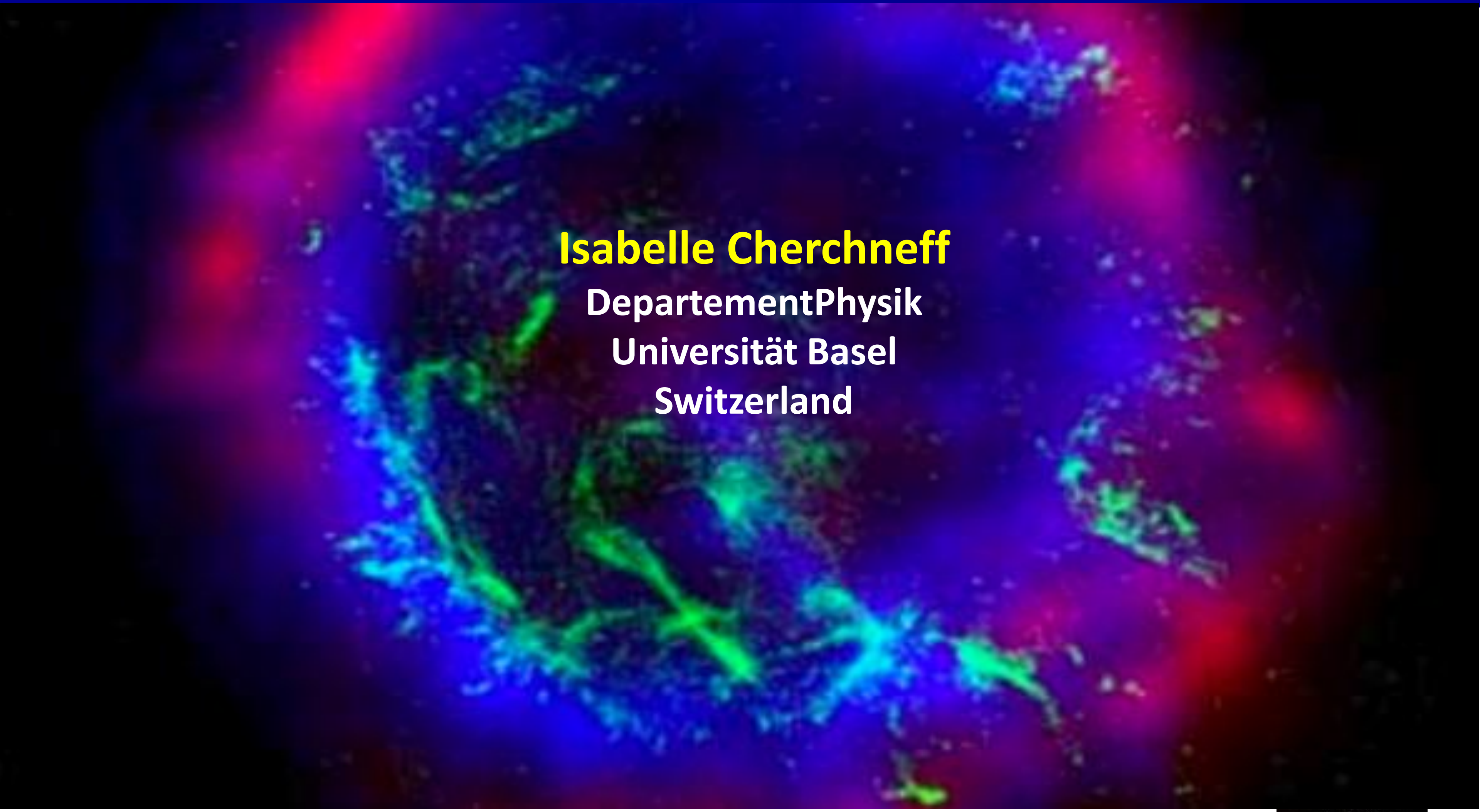
Molecules in supernova ejecta



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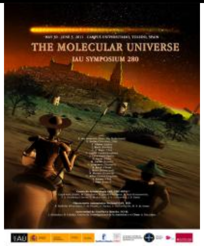


Overview

- Which supernovae ?
- Evidence for molecules from observations
- Modelling supernova ejecta: chemistry & mixing
- Results: molecules as tracers of dust synthesis?
- Conclusions

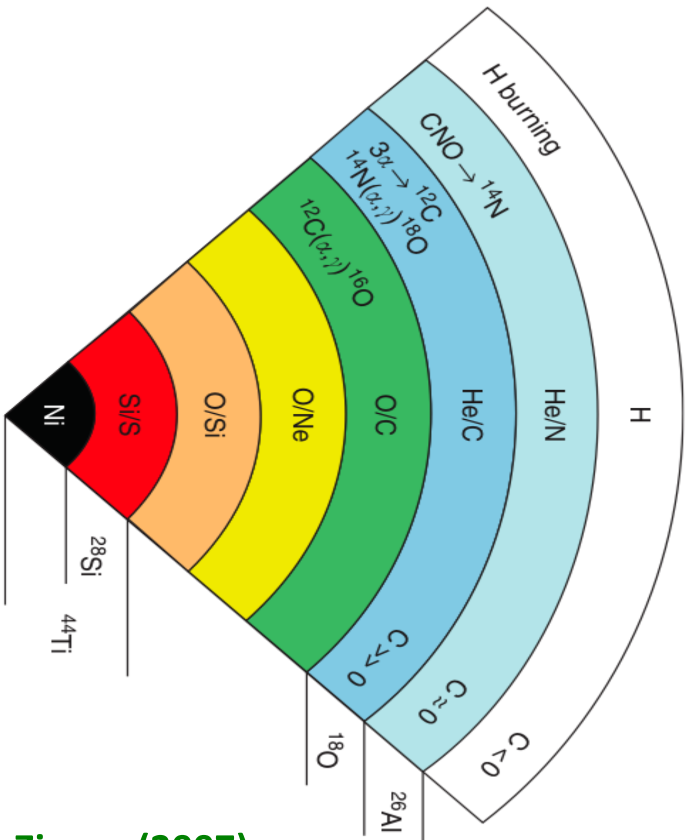
A ESF CoDustMas network collaboration – coll: ArkaprabhaSarangi
www.codustmas.eu

Which supernovae?

Core-collapse Type II supernovae

Progenitors: blue/red supergiants – typical mass ~ 10 - 25 M_{sun}

Pre-SN core



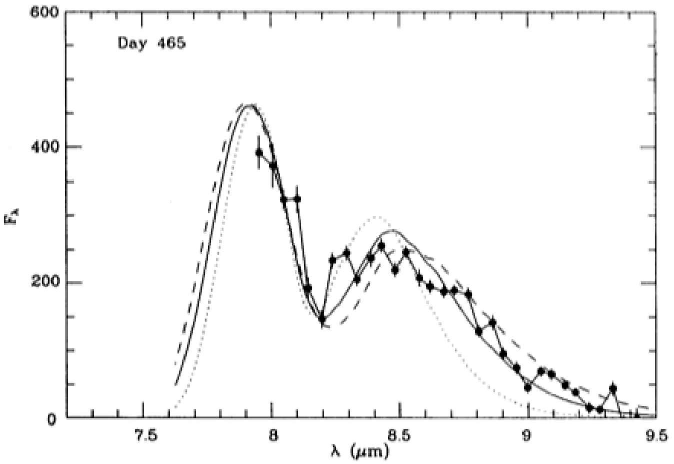
Zinner (2007)

- Few examples of type II supernovae: **SN1987A, SN2004dj, SN2005af**
- He core mass: **2 – 6 M_{sun}**
- Explosion energy ~ **$1x10^{51}$ ergs**
- Explosion nuclosynthesis products - ^{56}Ni drives **radioactivity** in the ejecta
- Large uncertainties on the ^{56}Ni mass and progenitor mass (e.g., 13 - 20 $M_{sun}$for SN2004et)

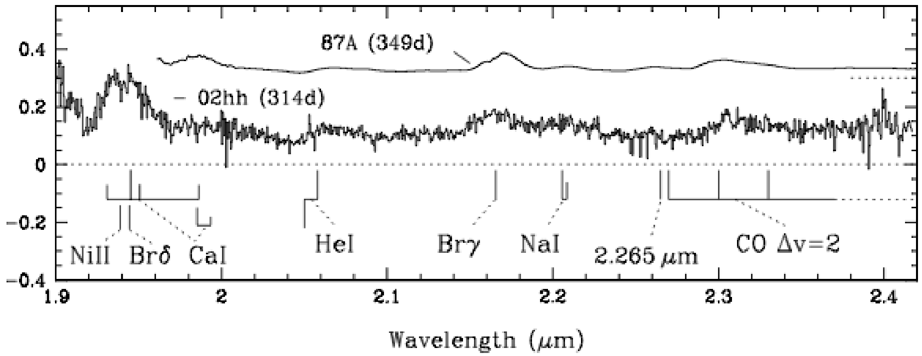
Dust and molecule formation observedin the infrared

Evidence for molecules from observations

- SN1987A: IR detection of CO, SiO and dust [10^{-4} - $10^{-3}M_{sun}$] from ~ 150 days to ~ 800 days post-explosion (Roche et al. 1991, Meikle et al. 1993, Ercolano et al. 2007)
- SN2005af: CO and SiO observed with Spitzer (Kotak et al. 2006)
- SN2004et: detection of CO and SiO, dust ~ $10^{-4}M_{sun}$ (Kotak et al. 2009)
- SN2003gd, SN2004dj: dust observed with Spitzer - $10^{-2}M_{sun}$ - $4\ 10^{-5}M_{sun}$ (Sugerman et al. 2006, Meikle et al. 2007)



SN1987A: SiO fundamental Δv=1 ro-vibrational bands from 7.5-9.5 μm (Roche et al. 1991)



SN2002hh: CO Δv=2 1st overtone band detection with Spitzer (Pozzo et al. 2006)

Evidence for molecules from observations

Molecules observed in SNRs: 330 years old remnant Cas A

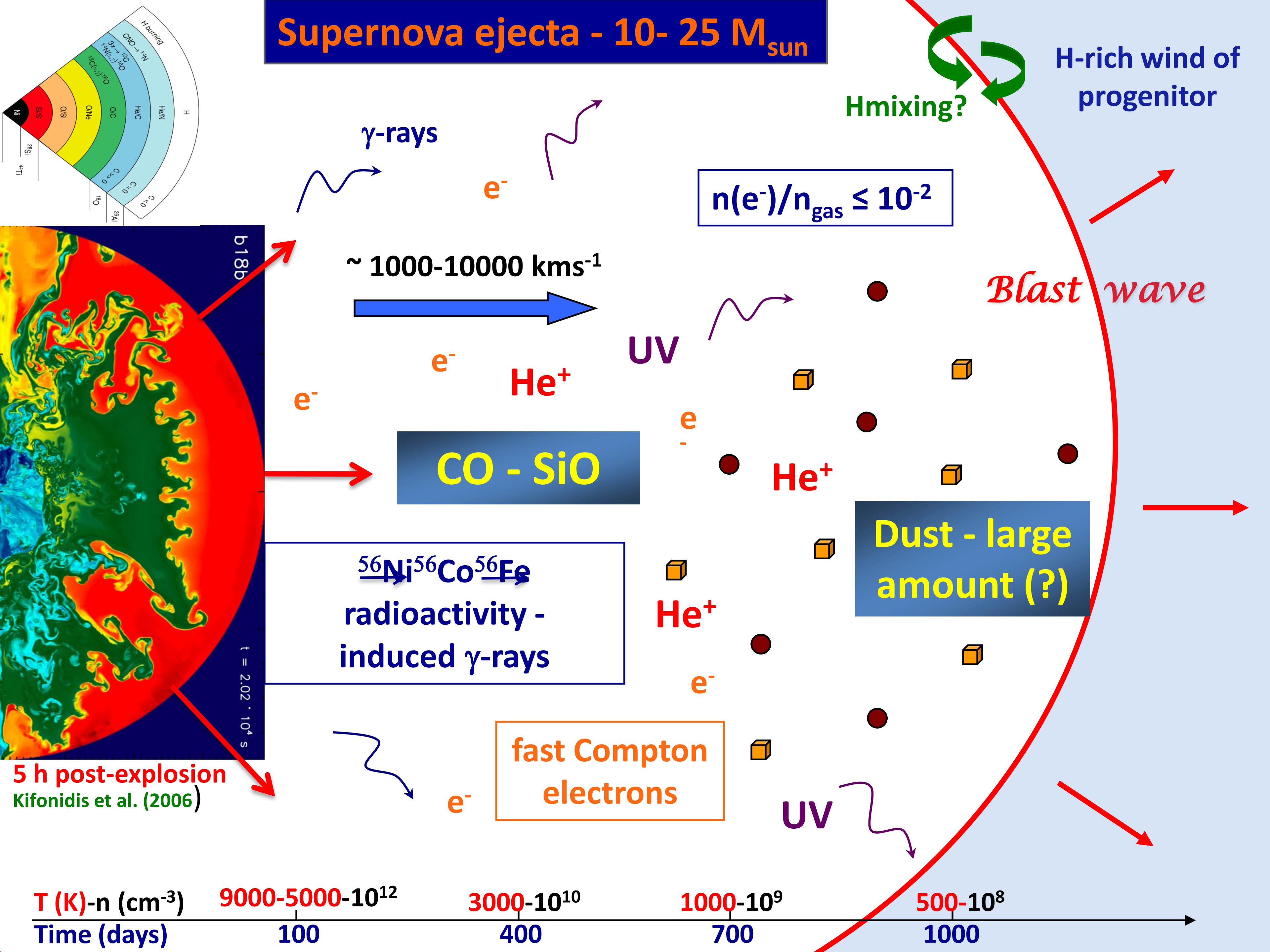
Observation of the CO 2.29 μm first overtone with Spitzer (Rho et al. 2008)

Evidence for ~ 0.08 M_{sun} of ejecta dust with Herschel (Barlow et al. 2010)

In supernova ejecta, the formation of CO and SiO (90 – 200 days) precedes the observation of dust (> 300 days)

Are molecules tracers of dust formation ?

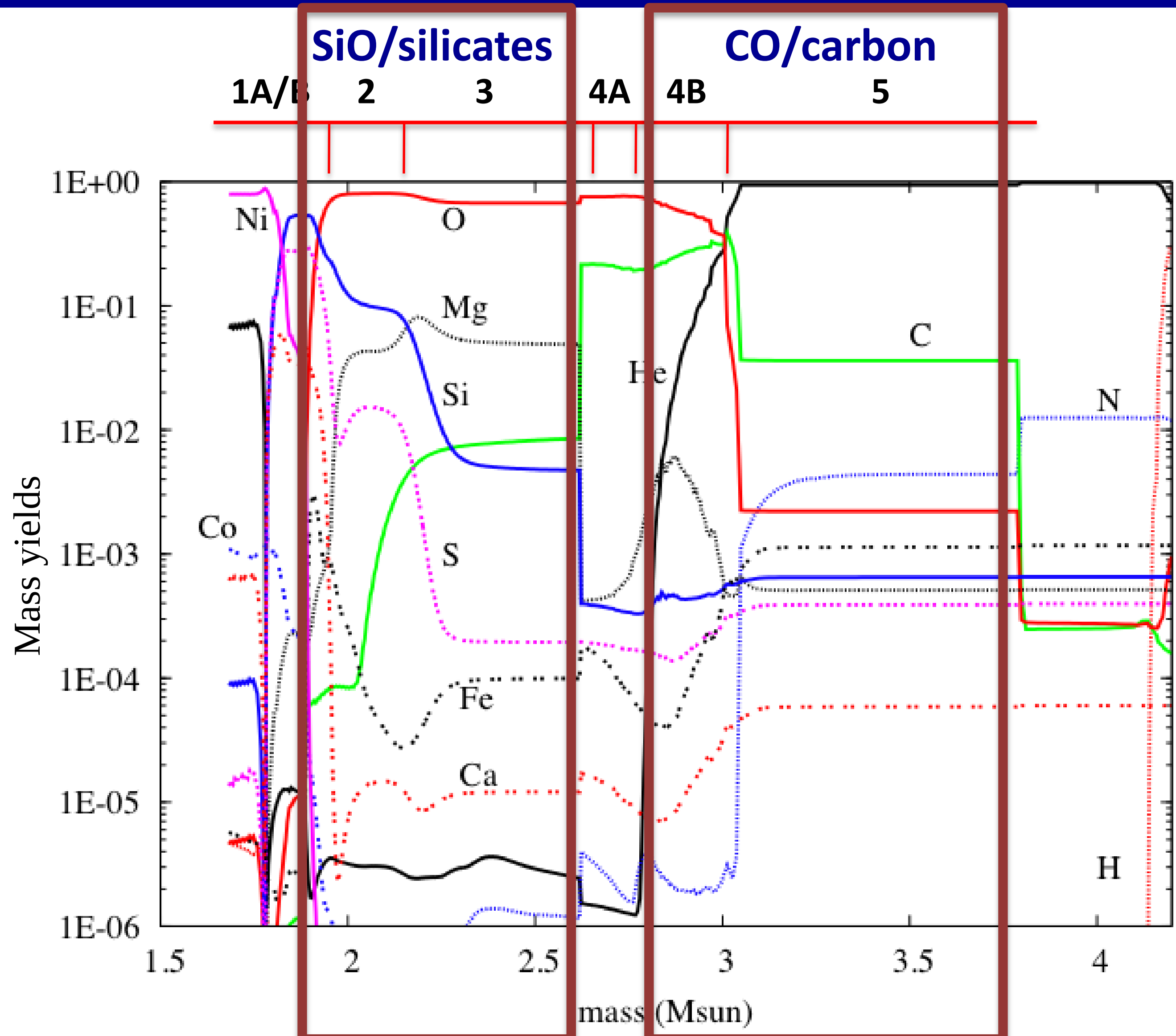
Supernova ejecta - 10- 25 M_{sun}



Modelling supernova ejecta: chemistry & mixing

15 M_{sun} progenitor He core zoning

1A: Fe/Si/S
1B: Si/S/Ca
2: O/Si/Mg
3: O/Mg/C/Si
4A: O/C
4B: O/C/He
5: He/C/Si



Yields can greatly vary depending on explosion models!
(Weaver &Woosley 1995, Umeda&Nomoto 2002, Heger et al. 2004)

Rauscher et al. (2002)

Modelling supernova ejecta: chemistry & mixing

Previous studies: Molecule formation in SN1987A

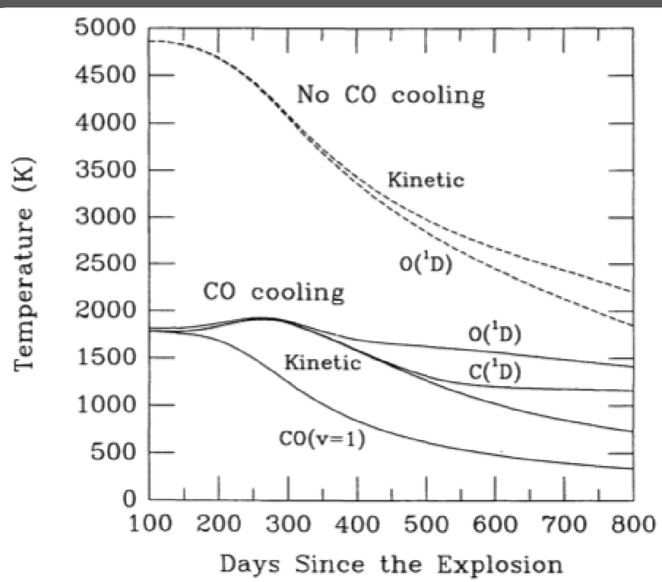
Petuchowski et al 1989 - Lepp, Dalgarno& McCray 1990 - Liu, Dalgarno&Lepp (1992) - Liu &Dalgarno (1994, 1995) - Gearhart et al. (1999)

Prevalent processes:

- radiative association reaction for formation of molecules
- dissociation/ionisation by Compton electrons as destruction

- No molecule can form when He^+ is present
- Molecules are important coolants: e.g., CO

Oxygen core - Liu &Dalgarno (1995)



Modelling supernova ejecta: chemistry & mixing

Physics:

- **15-20 M_{sun} progenitor – Explosion energy: ~ 10^{51} erg – 0.075 M_{sun} of ^{56}NI (SN1987A)**
- **Temperature and density derived from homogeneous explosion models of Nozawa et al. (2010):**
- **Compton electrons induced by γ-rays degradation**
- **UV field (10% of γ-rays - Kozma&Fransson (1992))**

Chemistry: high temperature & high density

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

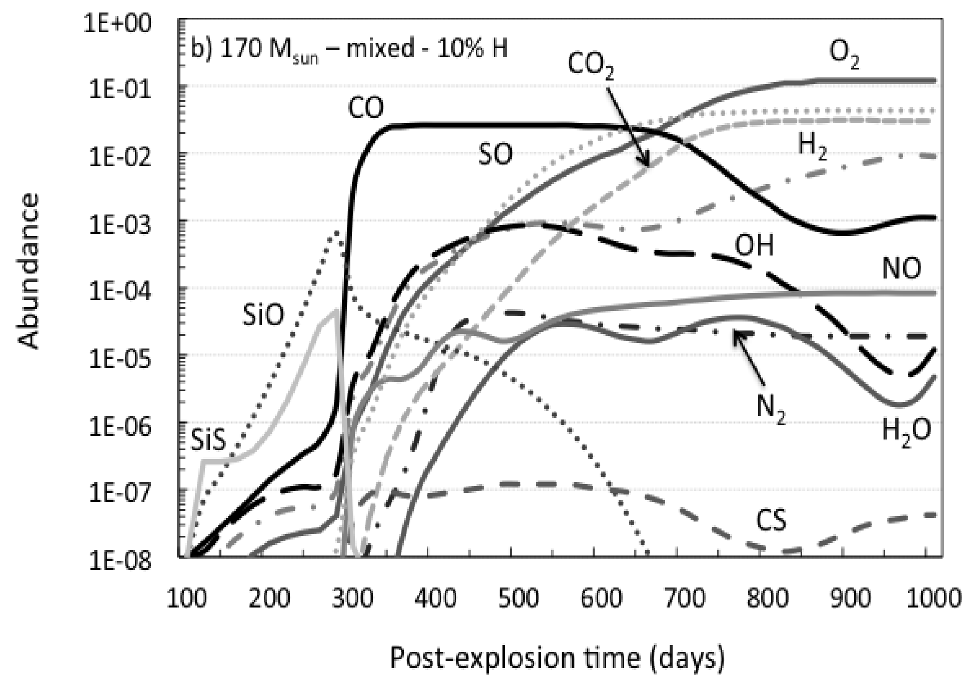
Modelling supernova ejecta: chemistry & mixing

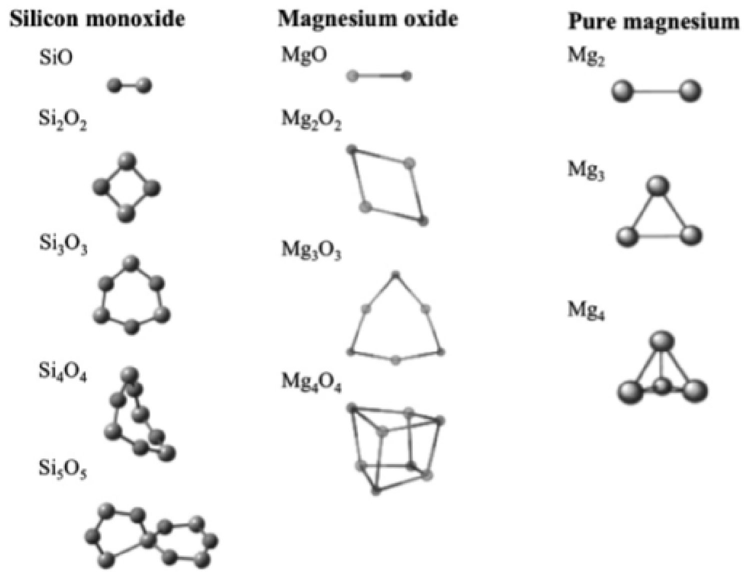
If hydrogen microscopically-mixed, species like **OH, CO_2 or H_2O should form and be observed…**

So far, only CO and SiO

H-free "poor" chemistry

Cherchneff&Dwek (2009, 2010)





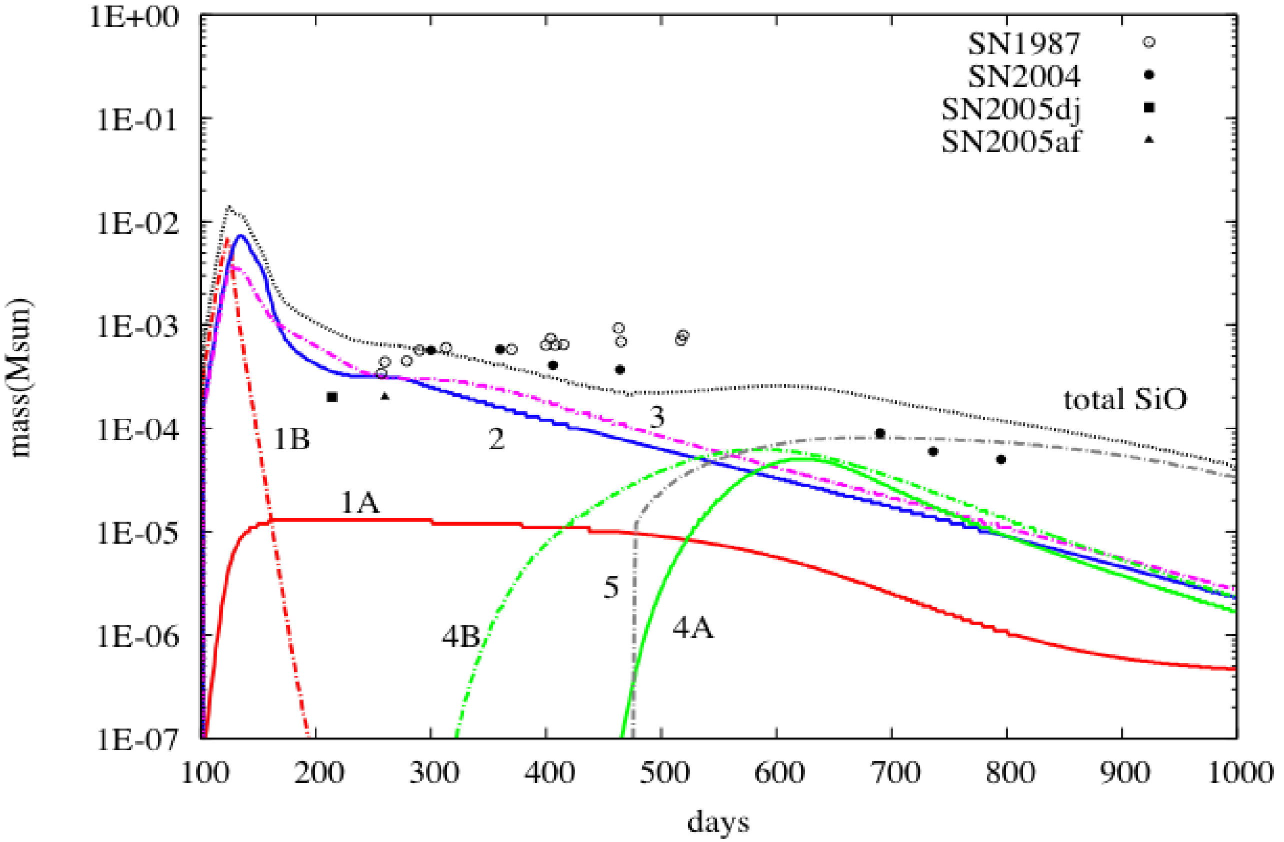
Molecules considered:

CO, SiO, SiS, CS, S_2, SO, O_2, CO_2, NO

Small clusters and carbon chains/rings

Results: molecules as tracers of dust synthesis?

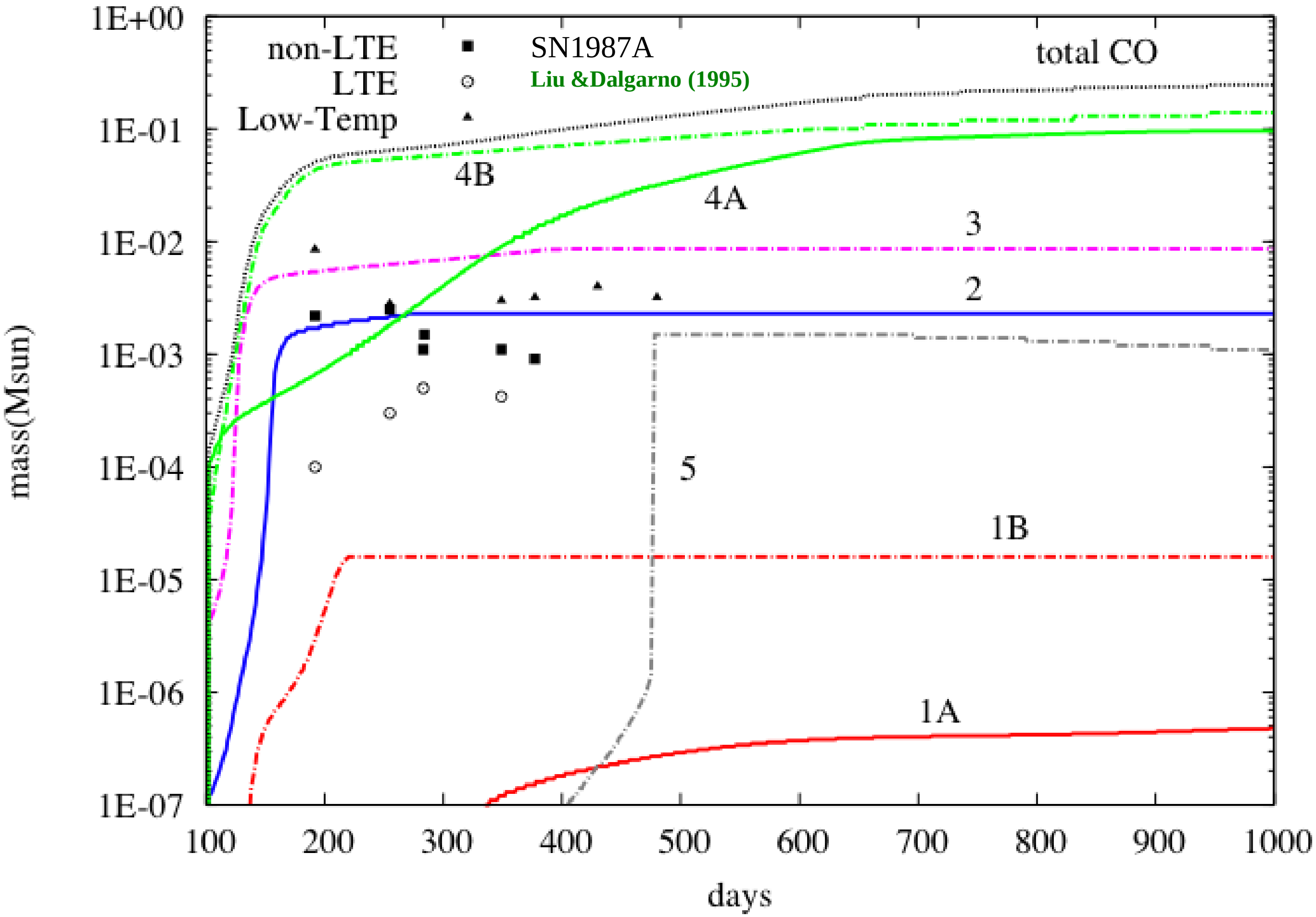
SiO



- Formation by neutral-neutral &radiative association reactions
- Destruction by thermal fragmentation, Compton e^-, and cluster formation
- SiO masses are in **good agreement** with observations → **rapid formation of silica clusters** in innermost mass zones – **SiO tracer!**

Results: molecules as tracers of dust synthesis?

CO

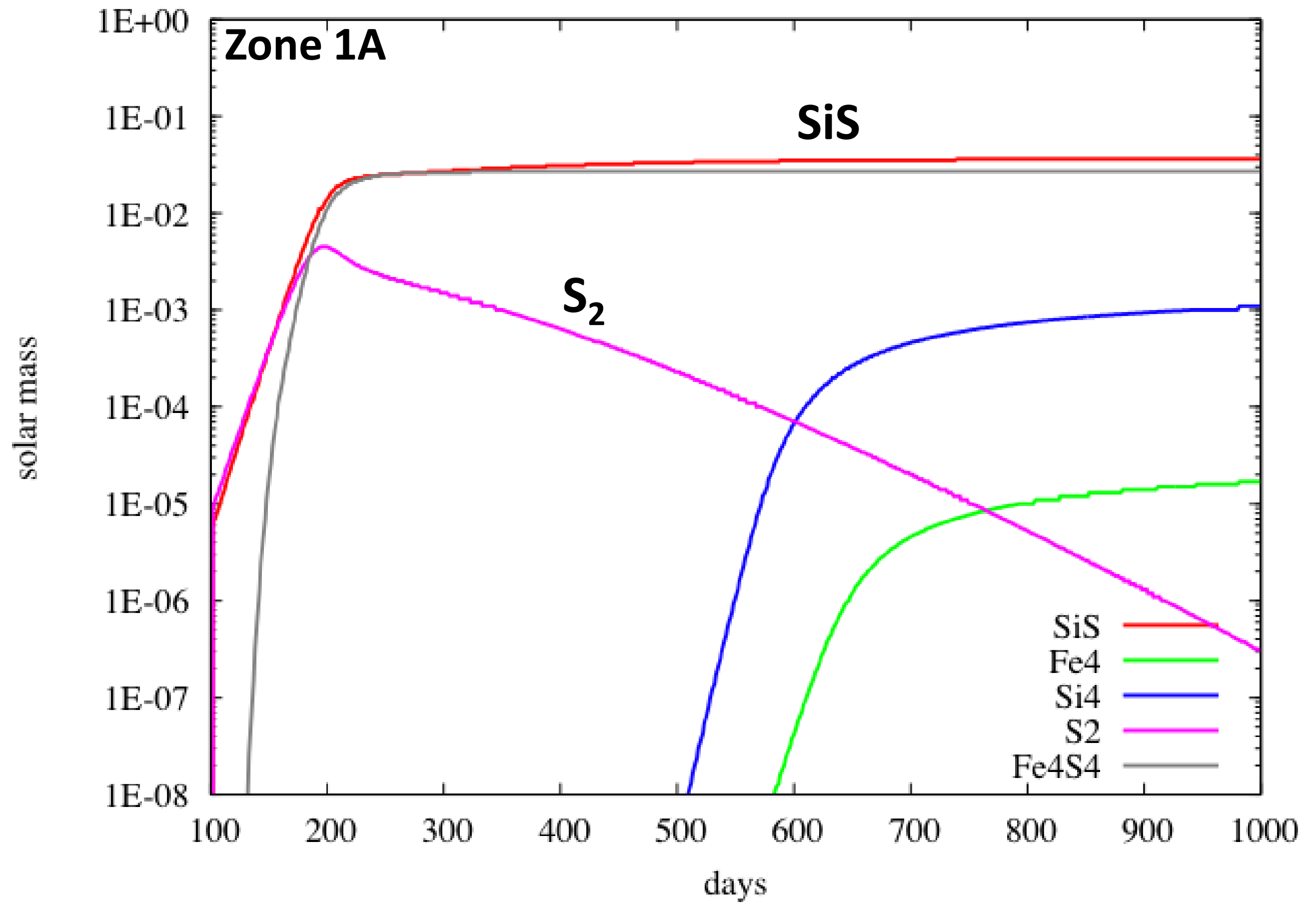


- Formation by neutral-neutral ($O + C_2 \rightarrow CO + C$) and R.A. reactions
- Destruction by He^+ and neutral-neutral reactions
- CO formation as **efficient** as that of SiO but in **different zones** (4A/B)
- **No direct tracer** of dust formation

Results: molecules as tracers of dust synthesis?

Other molecules:

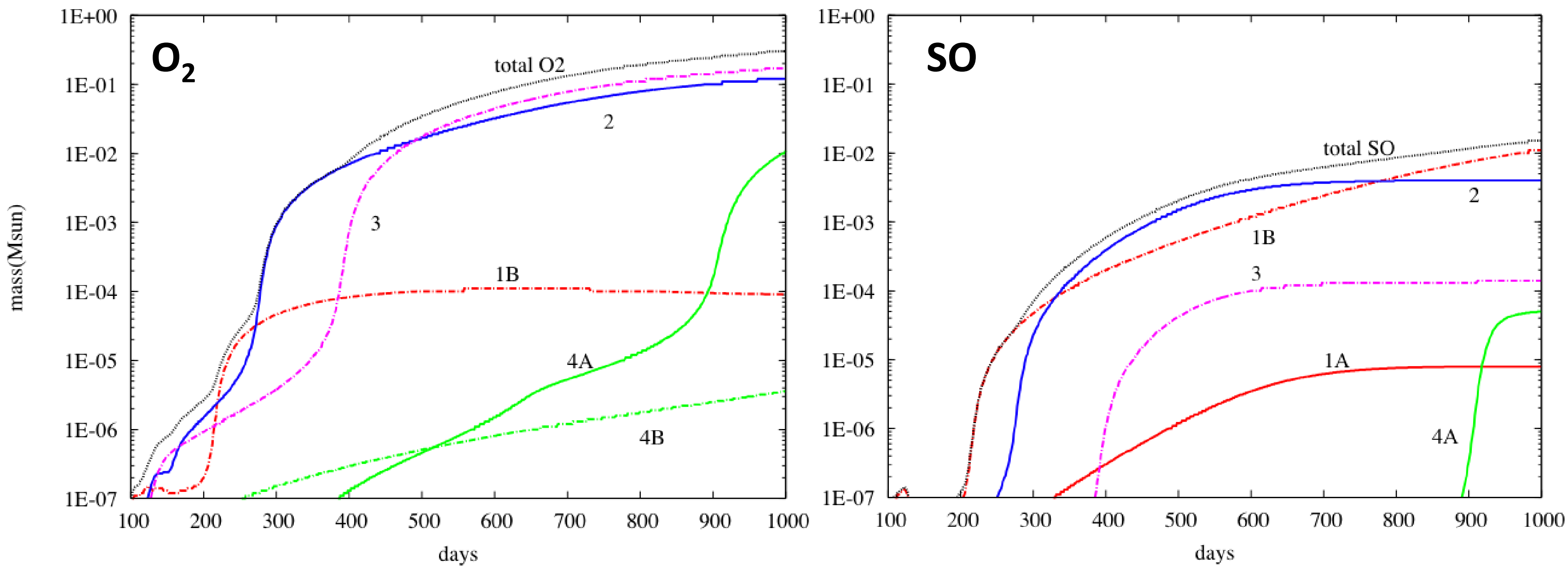
SiS



- Formation by neutral-neutral and R.A. reactions
- However, very few rates – rely on estimated values
- SiS is very efficiently formed and should be observable in the IR or in the submm in very young supernova remnants

Results: molecules as tracers of dust synthesis?

Other molecules: O_2 and SO



- Formation by neutral-neutral processes – SO related to O_2 via $S + O_2 \rightarrow SO + O$ in zone 2 (oxygen zone)

Modelling supernova ejecta: chemistry & mixing

Summary of molecular budget

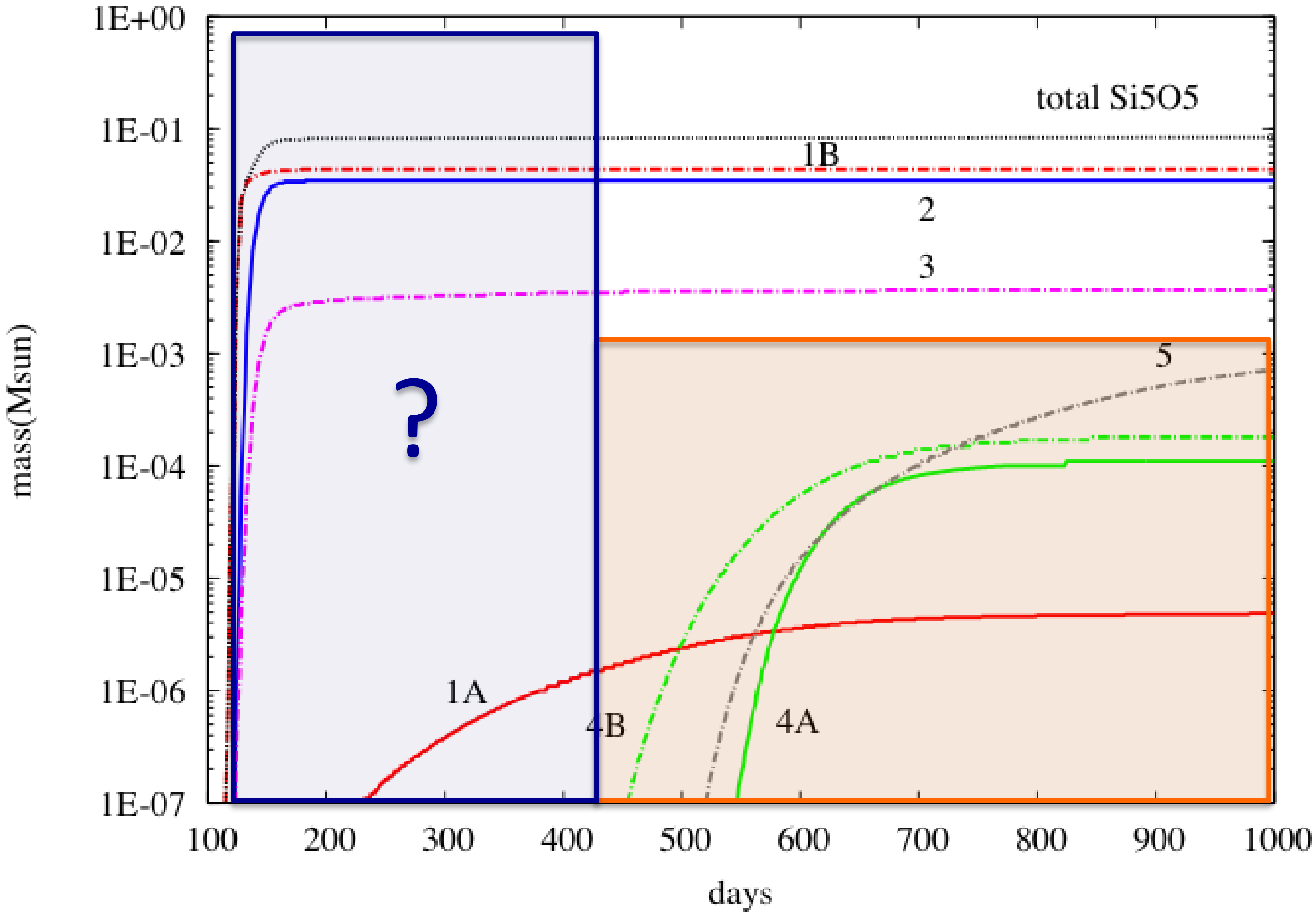
SiO							
CO							
SIS							
O2							
SO							
$(SiO)_5$							
C_{10}							
$m(M_{sun})$	1.78 - 1.9	1.9 - 1.98	1.98 - 2.3	2.3 - 2.6	2.6 - 2.8	2.8 - 3	3 - 3.8
M_{zone}	0.1	0.095	0.29	0.35	0.19	0.23	0.75
Zone	1A	1B	2	3	4A	4B	5

Molecules are chemical signatures of the various zones in the supernova ejecta

Ejecta molecular phase ~ 30% of ejected mass

Results: molecules as tracers of dust synthesis?

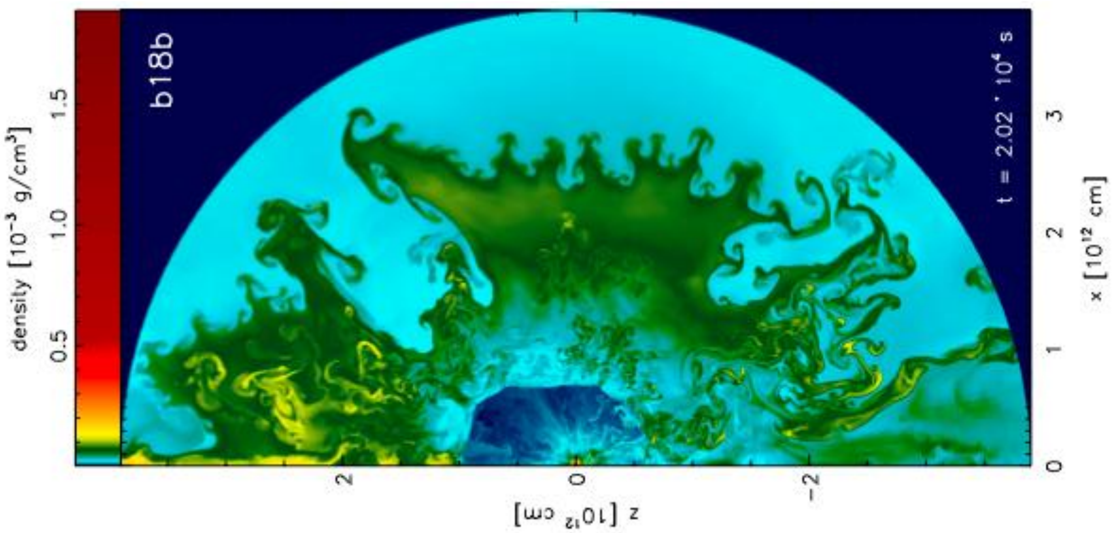
SiO clusters



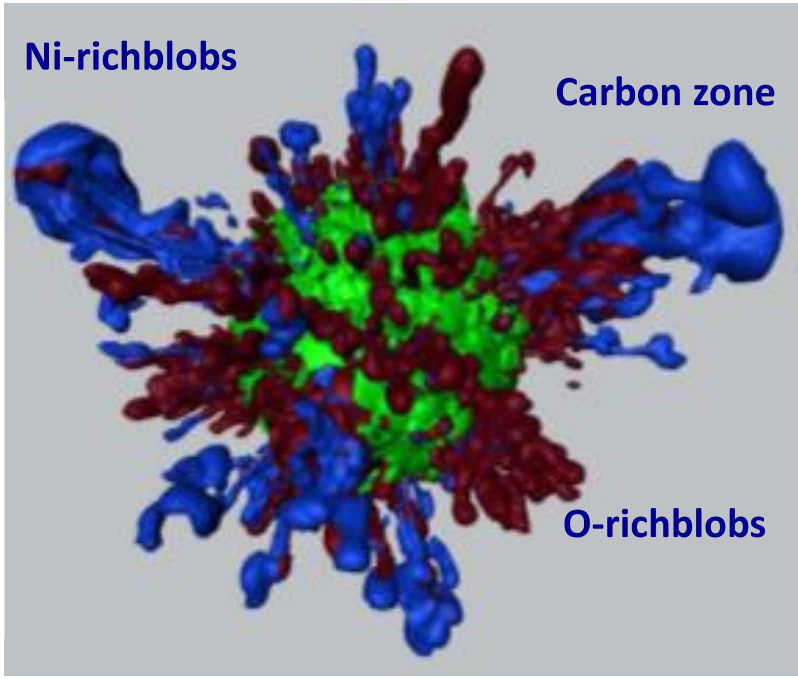
In the infrared, small dust masses (silicates + AC) detected: 10^{-5}–$10^{-2} M_{sun}$

Results: molecules as tracers of dust synthesis?

Mixing due to Rayleigh-Taylor instabilities



Kifonidis et al. (2006)



Hammeret al. (2010)

- Early fragmentation of the ejecta– fragments have various velocities
- Homogeneities (blobs, filaments) may have **very different density & temperature histories** than homogeneous flows

Next step: follow the chemistry in 3D blobs + condensation of clusters

Conclusions

- **Efficient formation of molecules** in supernova ejecta
- Prevalent molecules: O_2, CO, SO&SiS - ~ 30% of ejecta
- Agreement of predicted SiO masses with observations

→ implies SiO depletion in ~ 0.1 M_{sun} of silica precursors – SiO is a good **dust formation tracer**

- Carbon rings (C_{10}) form when no He^+
- Need for high T chemical rates of key reactions
- Need to model **the chemistry of 3D ejecta fragments** to reconcile predicted dust masses with IR observations

Implication for the dust and molecular budget of the early universe!