Oxygen-rich dust processing and evolution in the interstellar medium

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Oxygen-rich dust processing and evolution in the interstellar medium

colloborators:

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Elisabetta Micelotta
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History of the subject

- **The dirty ice dust model - van de Hulst (1943)**

- **Dust destruction in ISM - Oort & van de Hulst (1946)**
  ice grain accretion to form grains of radius ≈ 100 nm in 10^8 yr,
  is balanced by dust destruction in cloud-cloud collisions (≈ once every 10^8 yr)

- **Dust destruction studies since then:**
  - Aannestad (1973a,b)
  - Barlow (1978a,b,c)
  - Draine & Salpeter (1979a,b)
  - Dwek & Scalo (1979, 1980)
  - Seab & Shull (1983)
  - Mckee, Hollenbach, Seab & Tielens (1987); Tielens, McKee, Seab & Hollenbach (1994),
  - Jones & Tielens (1994); Jones, Tielens, Hollenbach & McKee (1994); Jones, Tielens & Hollenbach (1996)
  - Borkowski & Dwek (1995)
  - Flower, Pineau des Forêts Field & May (1996); Field, May, Pineau des Forêts & Flower (1997)
  - Waxman & Draine (2000); Draine & Hao (2002)
  - Jones (2000); Slavin, Jones & Tielens (2004); Serra Diaz-Caño & Jones (2008)
  - Guillet, Pineau des Forêts & Jones (2007, 2011); Guillet, Jones & Pineau des Forêts (2009)
  - Micelotta, Jones & Tielens (2010a,b, 2011); Jones & Nuth (2011)

Outline

- **interstellar dust**
  - lifecycle, composition & origin
  - shock processing
- **silicate dust**
  - evolution
  - implantation
  - annealing
- **the dust lifetime**
  - time-scales?
  - what do they mean?

Related talks:

Katharina Lodders

Bruce Fegley

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if time permits ?

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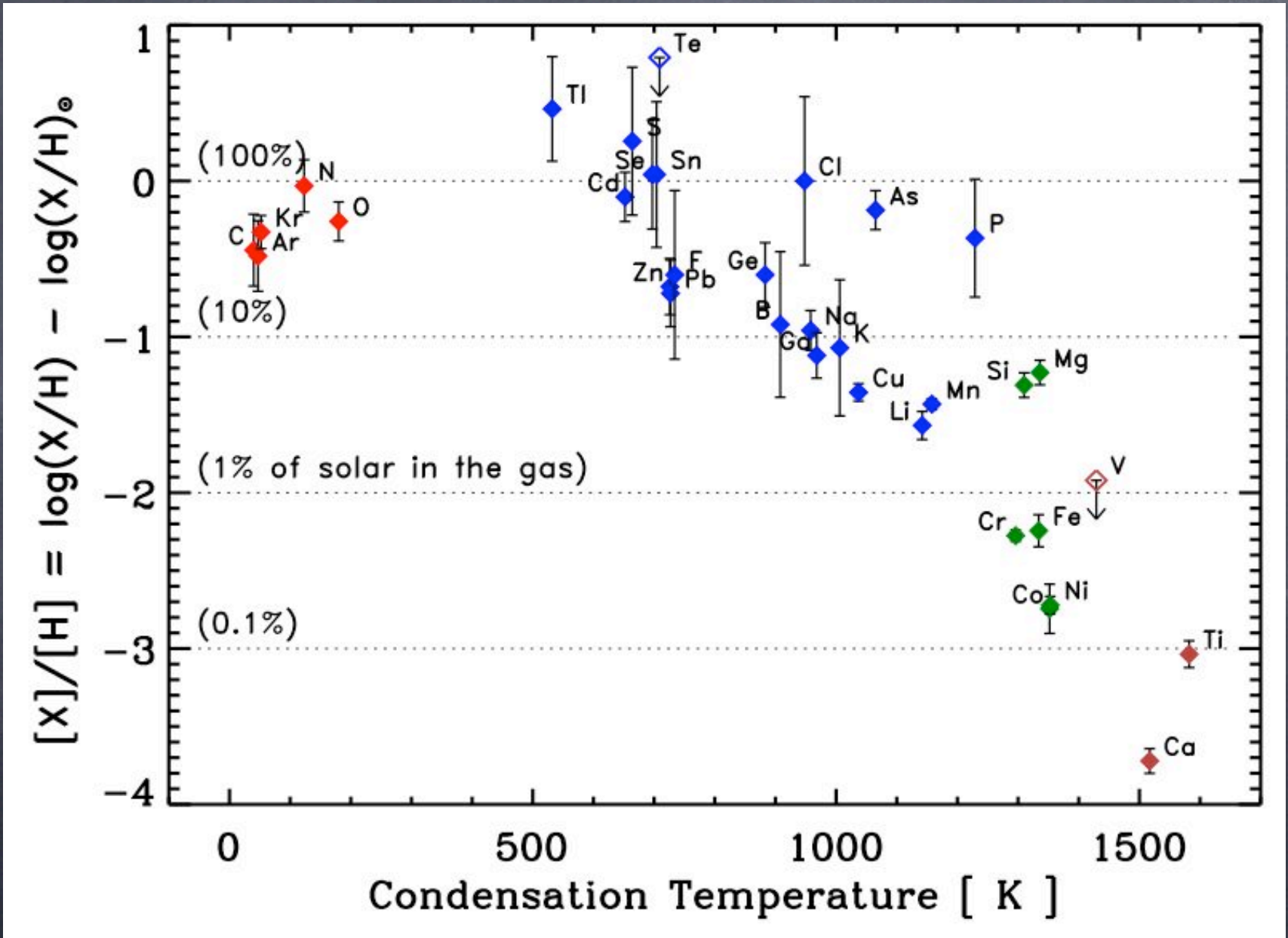
skeletons or scary monsters?

- dust formation
- dust composition
- dust evolution
- ISM mass transfer

Elemental depletions in the ISM



Palme, Lodders & Jones (2013)

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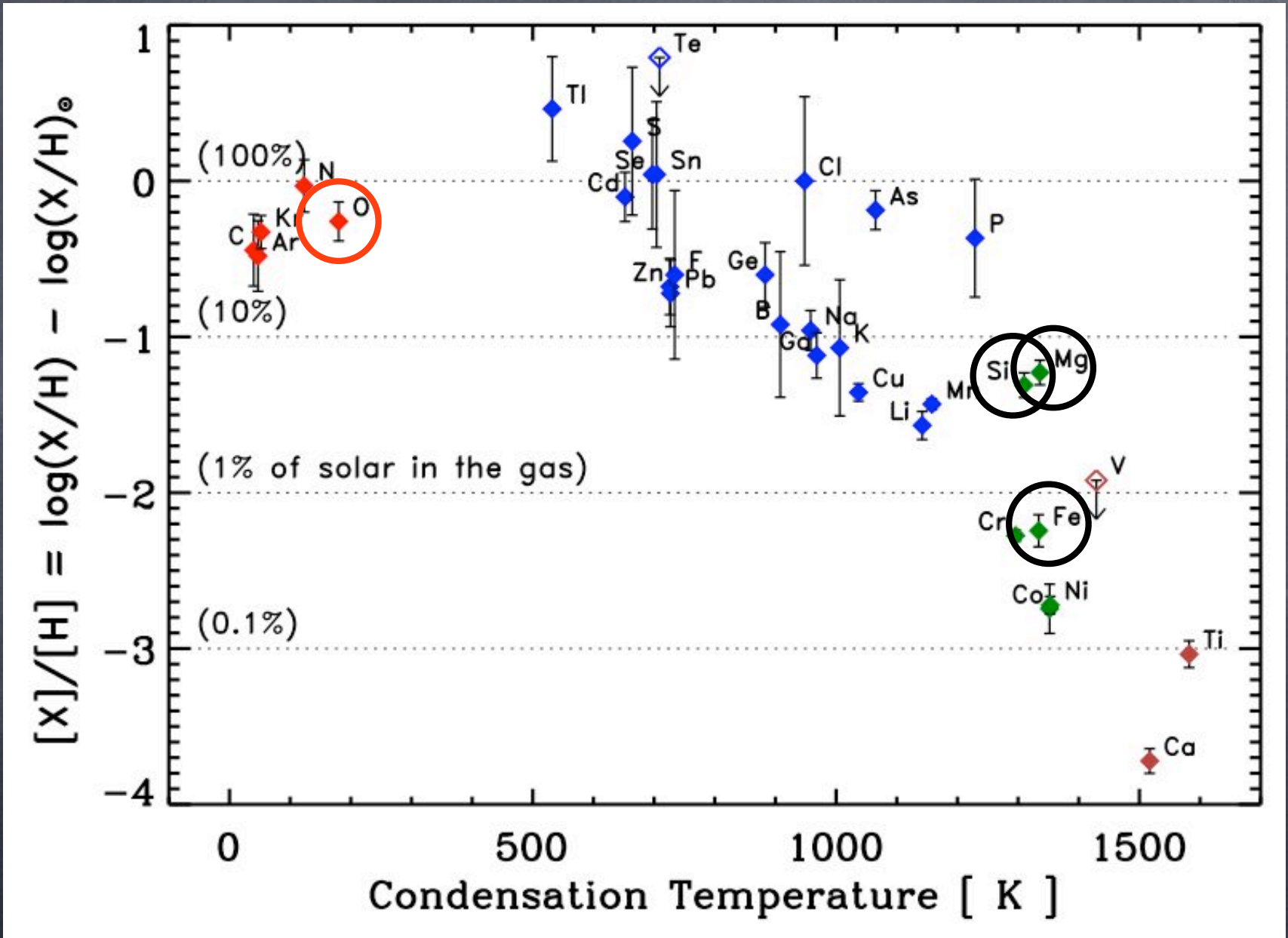

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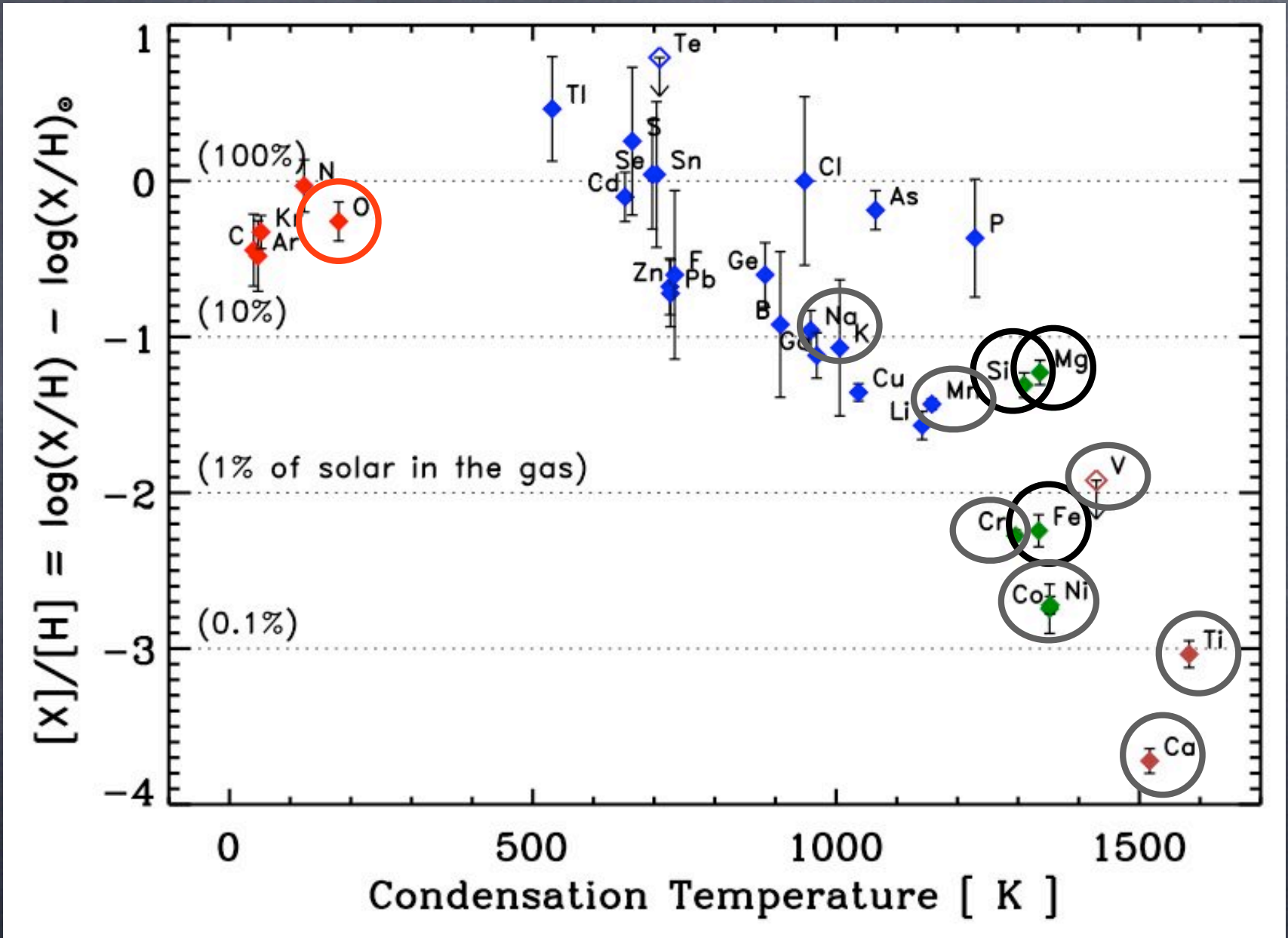

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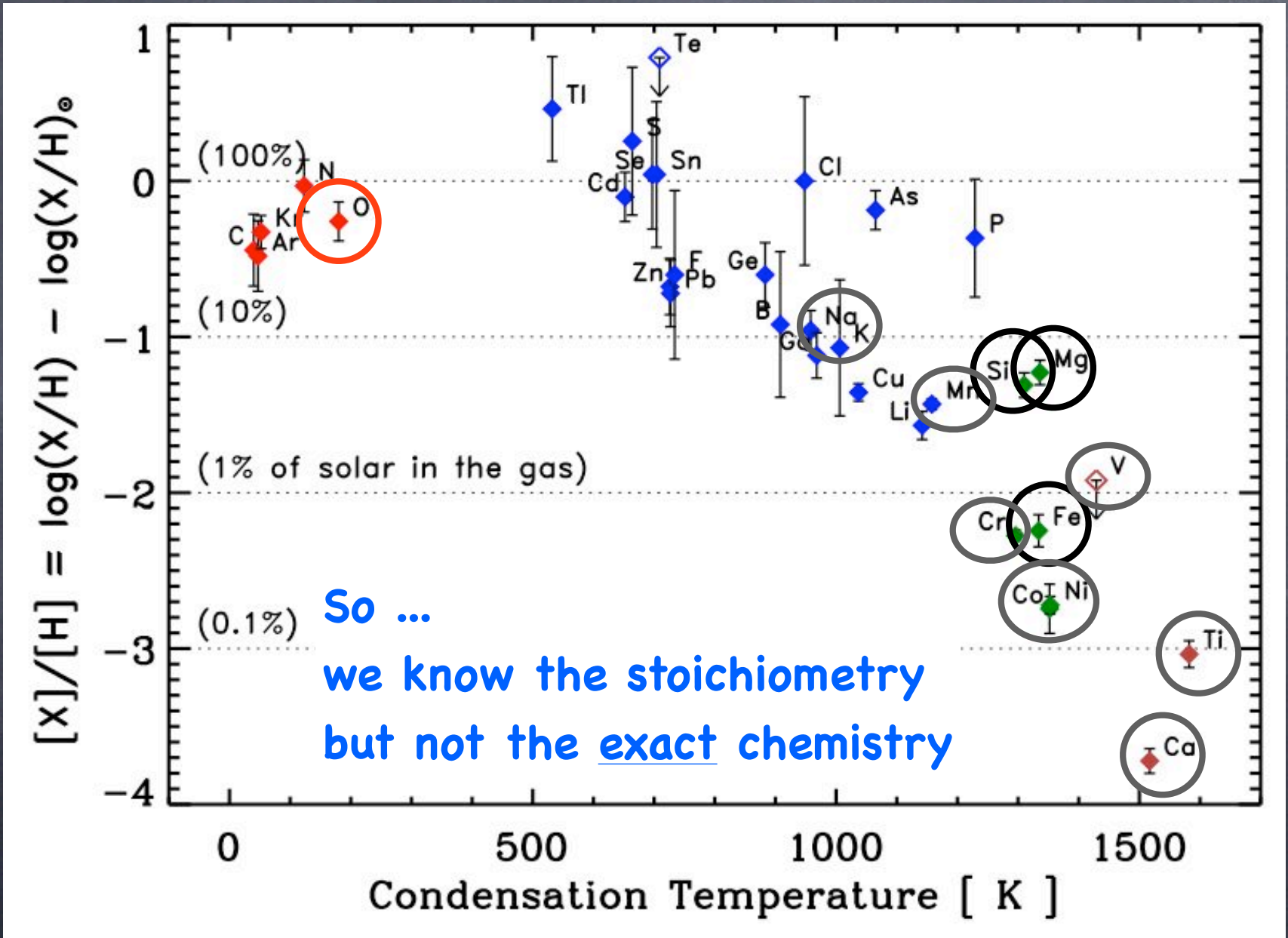

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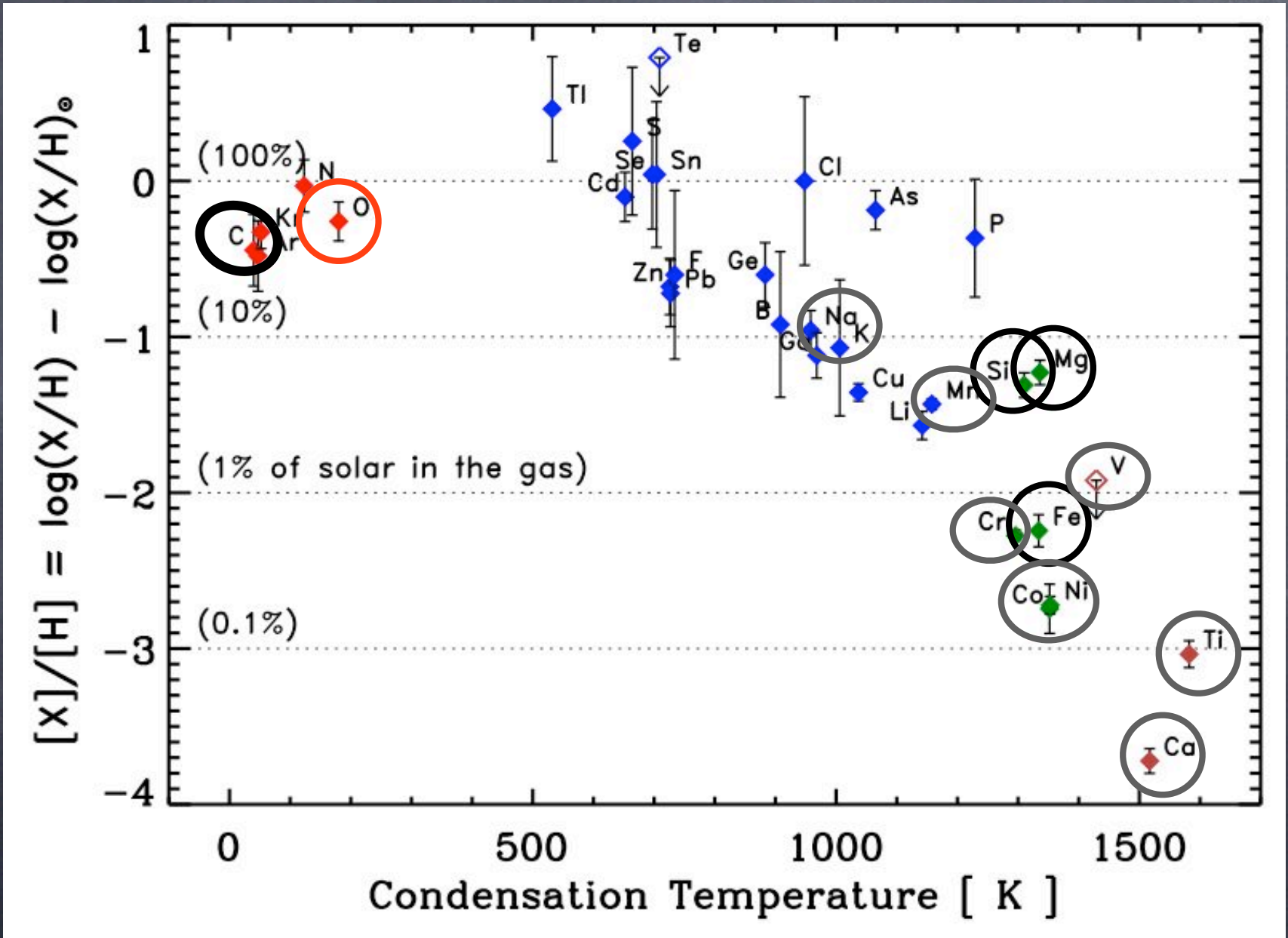
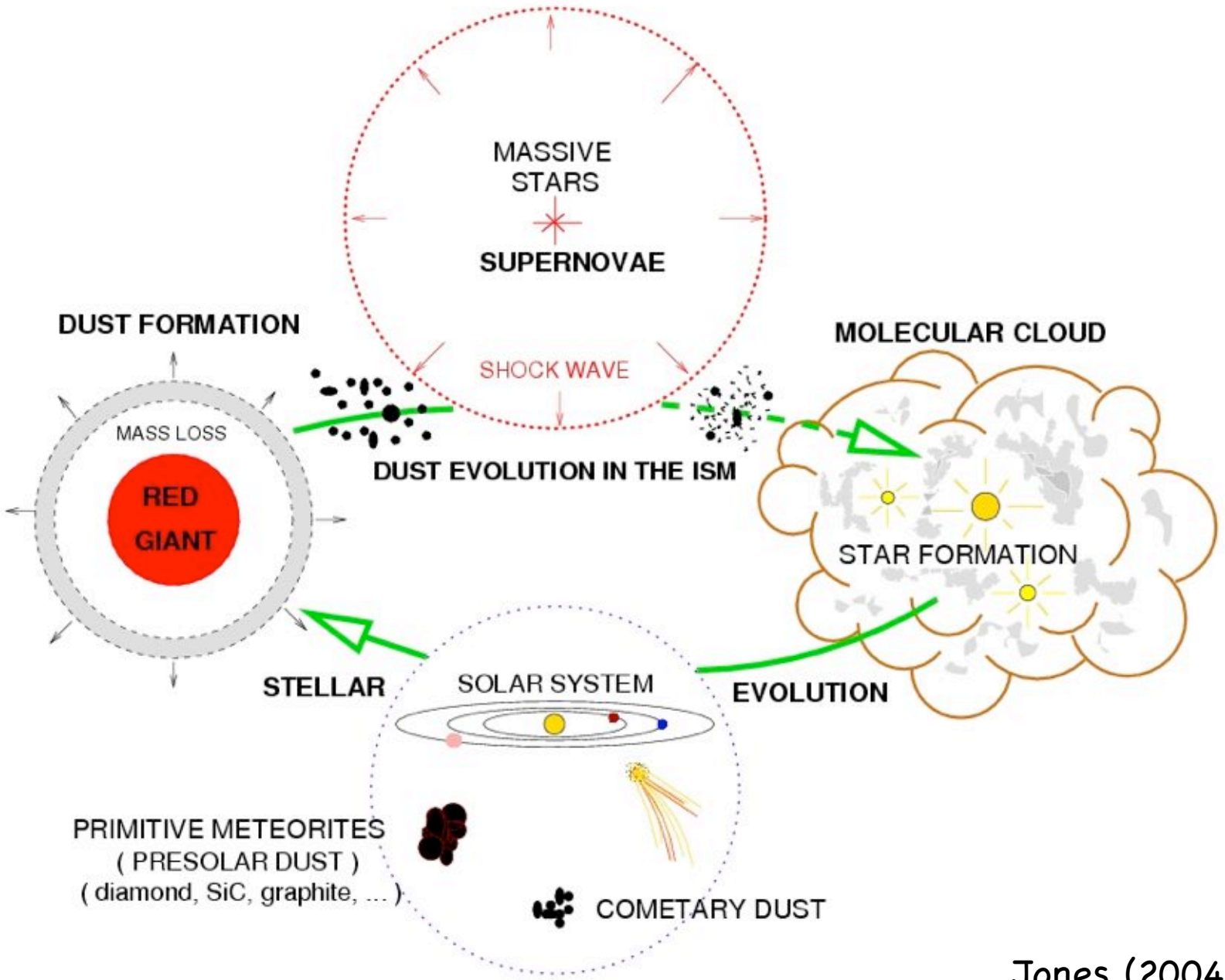


Palme, Lodders & Jones (2013)

The dust lifecycle



Jones (2004)

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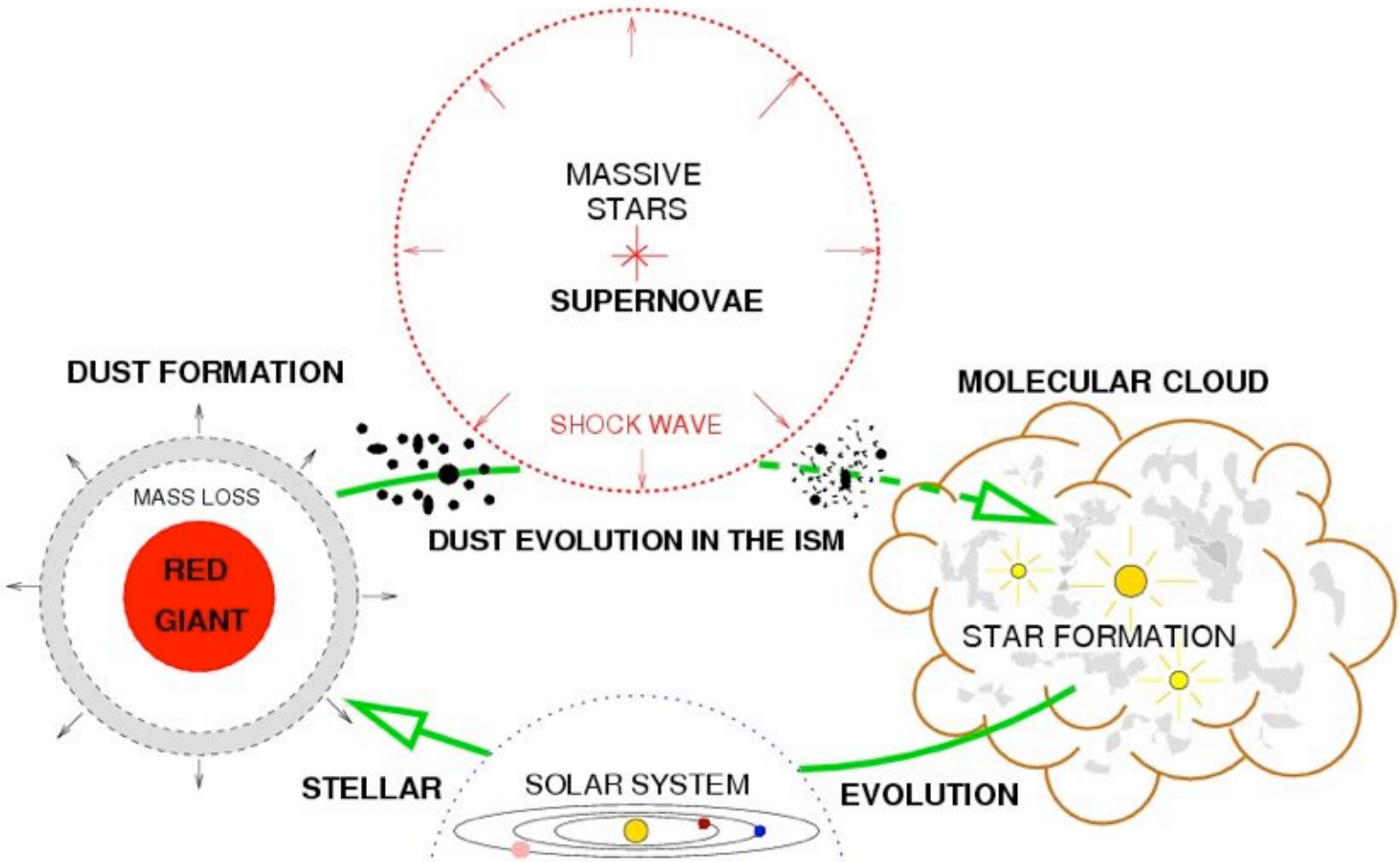


Crystalline silicates (evolved stars and proto-planetary discs) **are Mg-rich.**

Amorphous silicates (in the ISM) **appear to be Mg-rich.**

Crystalline Fe-containing silicates are never observed.

Where then is the iron hiding?

Jones (2004)

Sources of stardust

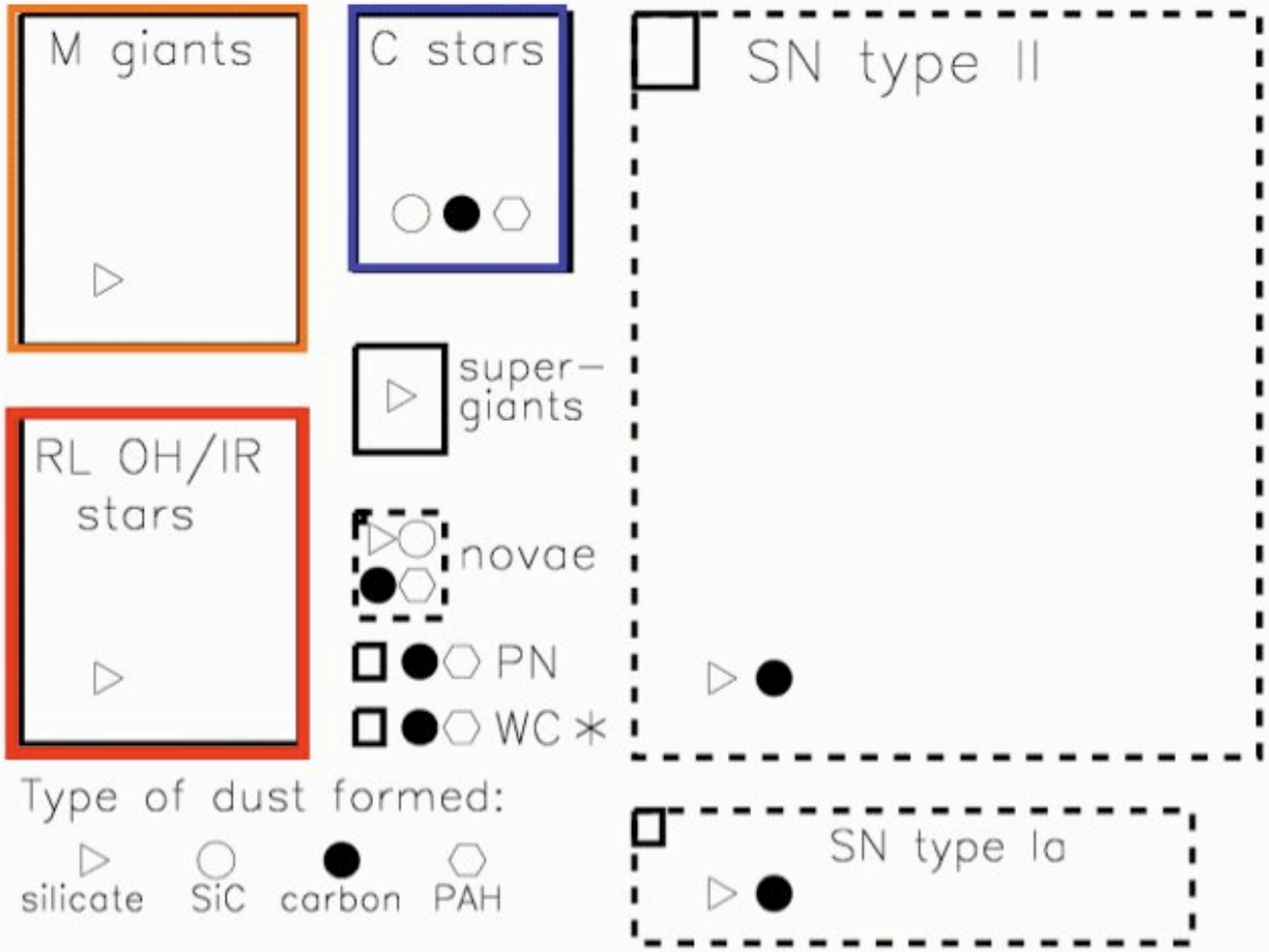
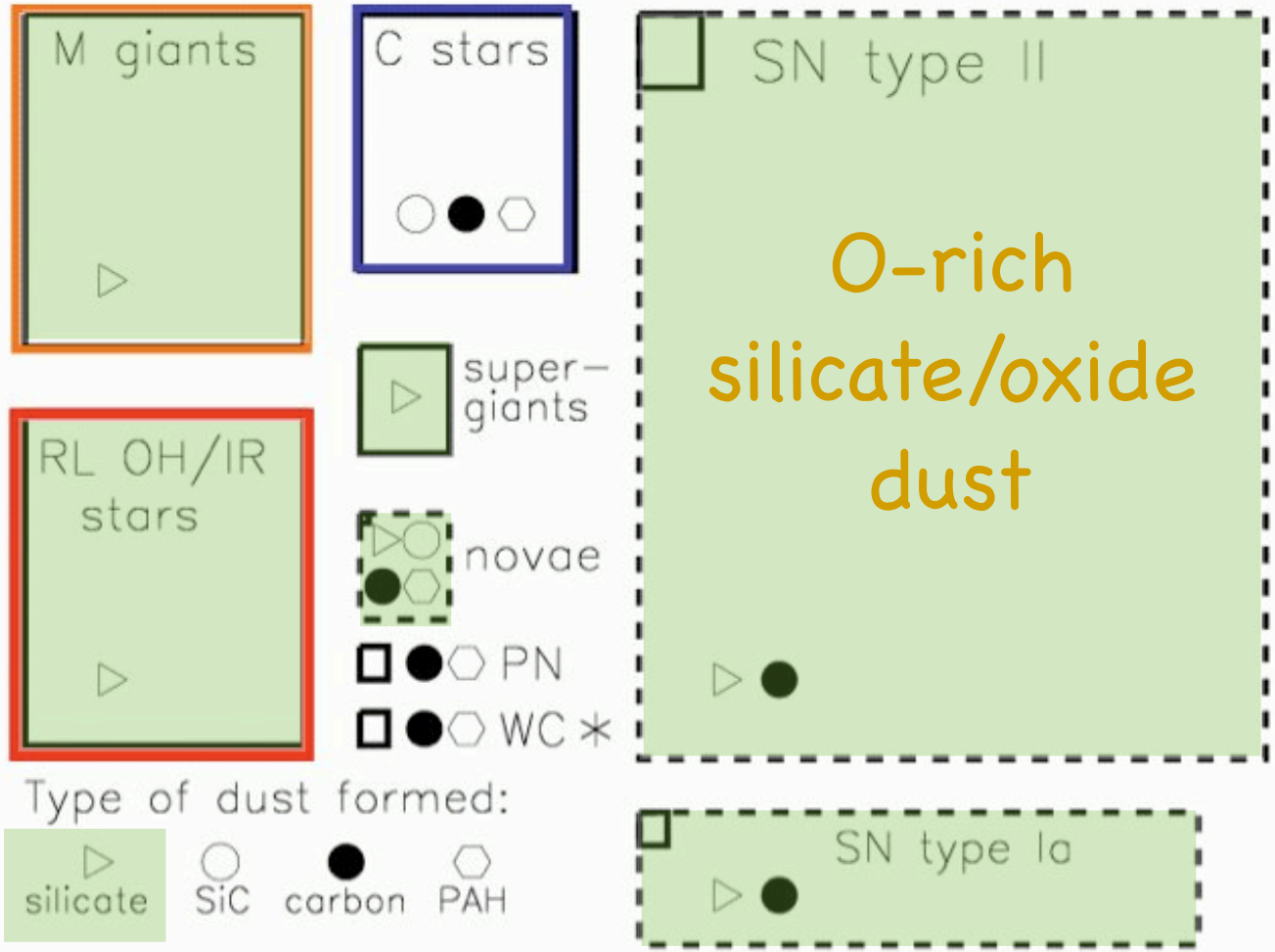


Figure 1: Relative contributions, by boxed area, of stardust sources in the ISM. C stars refers to carbon star sources, and PAH refers to polycyclic aromatic hydrocarbon species. The dashed lines indicate possible upper limit contributions.

Jones et al. (1997)

Sources of stardust



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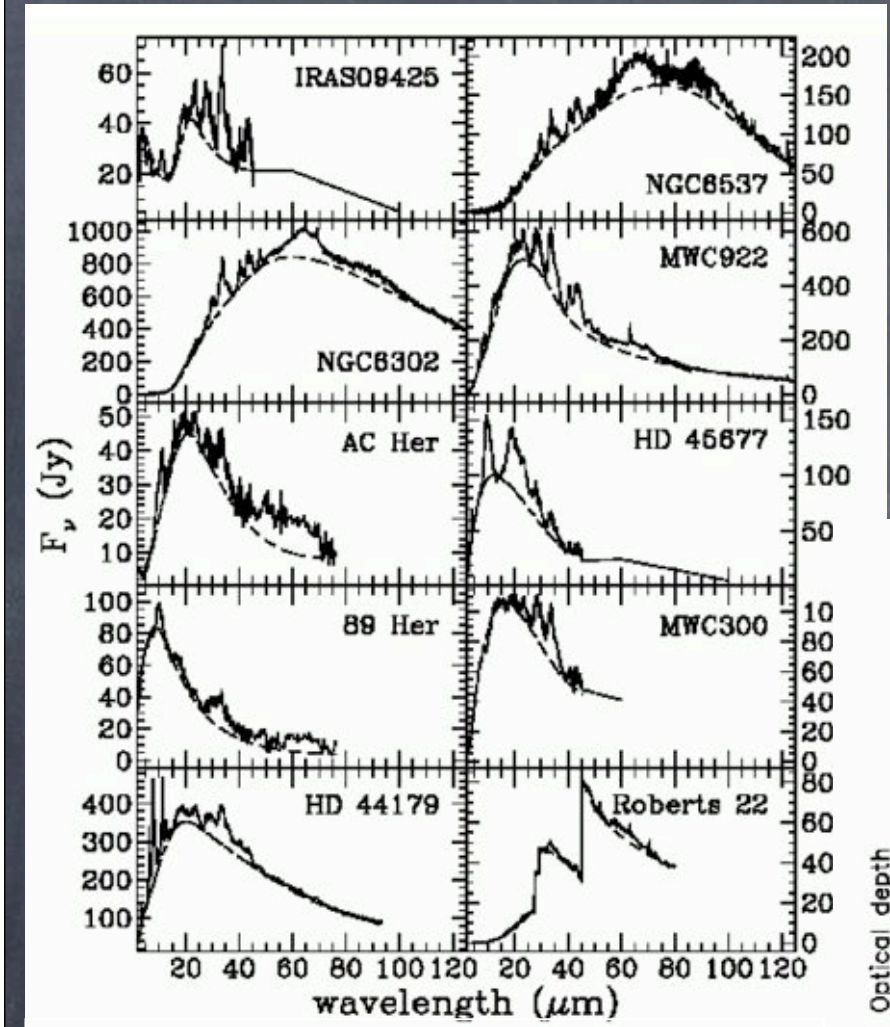

new dust around 'old stars' (AGBs)

10-20% crystalline Mg-rich silicates

old dust around massive 'young stars' (YSOs)

dust that has been processed in the ISM

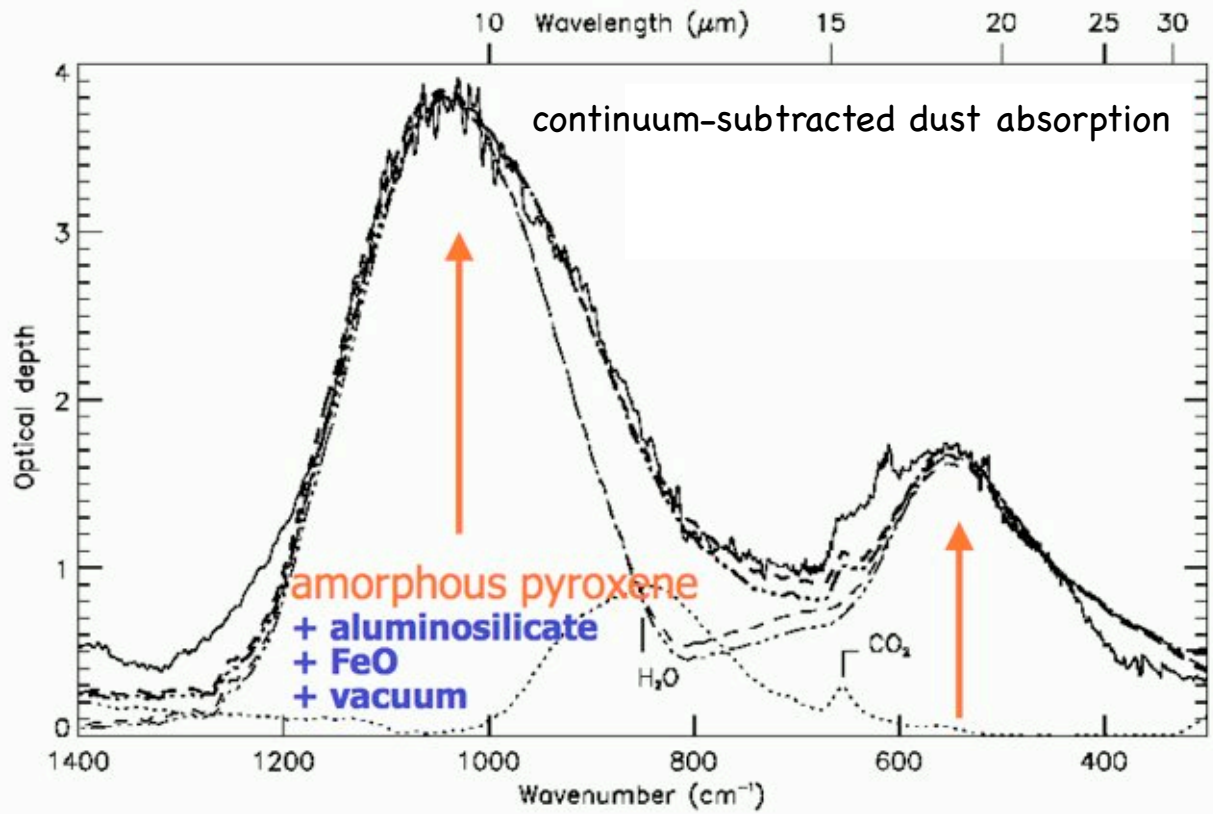

Fig. 6. Comparison of the ISO-SWS01 spectrum of IRAS 19110 (the continuum has been subtracted) with models of spherical oxide-silicate grains. Long dashed line: two grains populations, one of cosmic pyroxene grains with 3% of FeO and 15% of vacuum and the other of aluminosilicate grains ($Mg_2Fe_2Al_2Si_4O_{15}$). Dotted-dashed line: two grains populations, one of cosmic pyroxene grains with 3% of FeO and 15% of vacuum and the other of aluminosilicate grains ($Mg_4Fe_4Al_2Si_8O_{27}$) with 15% porosity. The thin lines represent the silicate models and the thick ones the models plus the ice absorption. The dotted line is the ice spectra we added to the silicate models.

interstellar	circumstellar	pre-solar
aromatic hydrocarbons	aromatic hydrocarbons	[aromatic hydrocarbons]
aliphatic hydrocarbons	aliphatic hydrocarbons	
		graphite
	[nano]diamond	Nanodiamond
amorphous silicates	amorphous silicates	amorphous silicates (GEMS)
	[aluminosilicate]	
	Mg-rich crystalline silicates (forsterite, Mg_2SiO_4 enstatite, $MgSiO_3$ diopside, $CaMgSi_2O_6$)	Mg-rich crystalline silicate (forsterite, Mg_2SiO_4, olivine, pyroxene)
[Mg & Fe oxides]	oxides ($Fe_{0.9}Mg_{0.1}O$, spinel, $MgAl_2O_4$ corundum, Al_2O_3)	crystalline oxides (spinel, $MgAl_2O_4$ hibonite, $CaAl_{12}O_{19}$, corundum, Al_2O_3)
	β-SiC	β-SiC
		TiC (as inclusions in graphite)
		Si_3N_4

interstellar	circumstellar	pre-solar
aromatic hydrocarbons aliphatic hydrocarbons	aromatic hydrocarbons aliphatic hydrocarbons	[aromatic hydrocarbons]
	[nano]diamond	graphite Nanodiamond
amorphous silicates	amorphous silicates [aluminosilicate]	amorphous silicates (GEMS)
O-rich silicate dust	Mg-rich crystalline silicates (forsterite, Mg_2SiO_4 enstatite, $MgSiO_3$ diopside, $CaMgSi_2O_6$)	Mg-rich crystalline silicate (forsterite, Mg_2SiO_4, olivine, pyroxene)
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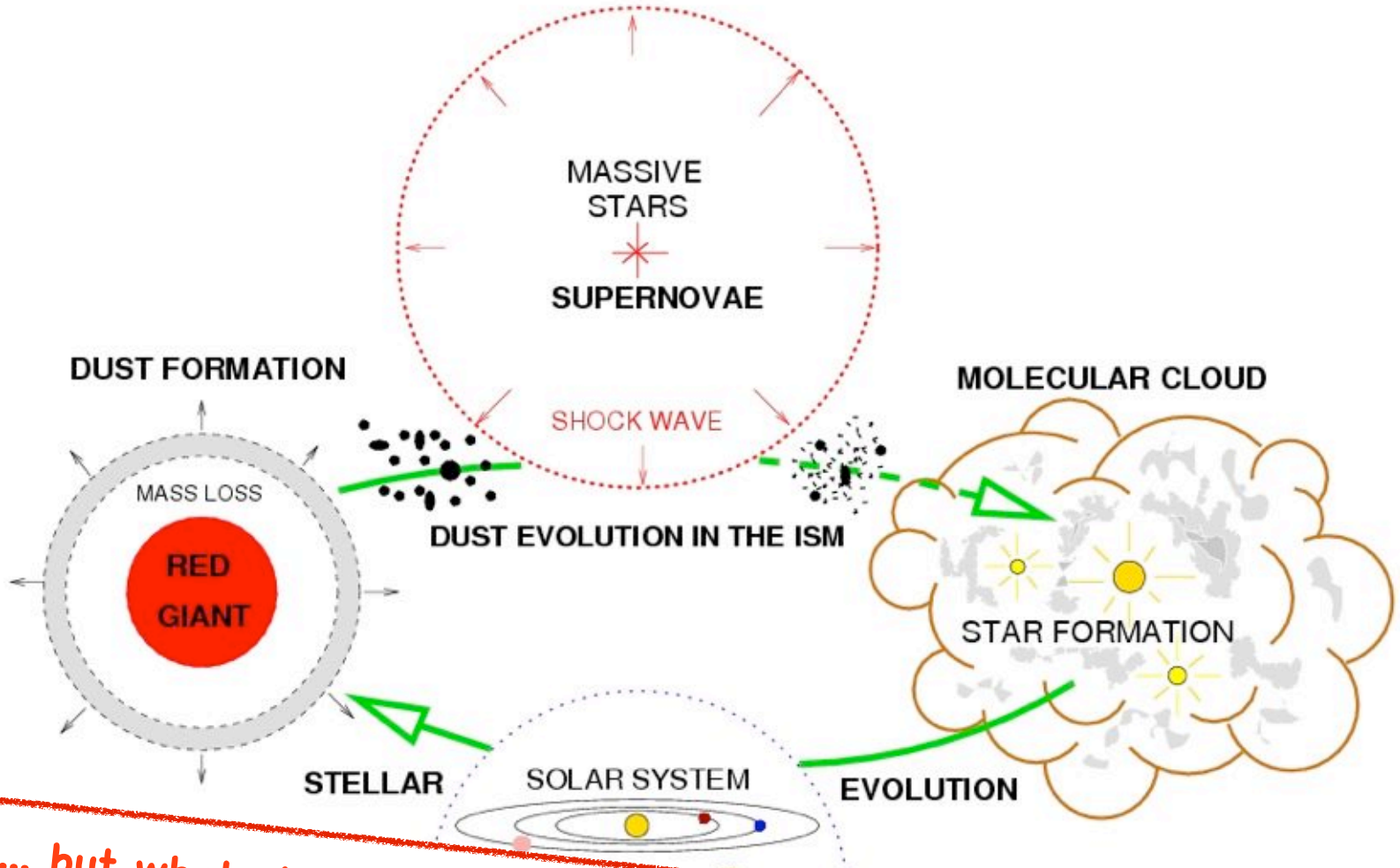
	β-SiC	β-SiC
		TiC (as inclusions in graphite)
		Si_3N_4

The dust lifecycle



... but what about the effects of cosmic rays?

Bringa et al. (2007)

~0.1-5.0 GeV heavy-ion cosmic rays can rapidly (~70 Myr) amorphize crystalline silicate grains ejected by stars

Jones (2004)

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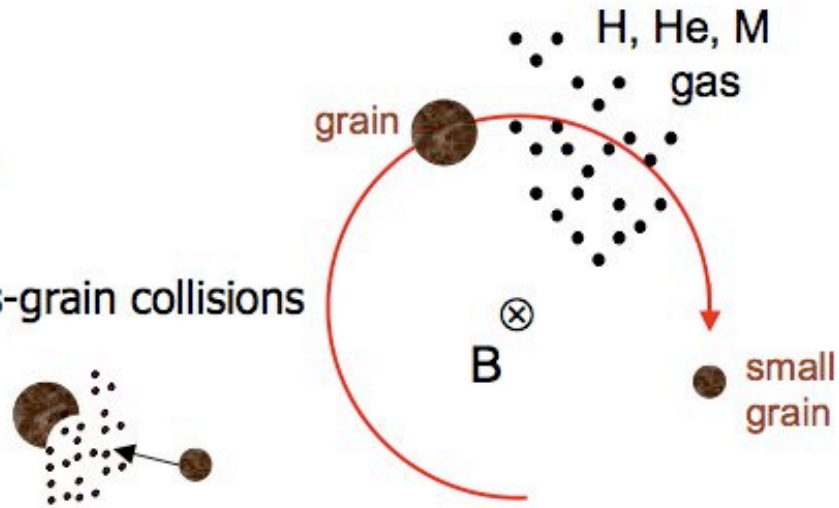
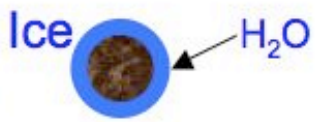
- the dust lifetime
  - time-scales?
  - what do they mean?

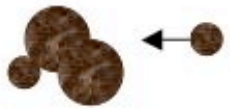
Key ISM processes that lead to changes in the dust composition (and structure)

- **energetic interactions (shocks) –**
  - sputtering/erosion, implantation in gas-grain collisions
  - fragmentation in grain-grain collisions



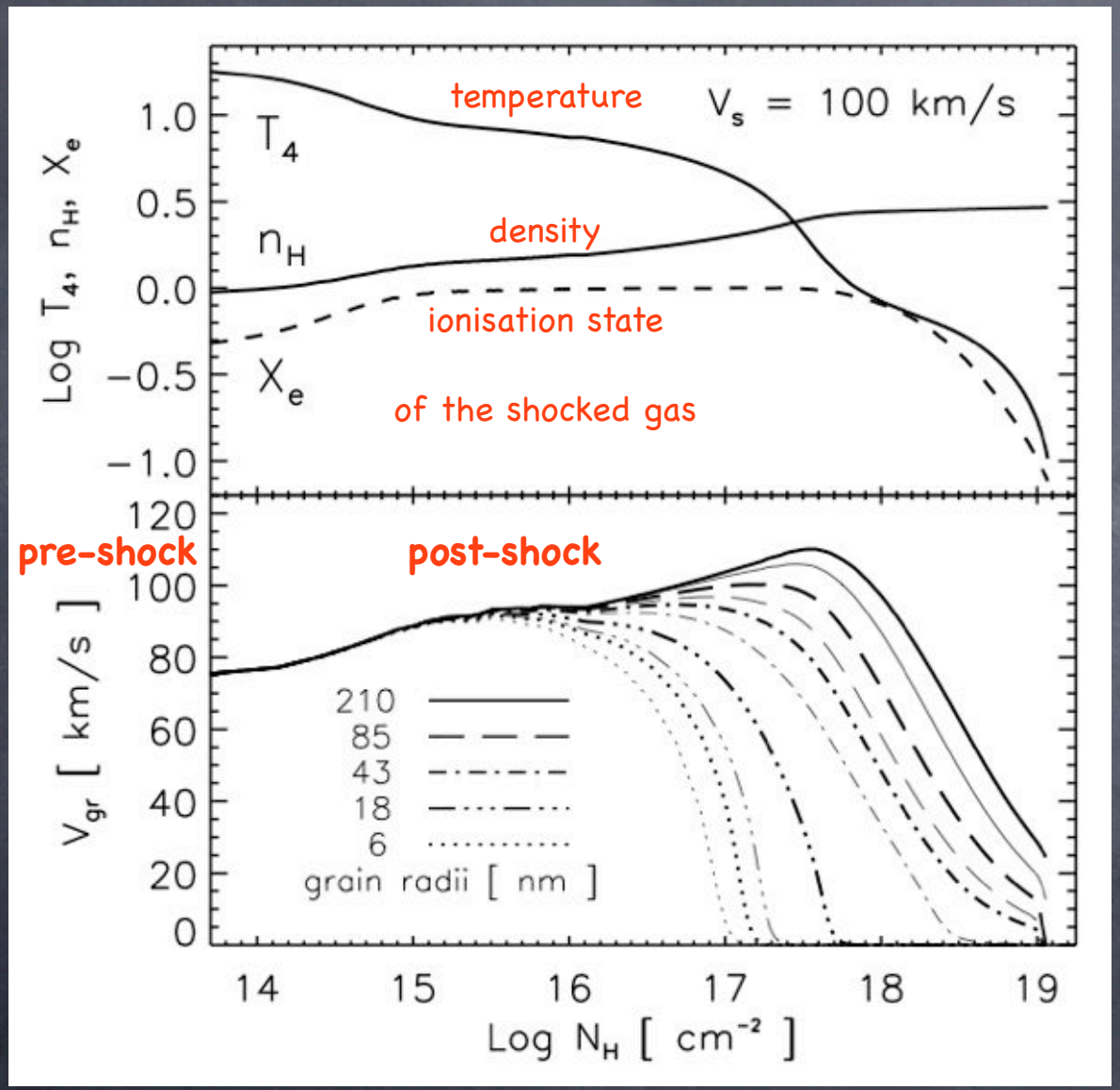
- **low-energy interactions (dense clouds) –**
  - accretion of gas species in gas-grain collisions
  - coagulation in grain-grain collisions





- **photo-chemical processing of dust (PDRs) -**

Ion-grain and grain-grain collisions in shocks



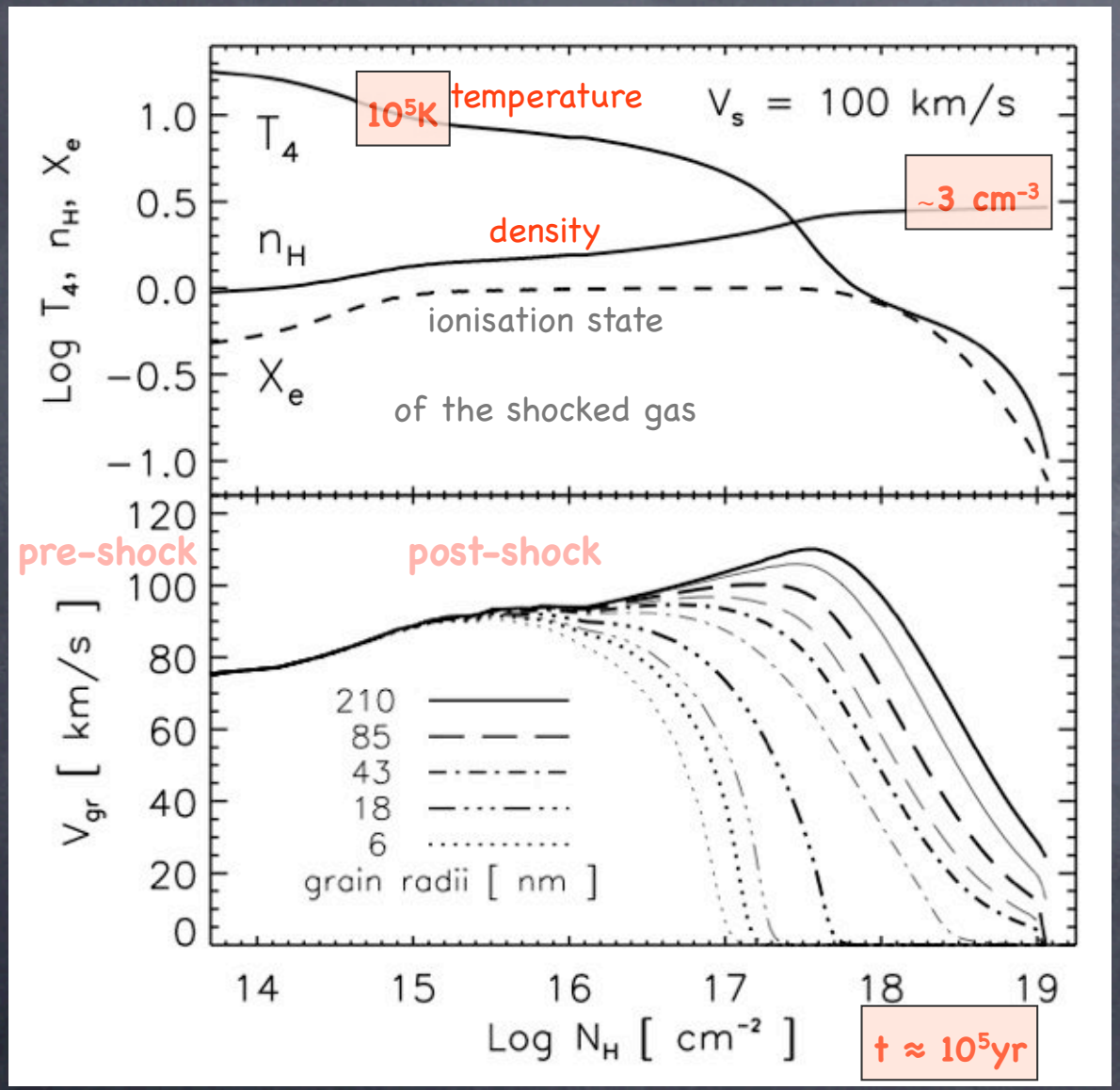
shocks in the
warm inter-cloud medium

$T_k \cong 10^4$K
$n_H \cong 0.3$ cm^{-3}
filling factor $\cong$ 0.3

ISM phase which
dominates dust destruction
and
determines the dust 'lifetime'

Jones (2004)

Ion-grain and grain-grain collisions in shocks



shocks in the
warm inter-cloud medium

$T_k \cong 10^4$K
$n_H \cong 0.3$ cm^{-3}
filling factor ≅ 0.3

ISM phase which
dominates dust destruction
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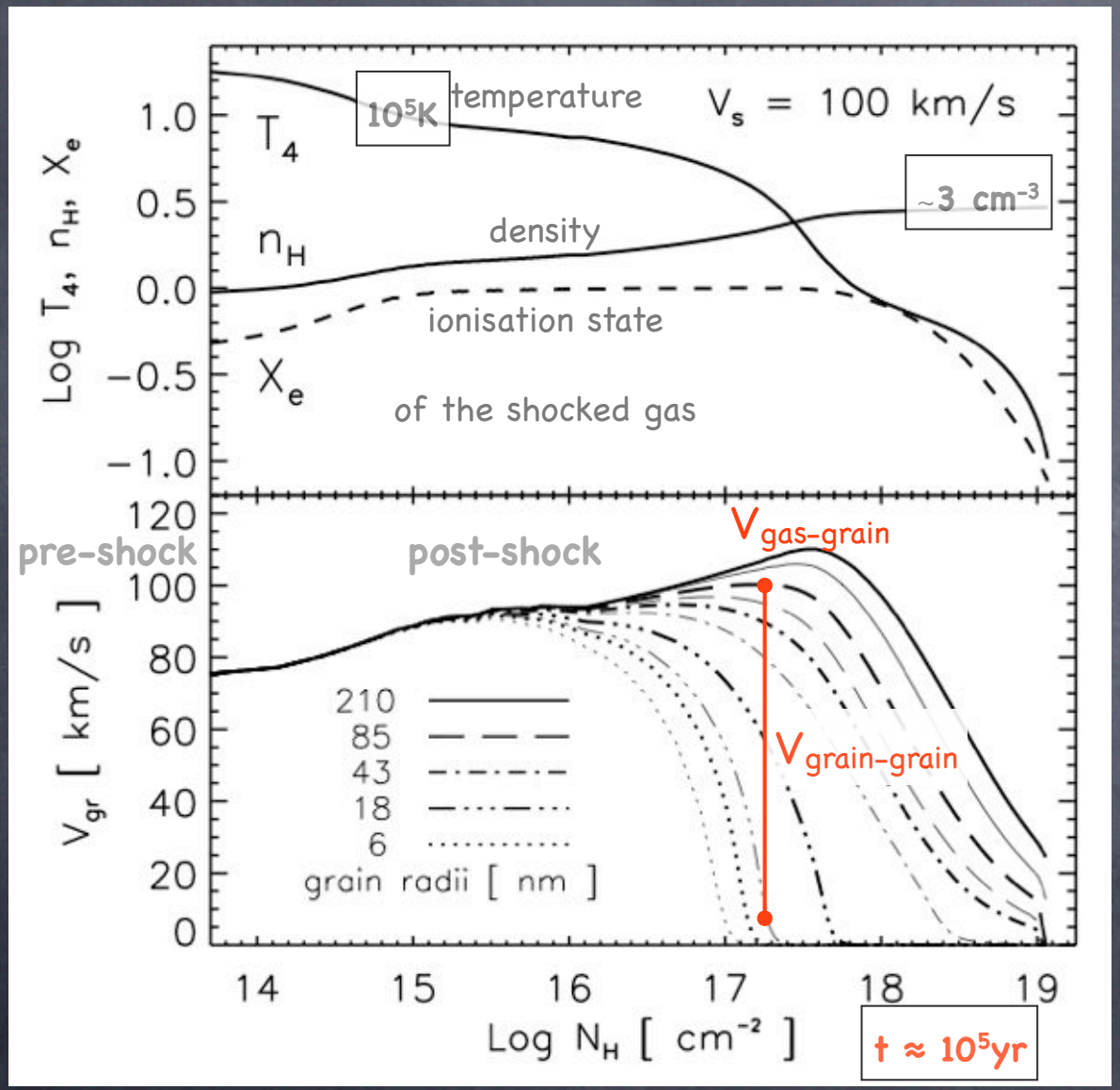
V = 100 km/s trade-off
V_{ISM} vs. F_{dest}

Jones (2004)

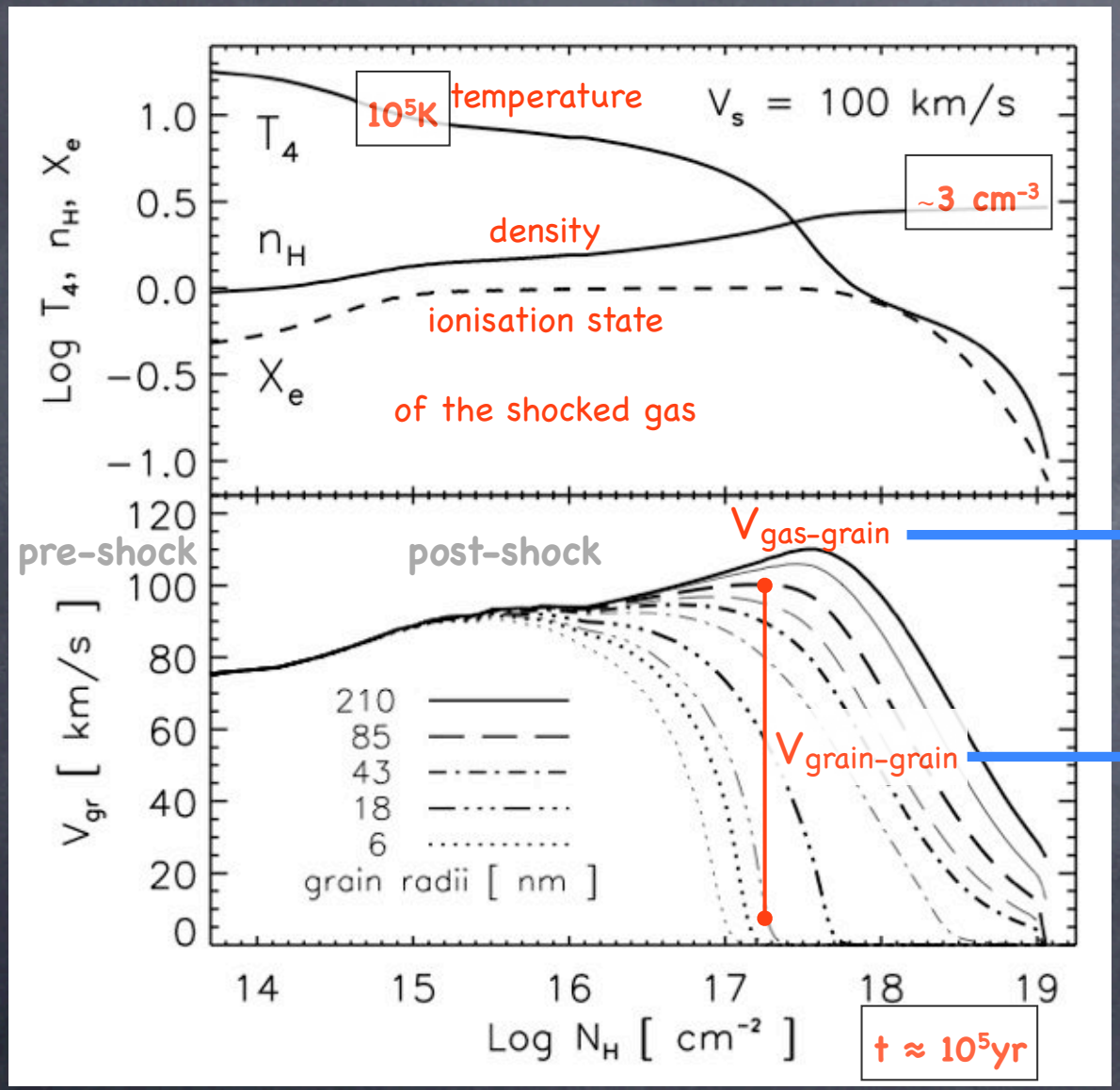
Ion-grain and grain-grain collisions in shocks



differential velocities

Jones (2004)

Ion-grain and grain-grain collisions in shocks

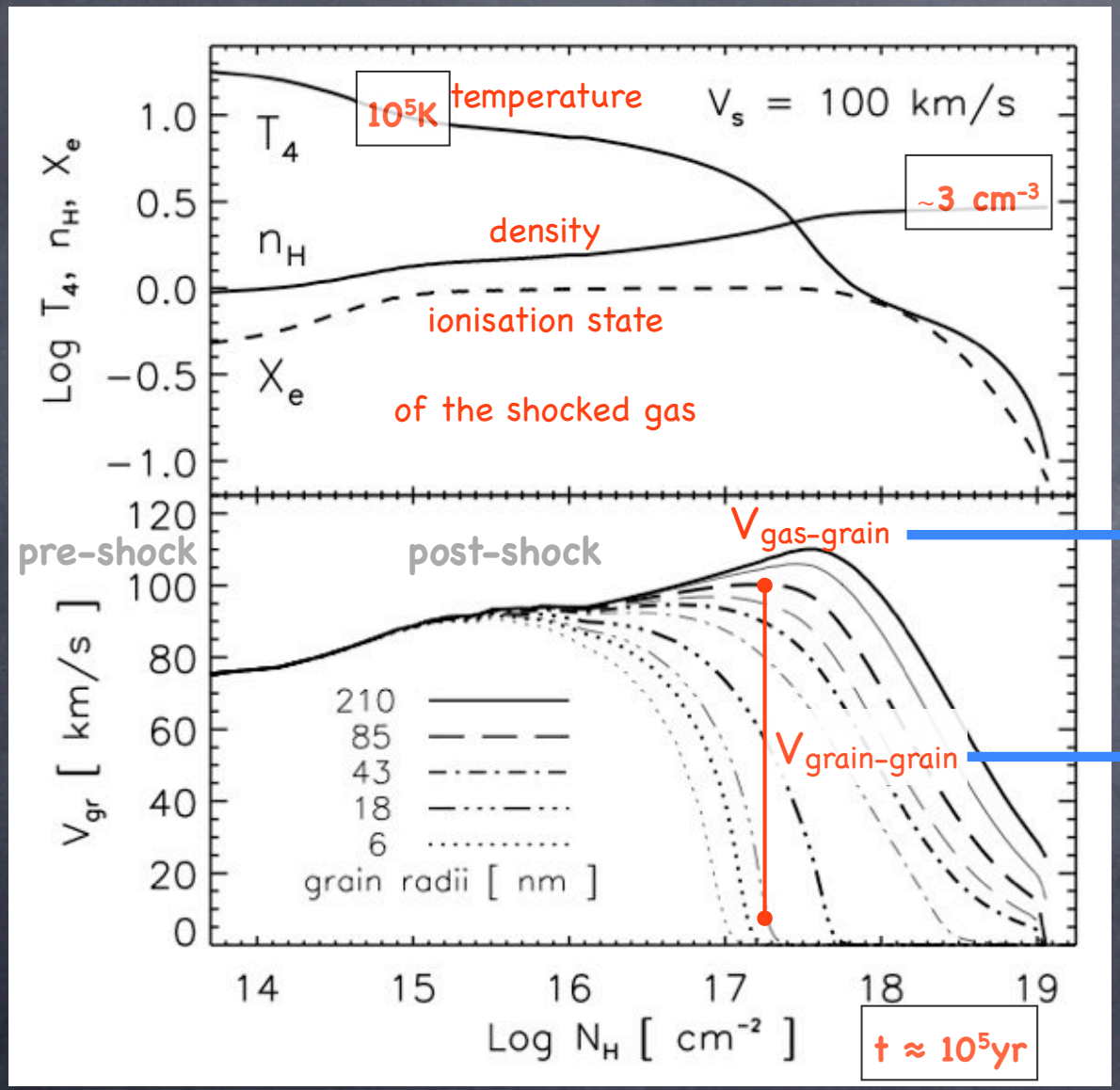


ion-grain collisions
--> sputtering

grain-grain collisions
--> fragmentation

Jones (2004)

Ion-grain and grain-grain collisions in shocks



H^+, He^+ & He^{++} ion irradiation

ion-grain collisions --> sputtering

grain-grain collisions --> fragmentation

Jones (2004)

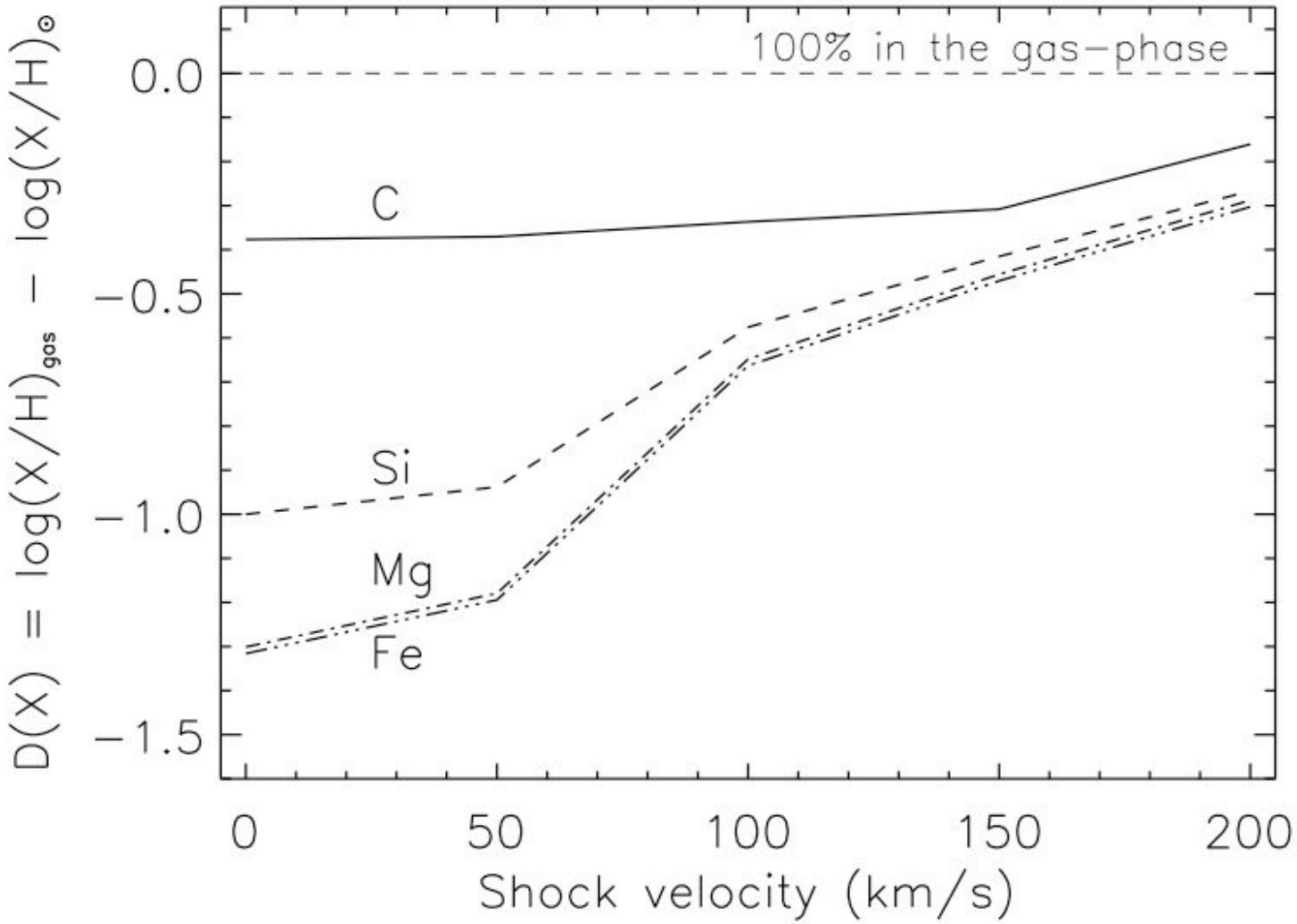
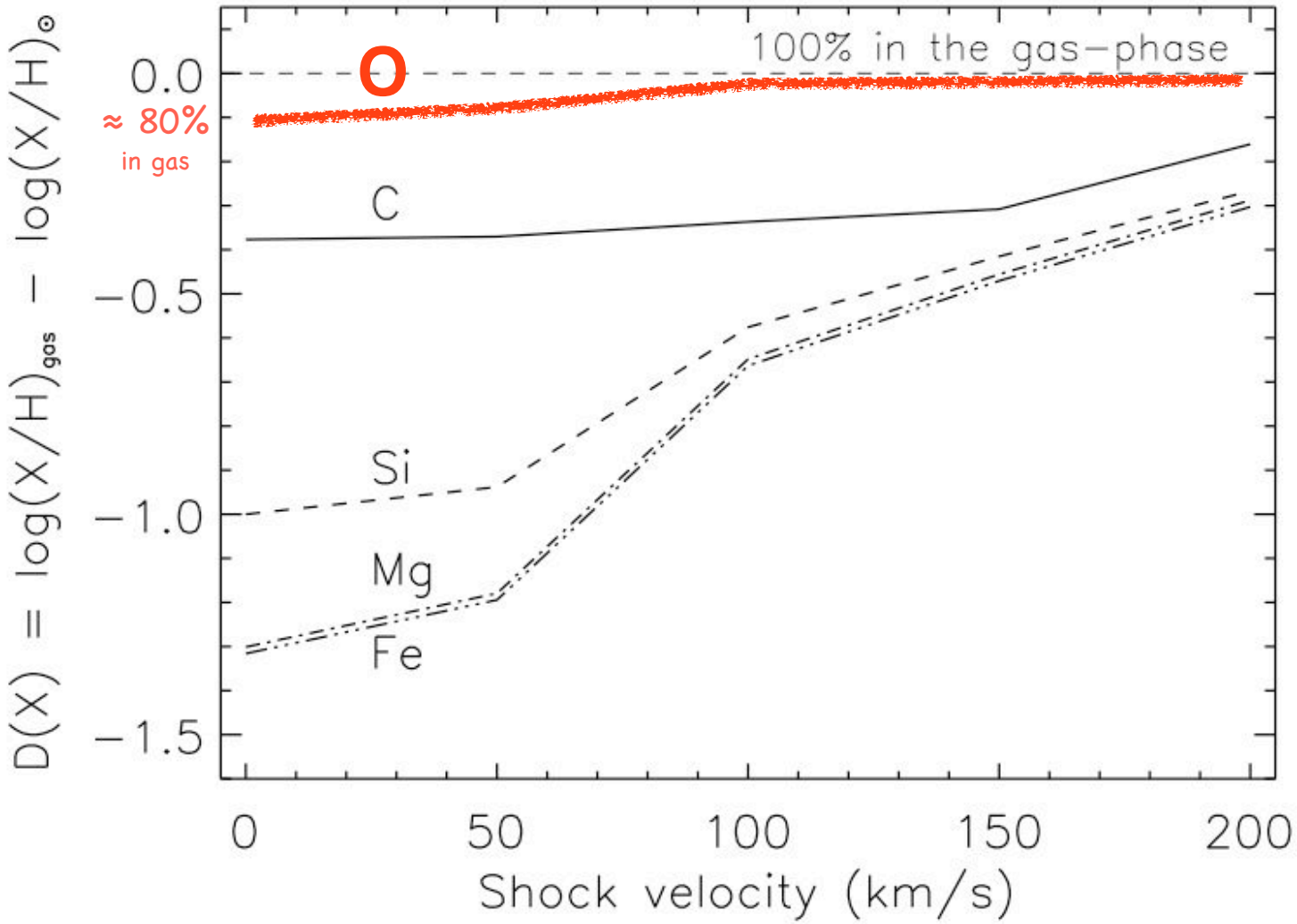


Figure 2. Depletions of the dust-forming elements as a function of shock velocity, assuming the results of *Jones et al.*, [1996]. Carbon (solid), silicon (short-dashed), magnesium (dotted-dashed), and iron (triple dotted-dashed). The preshock fractions of the elements assumed to be in dust are O (0.16), C (0.58), Fe (0.95), Si (0.90), and Mg (0.95) [*Draine and Lee*, 1984]. The results expressed in this form are independent of the assumed reference abundances. The sputtering of the silicate elements was assumed to be in their stoichiometric ratios.

Jones (2000, JGR, **105** no. A5, p10257)



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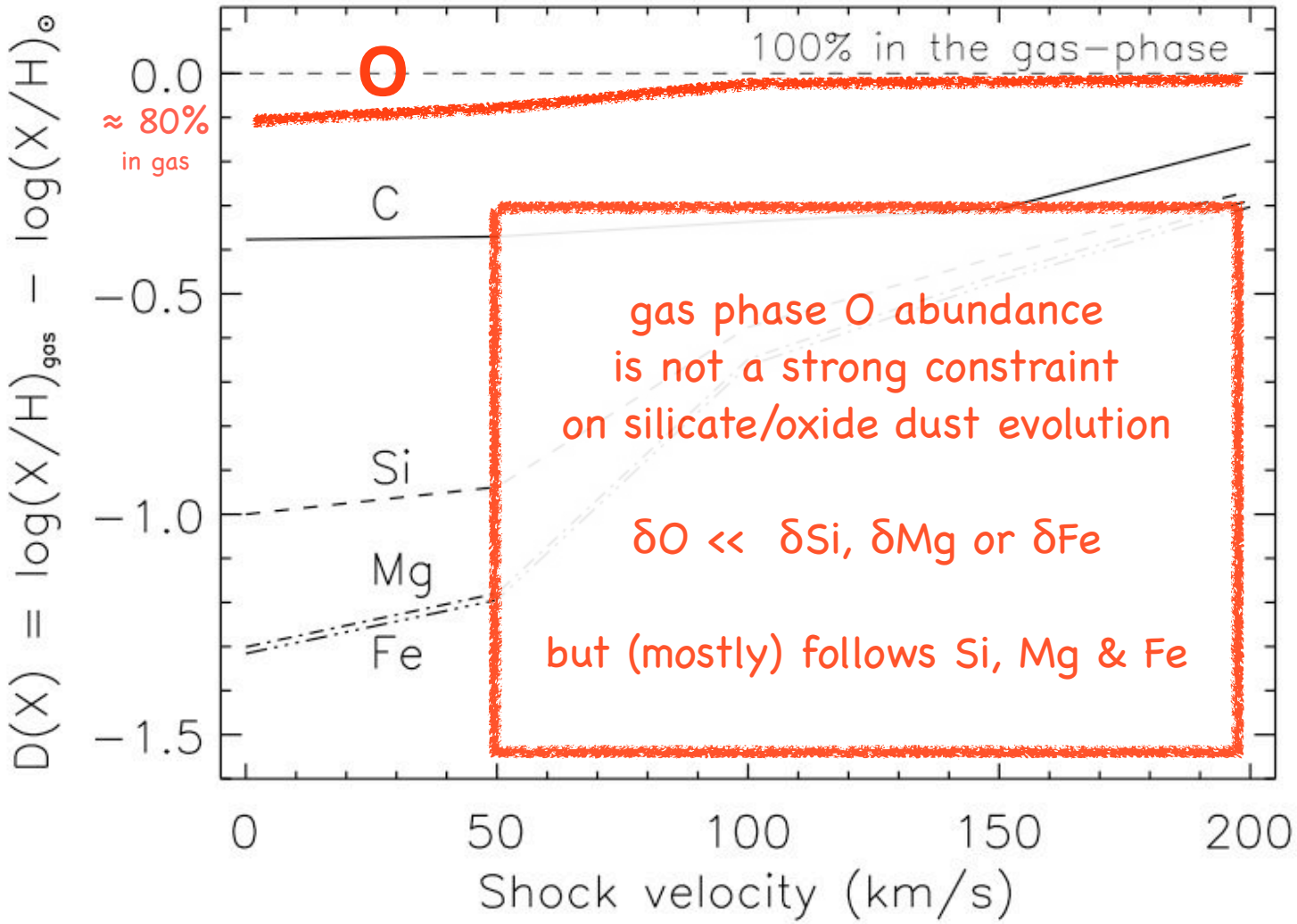

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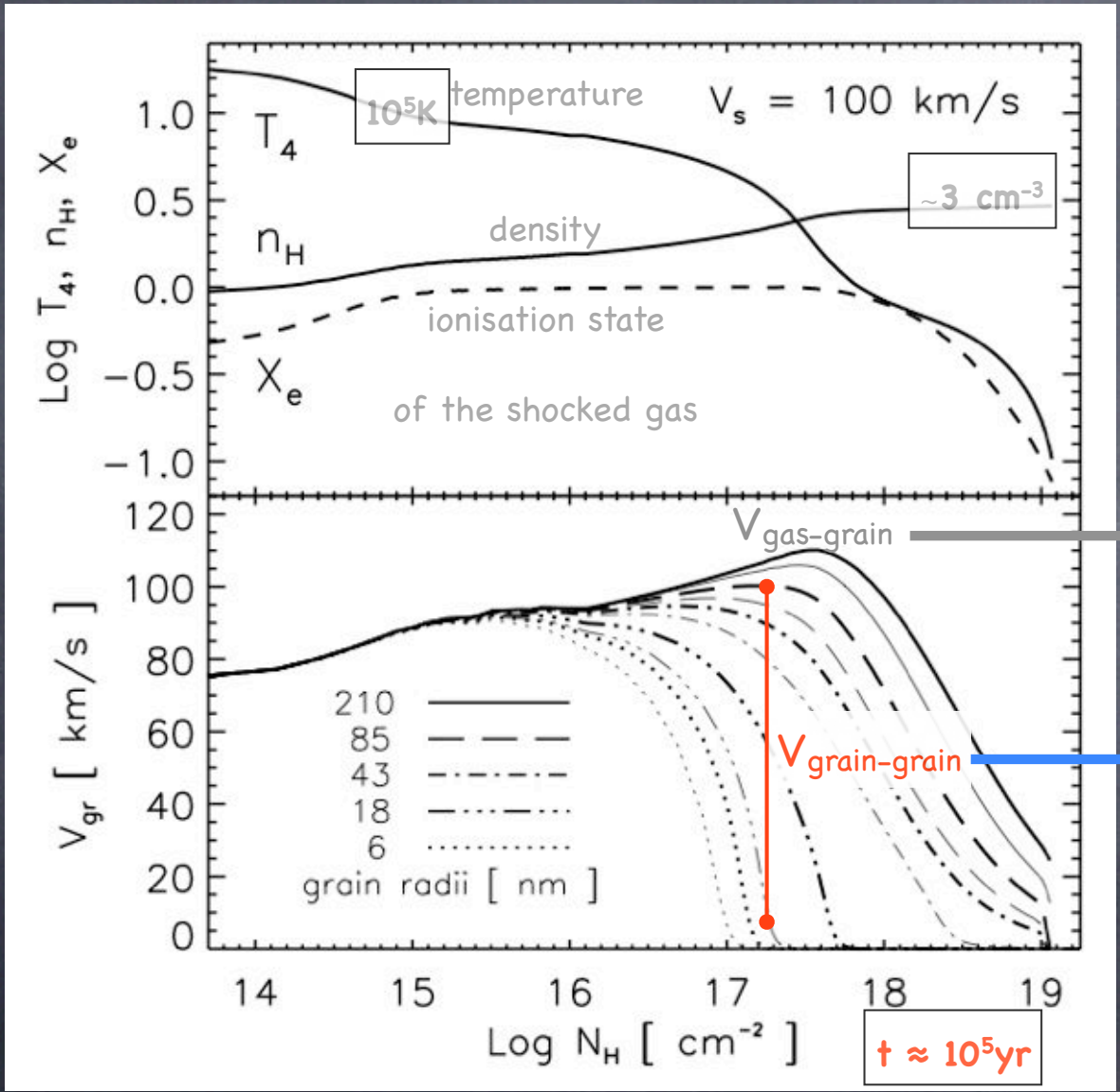
Grain-grain collisions in shocks

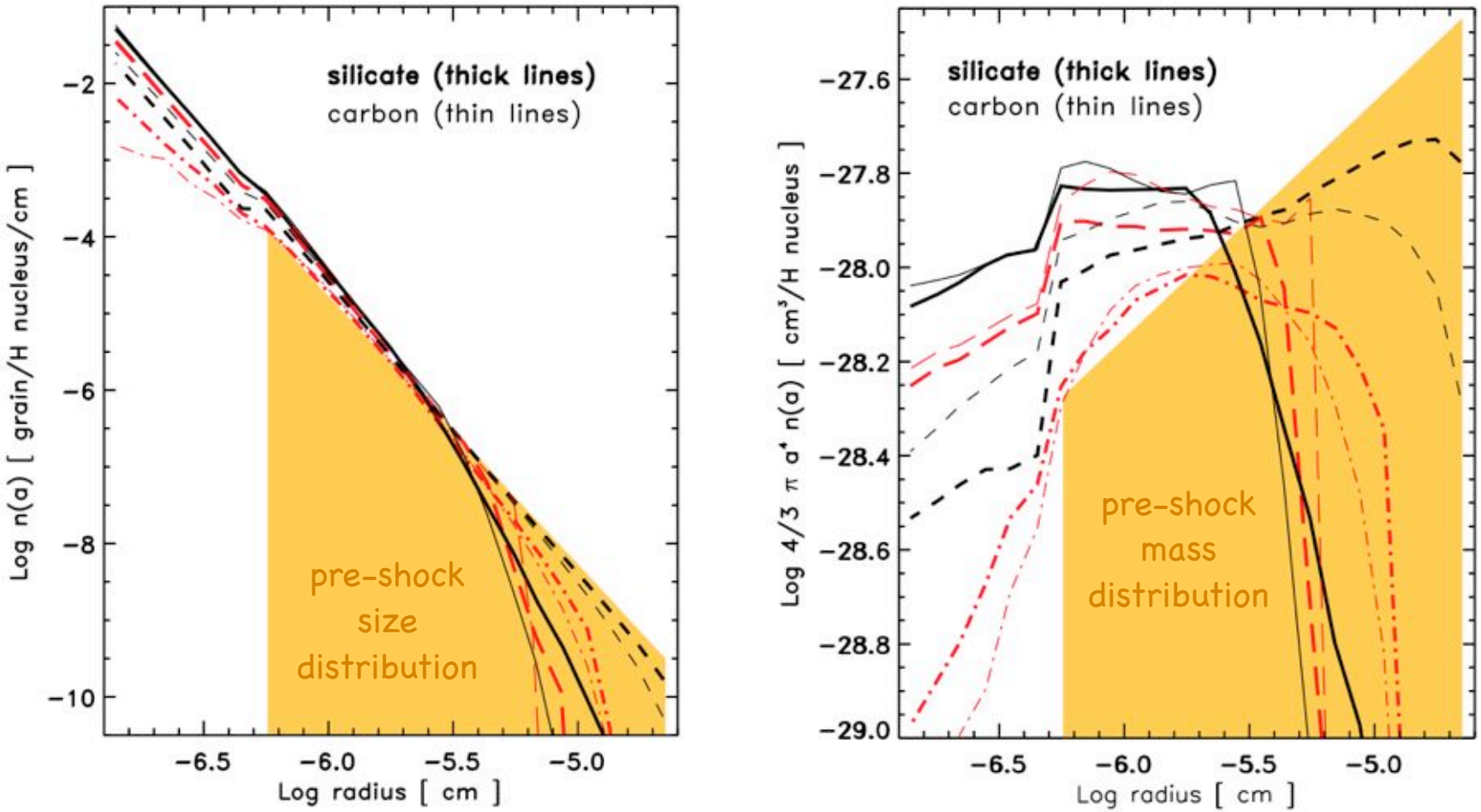


ion-grain collisions
--> sputtering

grain-grain collisions
--> fragmentation

Jones (2004)

Grain-grain collisions: vaporisation & fragmentation



Jones (2004)

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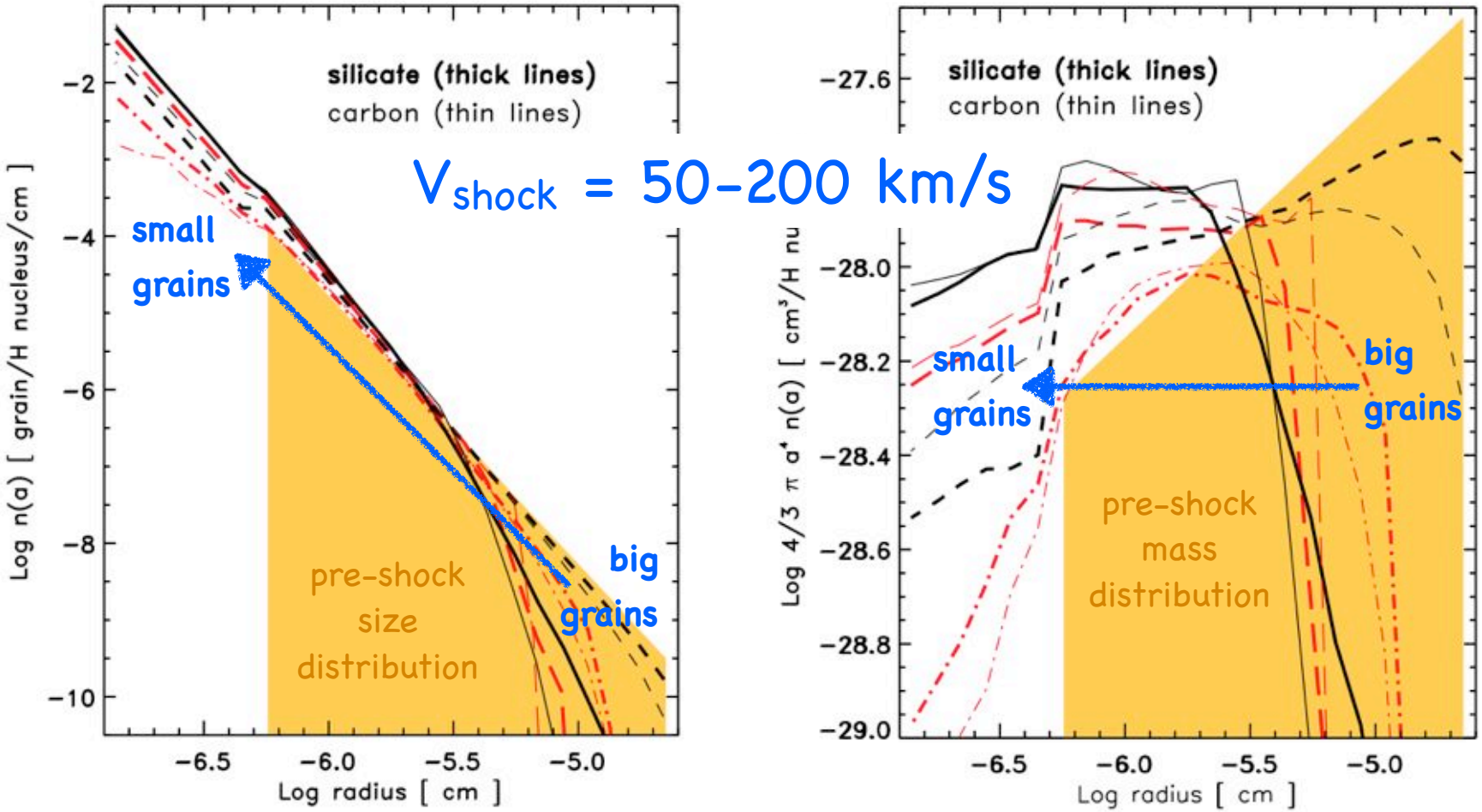


Jones (2004)

silicon and carbon in shocks Observational evidence

Welty et al. (2002) - ζ Ori cloud shocked to $v_{shock} \approx 100$ km/s
Podio et al. (2006) - dust in shocks in HH objects $v_{shock} \approx 20$-40 km/s
Slavin (2008) - Local Interstellar Cloud $v_{shock} \approx 150$ km/s

depletion/abundance studies in these regions indicate:

≈ 10% of Al, Si & Fe in dust ⇒ gas (i.e., ≈ 10% dust destruction)

≈ solar abundance of carbon in the gas (i.e., ≈ 100% dust destruction)

silicon and carbon in shocks: what the models predicts

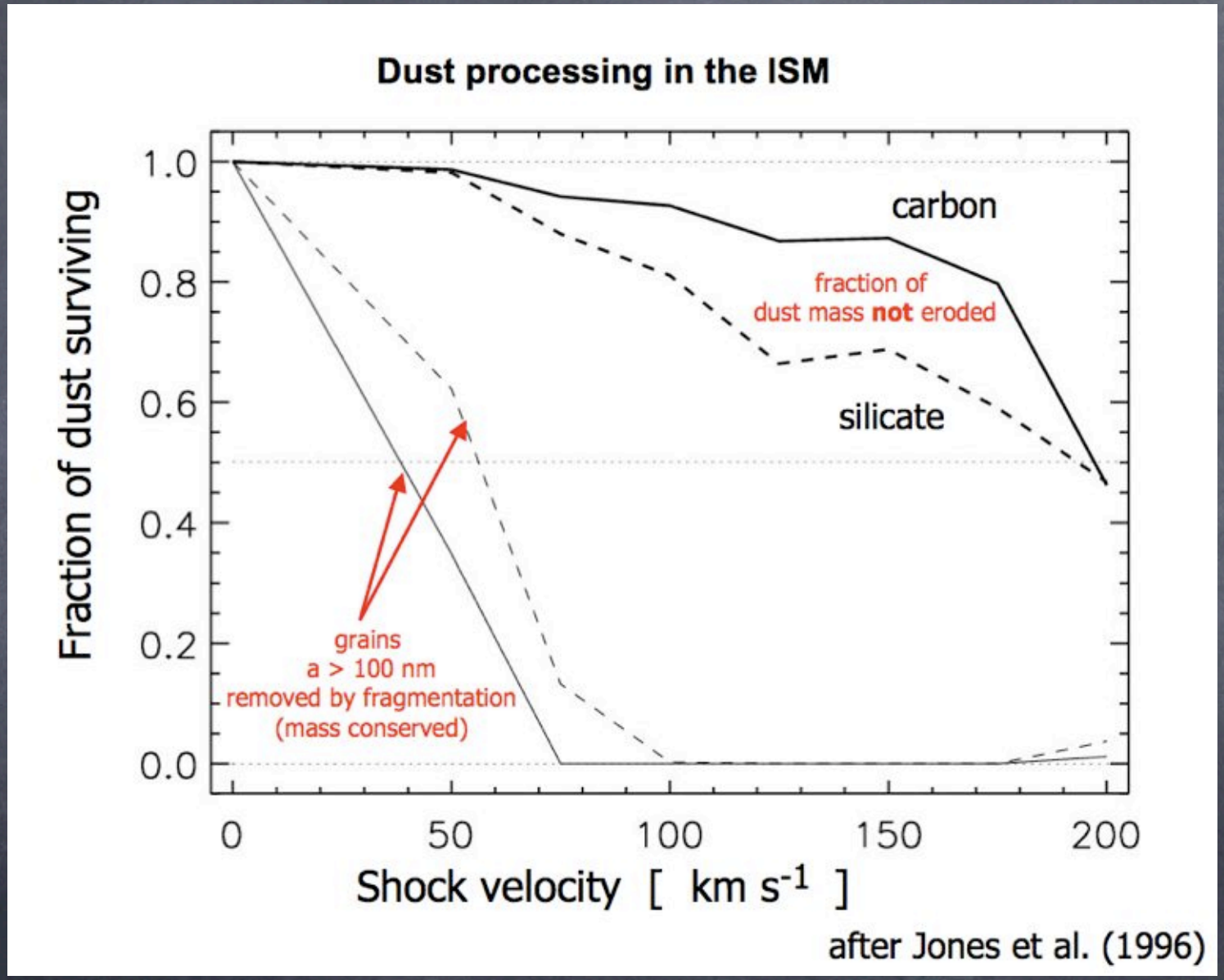
- **for a 100 km/s shock** (Jones et al. 1996)

  - the model predicts: 18% silicate dust destruction
  - observations indicate: ≈ 10% silicate dust destruction
  - the model predicts: 7% carbon dust destruction
    (≅45% carbon in the gas)
  - observations indicate: ≈ 90% destruction!

Model predictions are:

- about OK for silicate dust
- out by a large factor for carbonaceous dust

dust processing in shocks



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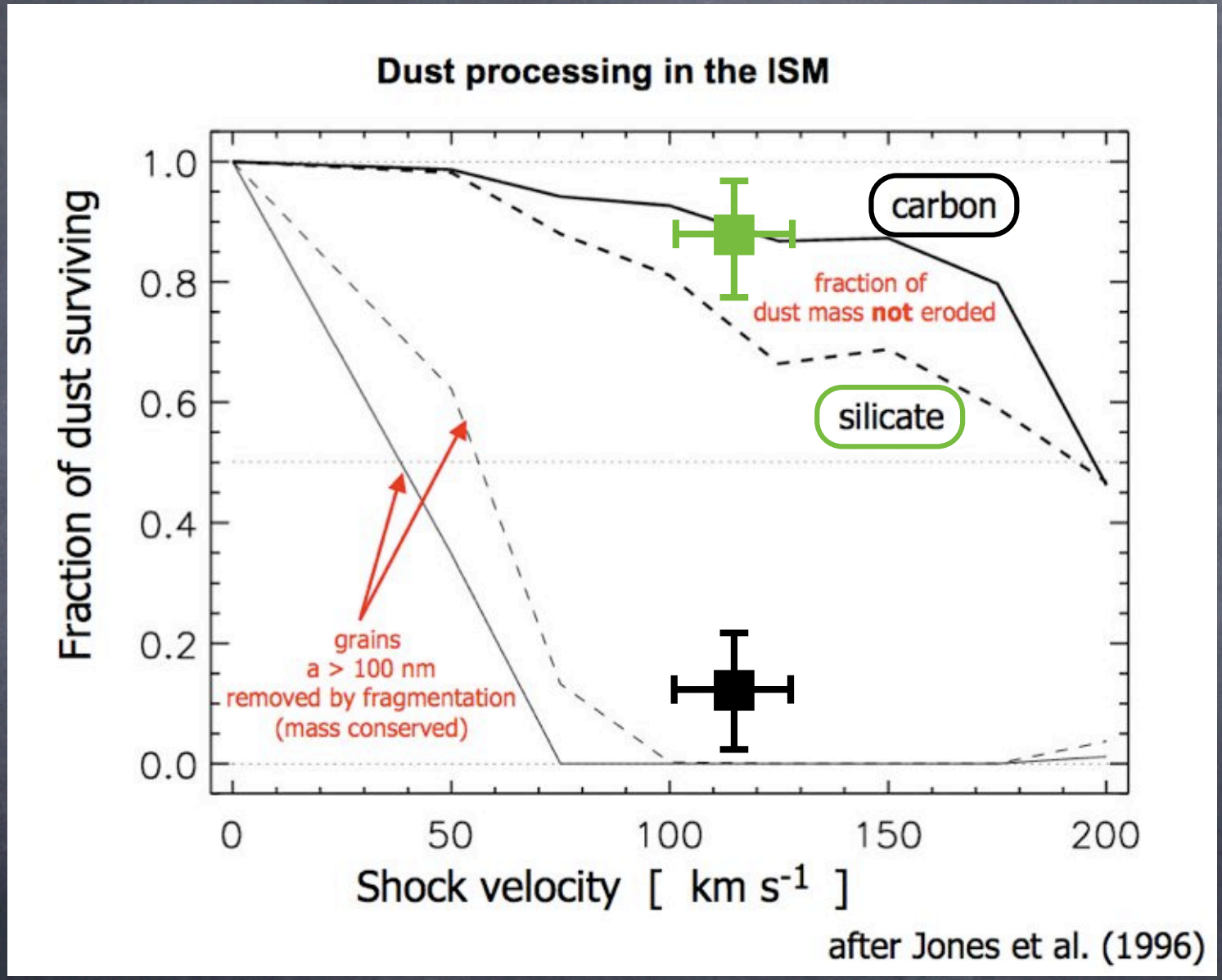

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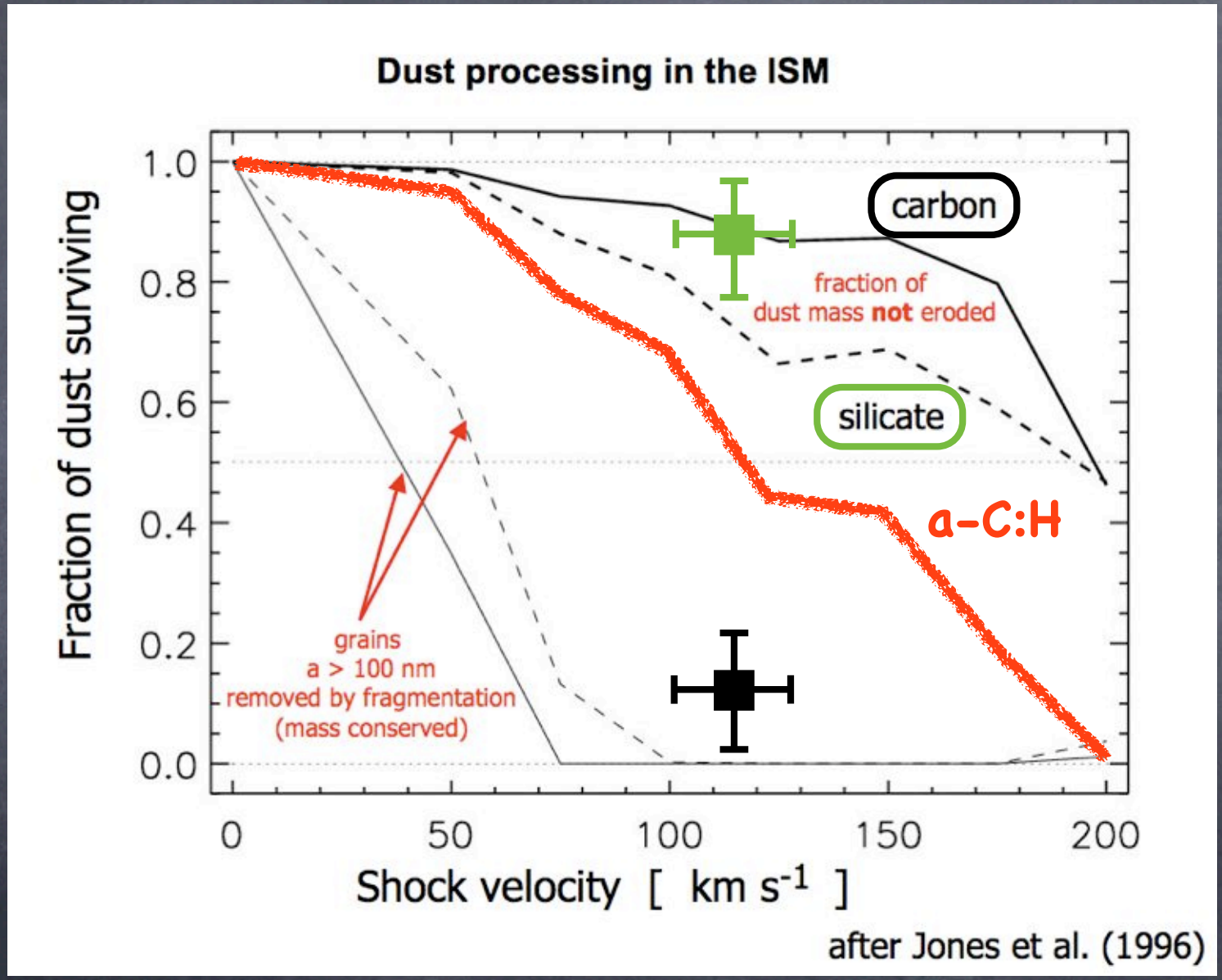

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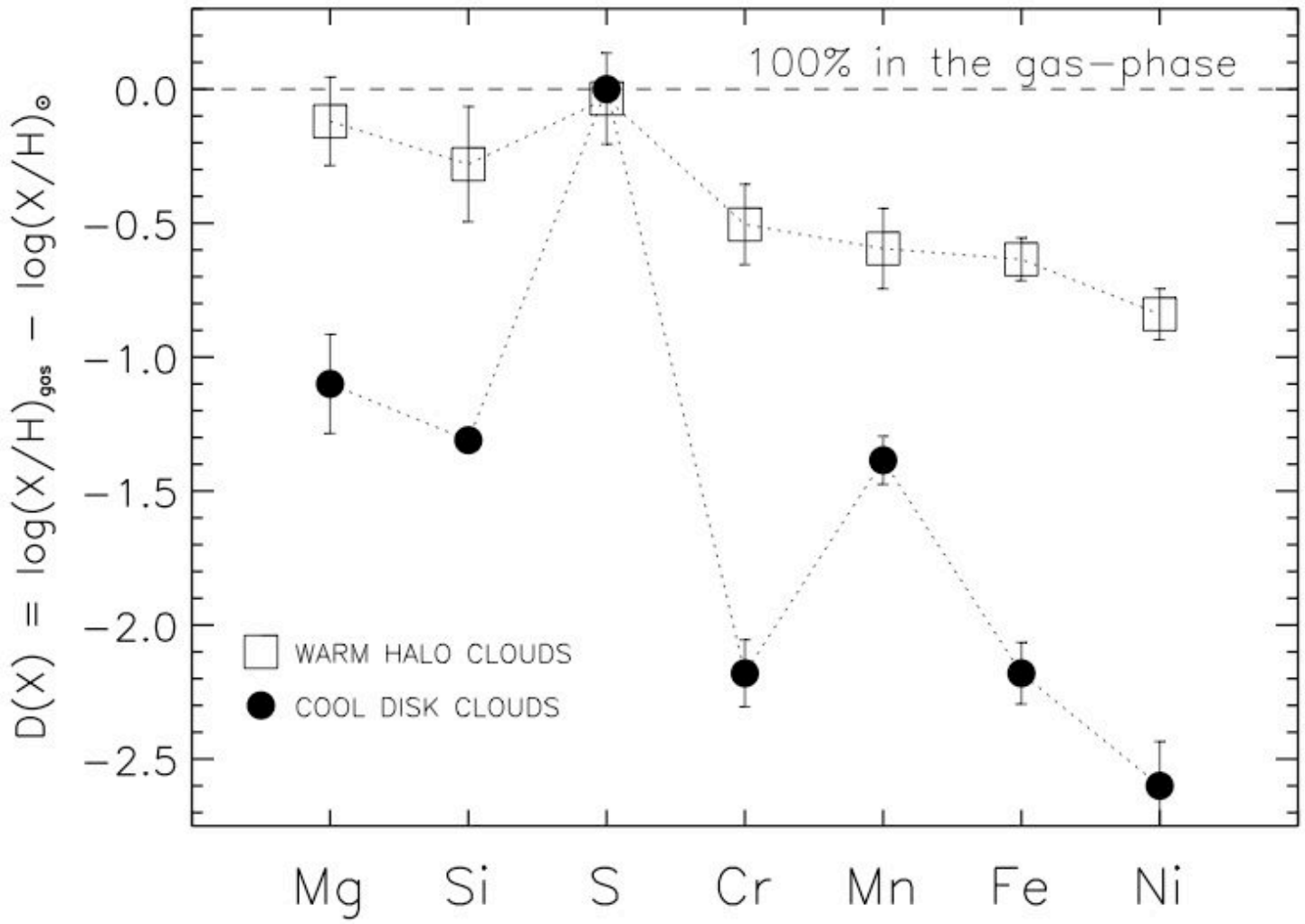
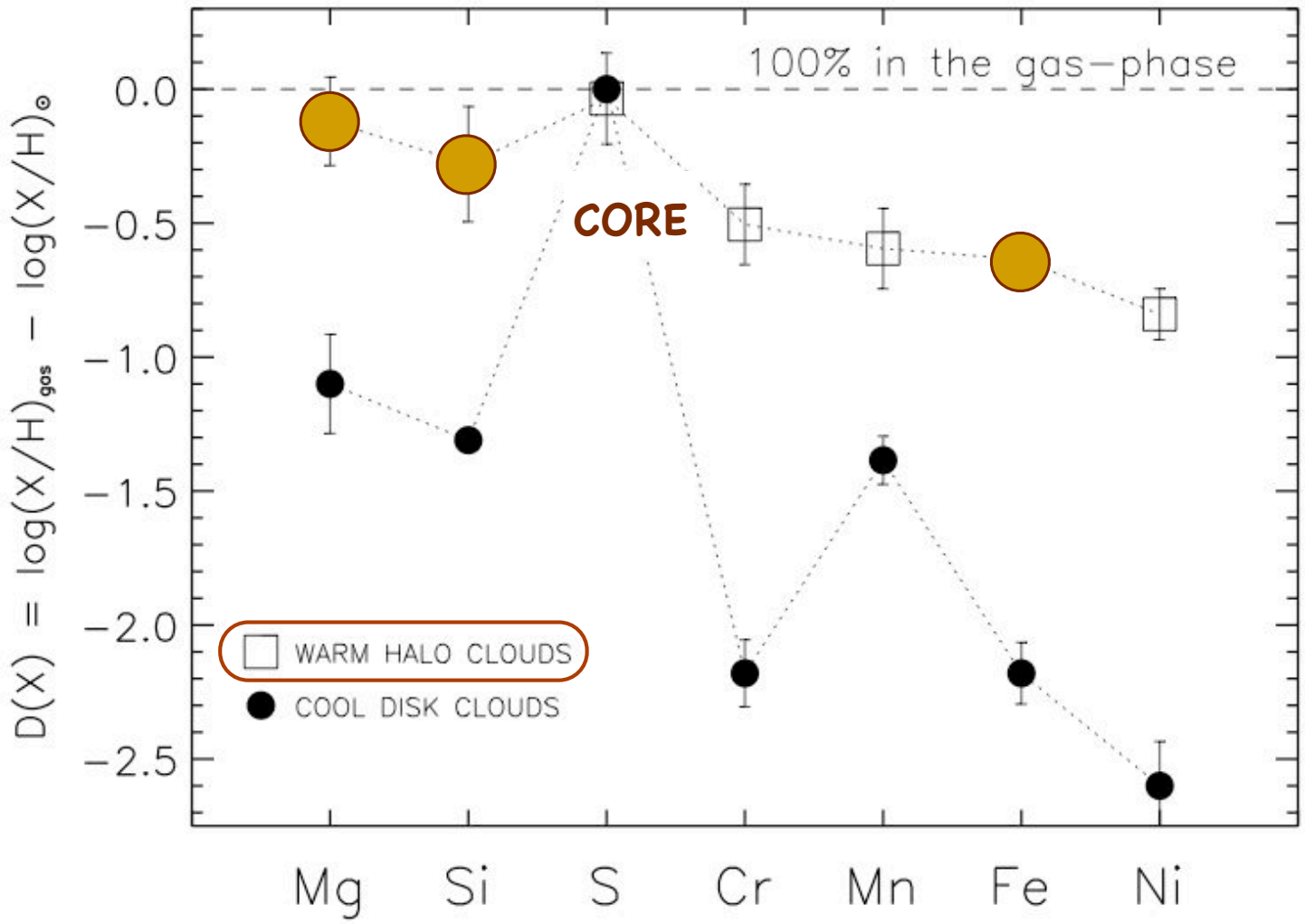


Figure 3. Gas phase abundances for the major (Mg, Si, and Fe), minor (Ni), and trace (Cr and Mn) dust-forming elements and S for diffuse lines of sight lines through cool clouds in the galactic disk (solid circles) and warm clouds in the galactic halo (open squares) for solar reference abundances. The vertical bars indicate the ranges of the observed values; data taken from *Savage and Sembach* [1996]. For the Mg data we have adopted the current best estimate for the Mg^+ oscillator strength from *Fitzpatrick* [1997].

Savage & Sembach, 1996, ARA&A, **34**, 279

Jones, 2000, JGR, **105** no. A5, p10257



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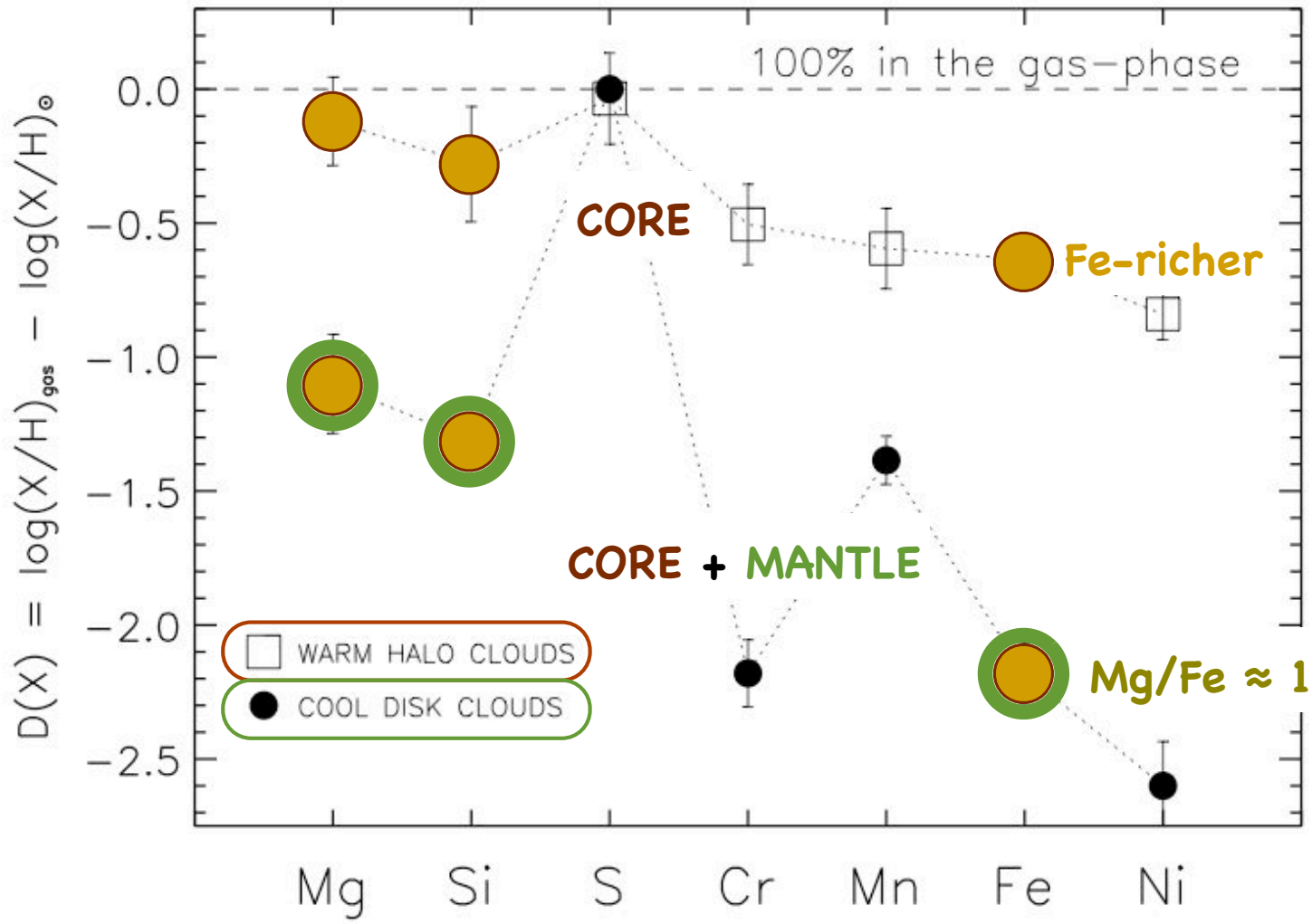
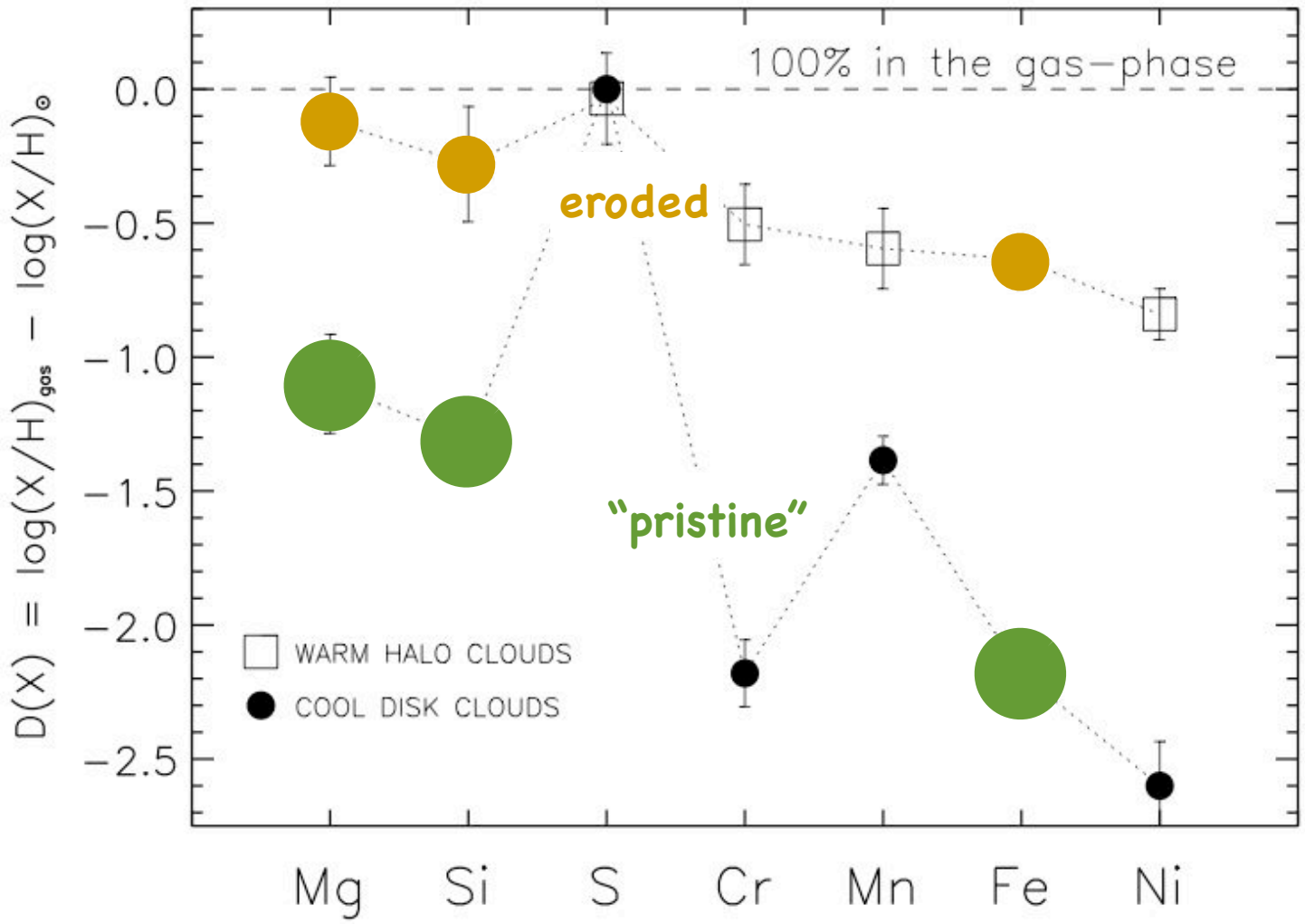


Figure 3. Gas phase abundances for the major (Mg, Si, and Fe), minor (Ni), and trace (Cr and Mn) dust-forming elements and S for diffuse lines of sight lines through cool clouds in the galactic disk (solid circles) and warm clouds in the galactic halo (open squares) for solar reference abundances. The vertical bars indicate the ranges of the observed values; data taken from *Savage and Sembach* [1996]. For the Mg data we have adopted the current best estimate for the Mg^+ oscillator strength from *Fitzpatrick* [1997].

Savage & Sembach, 1996, ARA&A, **34**, 279

Jones, 2000, JGR, **105** no. A5, p10257



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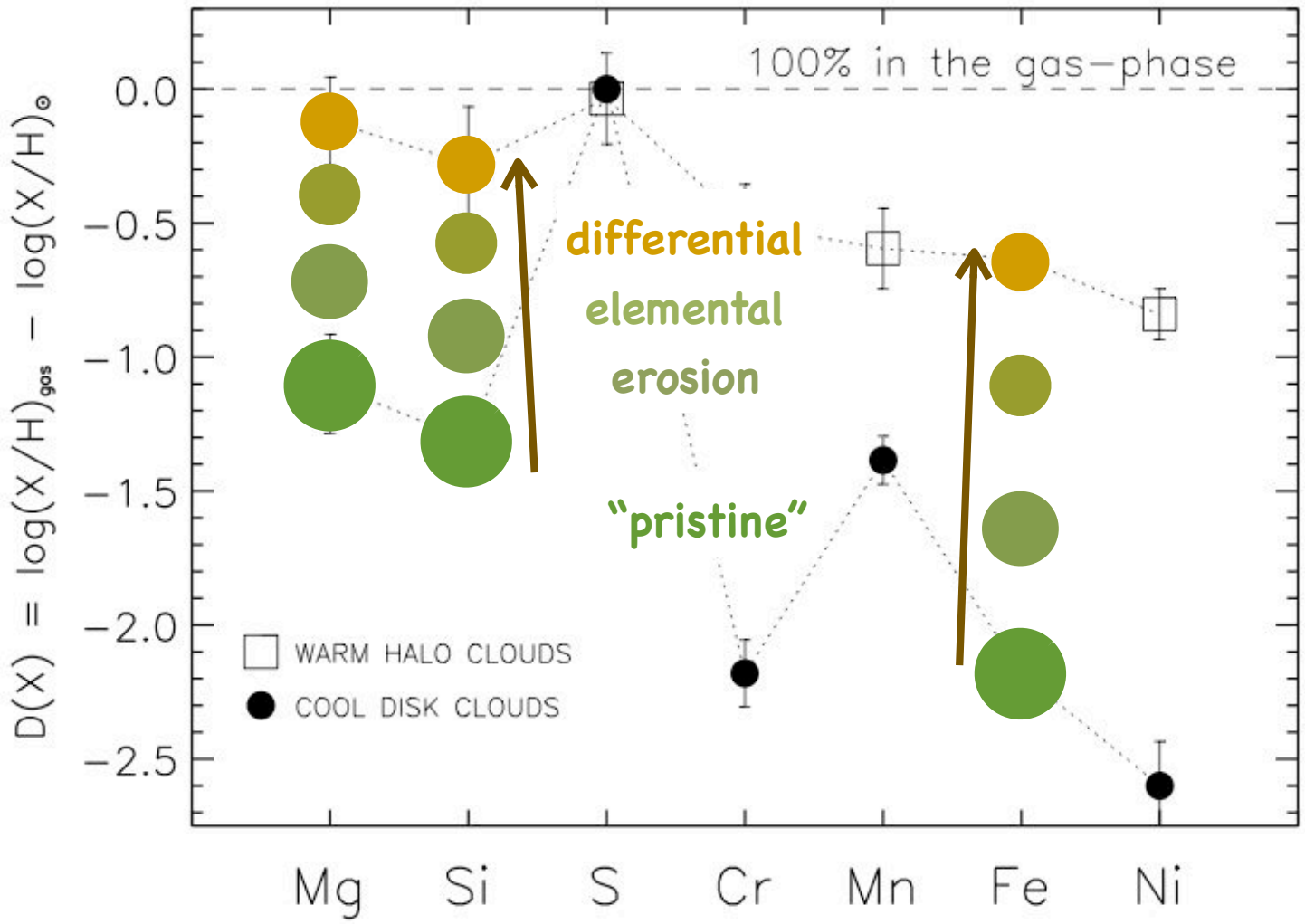

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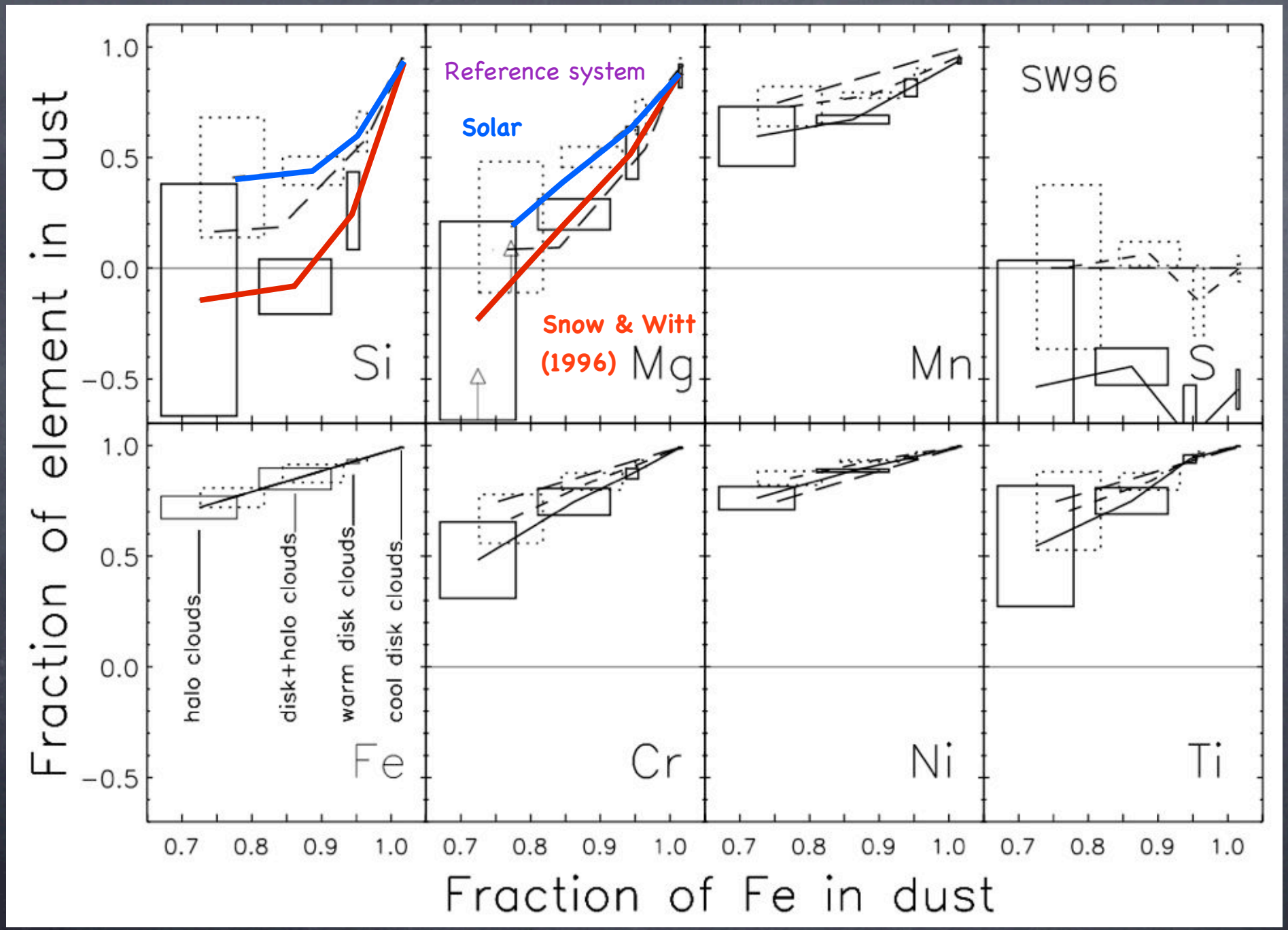
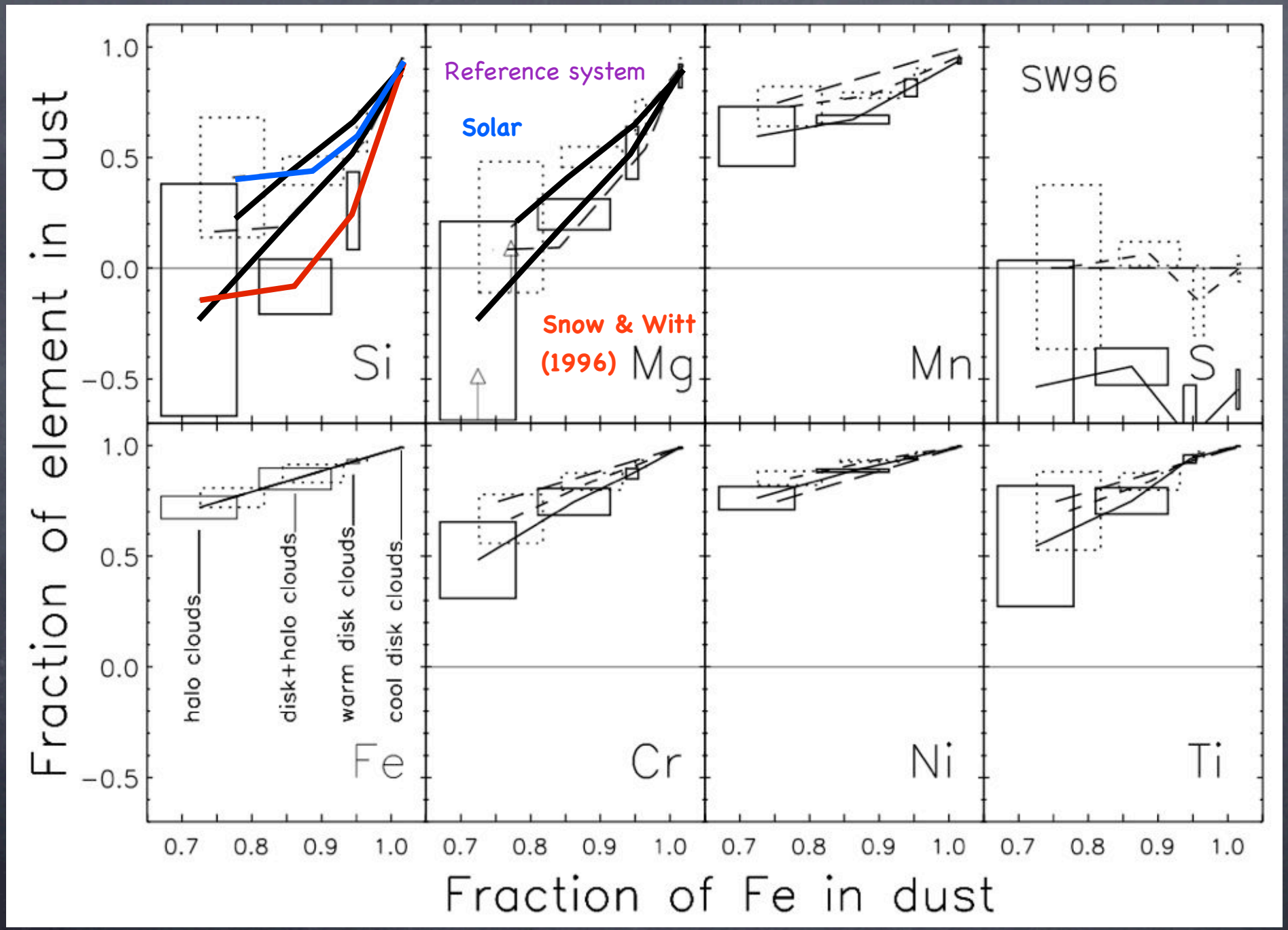


Jones (2000, JGR, **105** no. A5, p10257



Jones (2000, JGR, **105** no. A5, p10257

Thus the elemental sputtering sequence for the most abundant isotopes should be

$$\boxed{{}^{24}_{12}\mathrm{Mg} > {}^{28}_{14}\mathrm{Si}} \gg {}^{48}_{22}\mathrm{Ti} > {}^{52}_{24}\mathrm{Cr} > {}^{55}_{25}\mathrm{Mn} > {}^{56}_{26}\mathrm{Fe} > {}^{59}_{28}\mathrm{Ni}$$

but from the cool and warm disk cloud depletion data in Figure 4 the elemental sputtering sequence seems to be

$$\boxed{{}^{28}_{14}\mathrm{Si} > {}^{24}_{12}\mathrm{Mg}} \gg {}^{48}_{22}\mathrm{Ti} \sim {}^{52}_{24}\mathrm{Cr} > {}^{55}_{25}\mathrm{Mn} > {}^{56}_{26}\mathrm{Fe} \sim {}^{59}_{28}\mathrm{Ni}.$$

Si appears to be preferentially lost to the gas

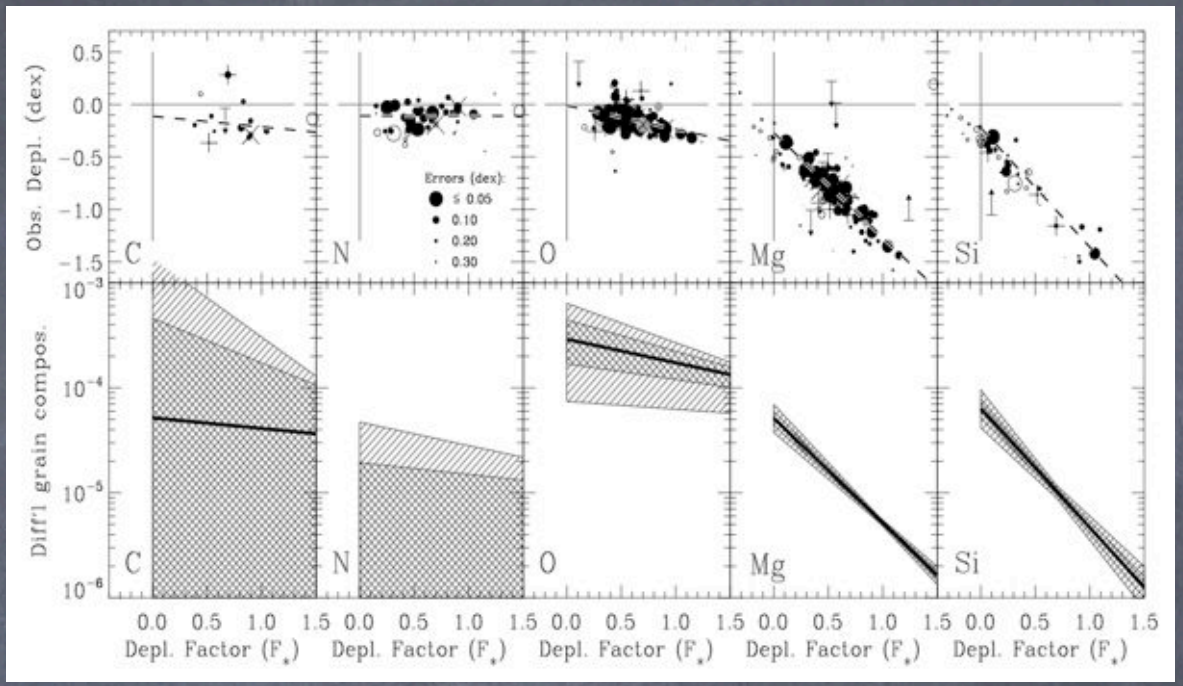
with respect to Mg and Fe - probably an effect of chemstry

Jones (2000, JGR, **105** no. A5, p10257

The "Oxygen problem"

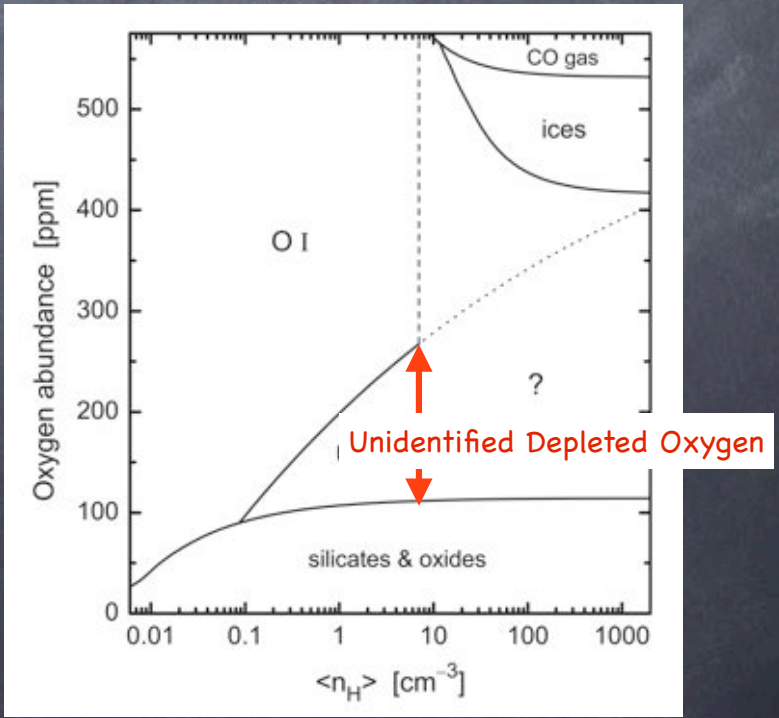
Jenkins (2009, ApJ, 700, 1299)

"The incorporation of oxygen into solid form in the densest gas regions far exceeds the amounts that can take the form of silicates or metallic oxides; this conclusion is based on differential measurements of depletion and thus is unaffected by uncertainties in the solar abundance reference scale."

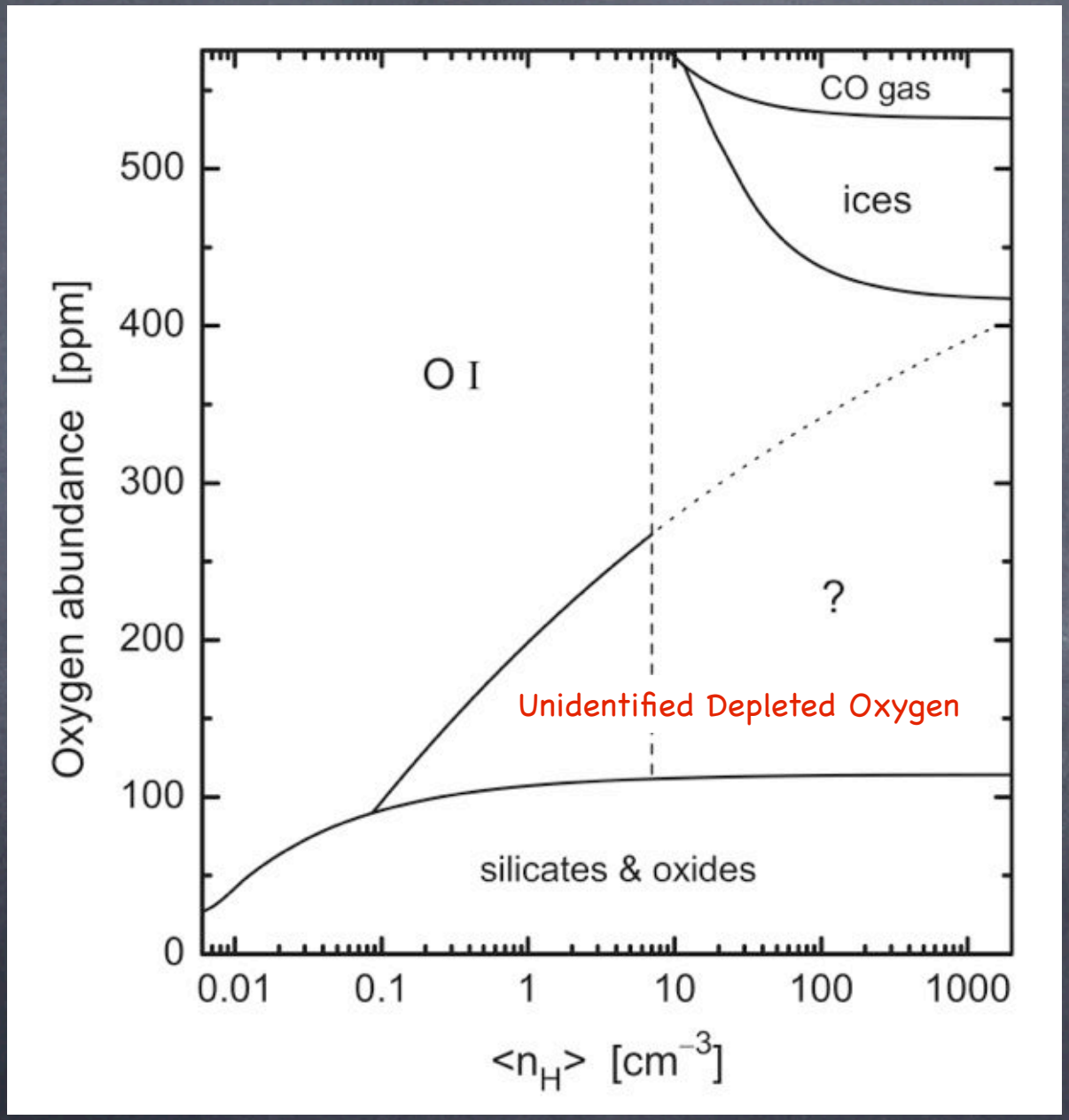


Whittet (2010, ApJ, 710, 1009)

"At the interface between diffuse and dense phases (just before the onset of ice-mantle growth) as much as ~160 ppm of the O abundance is unaccounted for. If this reservoir of depleted oxygen persists to higher densities it has implications for the oxygen budget in molecular clouds, where a shortfall of the same order is observed. Of various potential carriers, the most plausible appears to be a form of O-bearing carbonaceous matter ..."

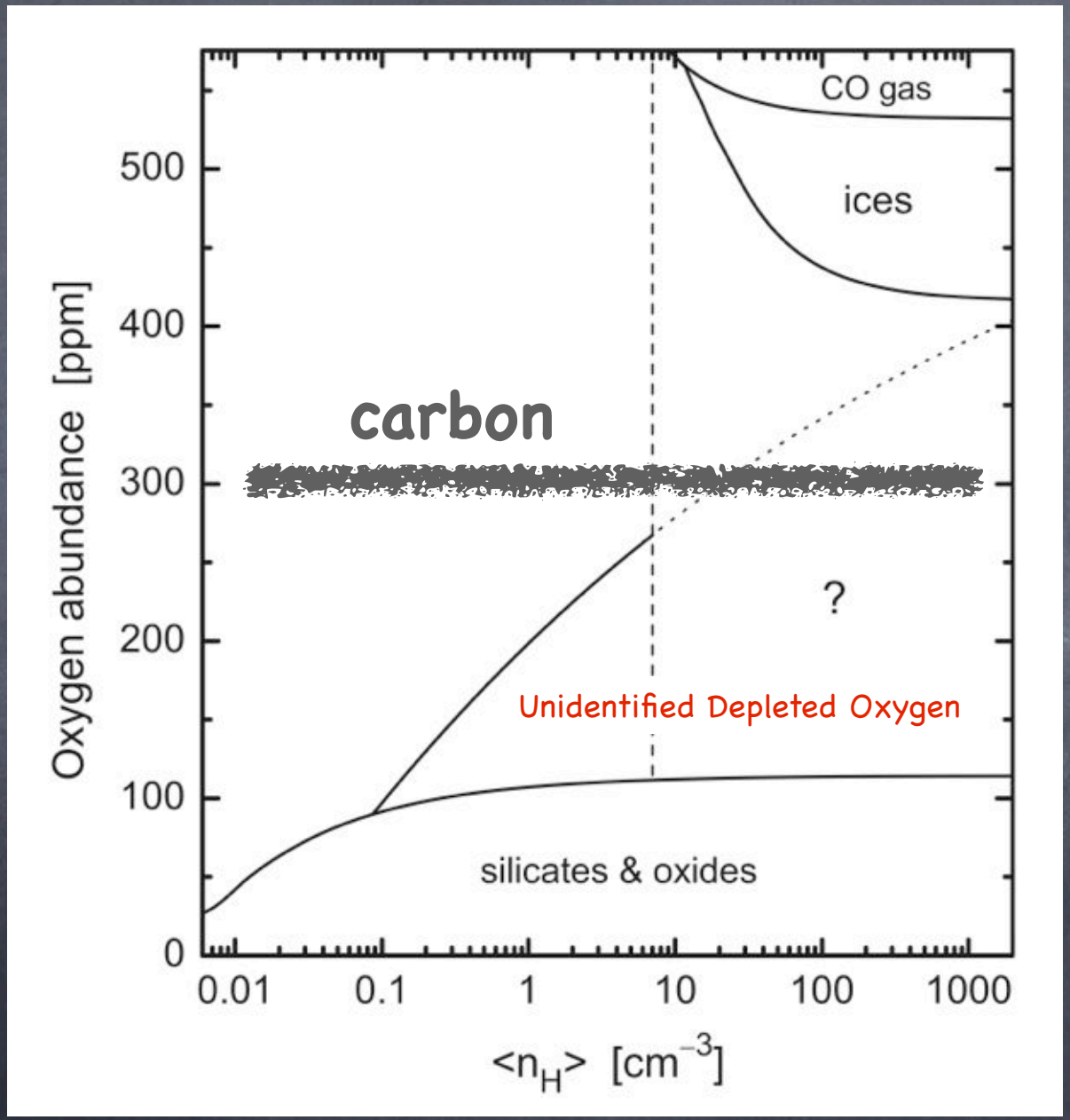


The "Oxygen problem"



Whittet (2010)

The "Oxygen problem"



Whittet (2010)

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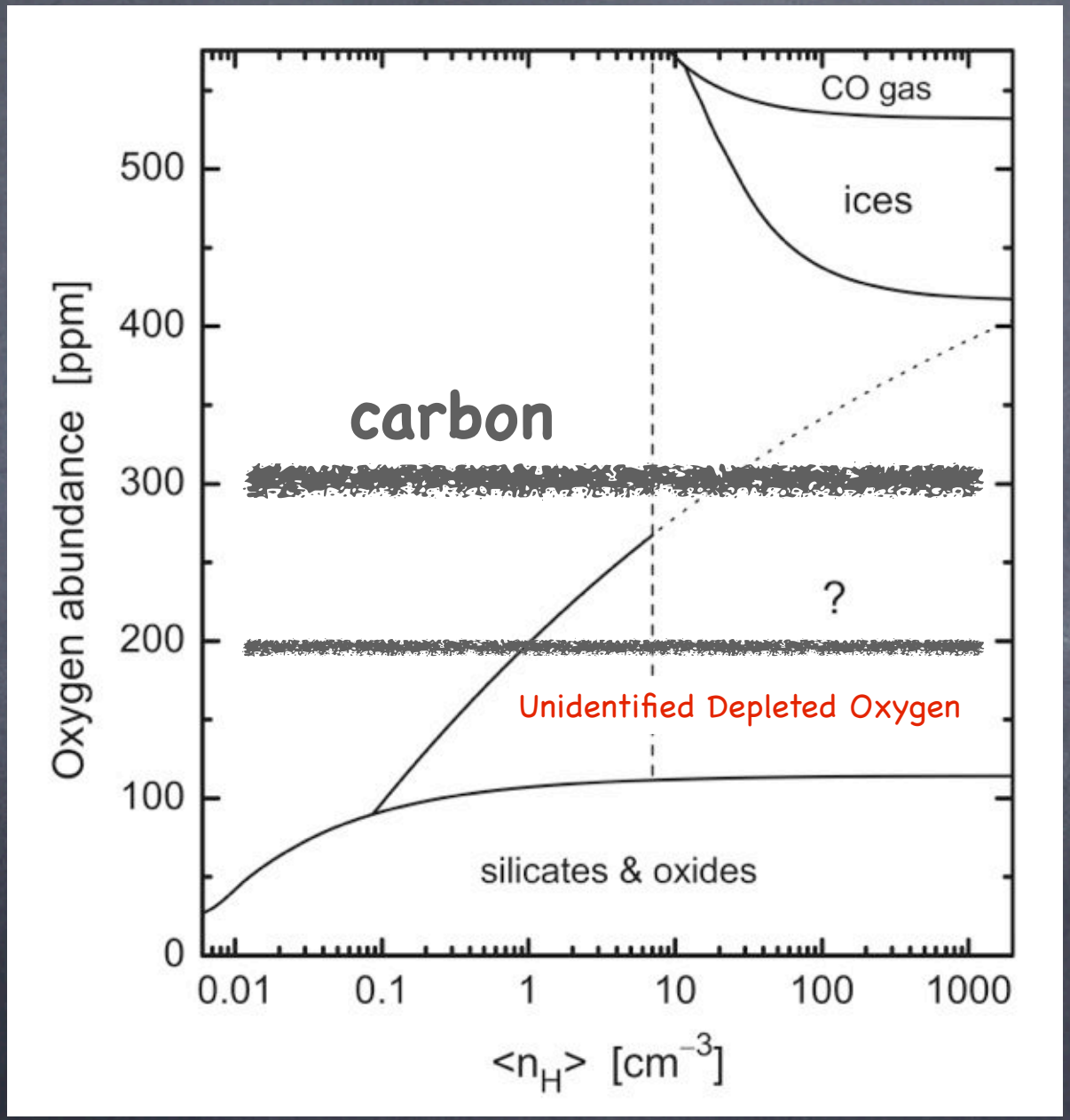
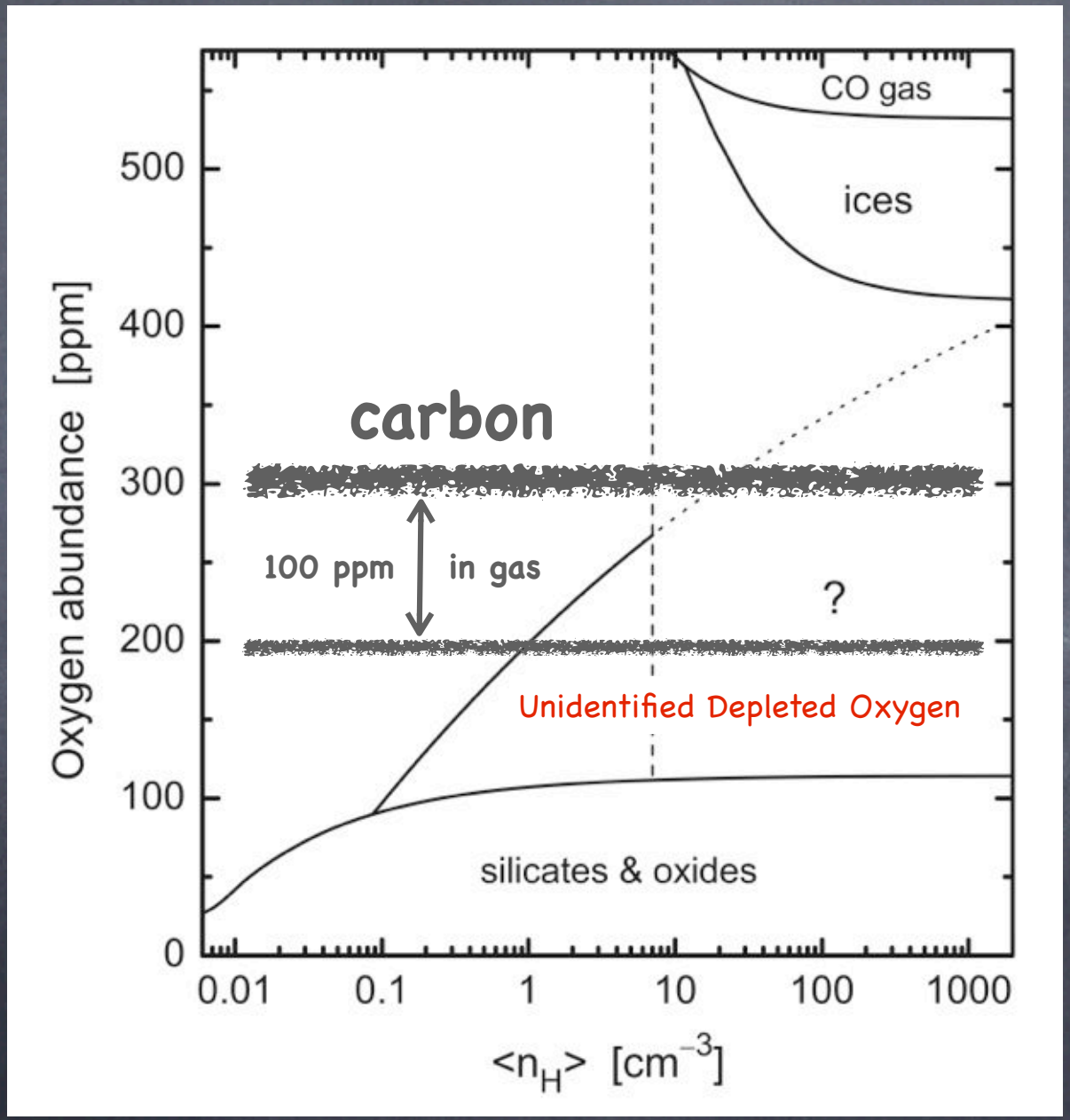


in dust

Compiègne et al. (2011)

Whittet (2010)

The "Oxygen problem"



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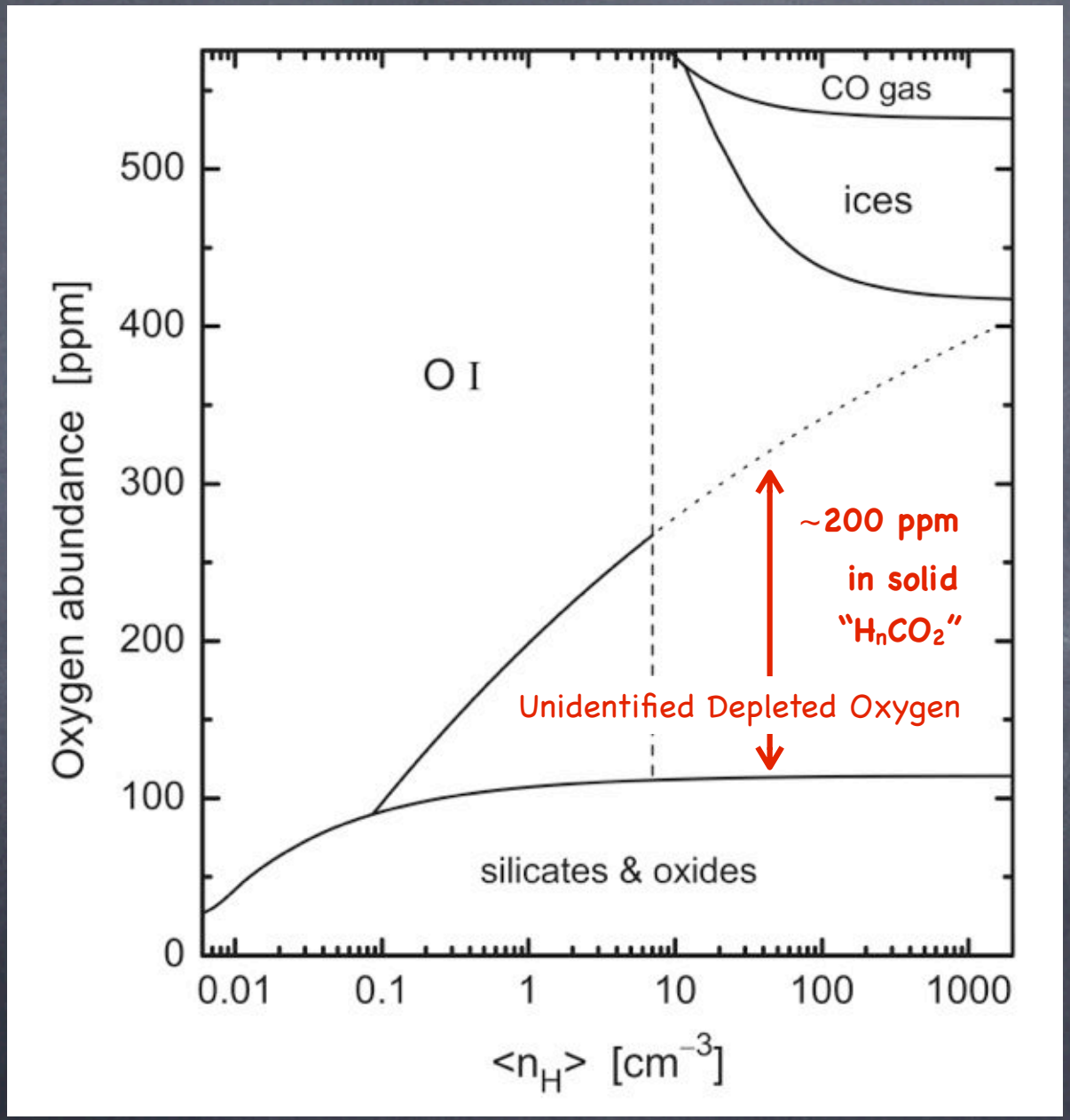


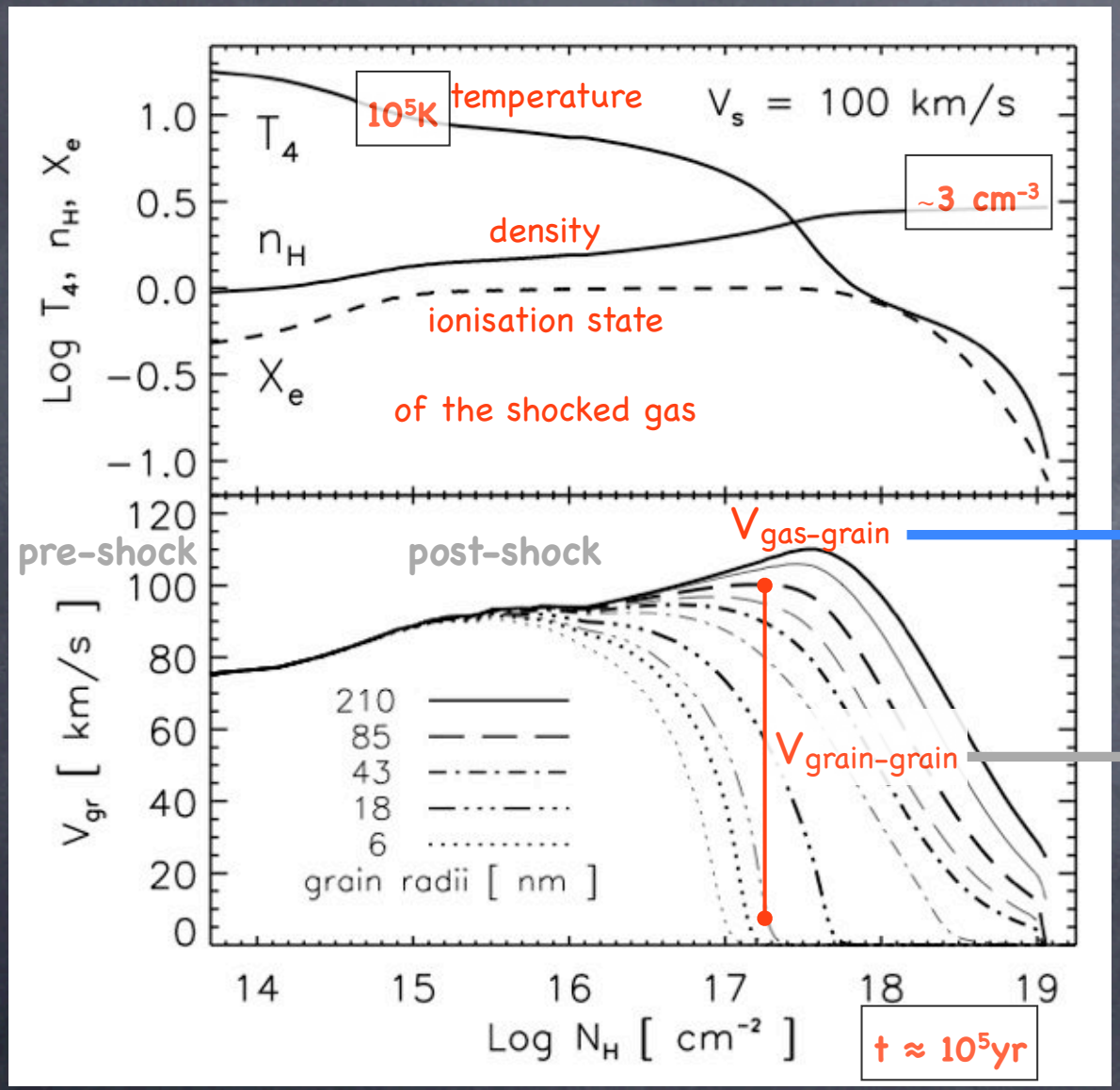
3-12 micron spectral signatures?
e.g.
-C-O-H
-C=O
-C-O-C-
...

Whittet (2010)

Outline

- interstellar dust
  - lifecycle, composition & origin
  - shock processing
- silicate dust
  - evolution
  - implantation
  - annealing
- the dust lifetime
  - time-scales?
  - what do they mean?

Ion-grain and grain-grain collisions in shocks



H^+, He^+ & He^{++} ion irradiation

ion-grain collisions --> sputtering

grain-grain collisions --> fragmentation

Jones (2004)

Silicate dust

Silicate ion irradiation & amorphisation

He^+ irradiation (in shocks)

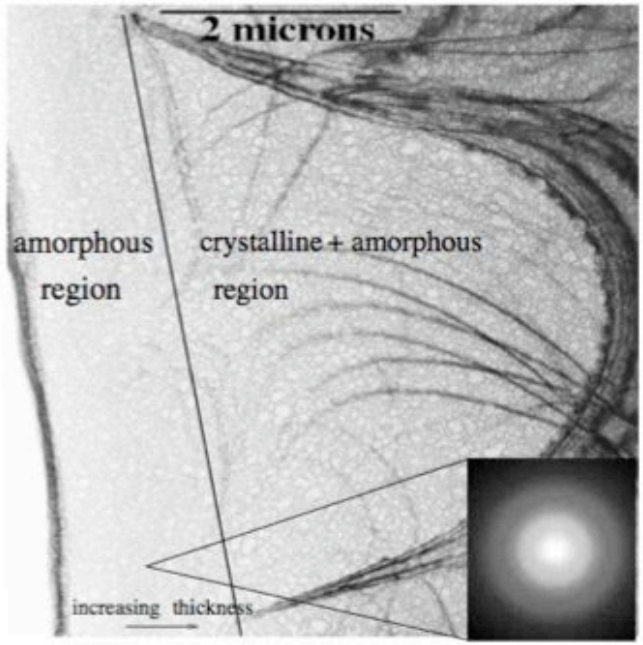
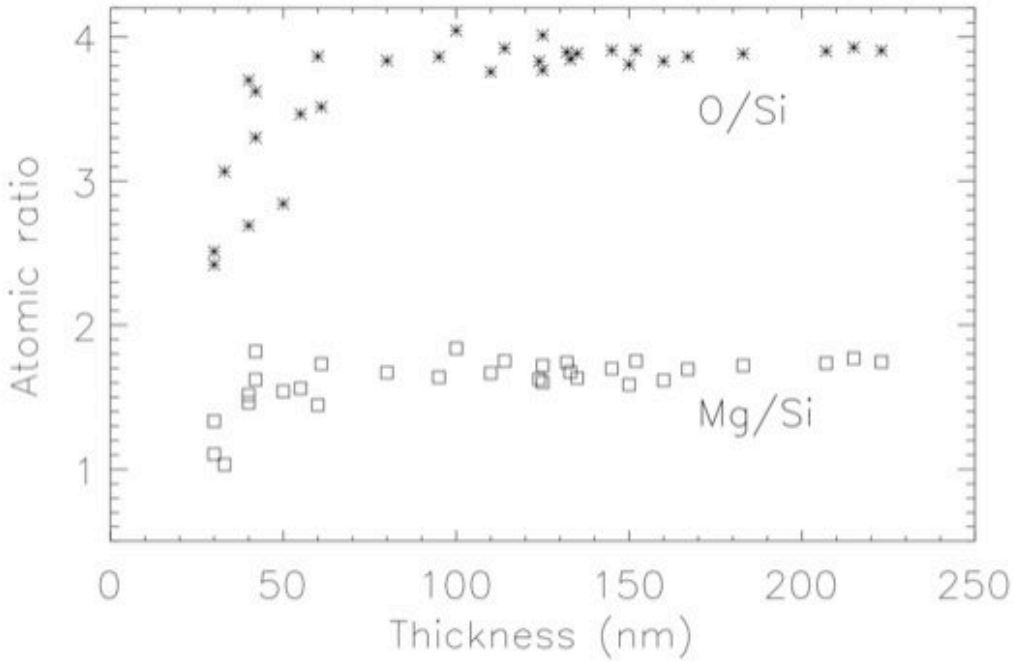
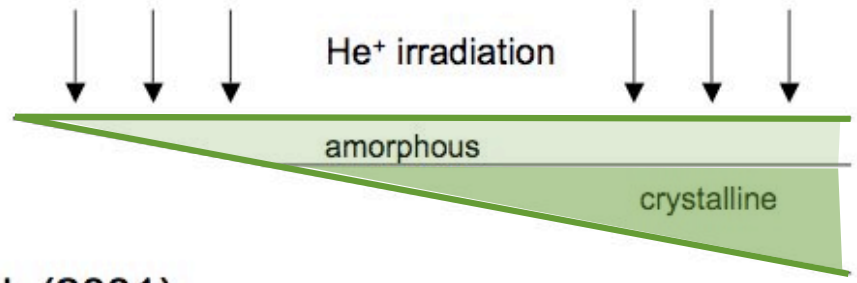


Fig. 2. TEM picture of a crystalline olivine sample irradiated with 10^{18} 10 keV He^+/cm^2. The dark lines at the right hand side are Bragg diffraction lines. The picture in the bottom right is the electron diffraction pattern of the irradiated sample taken in the amorphous region. The observed diffuse halo is characteristic of an amorphous material. Note the presence of bubbles in the sample

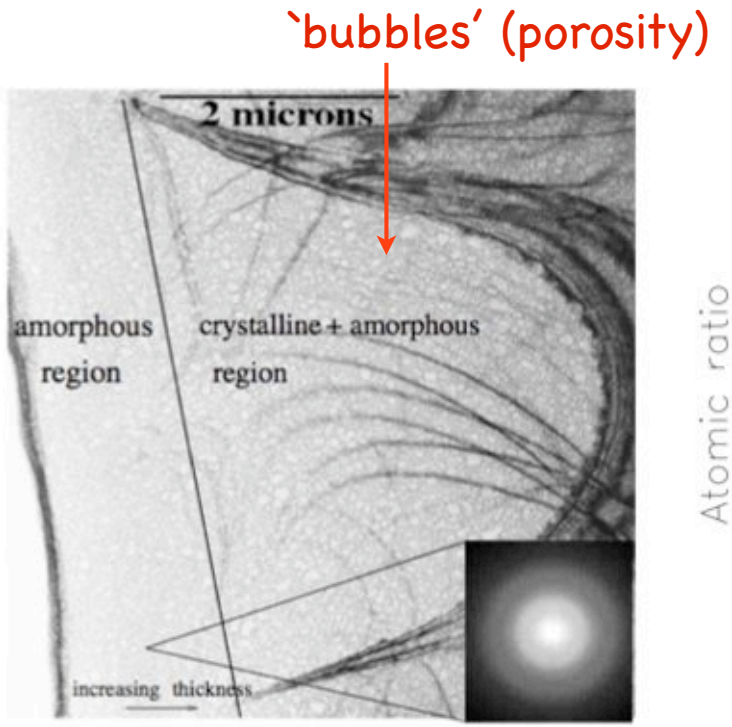




Demyk et al. (2001)

Silicate dust

Silicate ion irradiation & amorphisation



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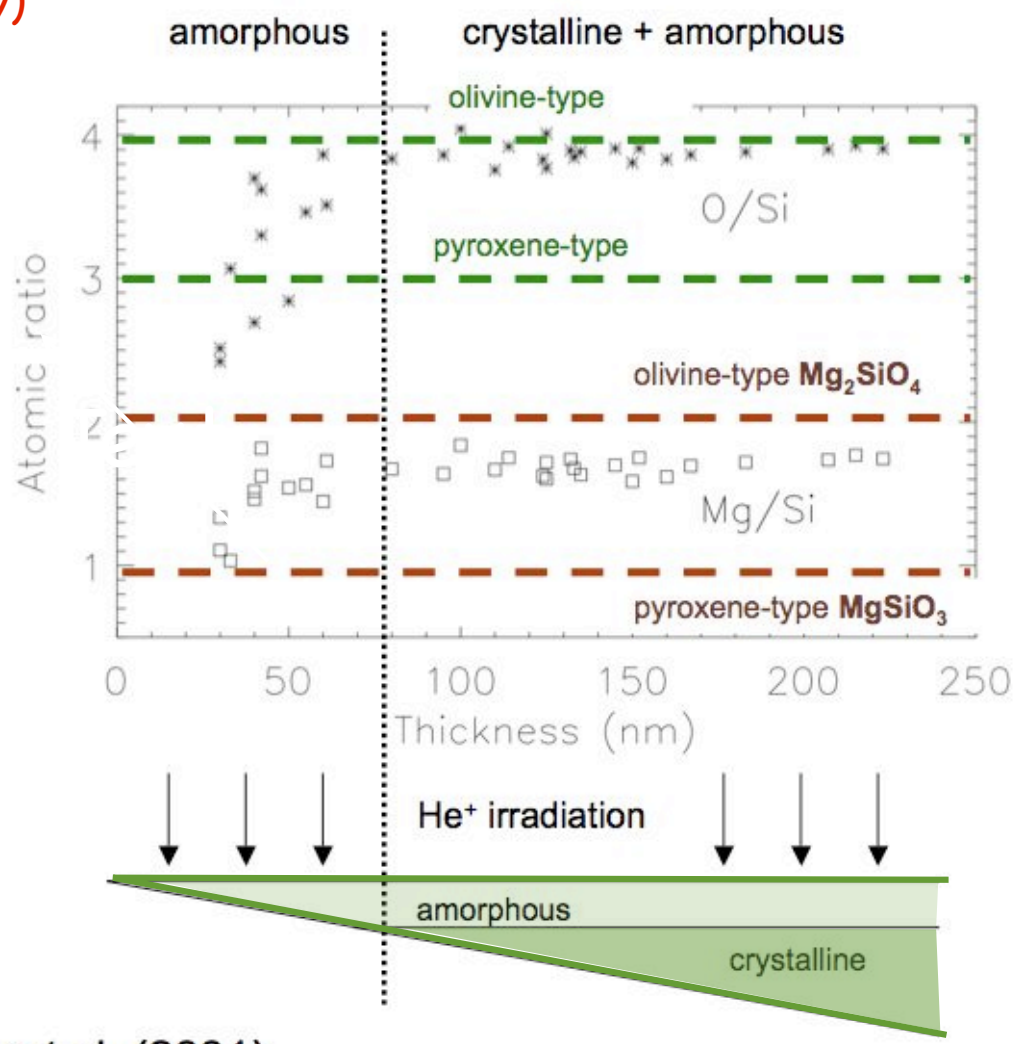

Demyk et al. (2001)

Silicate dust

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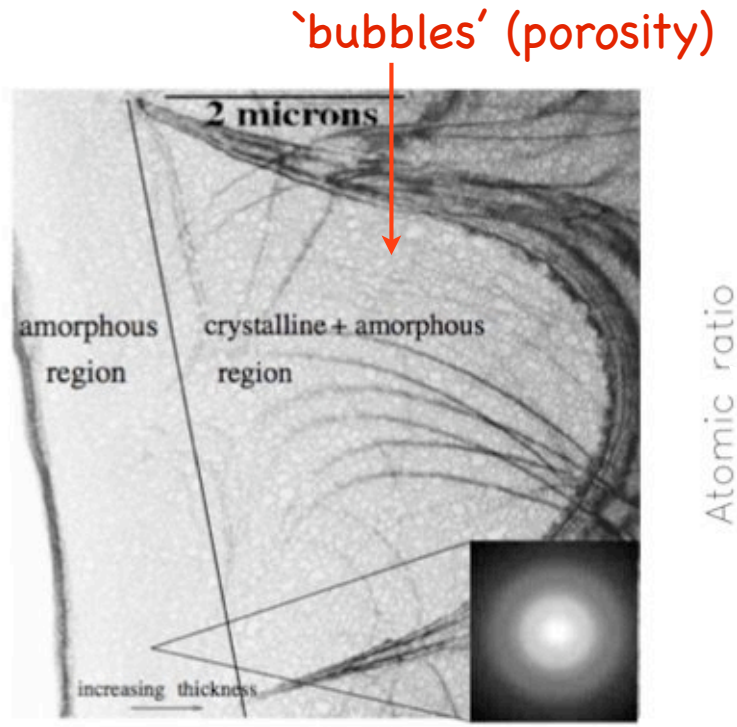

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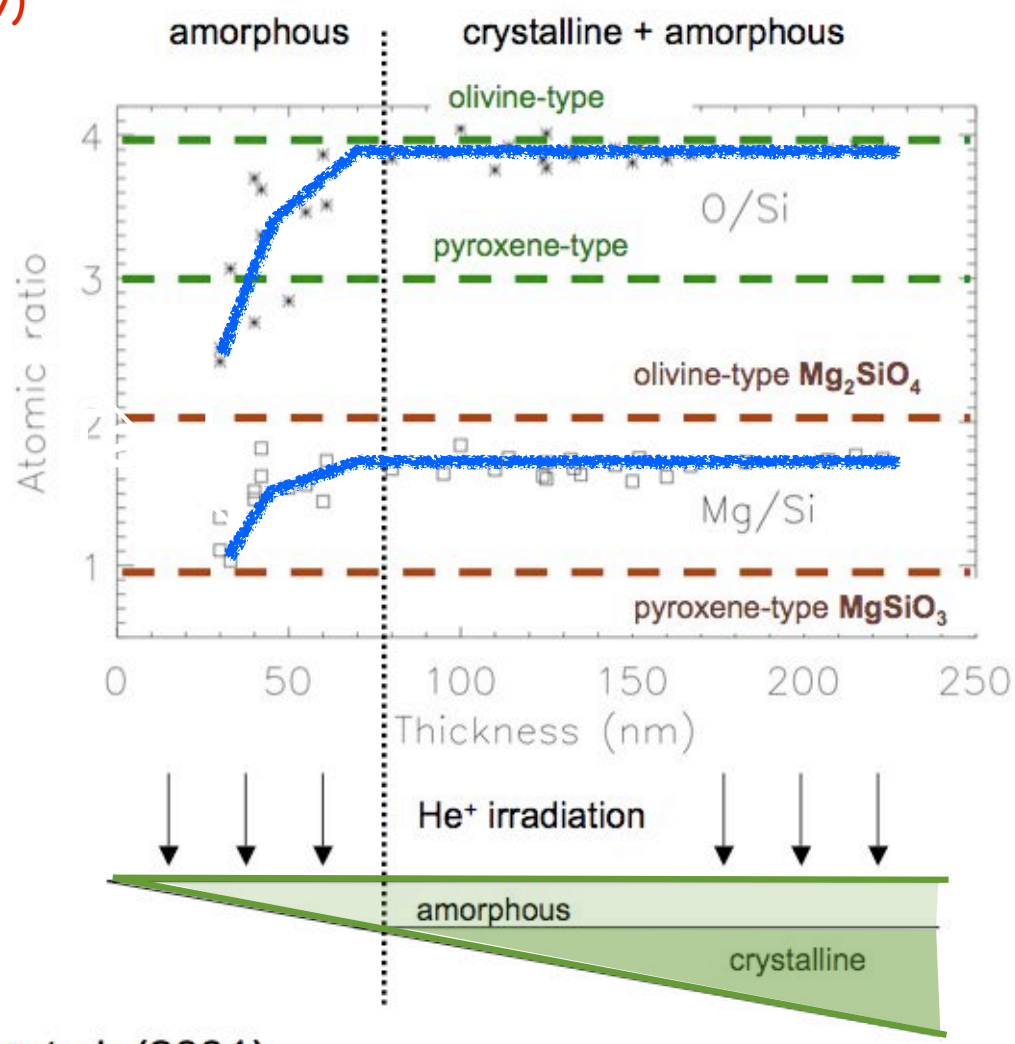


Demyk et al. (2001)

Ion irradiation leads to

amorphisation

and an

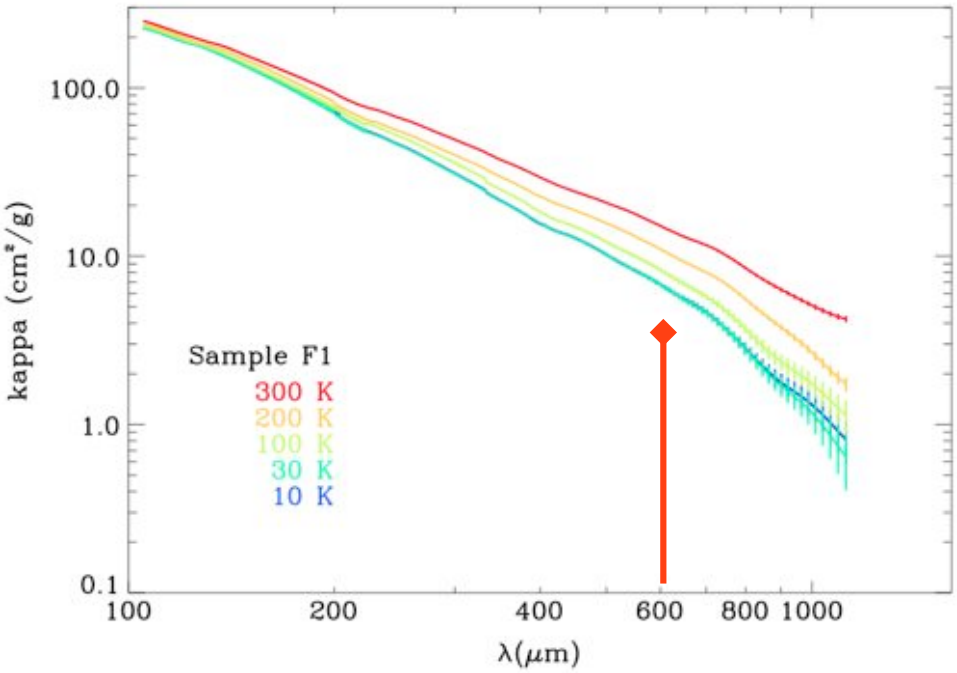
olivine-type --> pyroxene-type transformation.

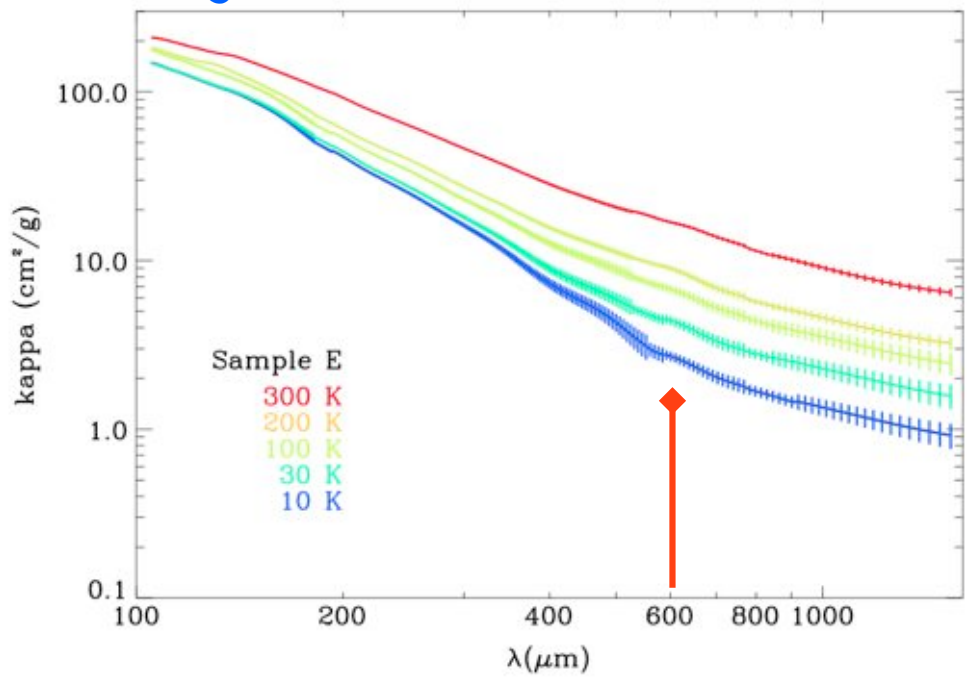
So what?

The long wavelength optical properties are totally different

olivine-type silicate pyroxene-type silicate

Far-infrared to mm wavelengths





and at shorter wavelengths too

Coupeaud et al. (2011)

... but what if the irradiating ion is chemically reactive?

protons are abundant

and in shock waves dust is irradiated with H^+ as well as He^+ ions.

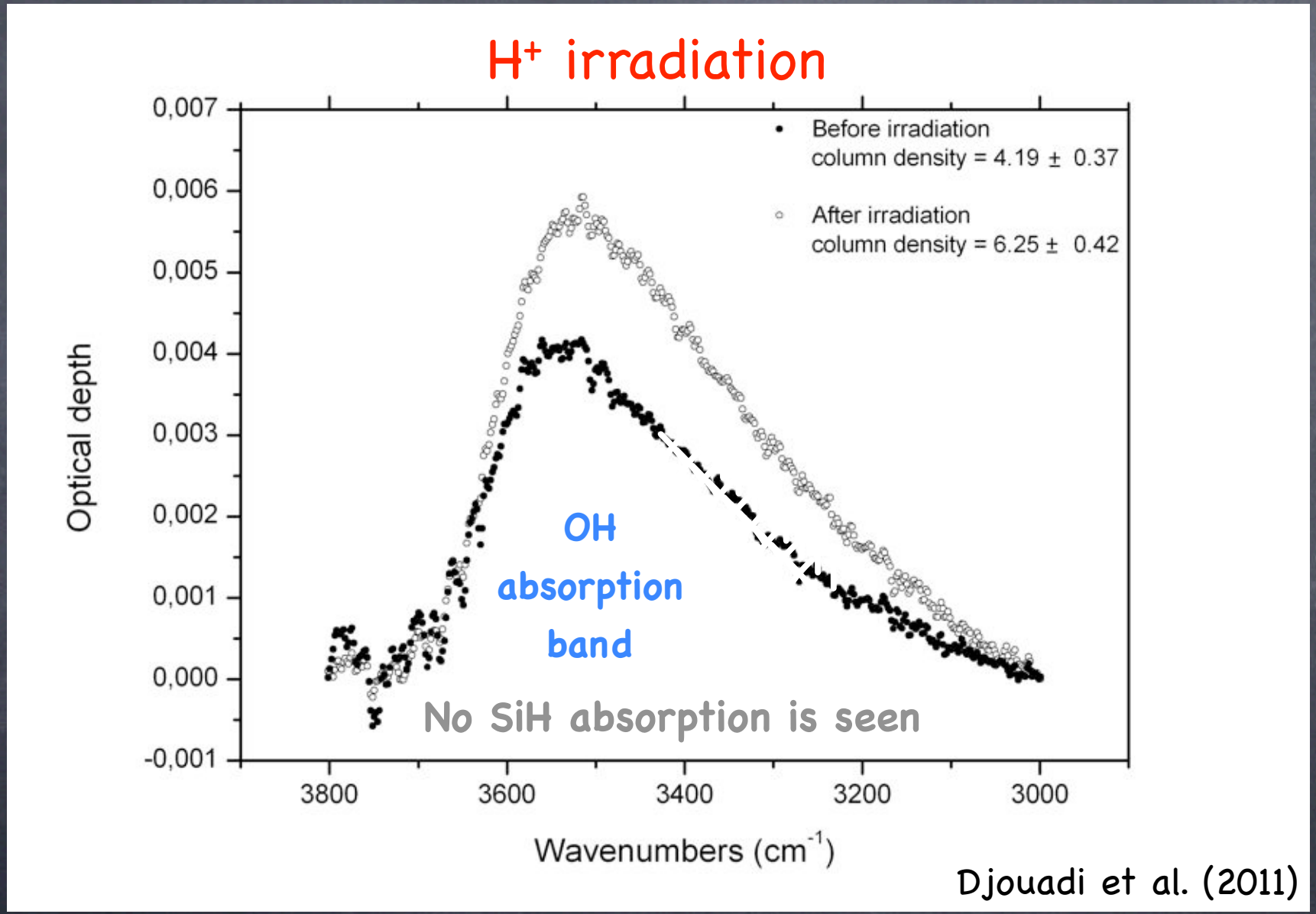
... but what if the irradiating ion is chemically reactive?

H^+ is the most abundant ion

and ought to form OH & SiH groups when implanted into a silicate.

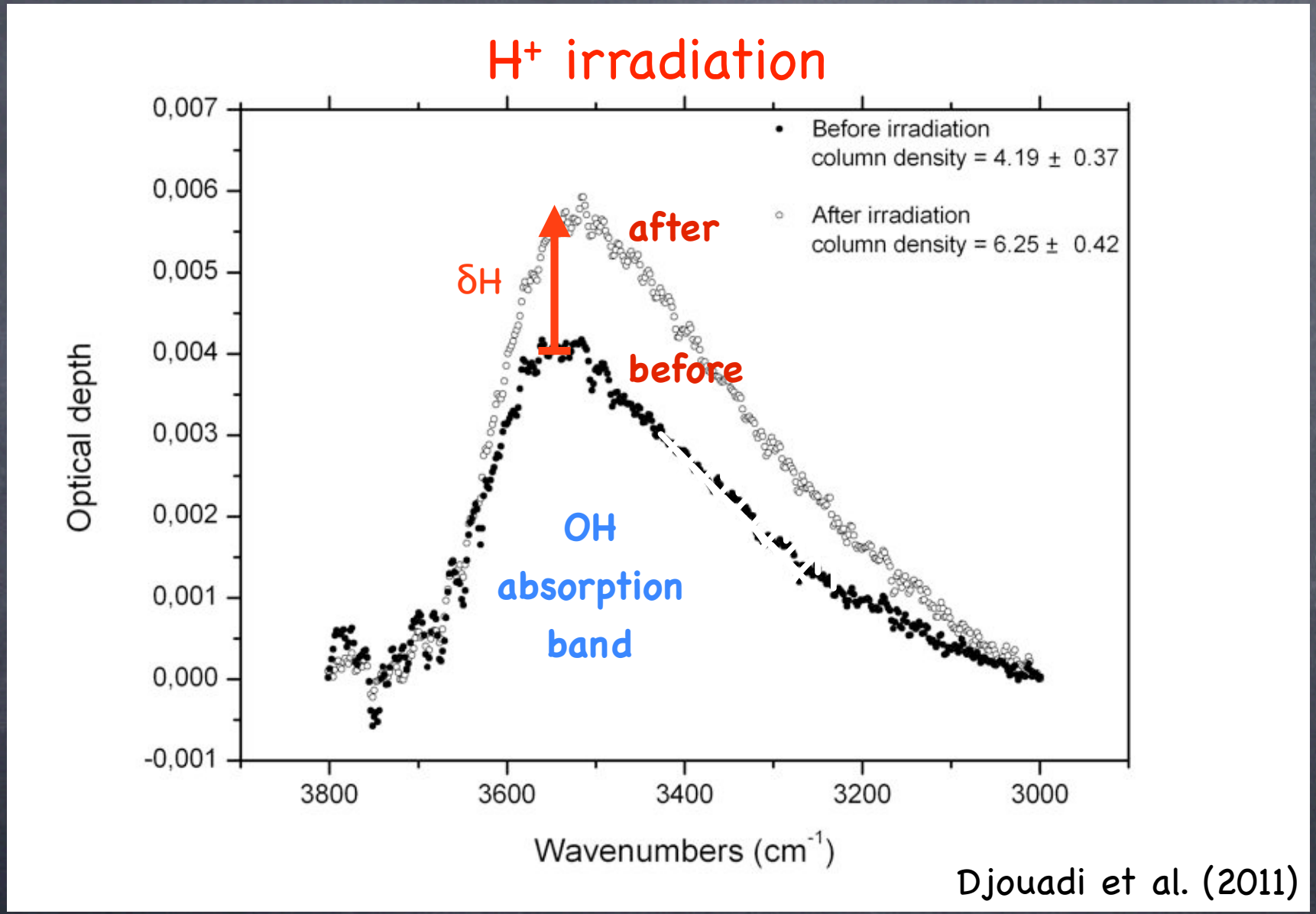
Worrisome - no OH absorption feature is observed in the ISM.

Silicate dust



Djouadi et al. (2011)

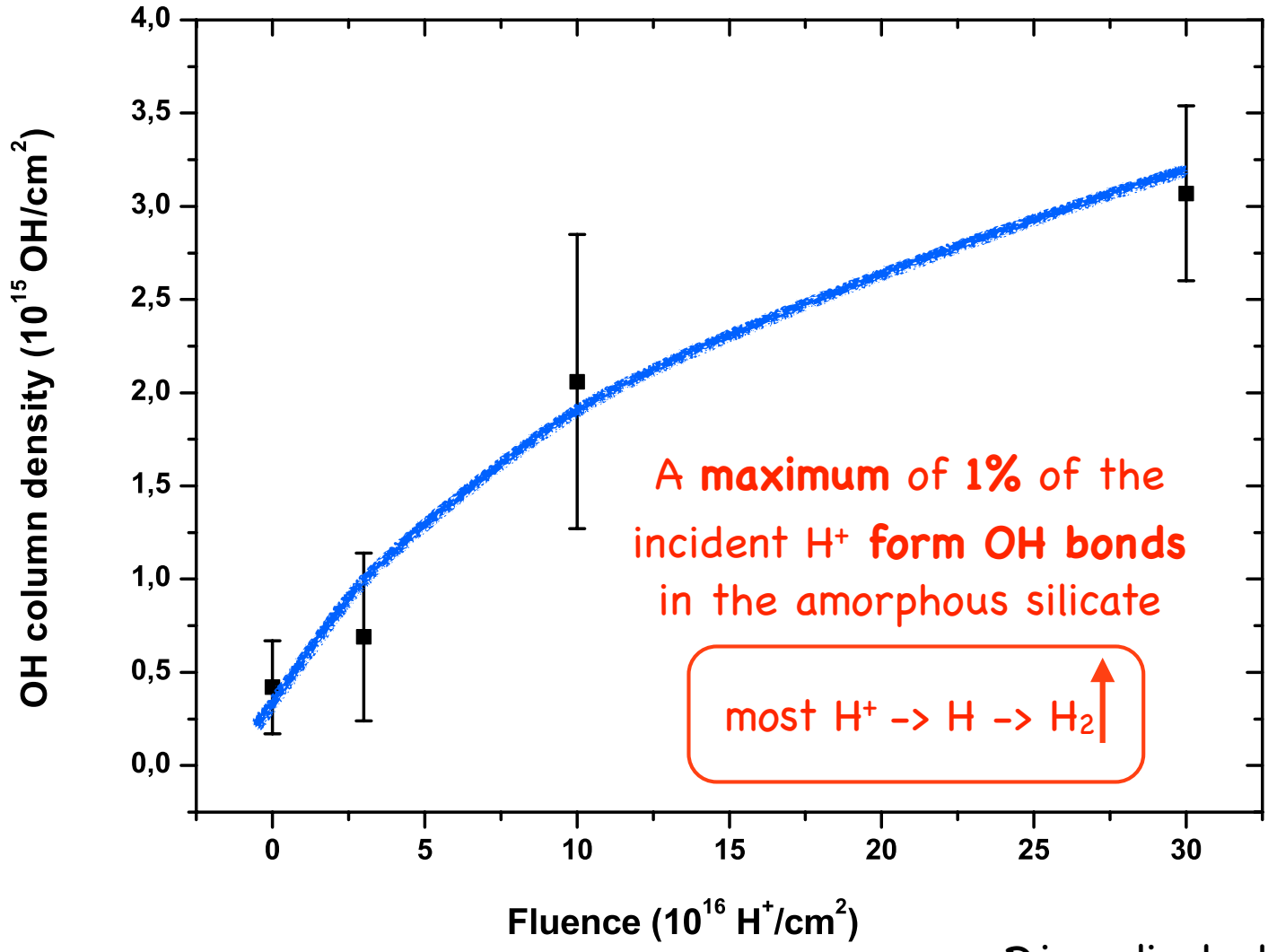
Silicate dust



Djouadi et al. (2011)

Silicate dust

H^+ irradiation



A **maximum** of **1%** of the incident H^+ **form OH bonds** in the amorphous silicate

most H^+ -> H -> H_2 ↑

Djouadi et al. (2011)

Outline

- interstellar dust
  - lifecycle, composition & origin
  - shock processing
- silicate dust
  - evolution
  - implantation
  - annealing
- the dust lifetime
  - time-scales?
  - what do they mean?

... but what happens to amorphous silicates

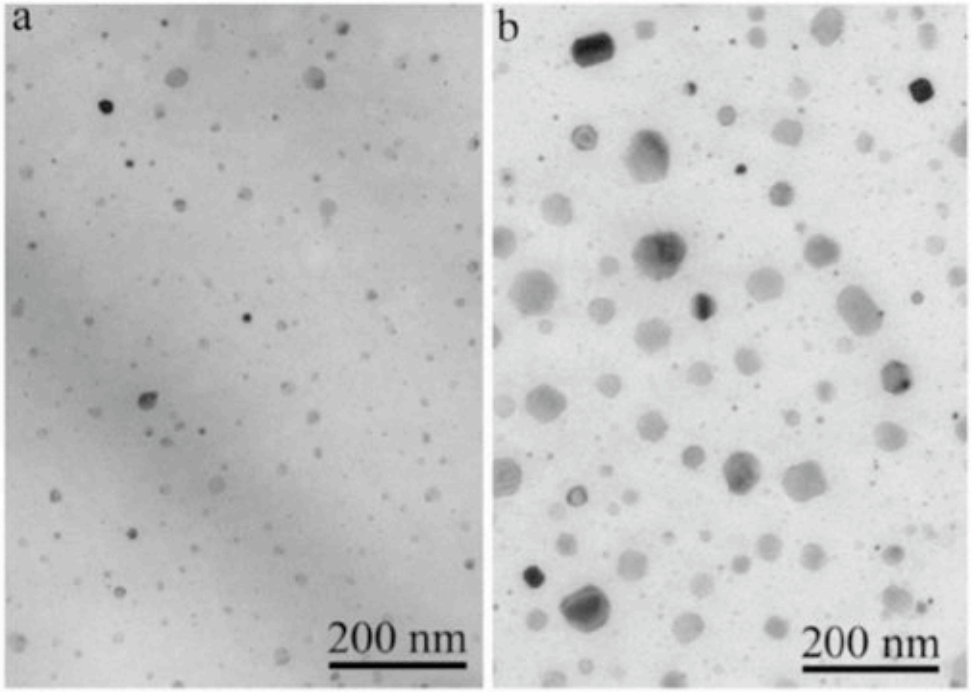
$Mg_xFe_{(1-x)}SiO_4$ $x \cong 0.8$

when you heat them?

... in the presence of carbon

Silicate dust

Annealing and reduction of amorphous silicates



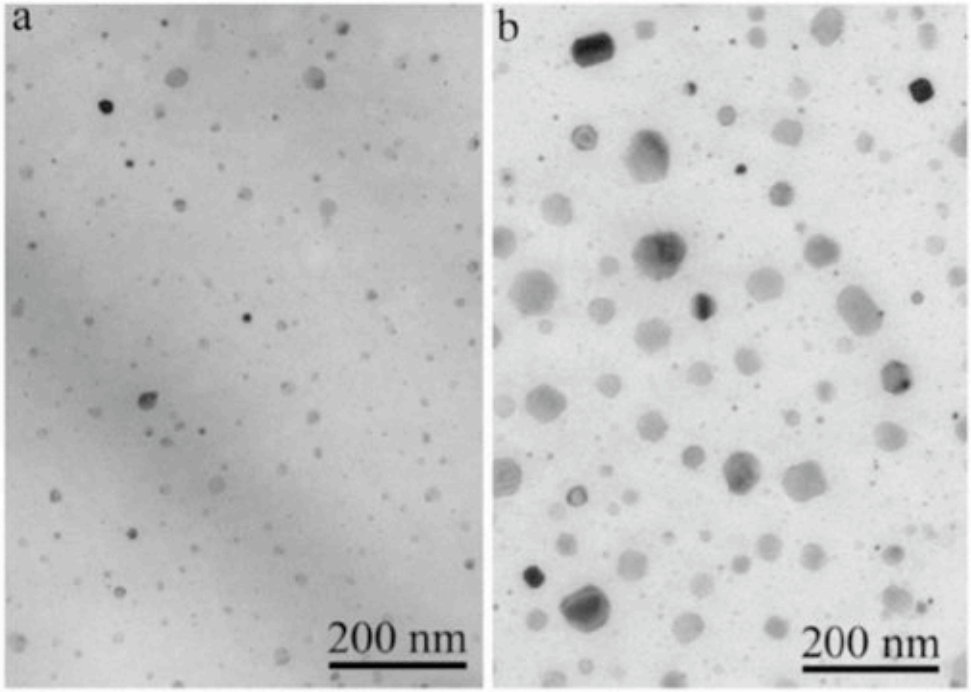
Fe nanoparticles in an amorphous silicate matrix

Fig. 1. TEM micrograph of annealed sample **a)** at 870 K for 780 h and **b)** at 1020 K for 3 h. Rounded metallic nano-particles enclosed in the amorphous silicate. They formed by a reduction reaction and further precipitation since metallic Fe is immiscible in silicates. The microstructure closely ressembles to those to GEMS found in IDPs.

Davoisne et al. (2006), Djouadi et al. (2007)

Silicate dust

Annealing and reduction of amorphous silicates



Fe nanoparticles in an amorphous silicate matrix

Mg-rich amorphous silicate with 'hidden' Fe!

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Silicate dust

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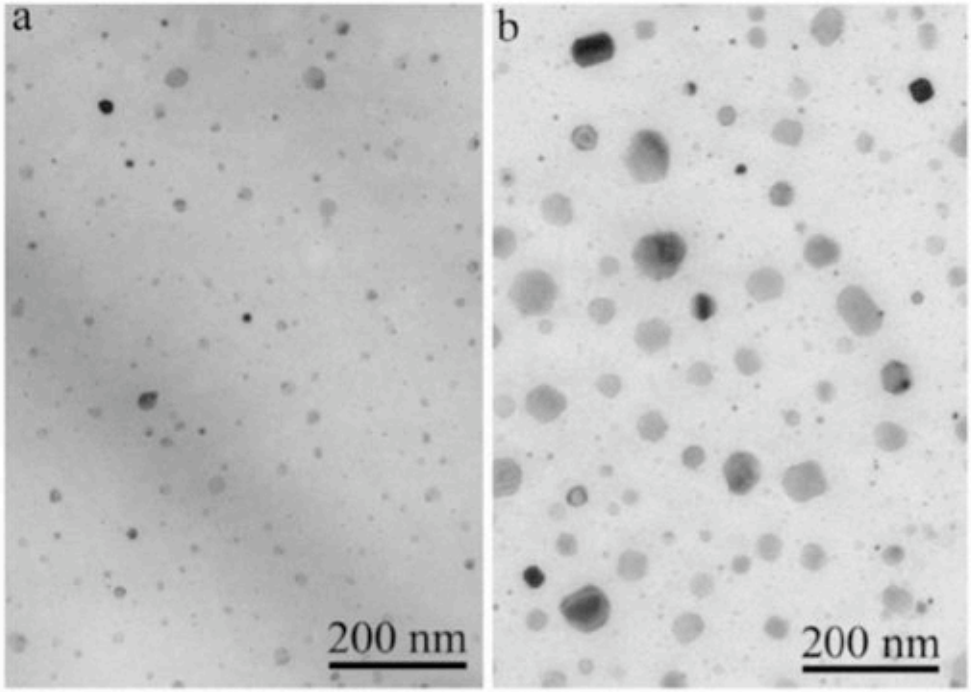

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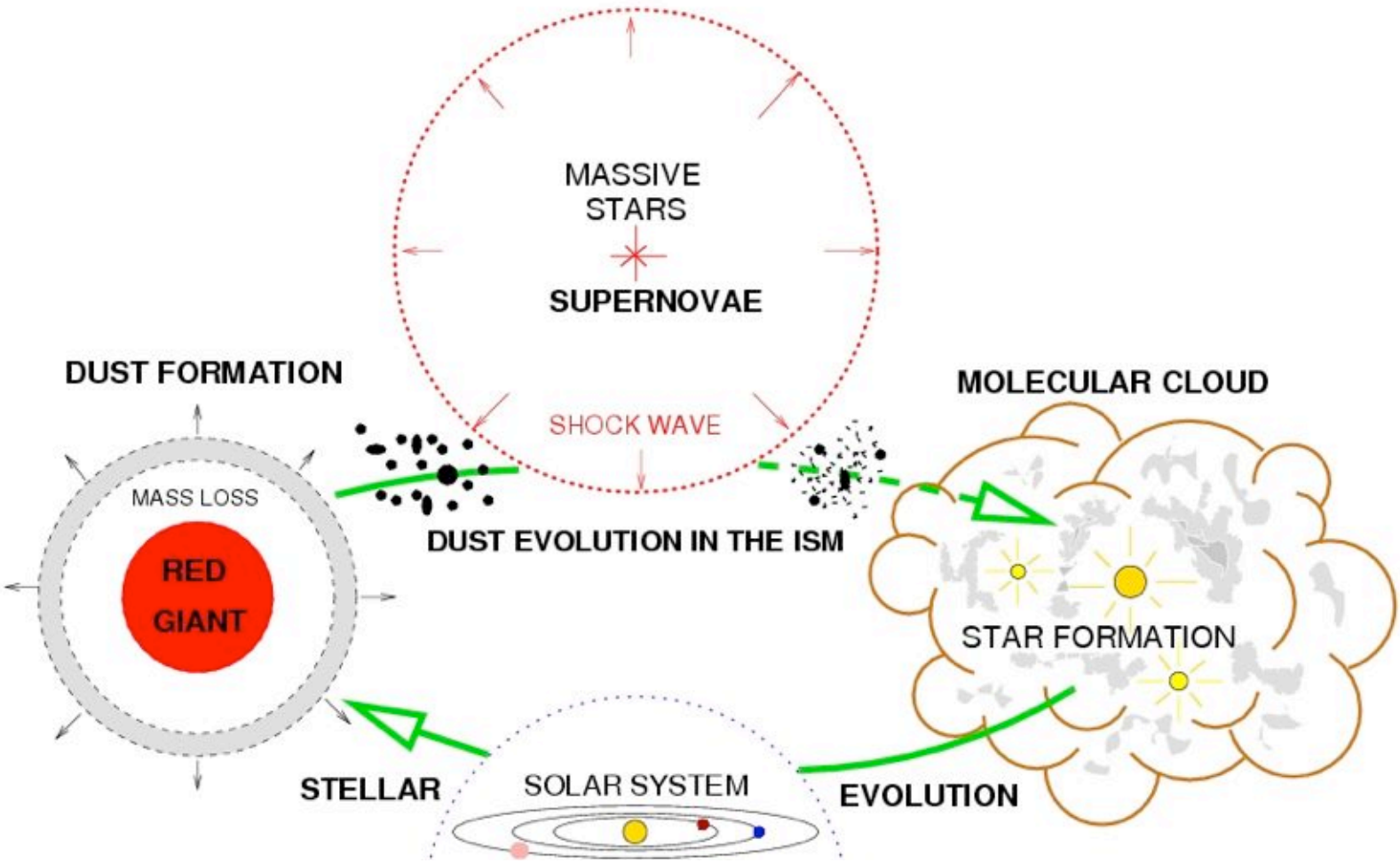
crystallisation
-->
Mg-rich crystalline silicate with Fe nano-particles

Davoisne et al. (2006), Djouadi et al. (2007)

The dust lifecycle



Crystalline silicates (evolved stars and proto-planetary discs) **are Mg-rich.**

Amorphous silicates (in the ISM) **appear to be Mg-rich.**

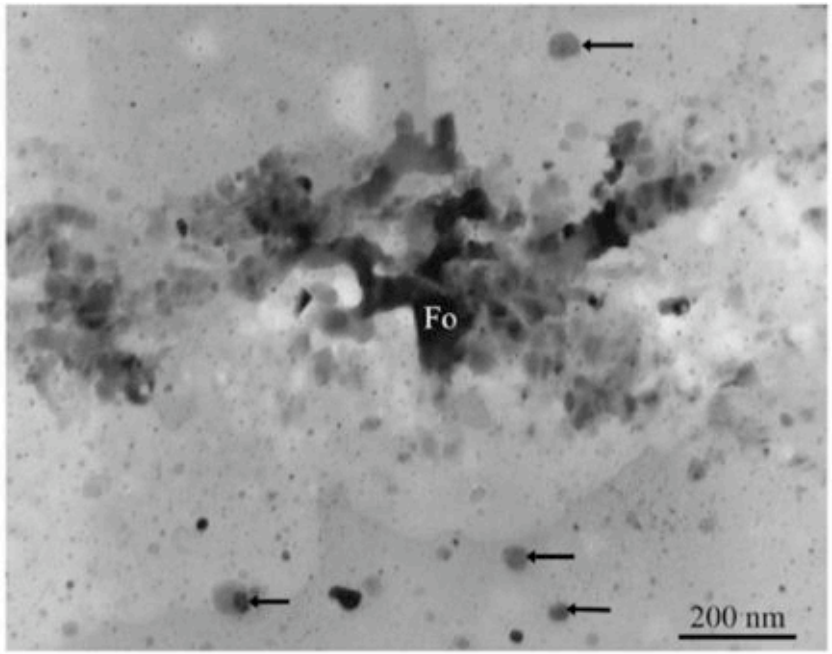
Crystalline Fe-containing silicates are never observed.

Where then is the iron hiding? **- as Fe metal nano-inclusions in silicates?**

Jones (2004)

Silicate dust

Comparison with GEMS in IDPs



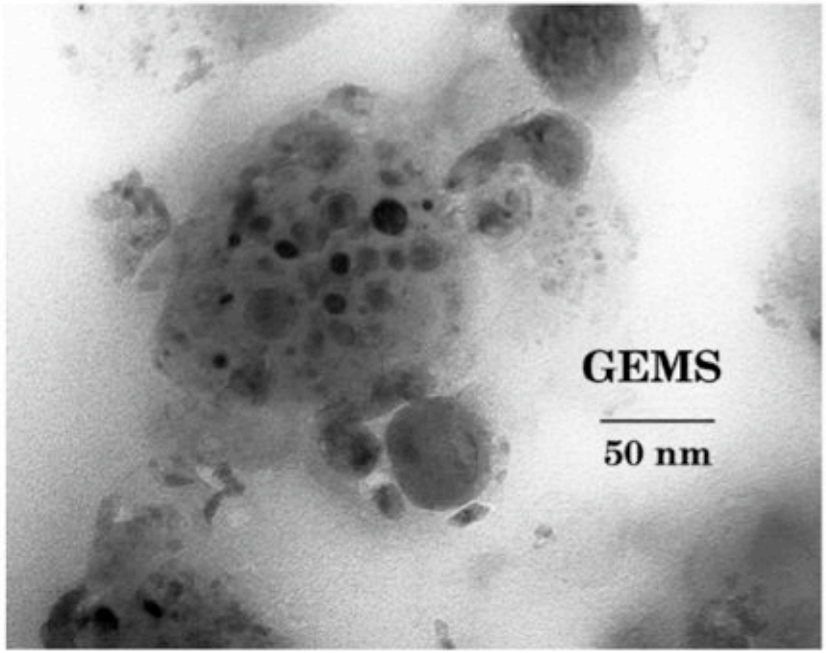


Fig. 2. TEM micrograph of sample annealed at 970 K (55 h) showing a forsterite crystal (Fo) embedded in a amorphous matrix. Note the dentritic structure at the edge of the grains. Some metal particles are also present in the amorphous phase (some of them are arrowed).

Davoisne et al. (2006), Djouadi et al. (2007)

Silicate irradiation

- He^+ and H^+ irradiation **does**
  - --> amorphisation of crystalline silicates
  - --> atom implantation (grain growth)
  - --> porosity (`bubble formation')
- H^+ irradiation **does not**
  - --> form SiH bonds
  - --> lead to major OH bond formation
- Annealing of $Mg_{1.8}Fe_{0.2}SiO_4$ in the presence of carbon
  - --> amorphous (crystalline) Mg-rich silicate
  - --> Fe nano-particle inclusions

Outline

- **interstellar dust**
  - lifecycle, composition & origin
  - shock processing
- **silicate dust**
  - evolution
  - implantation
  - annealing
- **the dust lifetime**
  - time-scales?
  - what do they mean?

?

The dust lifetime calculation

- Using the McKee (1987) approach

$$t_{\mathrm{SNR}} = \frac{M_{\mathrm{ISM}} \times \tau_{\mathrm{SN}}}{\int \epsilon(v_{\mathrm{s}}) \mathrm{d}M_{\mathrm{s}}(v_{\mathrm{s}})} \ \mathrm{yr},$$

$$t_{\mathrm{SNR}} = \frac{4.5 \times 10^{9}\ M_{\odot} \times \tau_{\mathrm{SN}}}{2 \times 2914 \times \int (\epsilon(v_{\mathrm{s}7})/v_{\mathrm{s}7}^{3}) \mathrm{d}v_{\mathrm{s}7}} \ \mathrm{yr},$$

Mass of the ISM 1/SN rate

$$t_{\mathrm{SNR}} = \frac{4.5 \times 10^{9}\ M_{\odot} \times \tau_{\mathrm{SN}}}{2 \times 2914 \times (1.1/n)} \ \mathrm{yr}.$$

Mass of the ISM shocked by a SN

(where $n = 6$ for silicate dust and 3 for a-C:H dust)

Jones & Nuth (2011)

The dust lifetime calculation

- With an estimation of the uncertainties

Mass of the ISM 1/SN rate

$$t_{\mathrm{SNR}} = \frac{n \times [(4.5 \pm 2.2) \times 10^9] \times (125 \pm 62)}{2 \times (2914 \pm 870) \times (1.1 \pm 0.6)}\ \mathrm{yr},$$

Mass of the ISM shocked by a SN

uncertainties are of the order of

±30-50%

$$t_{\mathrm{SNR}} \approx n \times (8.8 \pm 7.9) \times 10^7\ \mathrm{yr}.$$

(where n = 6 for silicate dust and 3 for a-C:H dust)

- **… which yields lifetimes of**
  - **30 - 1000 Myr for silicate dust**
  - **20 - 500 Myr for carbonaceous dust**

Jones & Nuth (2011)

The dust lifetime calculation

- With an estimation of the uncertainties

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- … which yields lifetimes of
  - 30 - 1000 Myr for silicate dust
  - 20 - 500 Myr for carbonaceous dust

c.f. dust injection time-scale ≈ 1000 Myr

Jones & Nuth (2011)

The dust lifetime re-evaluation

- **Reforming IS carbon dust in the ISM?** … another talk entirely!
  - given time, hydrogenated amorphous carbon can form via accretion
- **Reforming IS silicates in the ISM? … is very difficult**
  - O, Si, Mg & Fe --> 'silicate' … but carbon will be incorporated too?
  - metallic films (vacuum condensation)
  - that do not match the extinction
- **The dust 'lifetime' estimation ≈ 5×10^8 yr, c.f. $\tau_{injection} \approx 10^9$ yr**
  - "might" just be viable for silicates but not for carbon grains
  - dust 'lifetime' appears to be a rather naïve concept
  - need a better knowledge of mass exchange between the ISM phases

Jones & Nuth (2011)

Summary

- **dust consists primarily of O, Si, Mg & Fe** ... & C-rich carbonaceous dust
  - primarily formed around evolved stars (AGB, SNe, ...) & in the ISM
  - good agreement between ISM, CS and pre-solar dust populations
- **SNe shock waves --> He^+ & H^+ ion irradiation of silicates -->**
  - erosion, implantation, amorphisation, porosity & no "chemistry"
  - evolution: Mg:Fe silicates --> Fe-richer silicates/oxides
  - annealing in the presence of C --> reduction of Fe & Mg-rich silicates
  - grain-grain collisions --> fragmentation: big grains --> small grains
- **problems**
  - the Oxygen problem; where is the extra-depleted O?
  - carbonaceous dust destroyed by shocks; re-formed in the ISM?
- **the dust "lifetime"**
  - what does it really mean? role of ISM dynamics & mass exchange?

The End