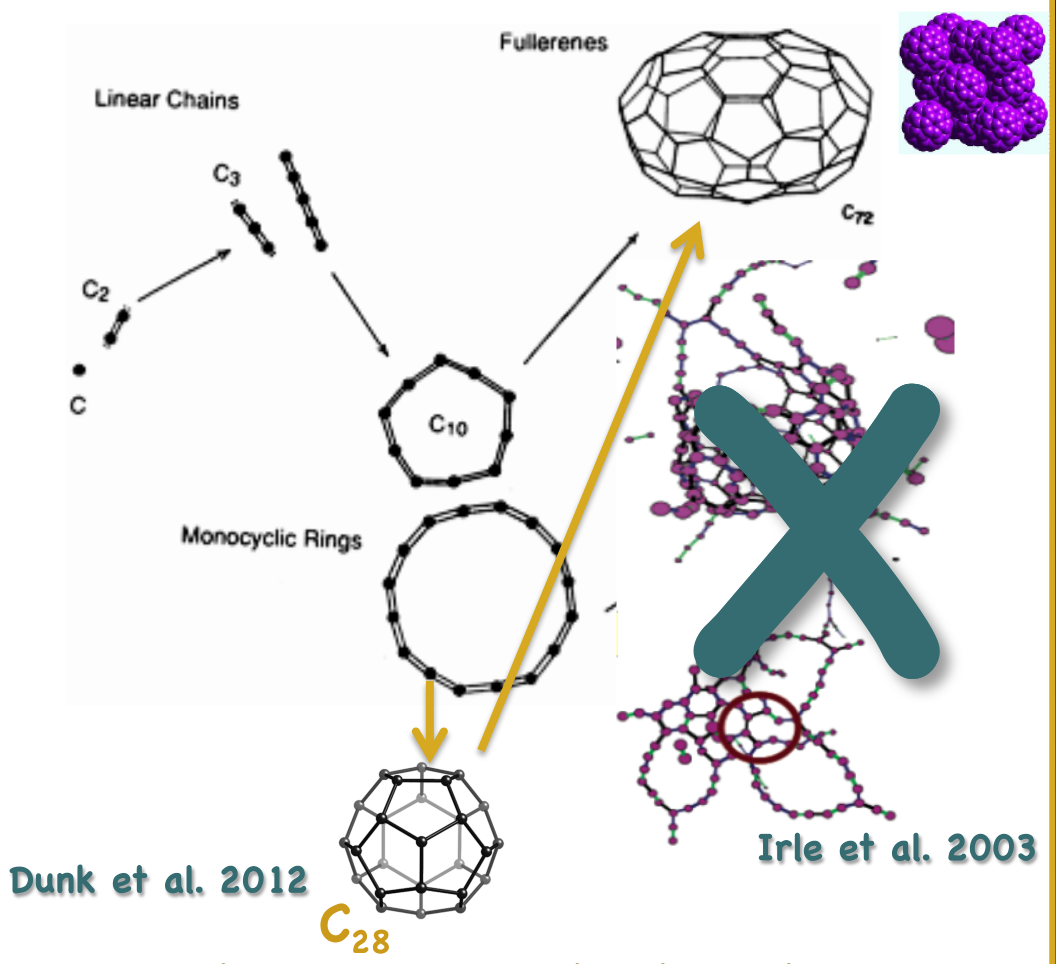
AGB carbon stars

Formation pathways

Chemical routes to Amorphous Carbon

Without hydrogen: carbon chains, rings & fullerene cages

(Kroto et al. 1985)



Dunk et al. 2012

Irle et al. 2003

Growing on C & C_2 ring inclusion

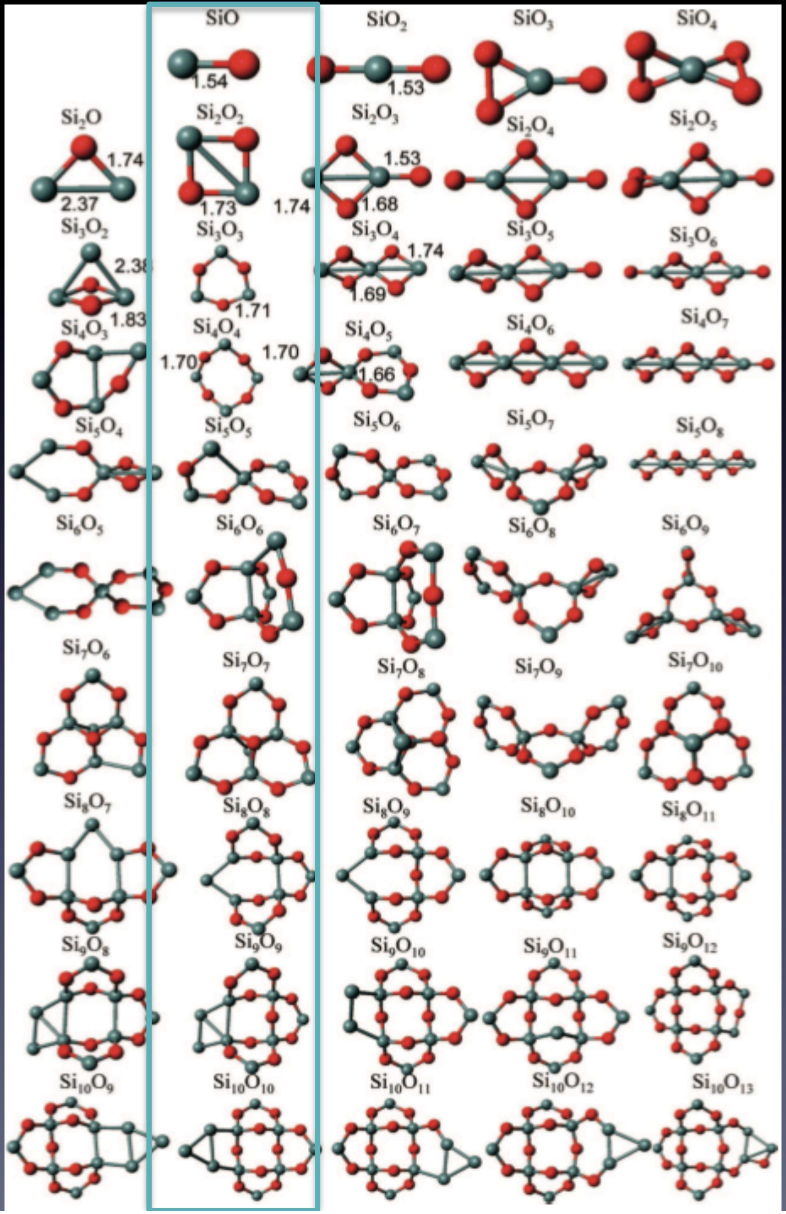
- ✓ Radiative association reactions to carbon chains

  $C + C_n \rightarrow C_{n+1} + h\nu$
- ✓ Growth from C_2 inclusion

Supernovae
R CrB stars
Carbon Wolf-Rayet stars (?)

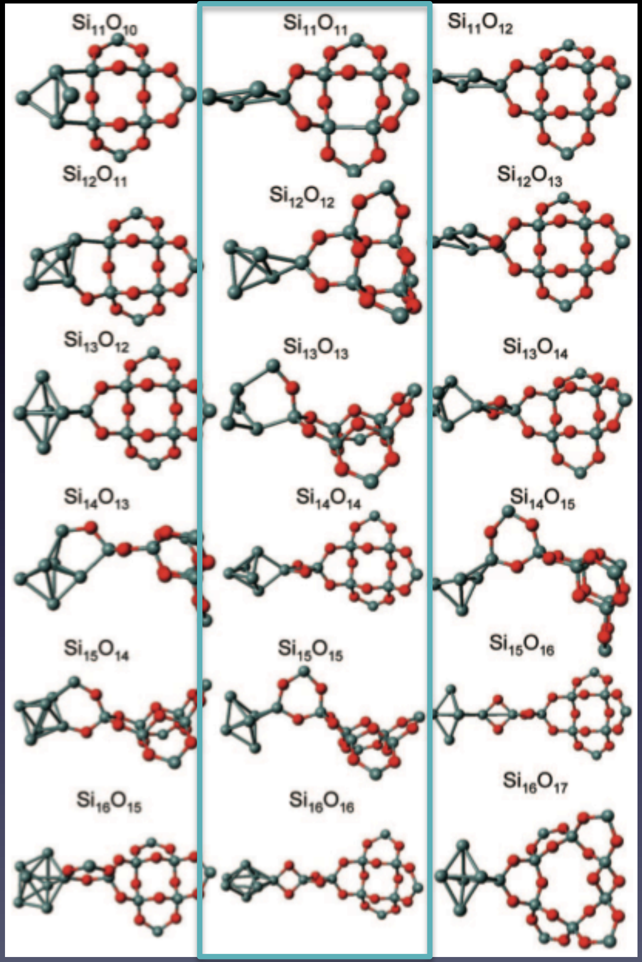
Formation pathways

Silica SiO_2



$(Si_xO_y)_n$

Reber et al. 2008



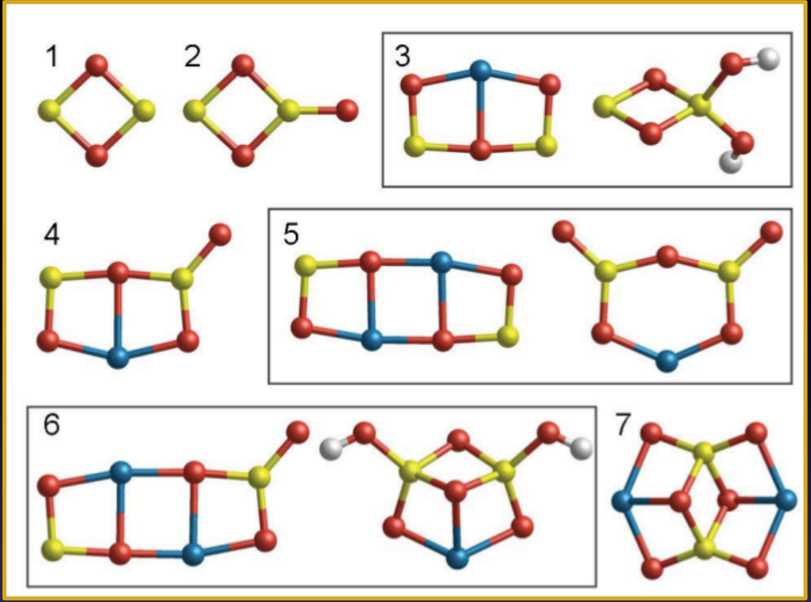
Early disproportionation of $(SiO)_n$ in $(SiO_2)_n$ and $(Si)_n$

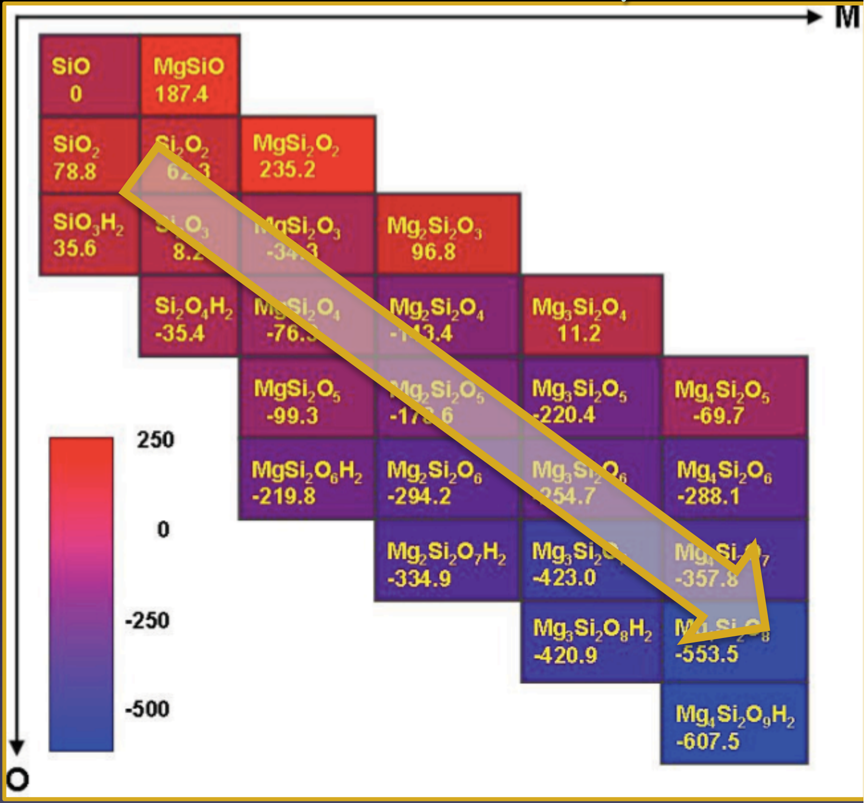
Formation pathways

Silicate: formation of forsterite (Mg_2SiO_4) dimers

Goumans & Bromley 2012

SiO





O addition via H_2O, O_2, SO

Mg addition

1. $2\,SiO \rightarrow Si_2O_2$
2. $Si_2O_2 + H_2O \rightarrow Si_2O_3 + H_2$
3. $Si_2O_3 + \left\{ \begin{array}{l} Mg \rightarrow MgSi_2O_3 \\ \hline H_2O \rightarrow Si_2O_4H_2 \end{array} \right\}$
4. $\left\{ \begin{array}{l} MgSi_2O_3 + H_2O \\ \hline Si_2O_4H_2 + Mg \end{array} \right\} \rightarrow MgSi_2O_4 + H_2$
5. $MgSi_2O_4 + \left\{ \begin{array}{l} Mg \rightarrow Mg_2Si_2O_4 \\ \hline H_2O \rightarrow MgSi_2O_5 + H_2 \end{array} \right\}$
6. $\left\{ \begin{array}{l} Mg_2Si_2O_4 + H_2O \rightarrow Mg_2Si_2O_5 + H_2 \\ \hline MgSi_2O_5 + H_2O \rightarrow MgSi_2O_6H_2 \end{array} \right\}$
7. $\left\{ \begin{array}{l} Mg_2Si_2O_5 + H_2O \\ \hline MgSi_2O_6H_2 + Mg \end{array} \right\} \rightarrow Mg_2Si_2O_6 + H_2$

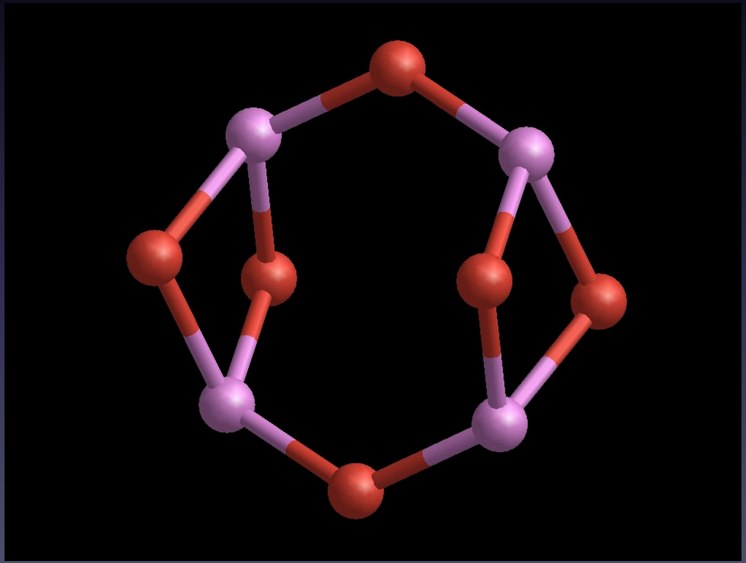
O addition by H_2O, O_2 & SO, and Mg addition are down-hill processes: no activation barrier

Formation pathways

Alumina Al_2O_3

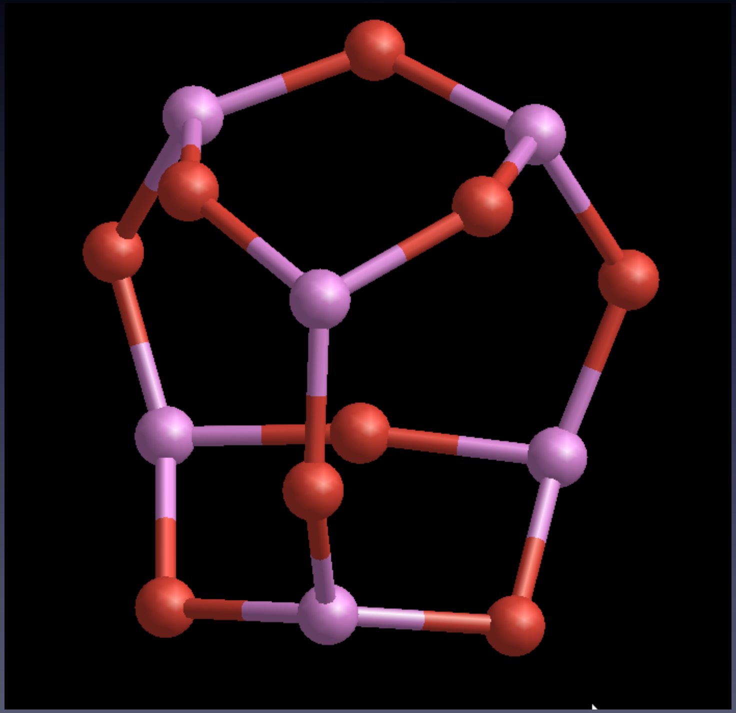
Start with AlO, $(AlO)_2$ and oxygen addition via H_2O, O_2?

Al_2O_6



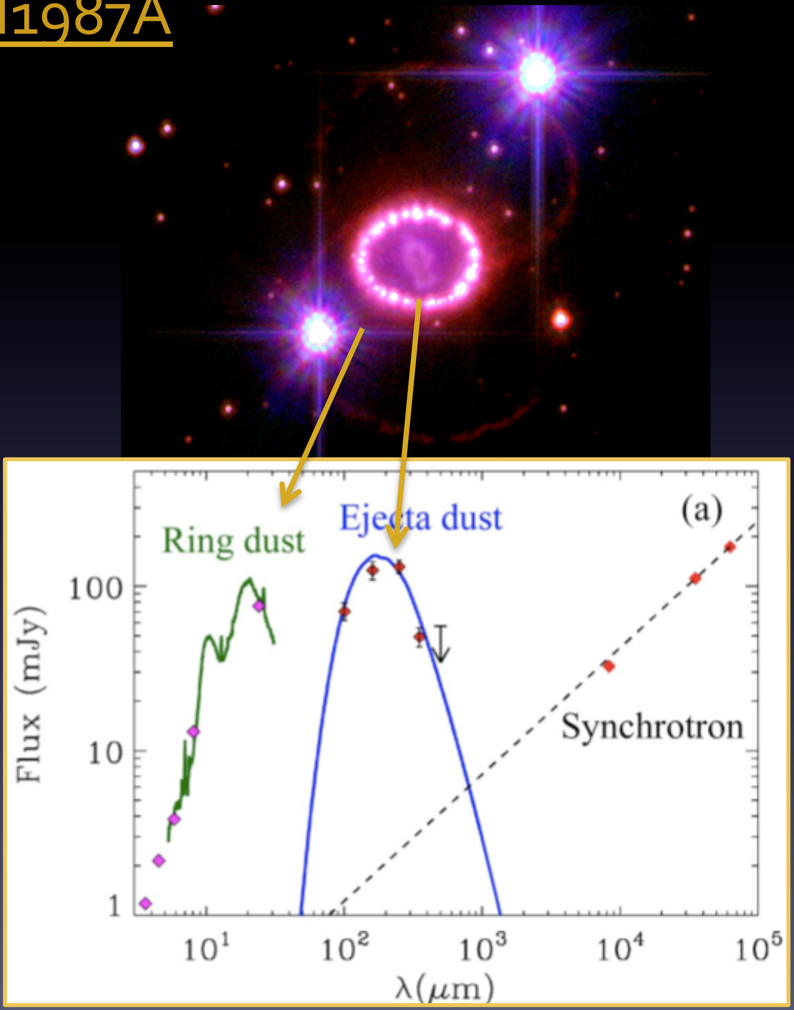
Gobrecht, Bromley & Cherchneff, in prep

Al_3O_9



A case study: Type IIP supernovae

SN1987A



0.4 - 0.7 M_{sun}

Matsuura et al. (2011)

Potential dust providers to the early universe

CO, SiO & dust detected > 100 days after explosion

- ✓ How much dust do SNe form?
- ✓ What kind of dust?

Much larger dust mass observed in supernova remnants with Herschel

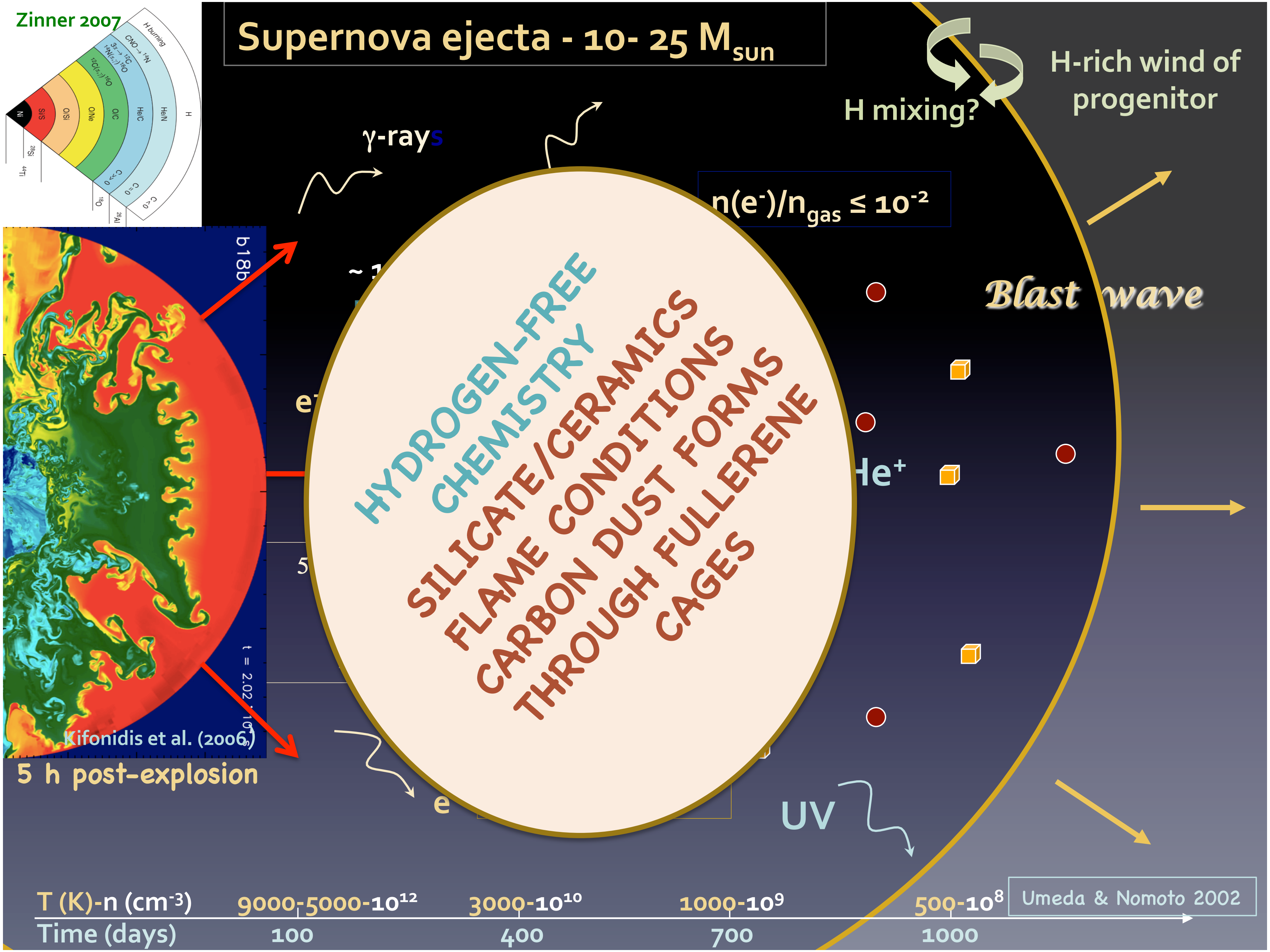
cool dust ~0.1 M_{sun}

than in supernova ejecta in the IR

warm dust ~10^{-6} – 10^{-2} M_{sun}

…Supernova dust dilemma…

Supernova ejecta - 10- 25 M_{sun}



HYDROGEN-FREE CHEMISTRY

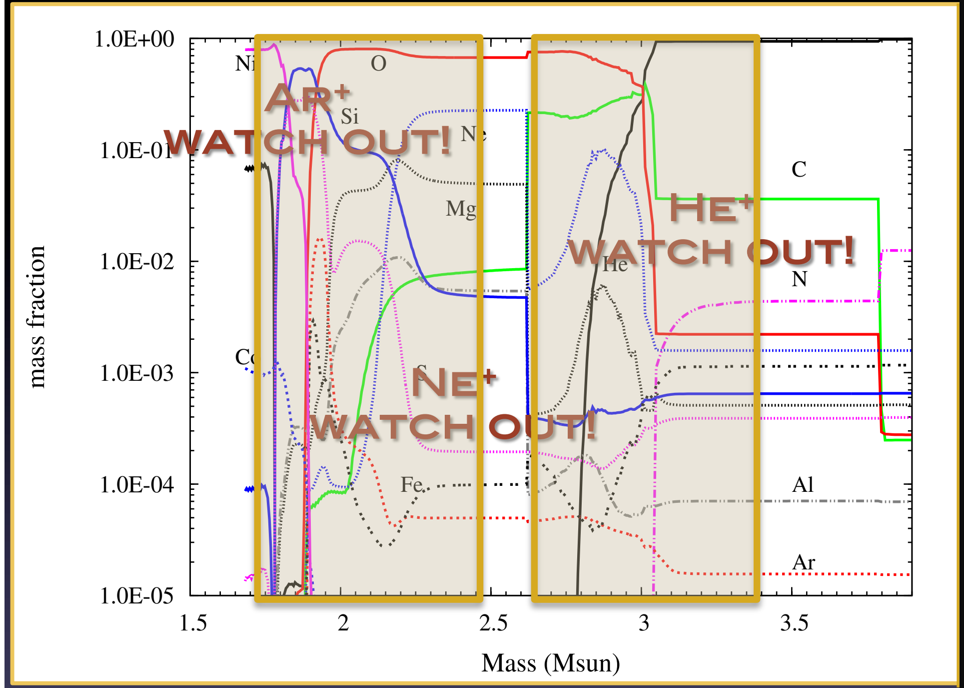
SILICATE/CERAMICS FLAME CONDITIONS

CARBON DUST FORMS THROUGH FULLERENE CAGES

A case study: Type IIP supernovae

15 M_{sun} progenitor - solar metallicity

SiO-Silicates CO-Carbon



Rauscher et al. 2002

High temperature & high density chemistry

- ✓ **Formation processes:** termolecular, neutral-neutral (activation barriers), radiative association, ion-molecules, charge exchange
- ✓ **Destruction processes:** thermal fragmentation, neutral-neutral, dissociation/ionisation by Compton e- and UV photons, charge exchange

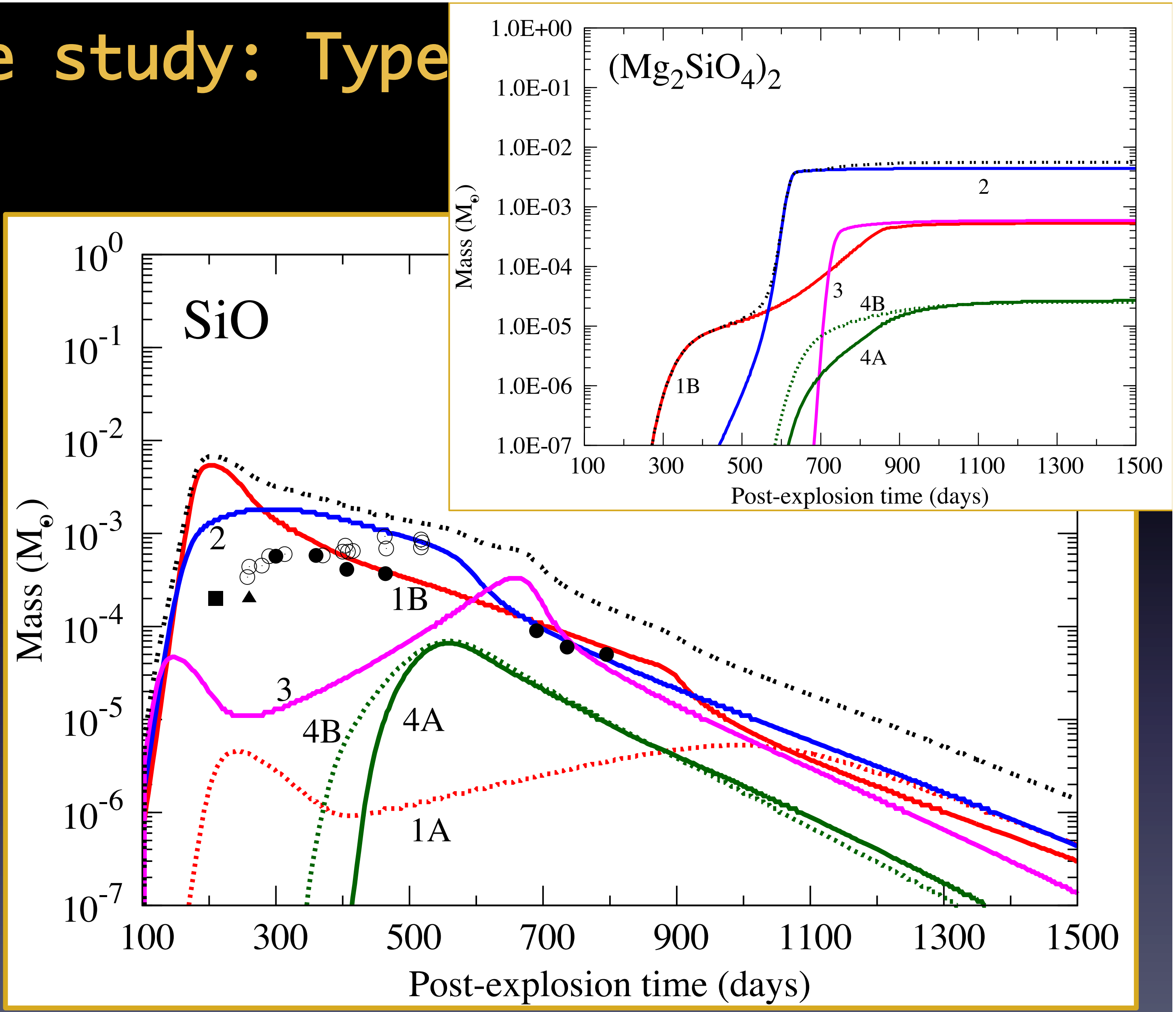
- ✓ **Molecules:** CO, SiO, SiS, CS, S_2, SO, O_2, CO_2, NO
- ✓ **Ions:** (CO+, SiO+, and all metals)
- ✓ **Small clusters:** $(FeO)_n$, $(MgO)_n$,$(SiO)_n$, $(SiO_2)_n$, AlO, $(Mg)_n$, $(Fe)_n$, $(Si)_n$, $(FeS)_n$, $(MgS)_n$; n=1-4
- ✓ **Silicate clusters** (enstatite & forsterite dimers)
- ✓ **Carbon chains** [C_2 - C_9] and ring C_{10}

A case study: Type

15 M_{sun} progenitor

Molecules

Sarangi & Cherchneff 2013



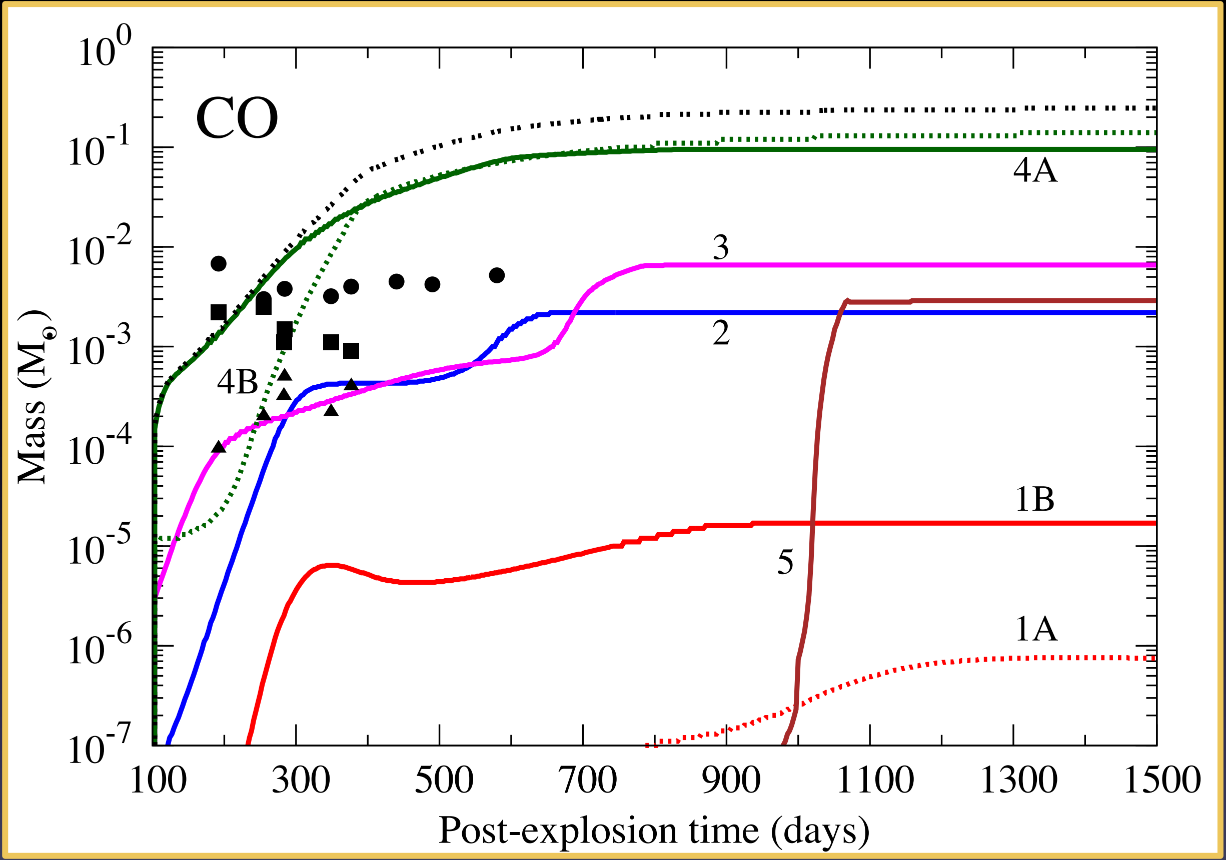
Good agreement with observations – SiO is a dust tracer

A case study: Type IIP supernovae

15 M_{sun} progenitor

Molecules

Sarangi & Cherchneff 2013



CO growth up to ~ 0.1 M_{sun} ⟶ pervades SN remnants

> 0.01 M_{sun} of CO just detected with ALMA in SN1987A

(Kamenetzky et al. 2013)

CO forms in zones where dust does not form

CO is not a carbon dust tracer

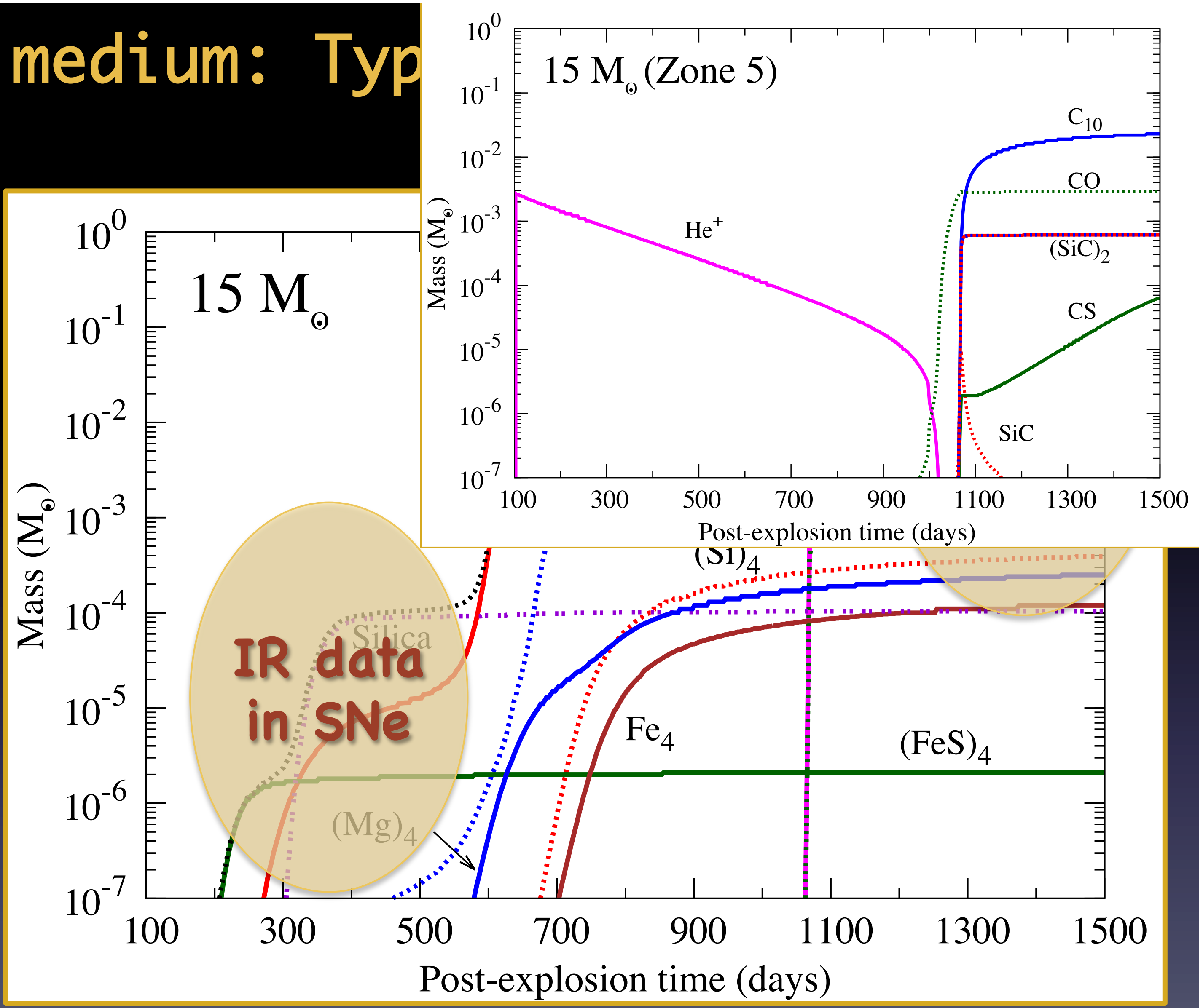
H-poor medium: Typ

$15\ M_{sun}$ progenitor

Dust

Ar^+, Ne^+, He^+ detrimental to molecular formation

Dust formation time & mass depend on ^{56}Ni



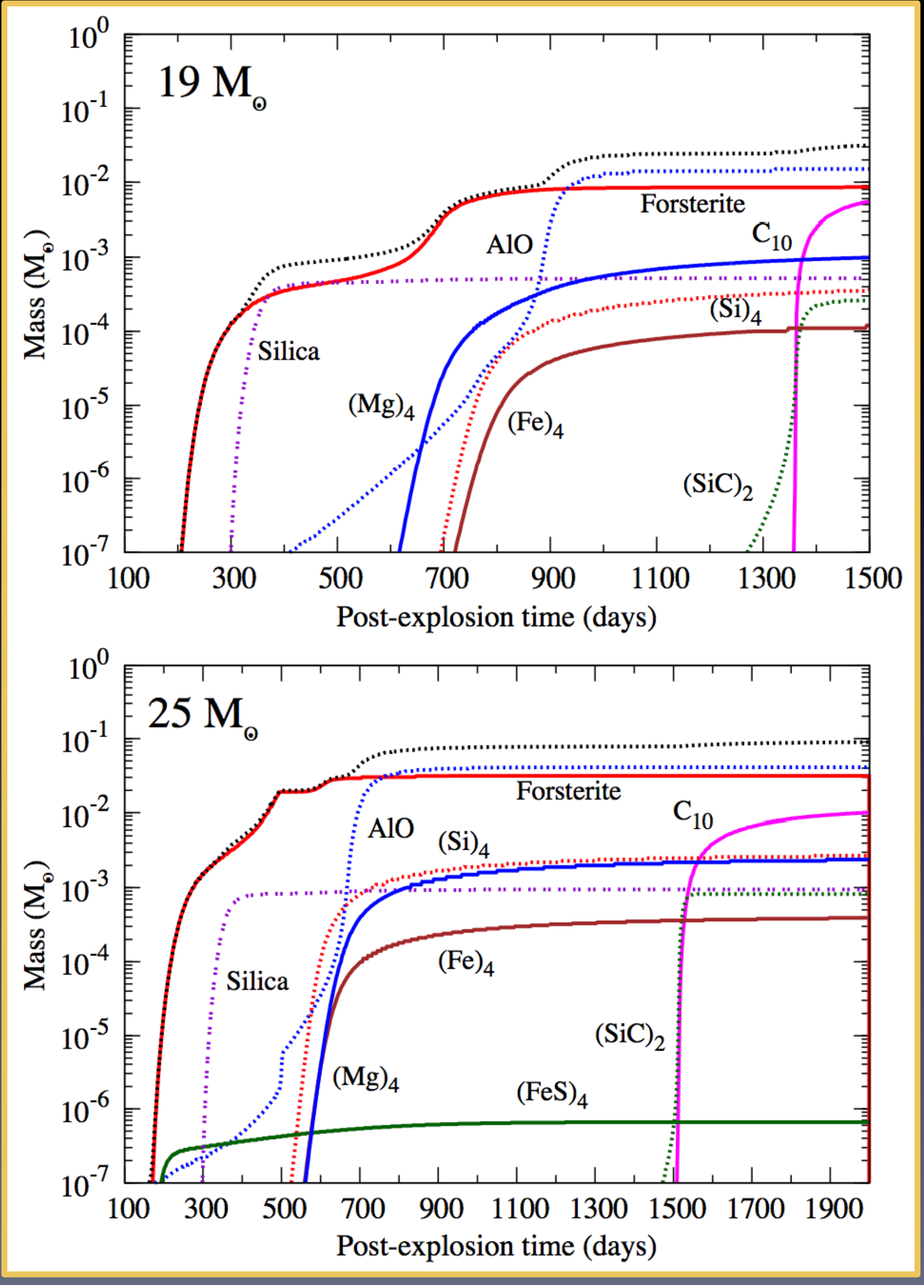
IR data in SNe

Sequence of dust formation events ⟶ gradual growth of dust mass from ~ 10^{-5} to $0.05\ M_{sun}$

Solution to the dust dilemma?

A case study: Type IIP supernovae

19 & 25 M_{sun} progenitors

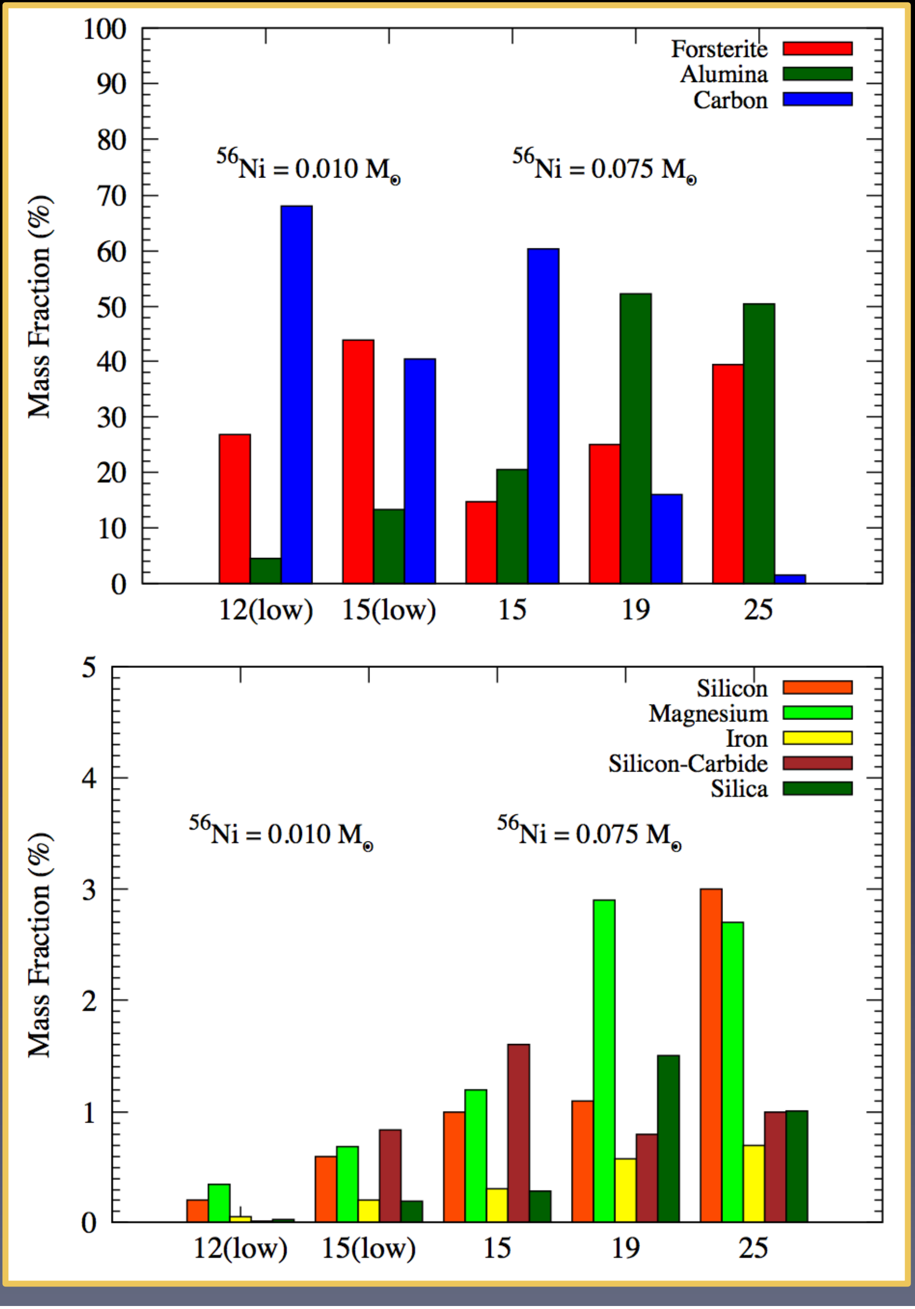


Sarangi & Cherchneff 2013

Similar trends but different dust composition

More massive, less carbon

A case study: Type IIP supernovae

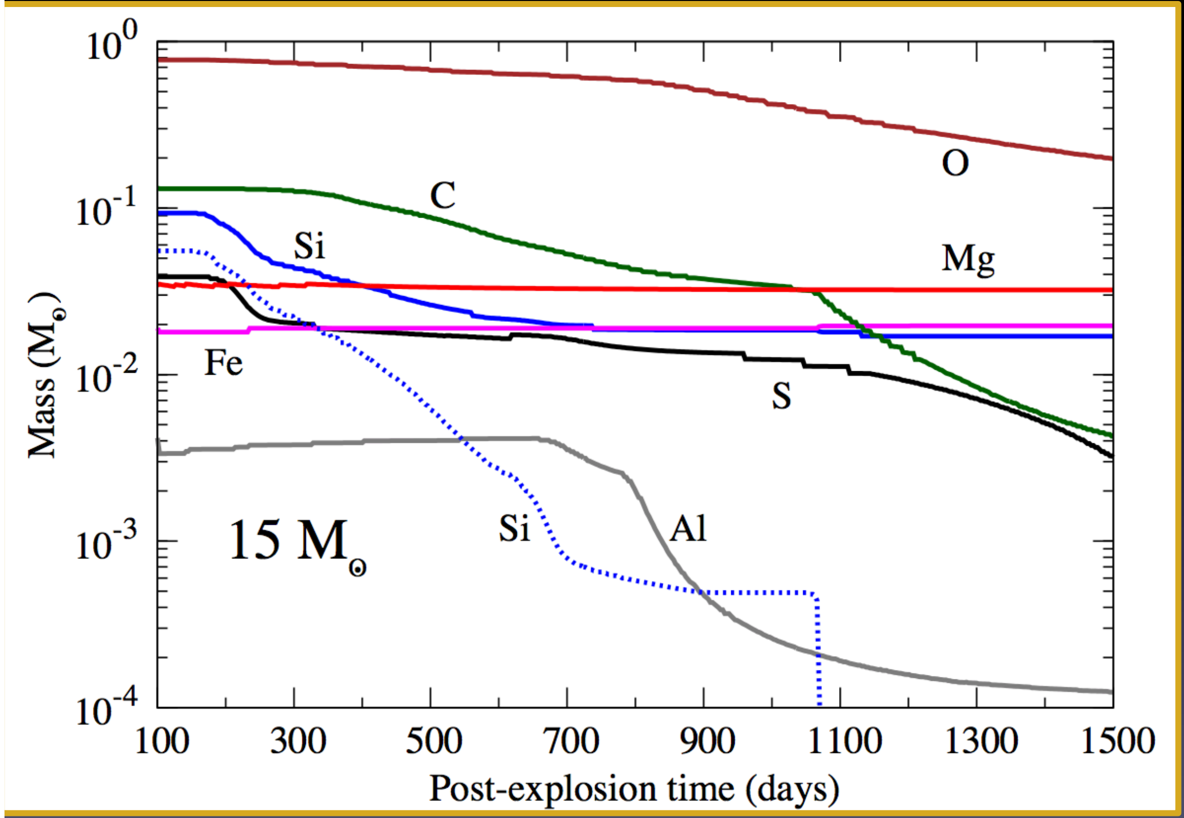


Dust chemical composition varies with ^{56}Ni and progenitor mass

Total dust mass: 0.04-0.09 M_{sun}

Sarangi & Cherchneff 2013

A case study: Type IIP supernovae



Sarangi & Cherchneff 2013

Depletion of elements not 100 %

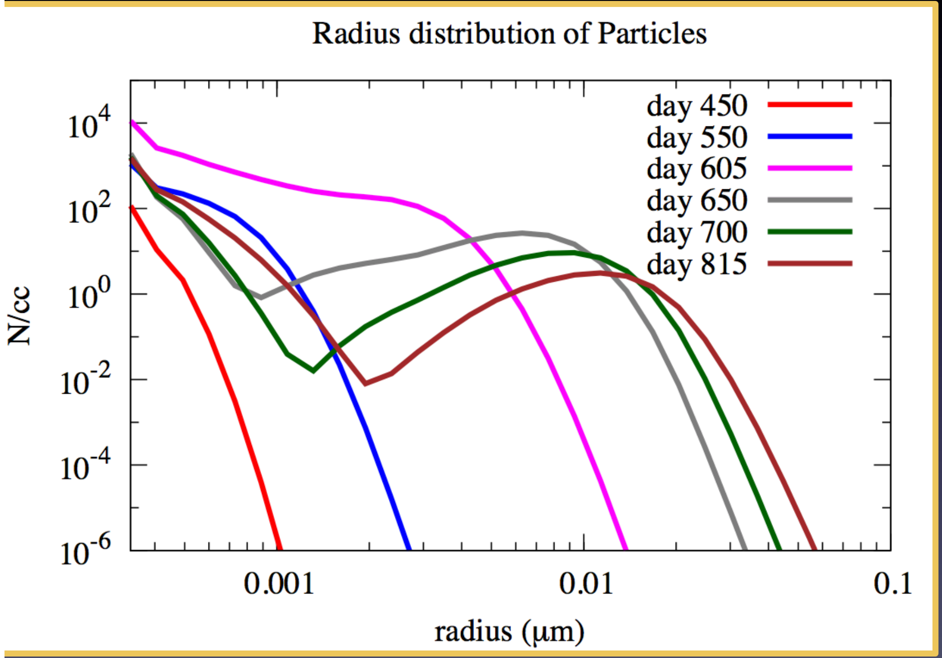
Depends on the chemistry of nucleation and ejecta zoning

A case study: Type IIP supernovae

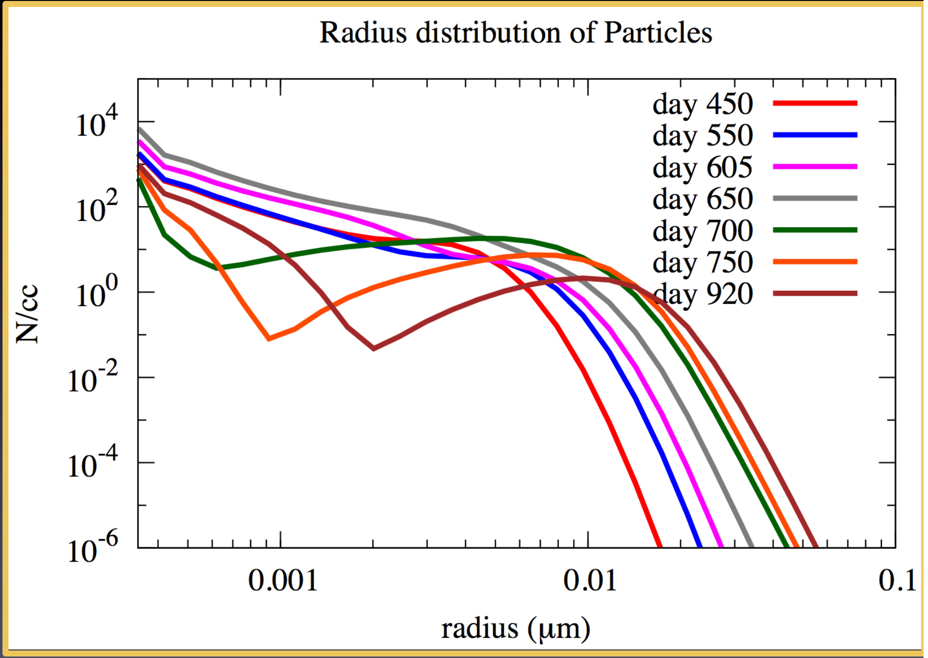
Condensation: coalescence & coagulation - volume conserved

15 M_{sun} progenitor - homogeneous ejecta

Forsterite



Alumina



Sarangi & Cherchneff in prep

Grain size distribution depends on dust chemical type & changes with time

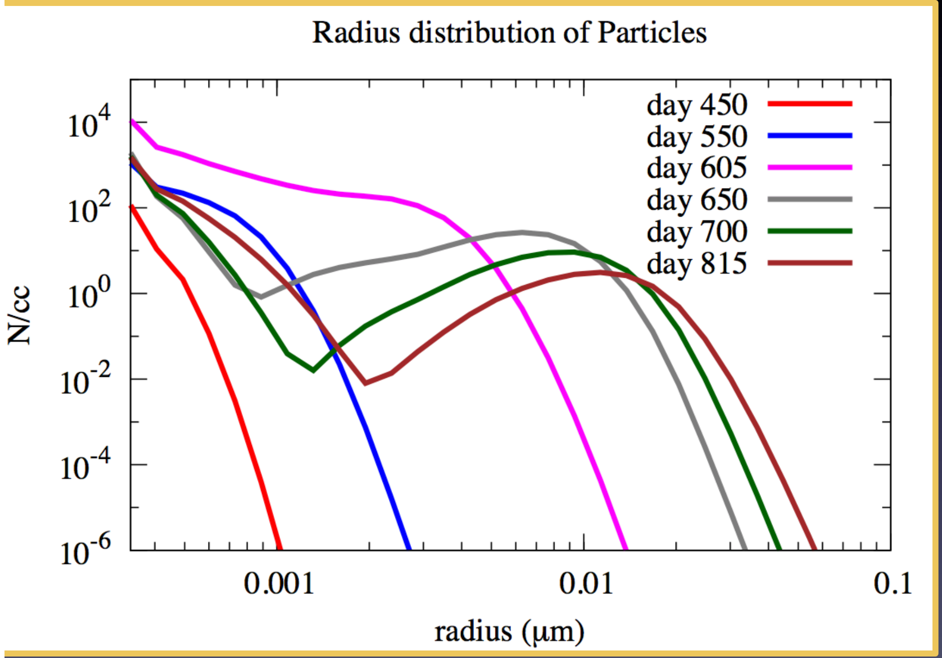
A case study: Type IIP supernovae

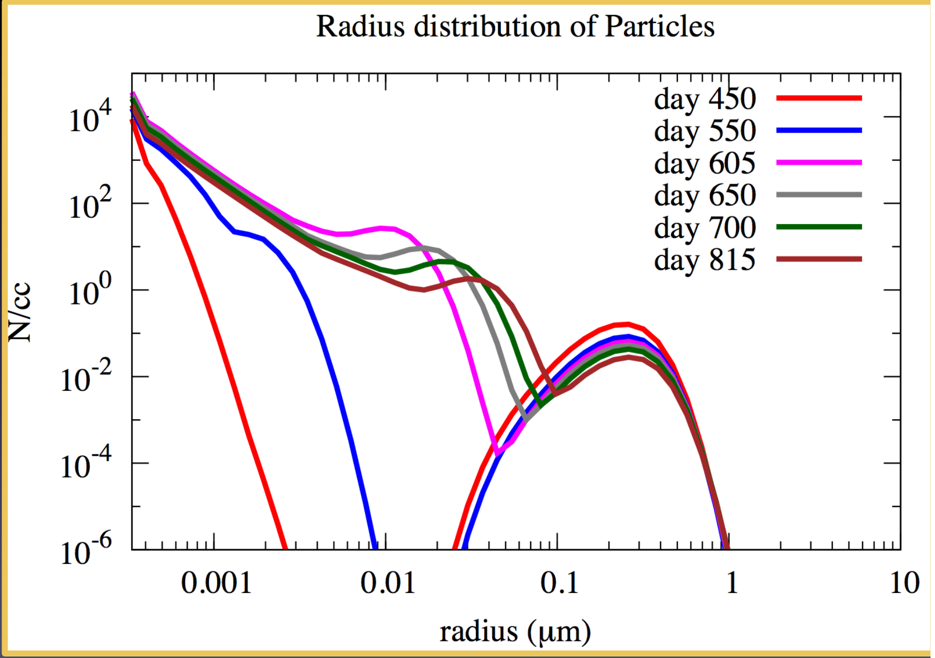
Condensation: coalescence & coagulation - volume conserved

15 M_{sun} progenitor

Forsterite: homogeneous ejecta

Clumpy ejecta - density x10



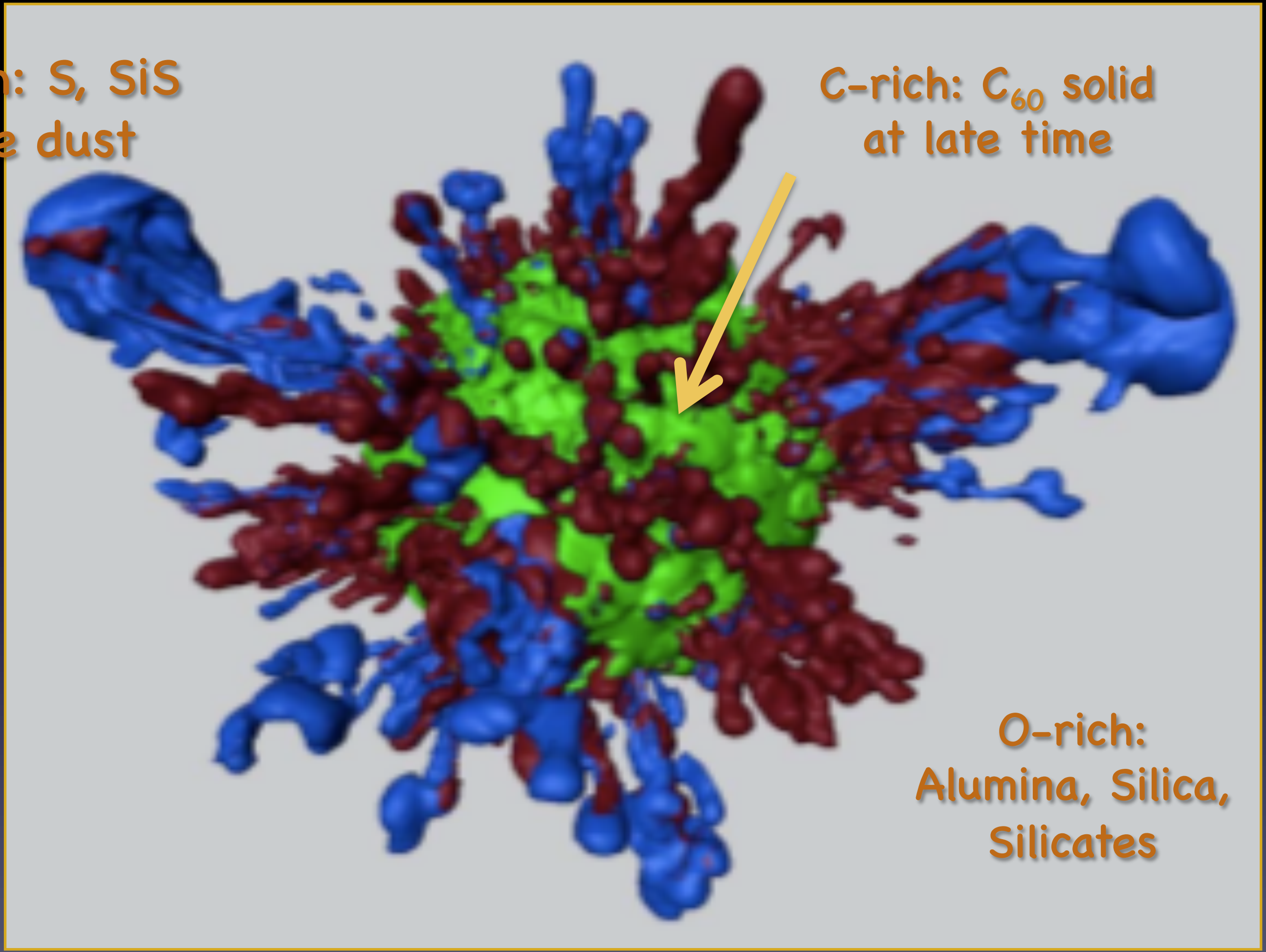


Sarangi & Cherchneff in prep

Clumpy ejecta form larger grains

A case study: Type IIP supernovae

More realistic ejecta



Fe-rich: S, SiS
Si & Fe dust

C-rich: C_{60} solid
at late time

O-rich:
Alumina, Silica,
Silicates

Various dust formation events over a 5 yr time span

Conclusions

- ✓ Dust formation in any evolved stellar environment is controlled by the chemistry of nucleation and local physics
- ✓ Carbon dust formation is more sensitive to local conditions because the nucleation chemistry is complex
- ✓ Silicates and metal oxides form readily once the right conditions are met (Supernovae, AGBs)

In type IIP supernovae:

- ✓ Dust formation is highly dependent on the ^{56}Ni mass and the elemental yields ⟶ agreement on various explosion nucleosynthesis models…?
- ✓ Gradual growth that reconciles IR and submm data – everything happens before ~ 5 years post-explosion
- ✓ Efficient but moderate dust makers ($M_{dust} < 0.1\ M_{sun}$)

⟶ need other dust providers at high redshift