From Dust to Planets:
Volatile element depletion in the inner Solar System

Dynamics and Evolution of Earth-like Planets
Feb. 12 , 2015

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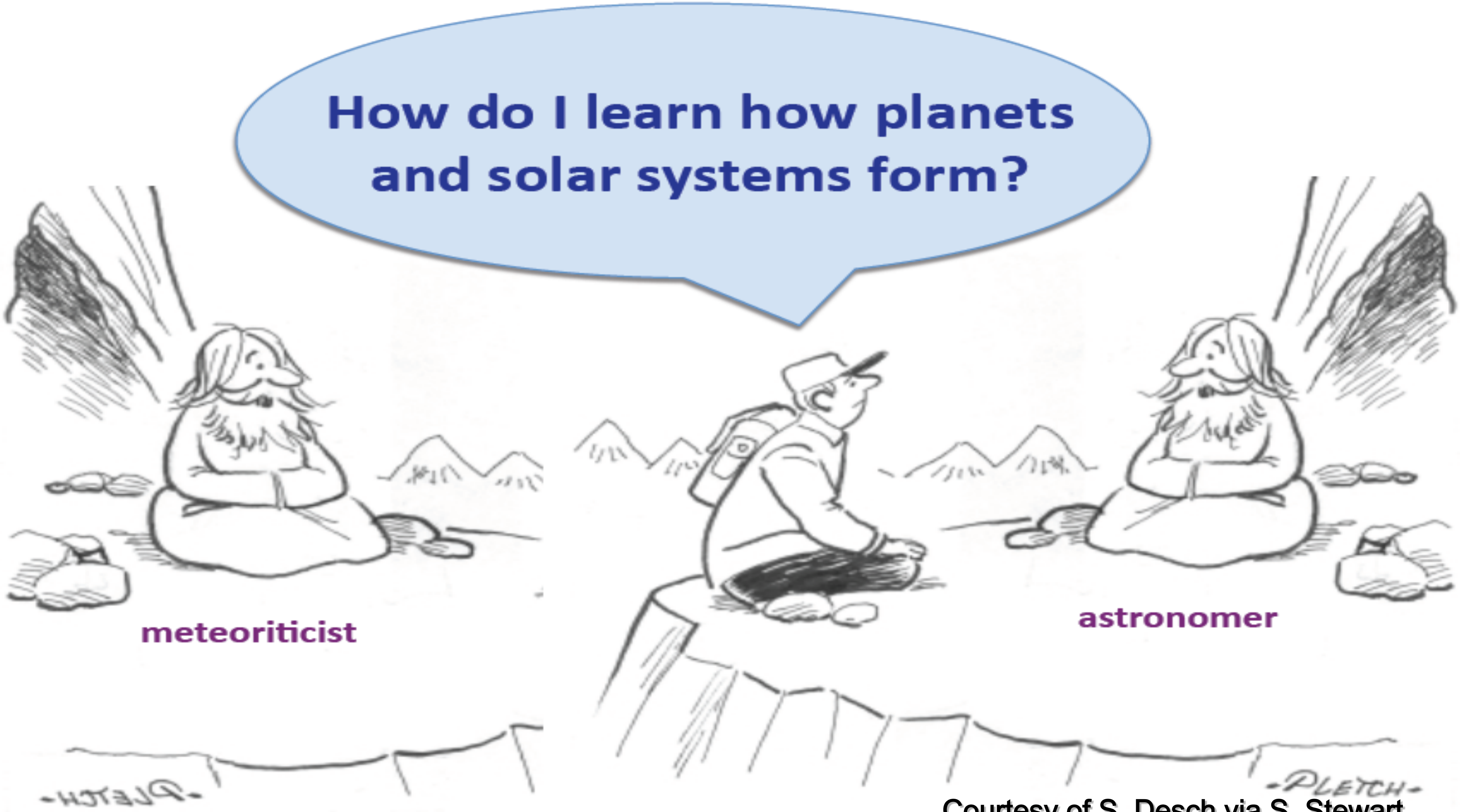
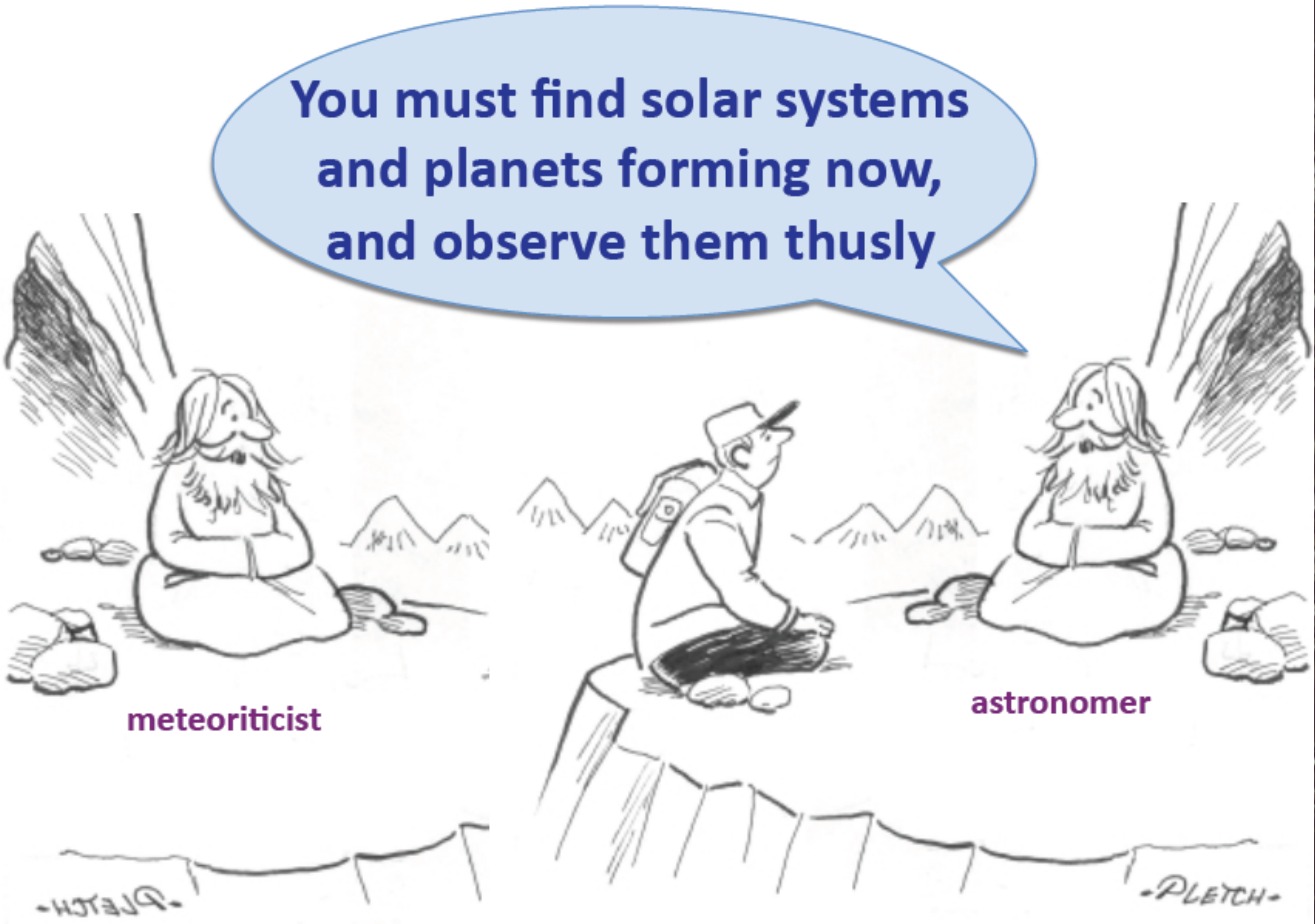
Outlines

1. **Nature of planetary building blocks** (chondrites min/pet)
2. **Volatile depleted nature and its current budget** (chemistry)
3. **Earth atmosphere is leftover from erosion** (isotopes)

Two paths to enlightenment



Courtesy of S. Desch via S. Stewart

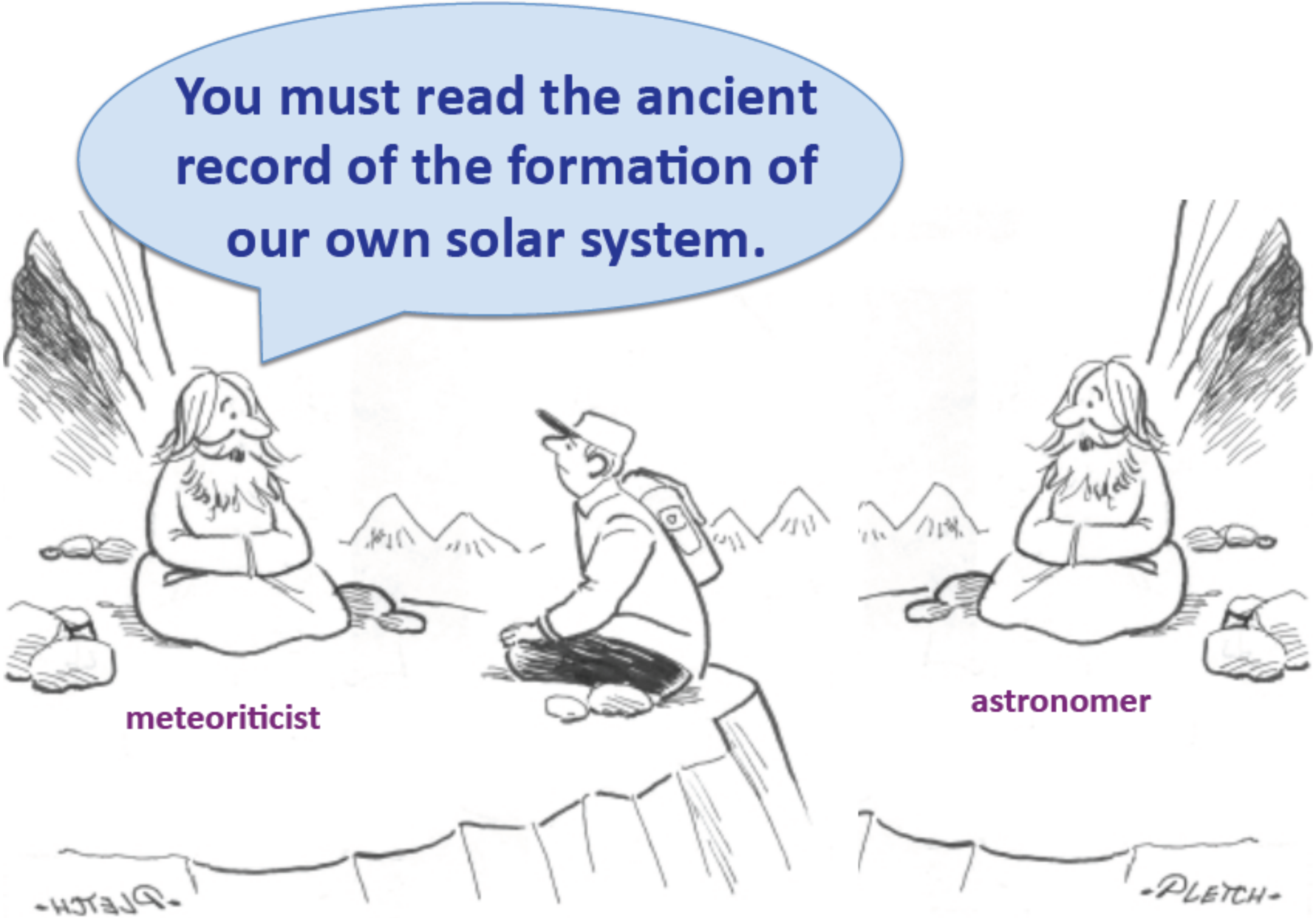


Courtesy of S. Desch via S. Stewart

Astronomer's View

(as understood by a meteoriticist)

- Super-Earths and Mini-Neptunes are everywhere, Jupiter-likes far less common.
- Disk run out of gas in only a few Ma.
- In this timeframe, dust grains grow from mm to Mars-sizes.
- Planets must form eventually because we see them everywhere, but we can't see how it was done nor where they formed.
- Migration requires gas, but if gas is around, runaway growth would make Jupiter instead of super-Earths and mini-Neptunes



Courtesy of S. Desch via S. Stewart

Galactic Chemical Evolution

X (H) = 71.10%
Y (He) = 27.41%
Z (Astronomers "metal": Li-U) = 1.49%

C, N, O, and Ne dominate more than half of Z, and C and O are most abundant "metals":
C: 0.247%
O: 0.657%

CO is second most abundant gas next to H_2
C/O<1 dominates galactic chemical evolution

Gaidos 2015

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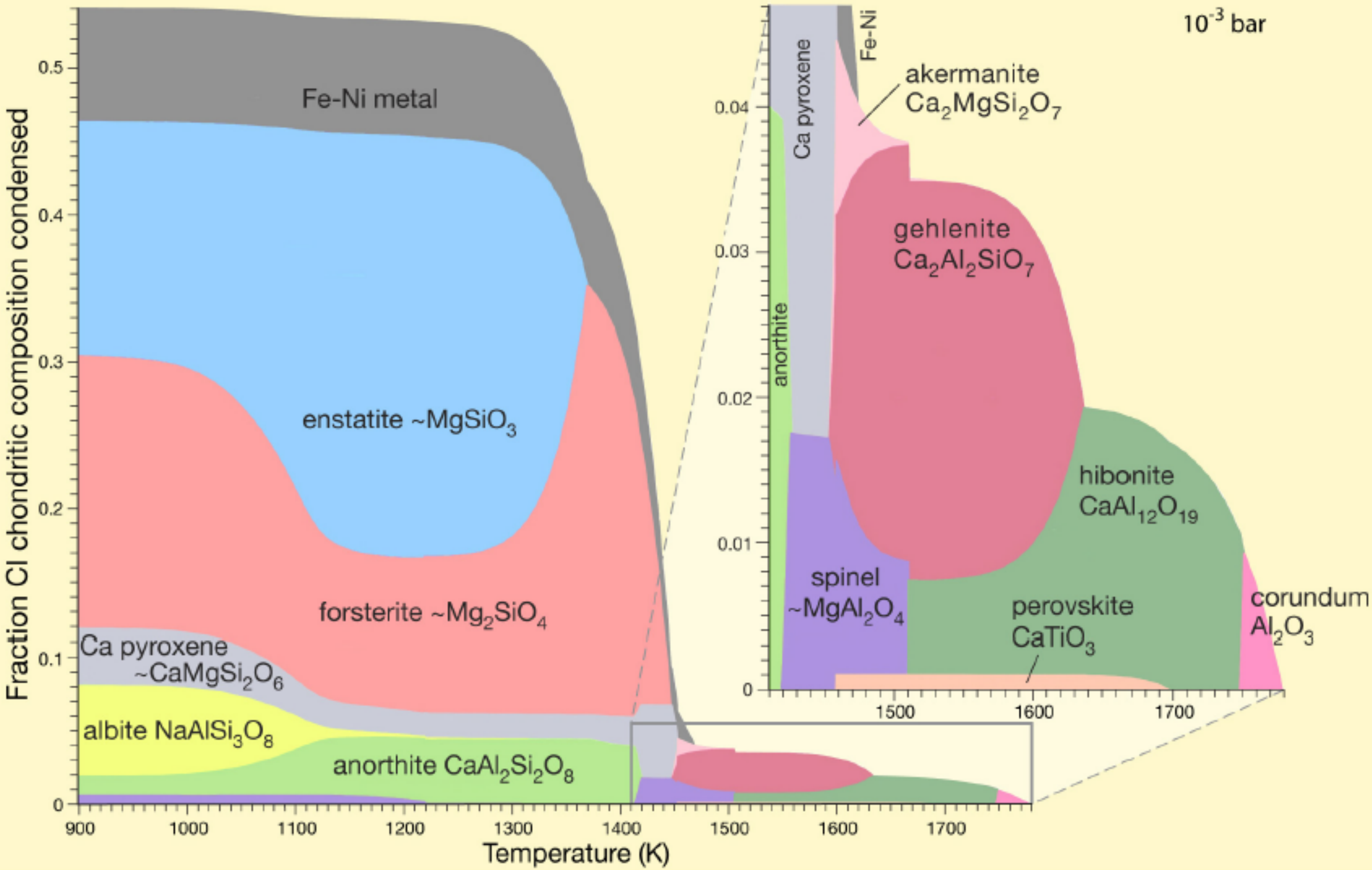
Concept

Primary Solids: Dust inherited from ISM.

Secondary Solids: Condensates, evaporation residue, molten chondrules, etc.
Results of further processing of the primary solids within solar nebula.

Mineral stability in solar nebula

(courtesy of Andy Davis)



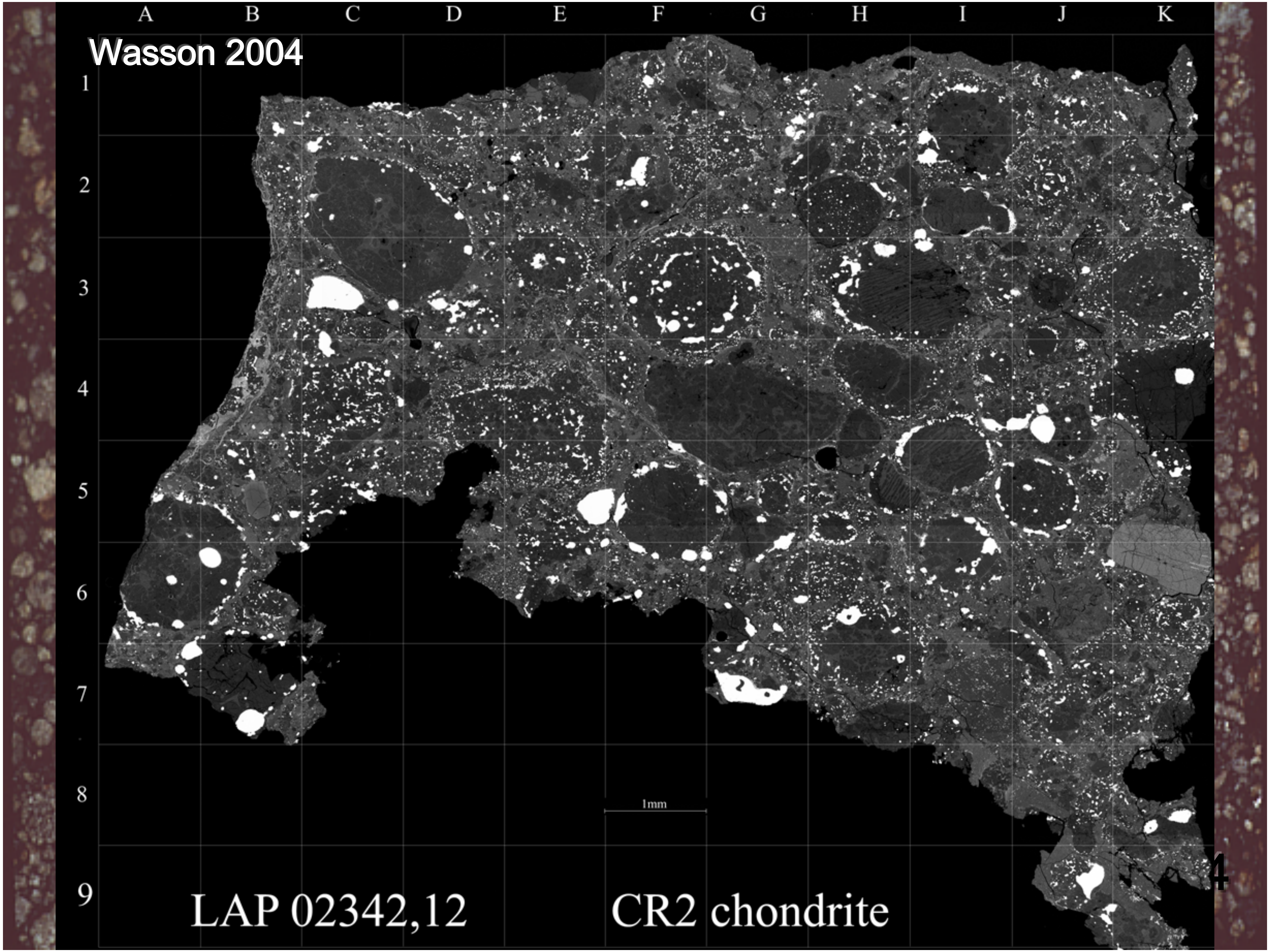
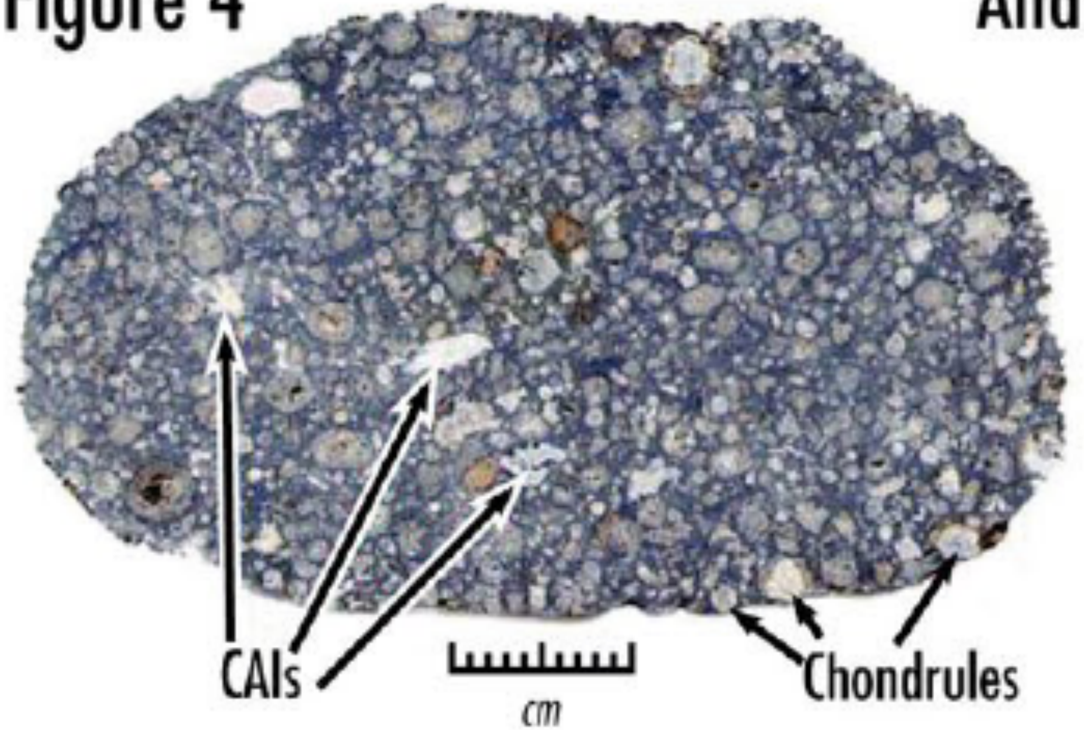

Wasson 2004
A B C D E F G H I J K
1 2 3 4 5 6 7 8 9
1mm
LAP 02342,12
CR2 chondrite
4

Figure 4

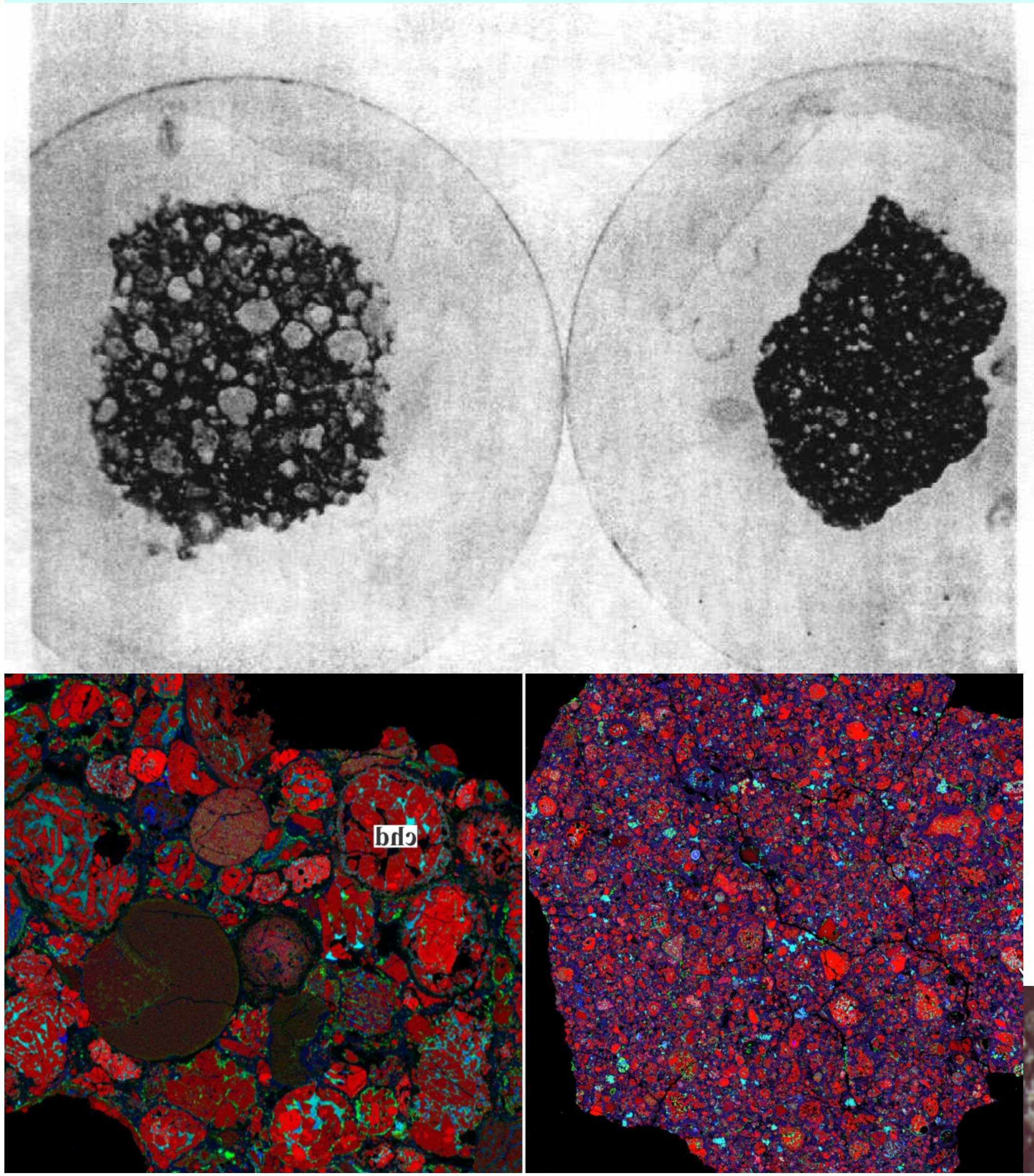


Anatomy of cosmic sediments:

1. High temperature refractory bits and pieces (CAIs, chondrules)
2. Low temperature fine grained dark matrix with pre-solar grains, organic matter and water

A key question is: ***How and when do these diverse components come together?***

J. A. Wood (1985)

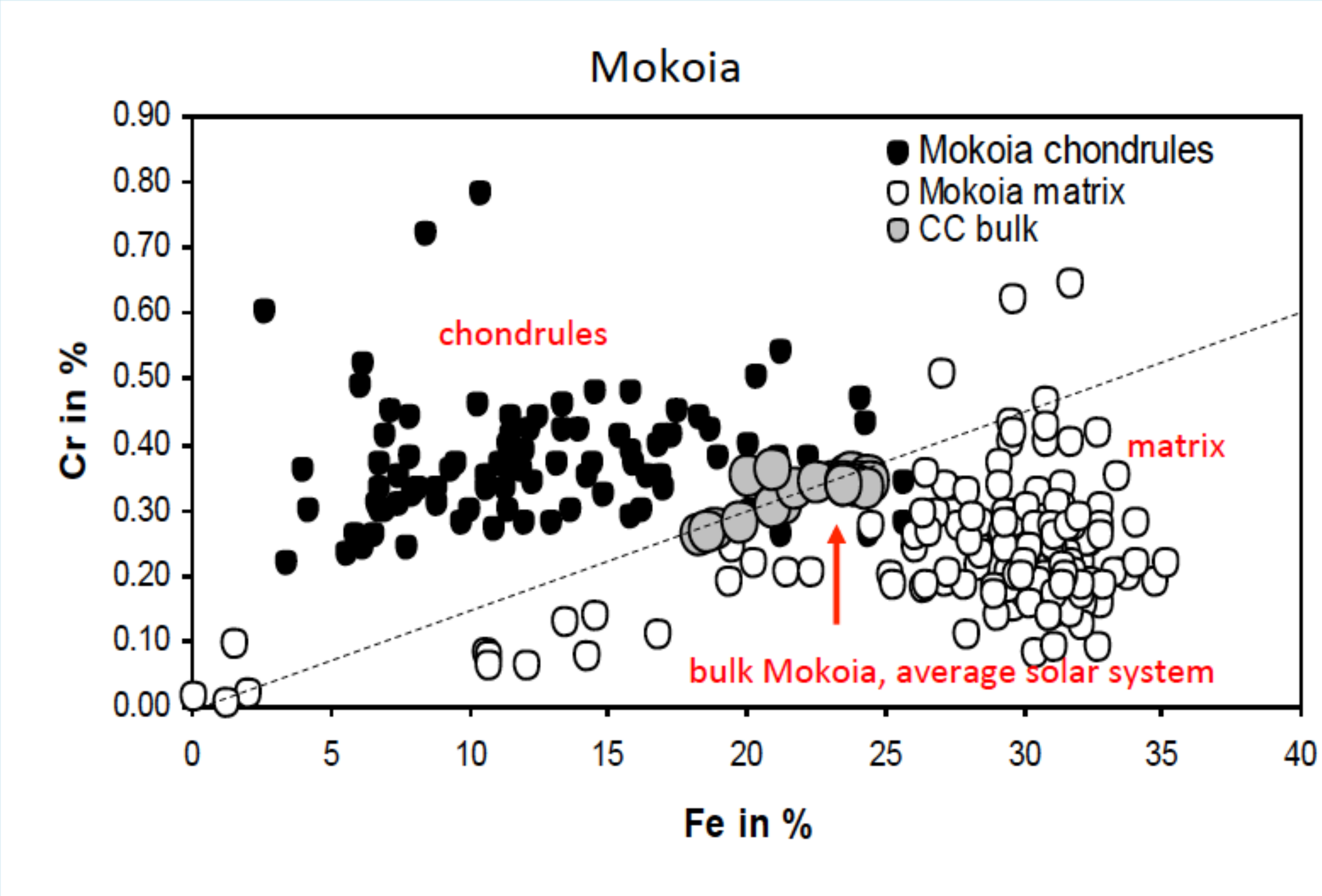


"Fredriksson's Paradox"

- **Different petrography;**
- **Variable proportions of chondrules to matrix;**
- **Identical bulk chemical composition**

Implying:

- **Prompt aggregation with the matrix after chondrules and CAIs formation (<< orbital period).**
- **If chondrules continued to orbit for thousands of years, expect aerodynamically sorted, thoroughly mixed morphology, textural identities lost!**
- **Local production, reflect local precursor reservoir chemistry**

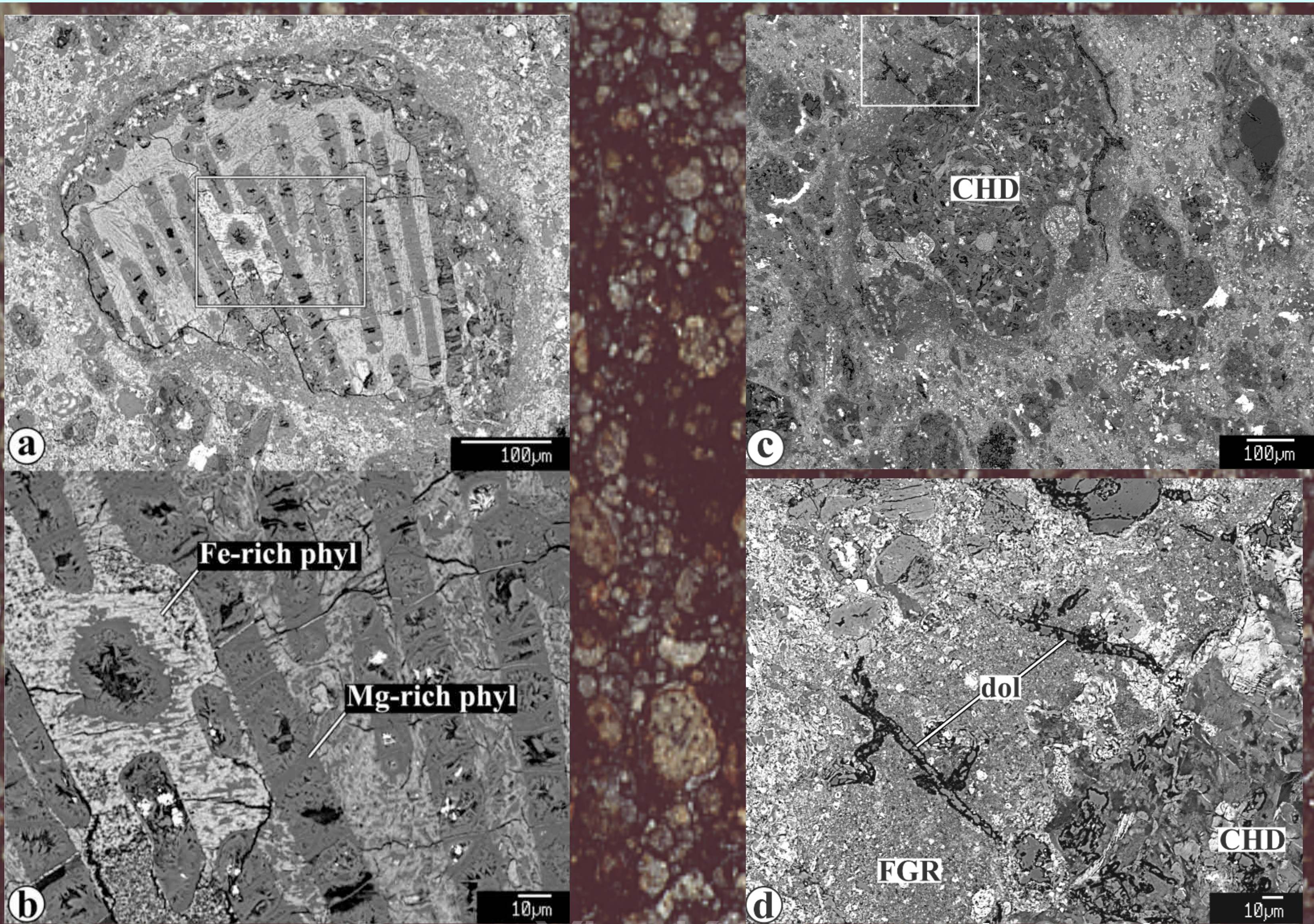


Parent body processes cannot produce forsteritic olivine.
Aqueous alteration may produce FeO-rich olivine.

Courtesy of Palme

chondrules: Jones and Schilk (2009)

Sutter's Mill (CM chondrites)



Jenniskens, Yin, Krot et al (2012)

$$Fe + H_2S = FeS + H_2$$

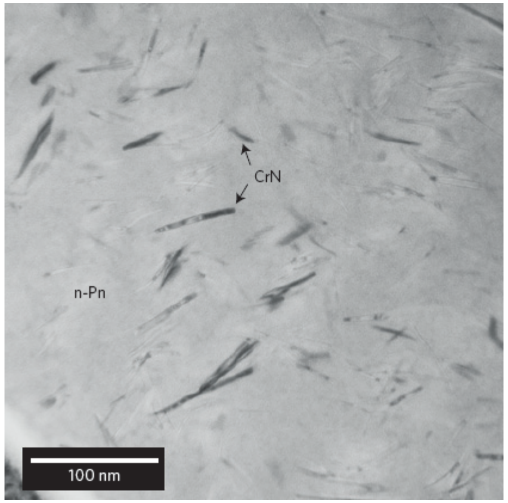
$$3Fe + 4H_2O = Fe_3O_4 + 4H_2$$

$$3FeS + 4H_2O = Fe_3O_4 + 3H_2S + H_2$$

Remnants of the Early Solar System Water Enriched in Heavy Oxygen Isotopes

Naoya Sakamoto,[1] Yusuke Seto,[1] Shoichi Itoh,[1] Kiyoshi Kuramoto,[2] Kiyoshi Fujino,[1] Kazuhide Nagashima,[3] Alexander N. Krot,[3] Hisayoshi Yurimoto[1,4]*

Science 2007



$$NH_3 \rightarrow N + 3/2\, H_2.$$

Carsbergite (CrN) a secondary mineral named after beer

Reactive ammonia in the solar protoplanetary disk and the origin of Earth's nitrogen

nature geoscience 2015

Dennis Harries[1,2]*, Peter Hoppe[3] and Falko Langenhorst[1]

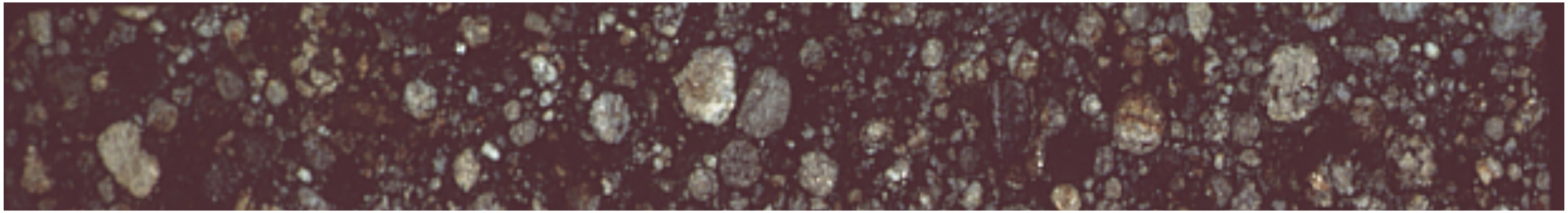
“Sponges” that store volatiles

Table 1. Aqueously formed minerals in CI, CM, CR, CV, CO, R, and ordinary chondrites.

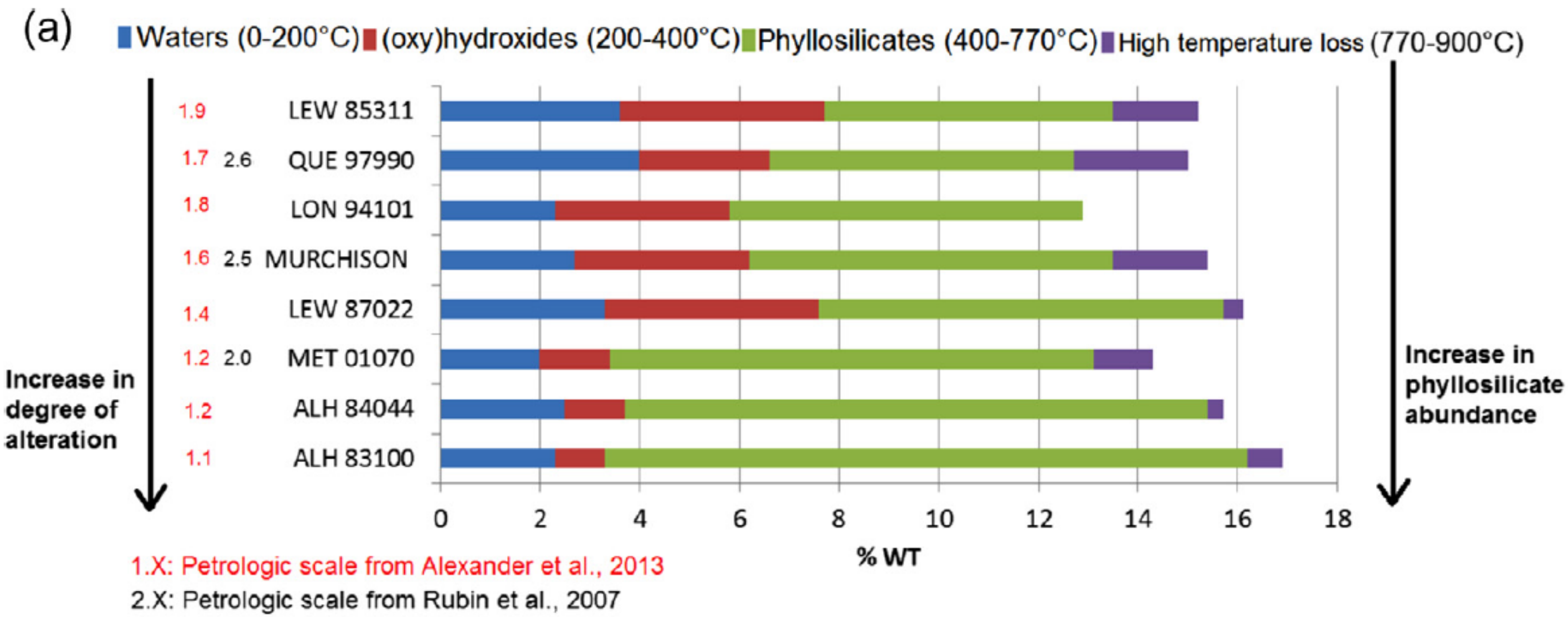
CI, CM, and CR chondrites

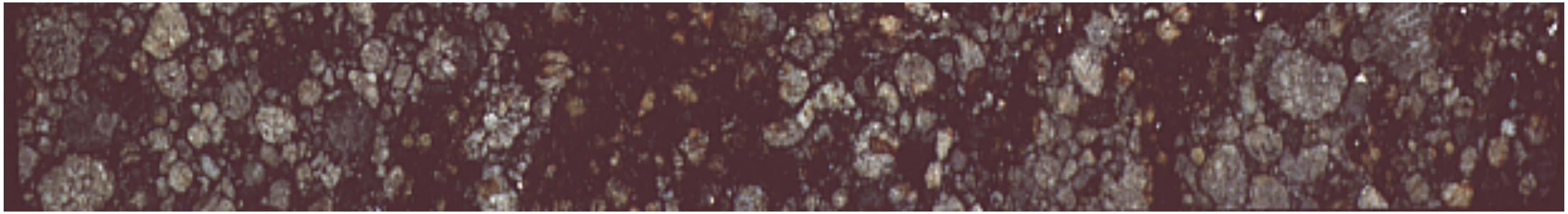
serpentine	$Mg_3Si_2O_5(OH)_4$
cronstedtite	$Fe_2^{2+}Fe^{3+}(Si,Fe^{3+})_2O_5(OH)_4$
saponite	$Ca_{0.25}(Mg,Fe)_3(Si_4O_{10})(OH)_2 \bullet nH_2O$
tochilinite	$2[(Fe,Mg,Cu,Ni)S] \bullet 1.57–1.85[(Mg,Fe,Ni,Al,Ca)(OH)_2]$
calcite	$CaCO_3$ (trigonal)
aragonite	$CaCO_3$ (orthorhombic)
dolomite	$CaMg(CO_3)_2$
siderite	$FeCO_3$
breunnerite	$(Mg,Fe,Mn)CO_3$
troilite	FeS
pyrrhotite	$Fe_{1-x}S$
pentlandite	$(Fe,Ni)_9S_8$
magnetite	Fe_3O_4
cubanite	$CuFe_2S_3$
sphalerite	$(Fe,Zn)S$

Krot et al 2015 Asteroid IV)



A. Garenne et al. / Geochimica et Cosmochimica Acta 137 (2014) 93–112





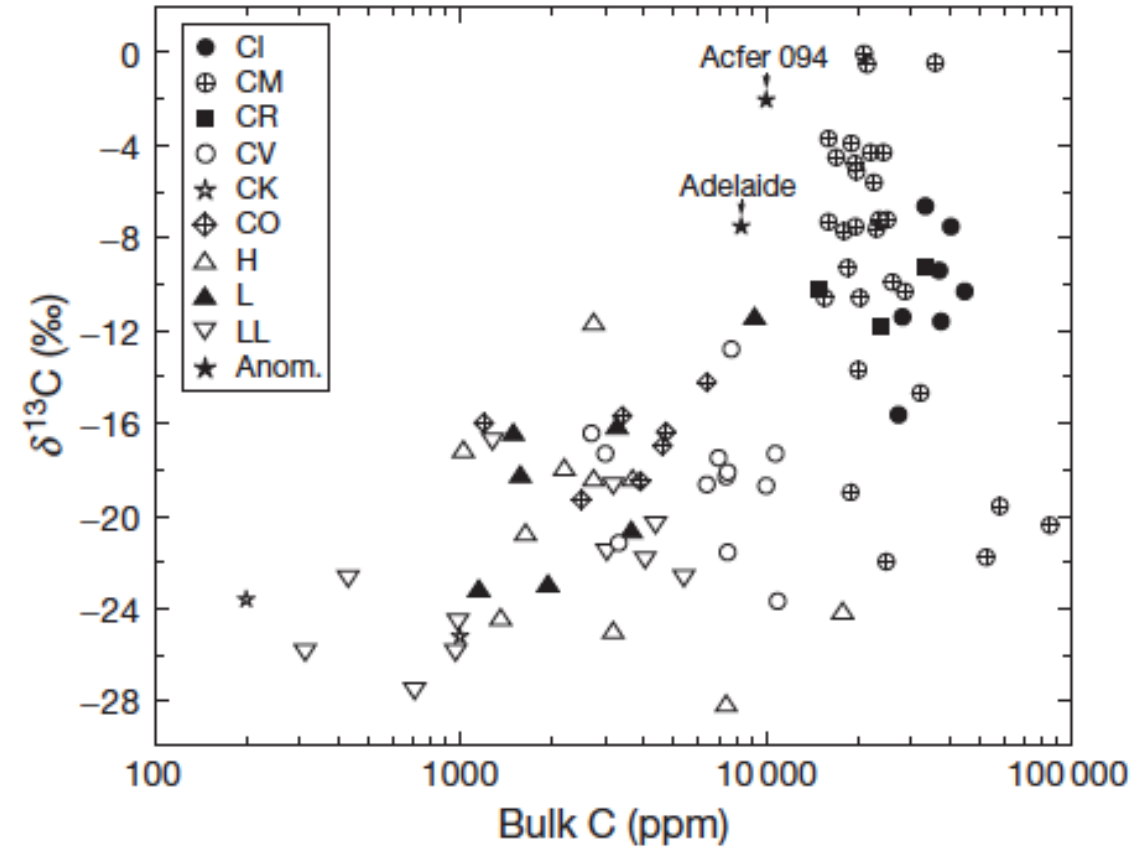
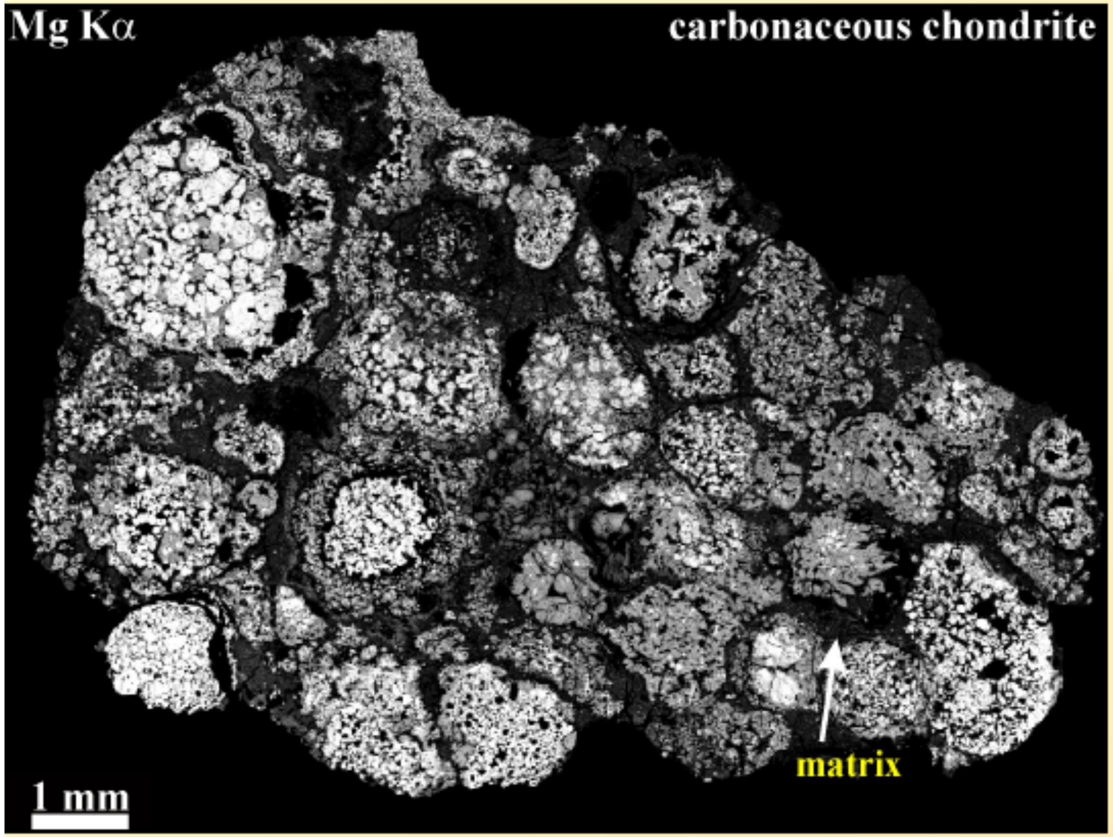


Figure 5 Bulk carbon contents (ppm) versus $\delta^{13}C$ (‰) in chondrites (Sources: Grady and Pillinger, 1986; Kerridge, 1985).

Krot et al (2014a ToG)

Matrix material

- Mixture of grains 10 nm - 5 µm in size with ~solar bulk composition which rims chondrules, CAIs, metal grains, etc.
- Only 4 out of 4,000 chondrites have pristine matrices (Acfer 094, ALHA77307, Adelaide, Kakangari).



- Pristine C chondrite matrices contain forsterite Mg_2SiO_4, enstatite $MgSiO_3$, and amorphous Fe-Mg-Si-O containing Fe-Ni metal or Fe-sulfides with admixture of carbonaceous material, refractory grains, and stardust (~0.001%).
- Complex mixture of grains that formed at different times and places; acquired when components accreted.

Ed Scott 2004

Comets and chondritic porous IDPs

- Chondritic porous IDPs closely resemble matrices of pristine carbonaceous chondrites.

- Both contain Mn-rich forsterite, rapidly cooled enstatite, and amorphous silicate material.

- Forsterite, enstatite, and amorphous silicate also present in comas of long-period comets: up to 30-50% crystalline (Wooden et al., 2004).

- Major fraction of silicate in comets formed in the disk at high temperatures, probably as condensates.

- Thermally processed dust was ubiquitous in the disk.

Ed Scott 2004

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Cosmochemical Classification of the Elements

Table 1. *Cosmochemical classification of the elements*

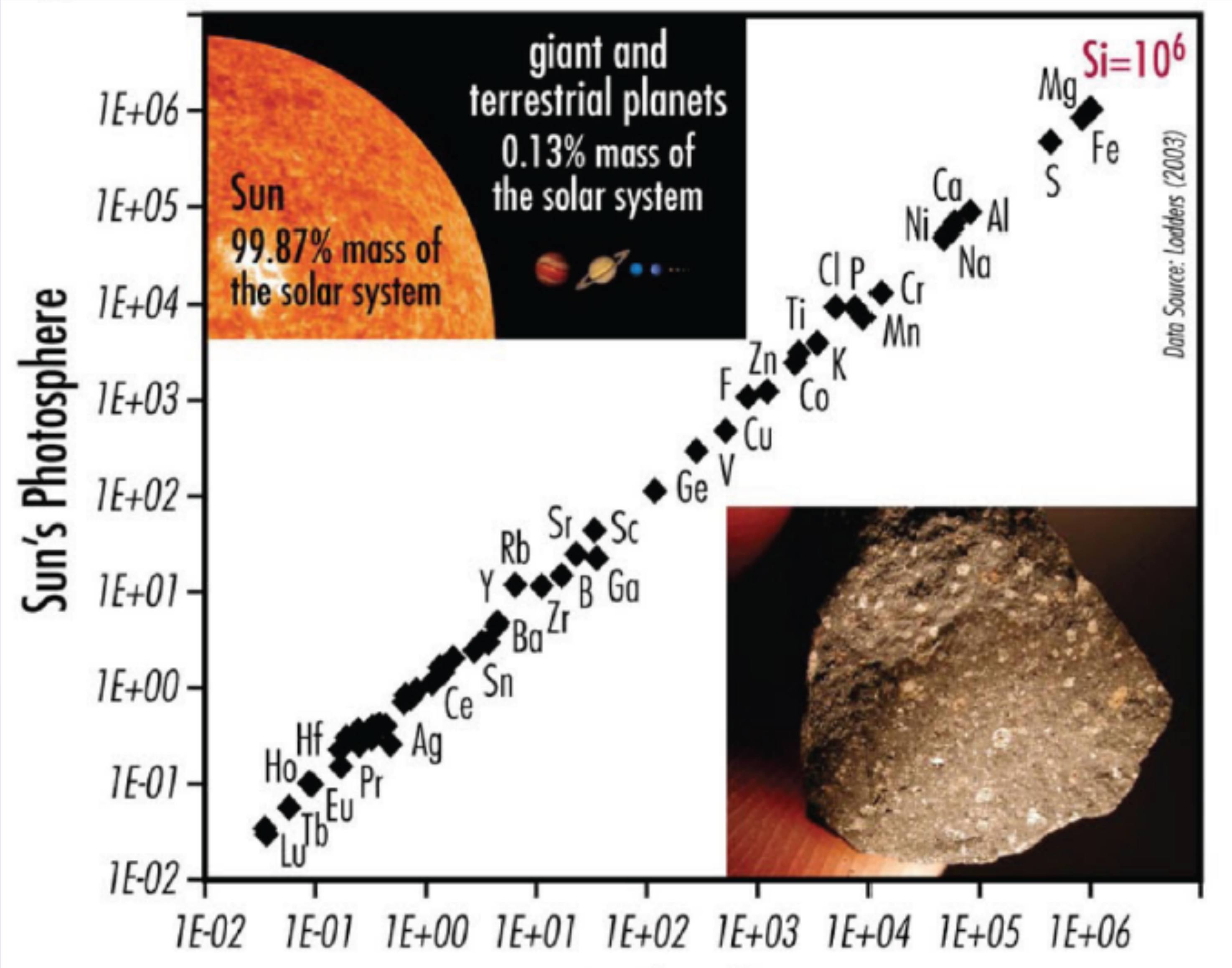
	elements	
	lithophile (silicate)	siderophile + chalcophile (sulphide + metal)
refractory	T_c = 1850–1400 K	
	Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Mo, Ru, W, Re, Os, Ir, Pt
main component	T_c = 1350–1250 K	
	Mg, Si, Cr, Li	Fe, Ni, Co, Pd
moderately volatile	T_c = 1230–640 K	
	Mn, P, Na, Rb, K, F, Zn	Au, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
highly volatile	T_c < 640 K	
	B, Cl, Br, J, Cs, Tl, C, O, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg, H

T_c denotes condensation temperatures at a pressure of 10^{-4} bar.

H. Palme (2001)

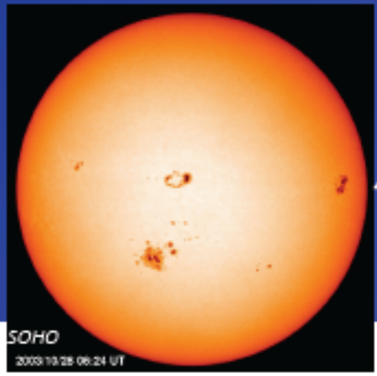
Chondrite (CHUR)=Bulk Solar System

2E30 Kg



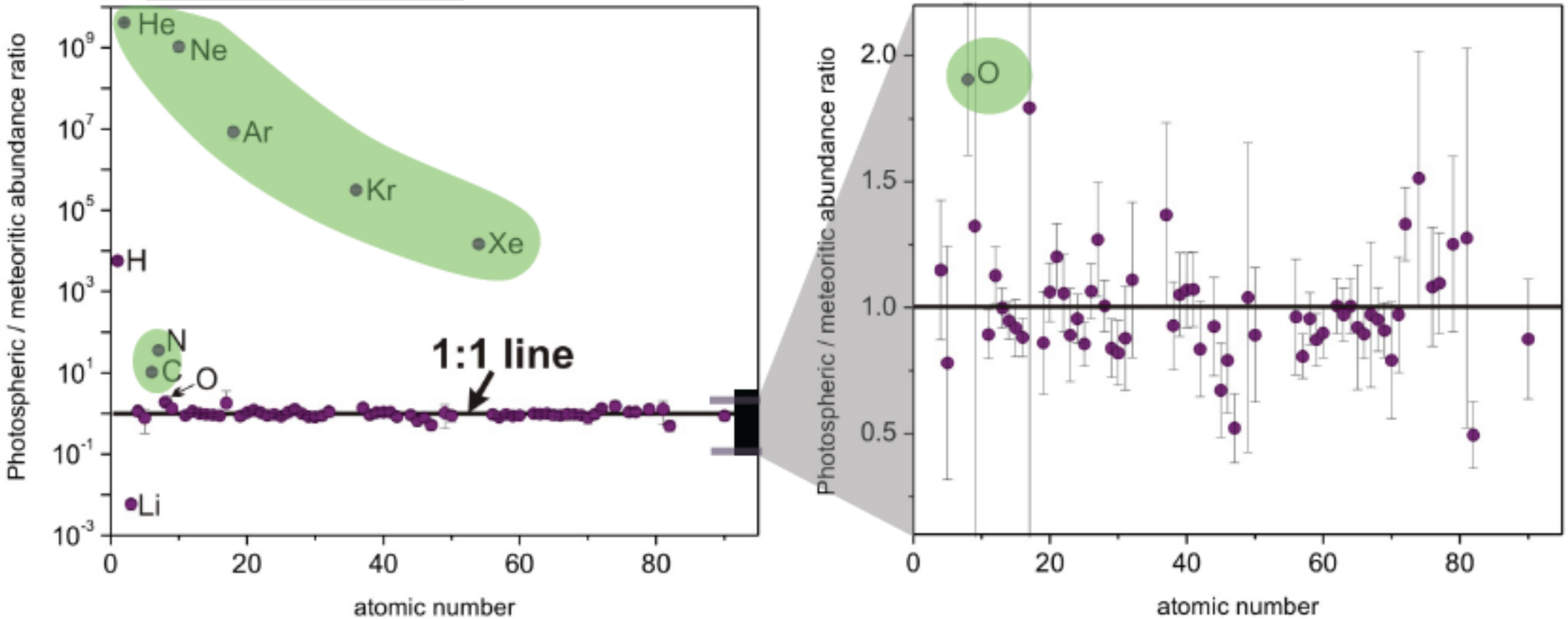
2E1 Kg

Yin et al (2009)



Sun's Photosphere (today)

CI chondrite (4.56 years old)



Asplund et al. 2009
Lodders et al. 2009

All subsequent processing is recorded in the deviation from this correlation

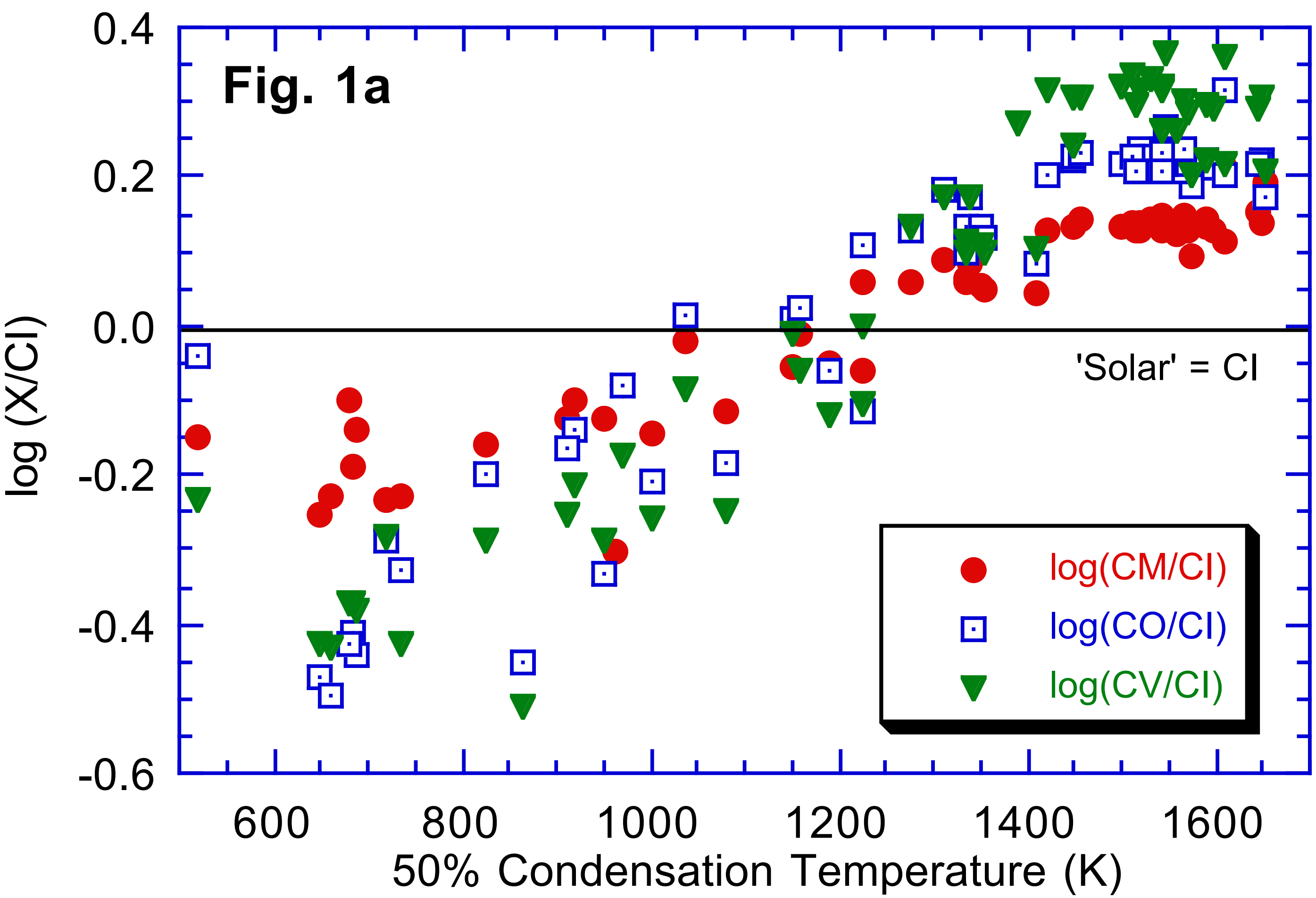
Courtesy of K. McKeegan

Where have all the volatiles gone?

Inner Solar System is fractionated relative to bulk Solar System

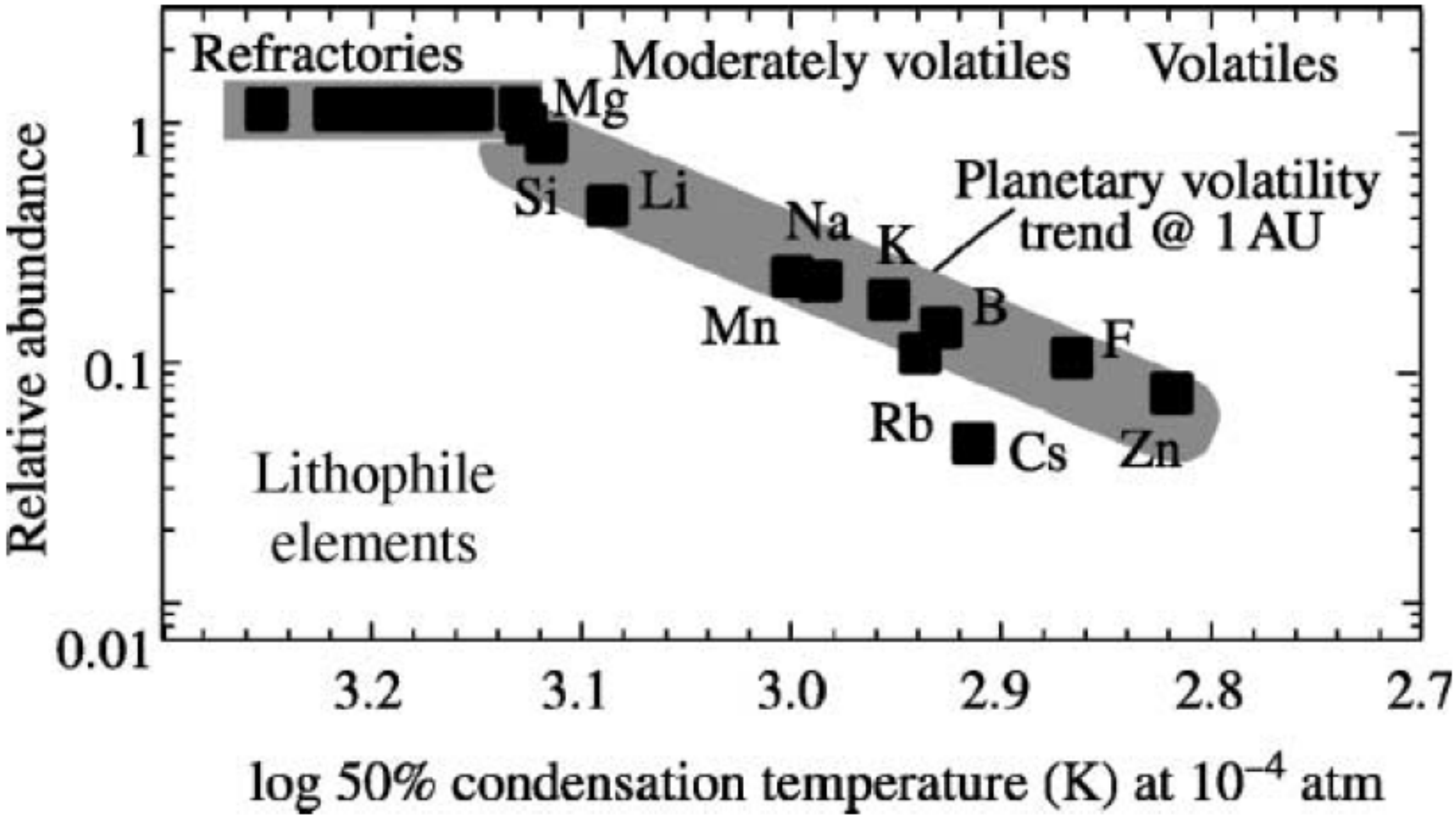
Refractory enriched

Volatiles depleted

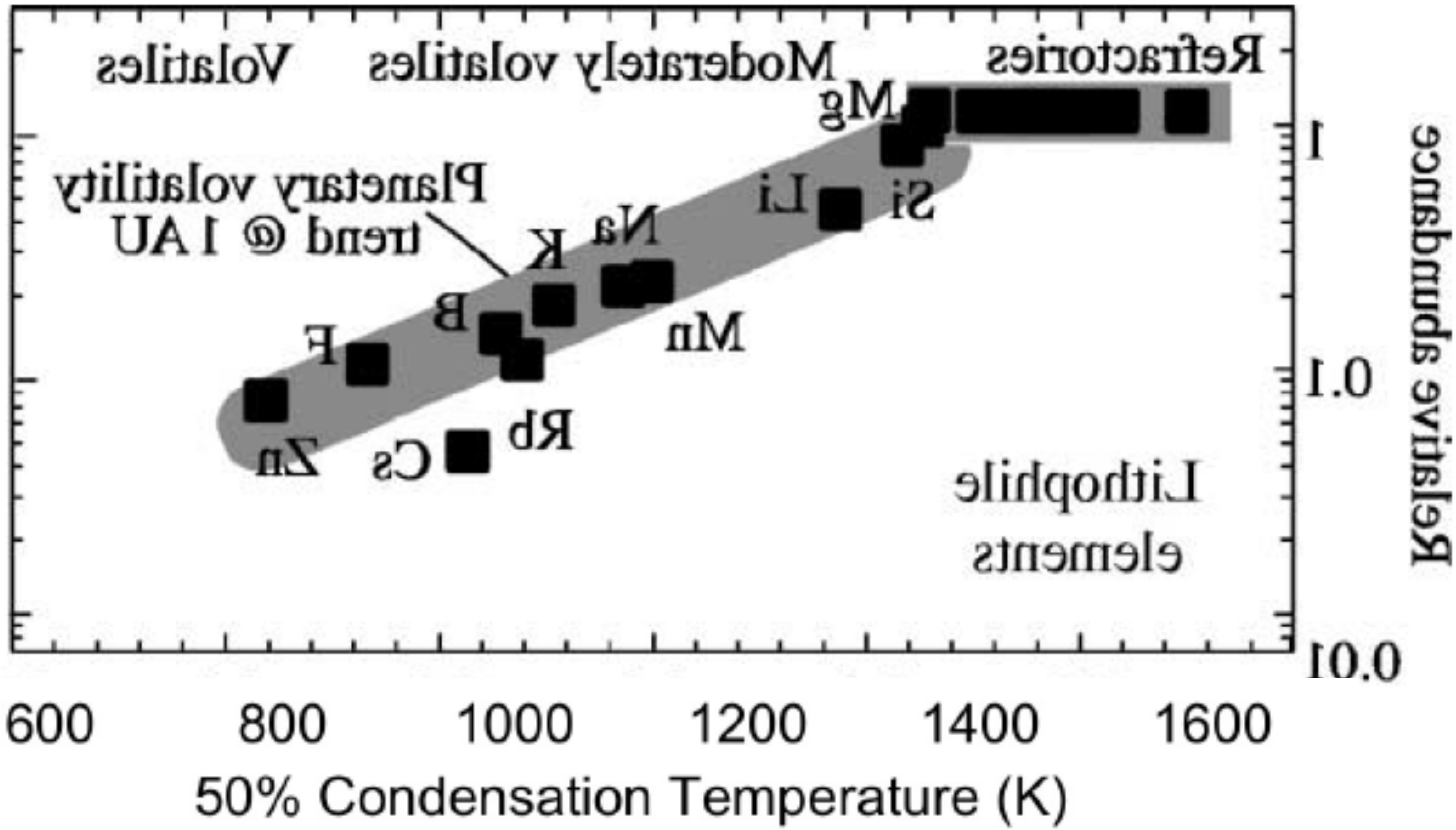


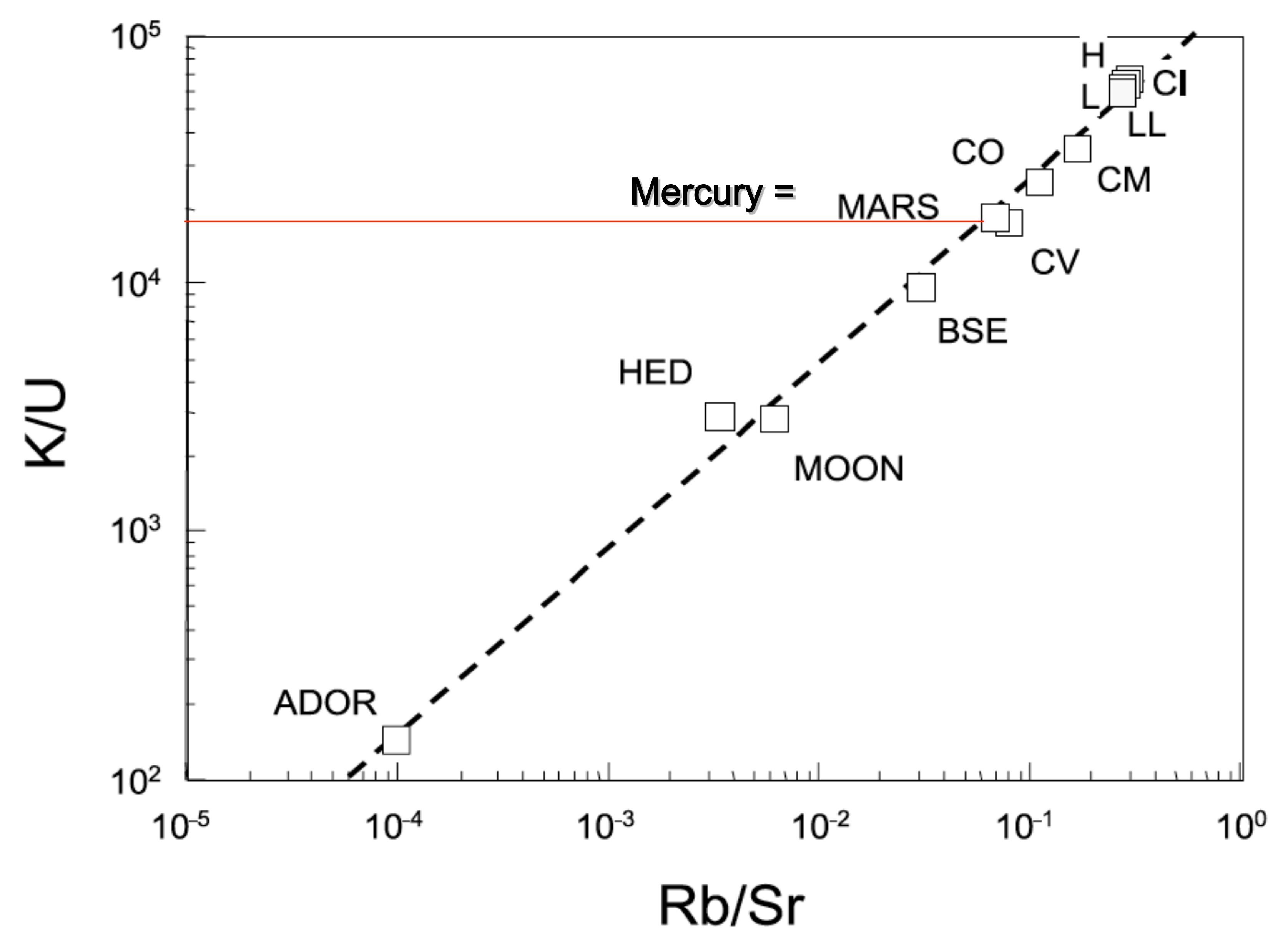
Yin (2005)

Silicate Earth (McDonough 2003)



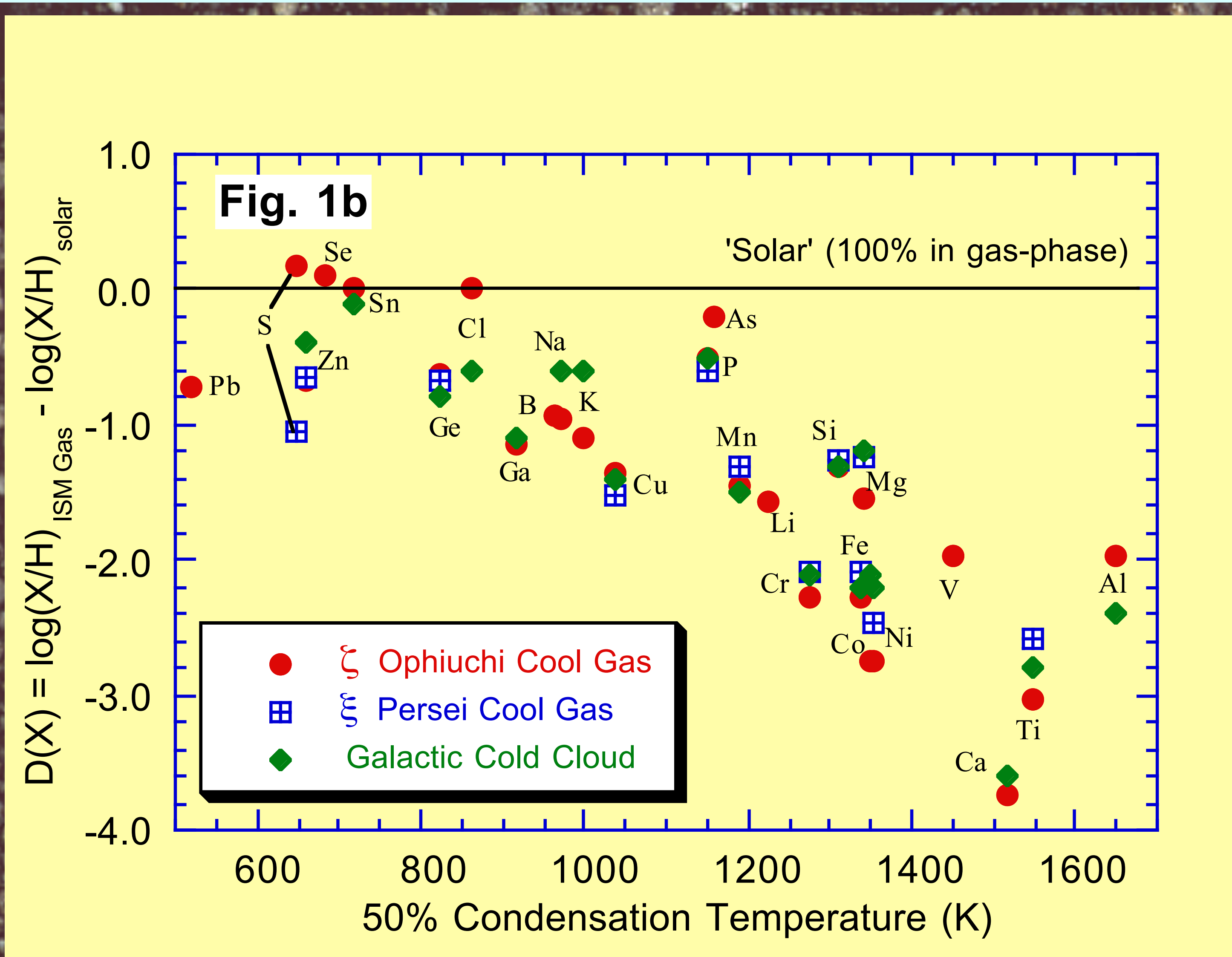
Silicate Earth (McDonough 2003)



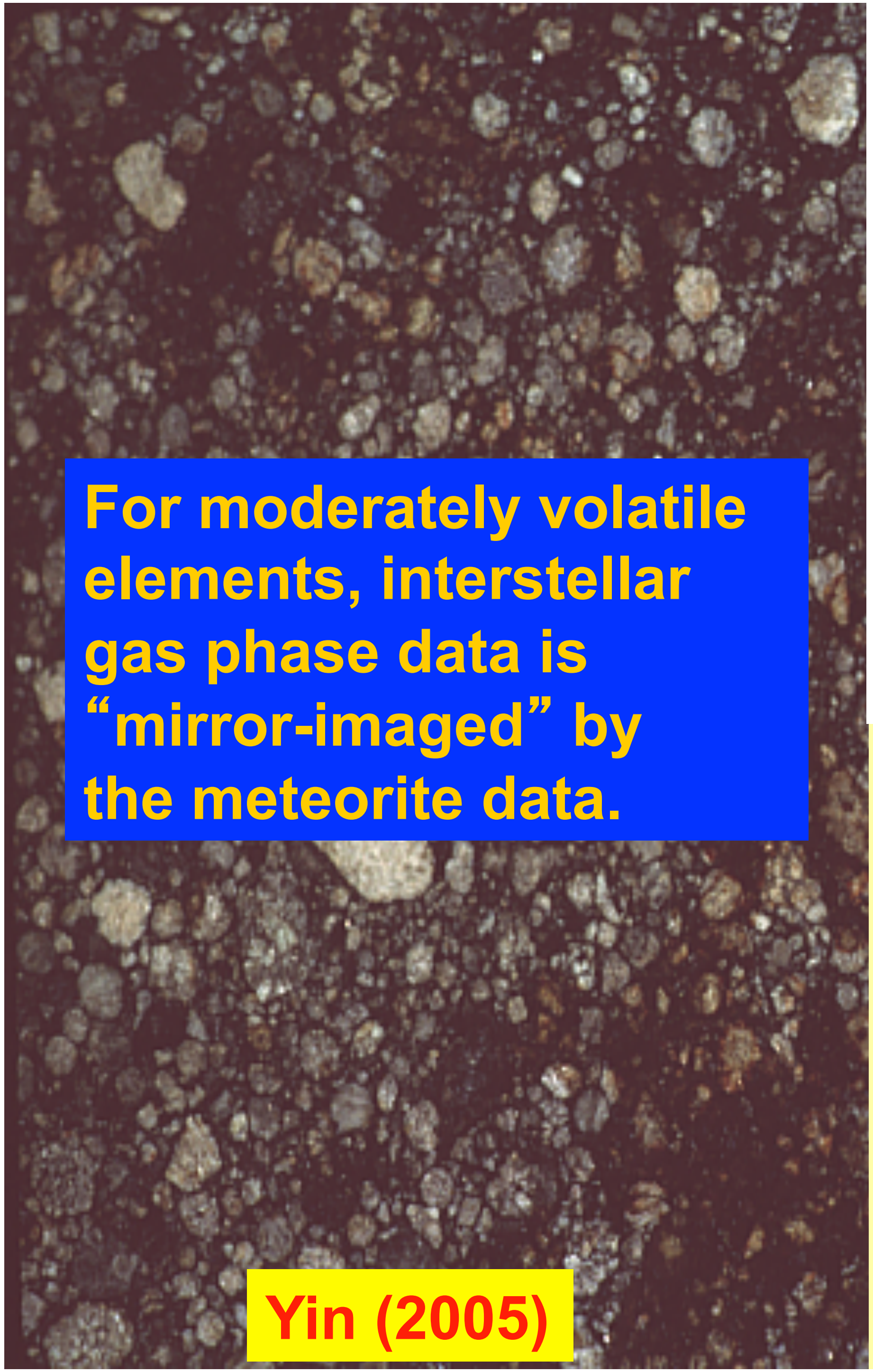


Halliday and Porcelli (2001)

ISM Gas Phase Composition

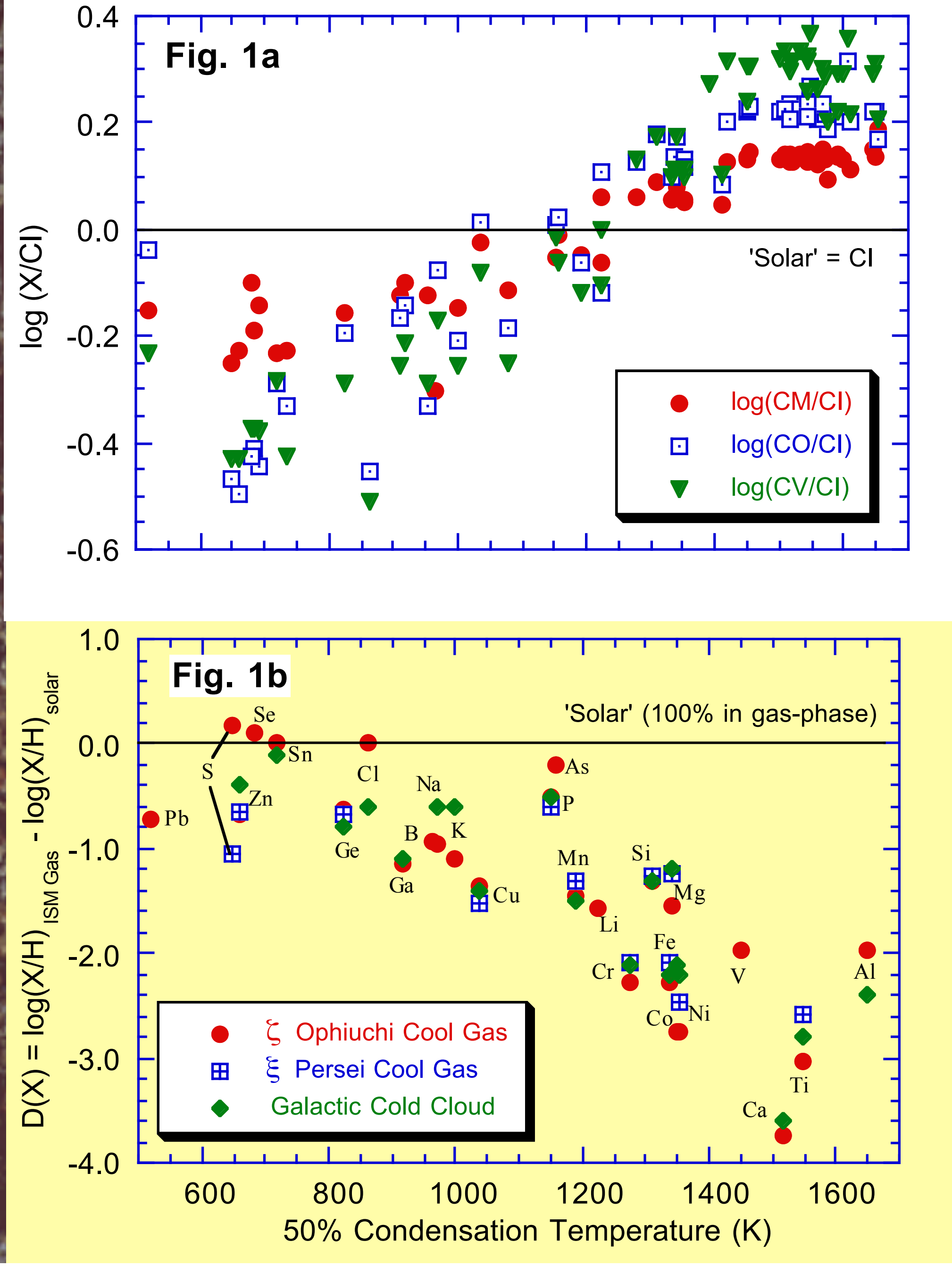


Data Source: Savage and Sembach (1996); Welty et al.(1999)

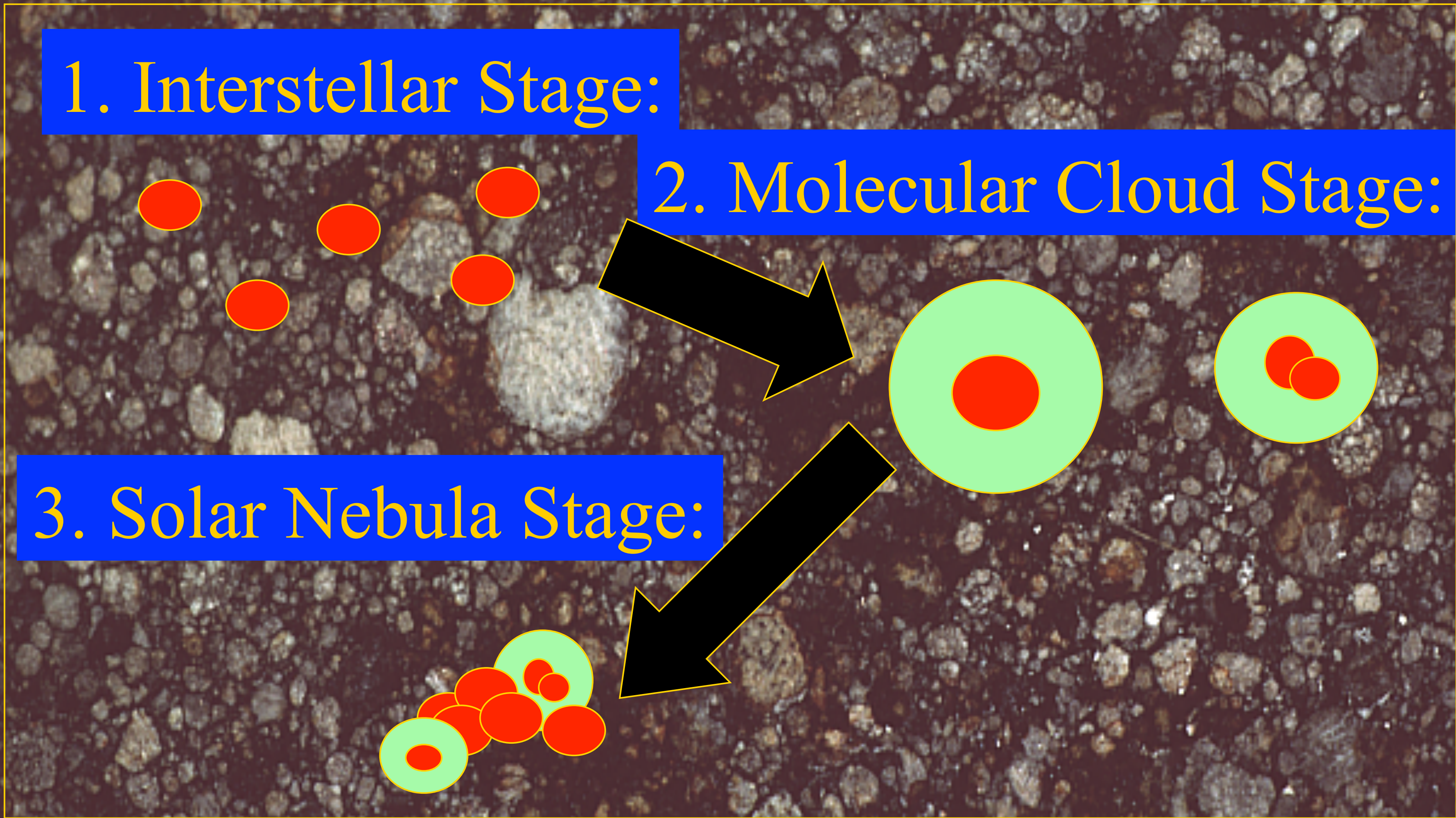


For moderately volatile elements, interstellar gas phase data is “mirror-imaged” by the meteorite data.

Yin (2005)

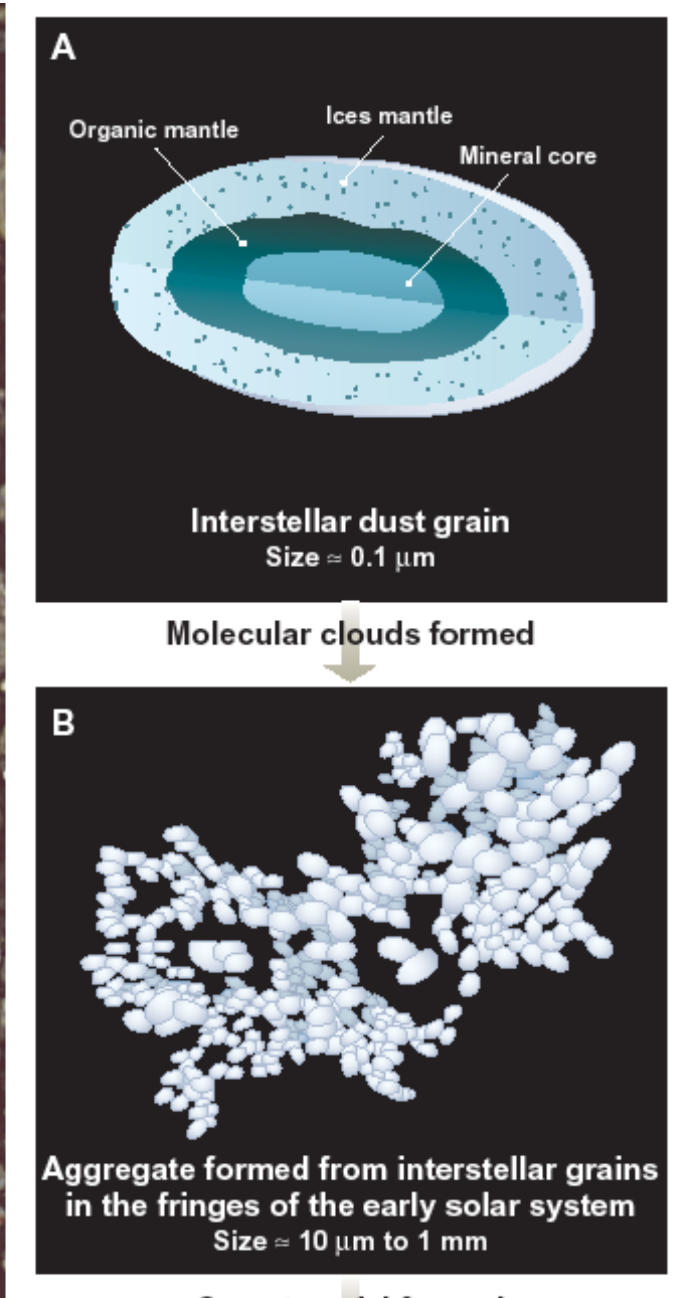


Inheritance Model



Red: Refractory Grains

Green: Ice mantle with volatiles



Levasseur-Regourd (2004)

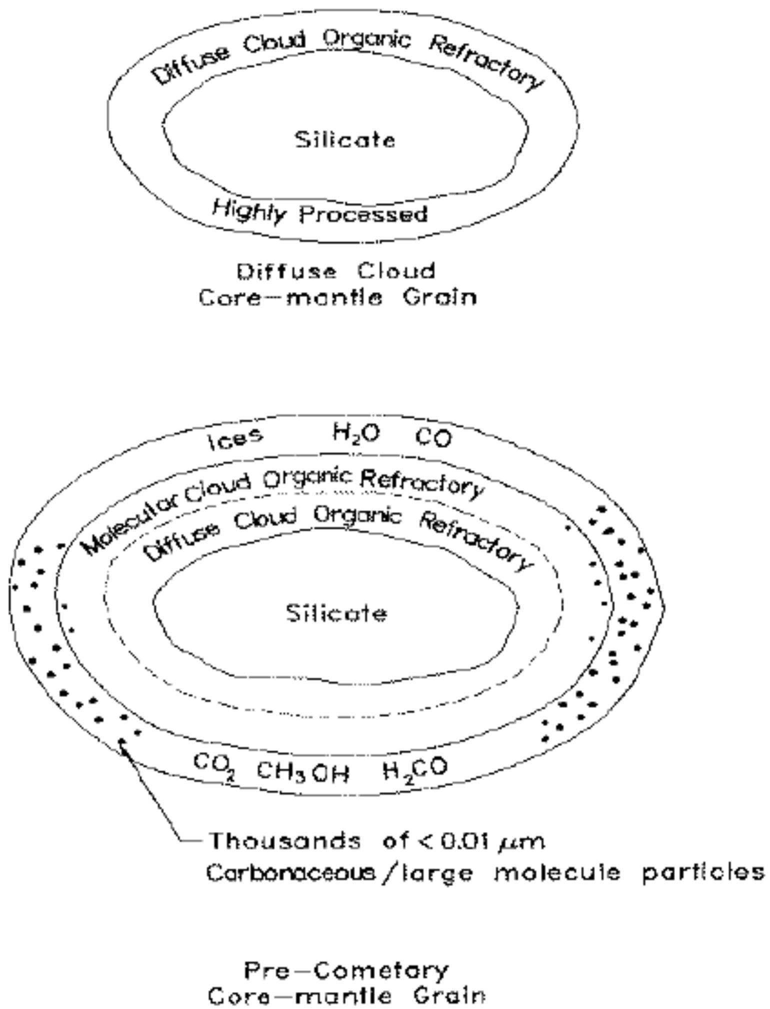
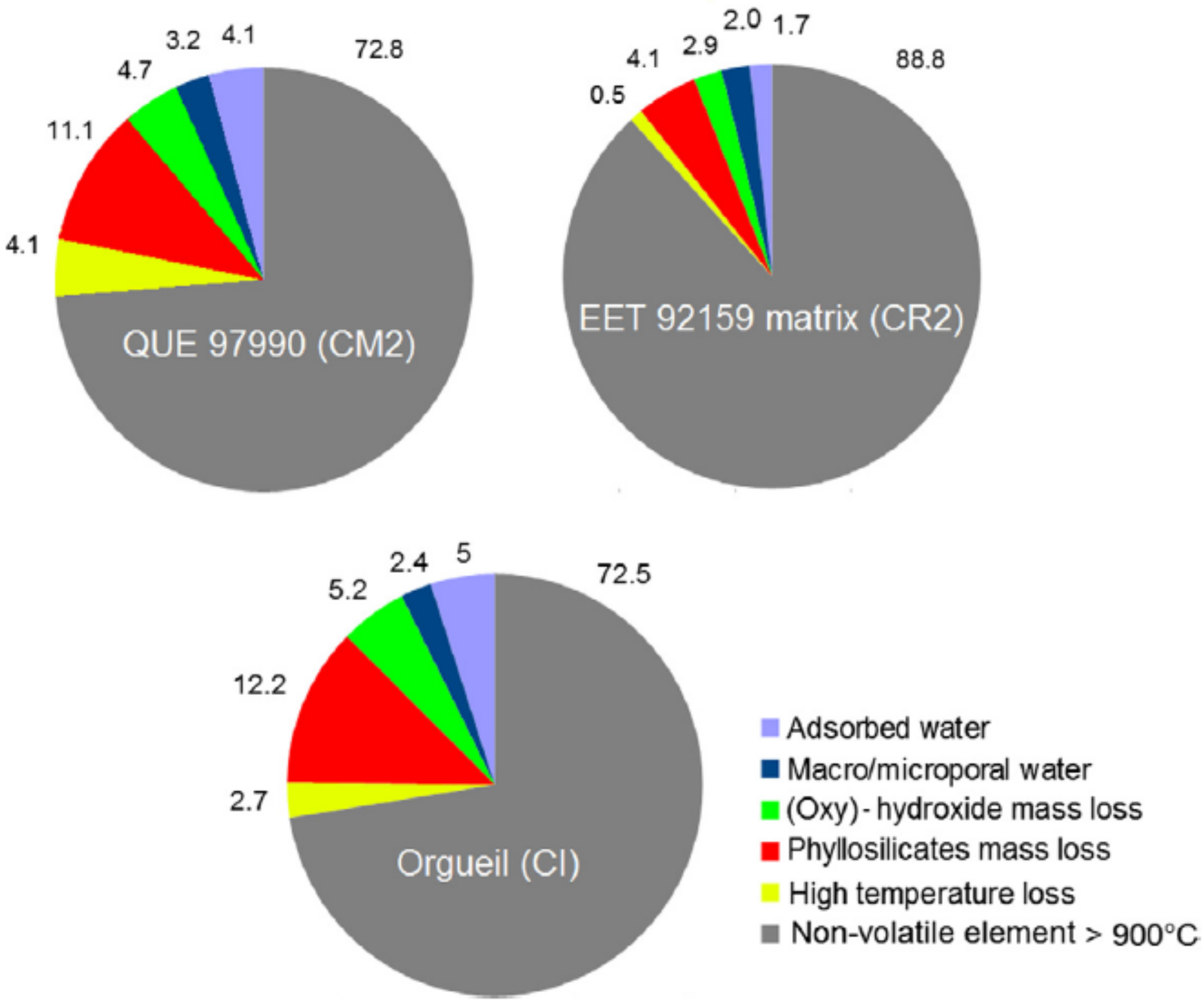


Fig. 1. A schematic description of the morphological and chemical structure of core-mantle interstellar dust grains in diffuse cloud regions and in the latest stage of the collapse of an interstellar cloud. The ices are both accreted and created along with the molecular cloud organics. The very small particle/large molecule components of the interstellar dust accrete along with the ices in the dense cloud.

J. M. Greenberg (1998)


3.2
4.1
72.8
4.7
11.1
4.1
QUE 97990 (CM2)
2.0
1.7
2.9
4.1
88.8
0.5
EET 92159 matrix (CR2)
2.4
5
72.5
5.2
12.2
2.7
Orgueil (CI)
Adsorbed water
Macro/microporal water
(Oxy)-hydroxide mass loss
Phyllosilicates mass loss
High temperature loss
Non-volatile element > 900°C

Outlines

1. Nature of planetary building blocks (chondrites)
2. Volatile depleted nature and its current budget (chemistry)
3. Earth atmosphere is leftover from erosion (isotopes)

Altwegg et al (2015)

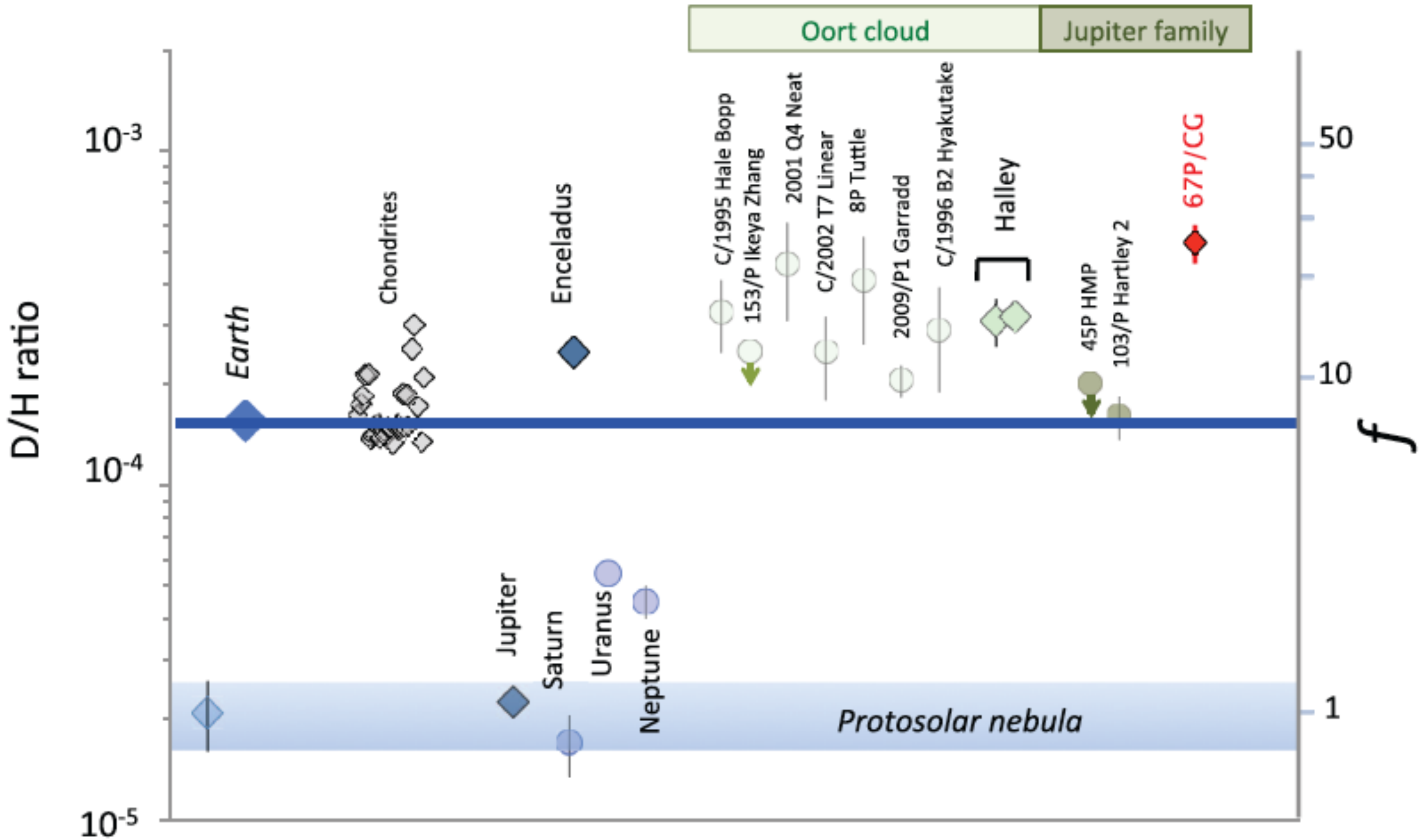
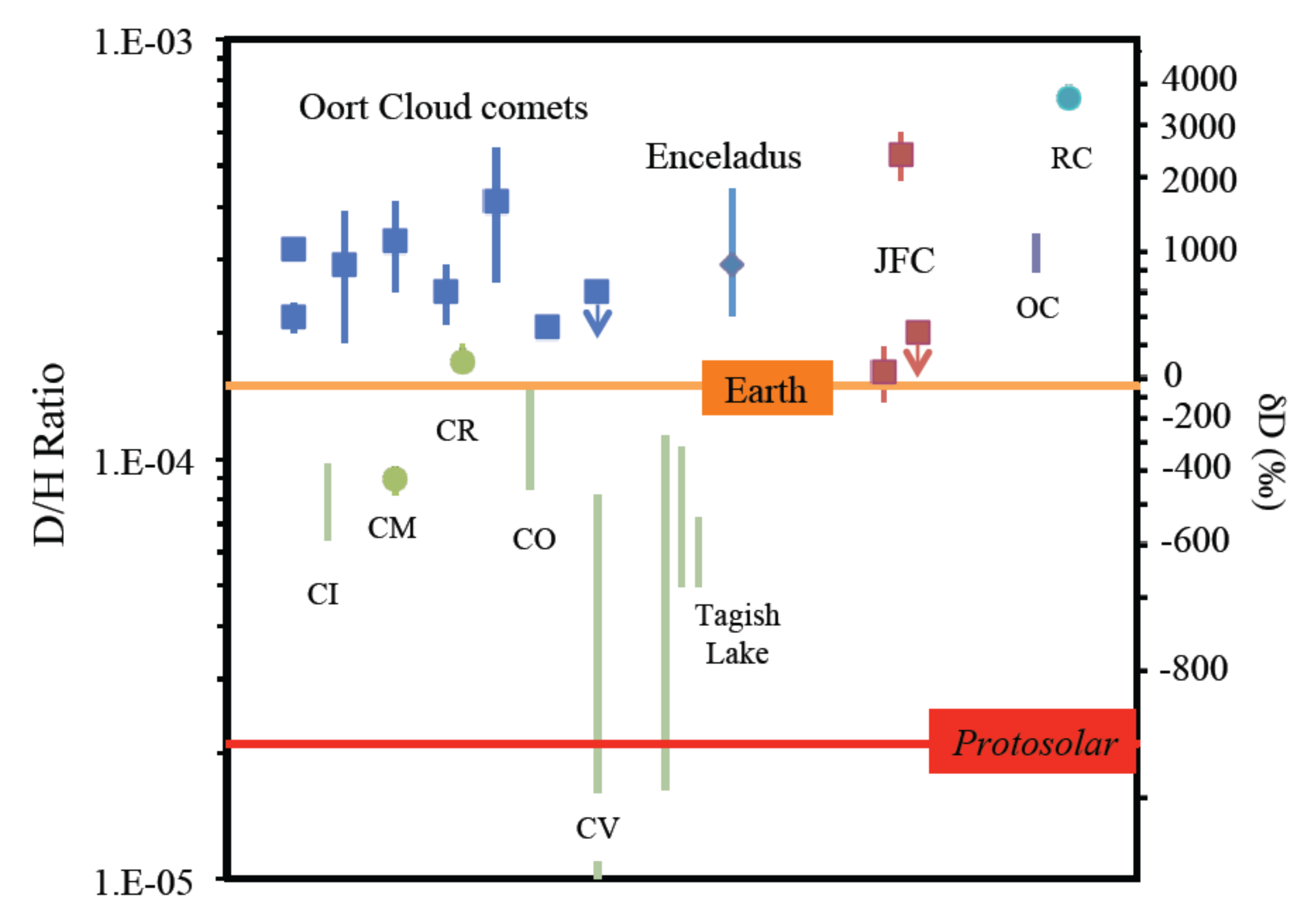


Fig. 3. D/H ratios in different objects of the solar system. Data are from (1, 2, 5–7, 26–28) and references therein. Diamonds represent data obtained by means of in situ mass spectrometry measurements, and circles refer to data obtained with astronomical methods.

Alexander et al (2012)



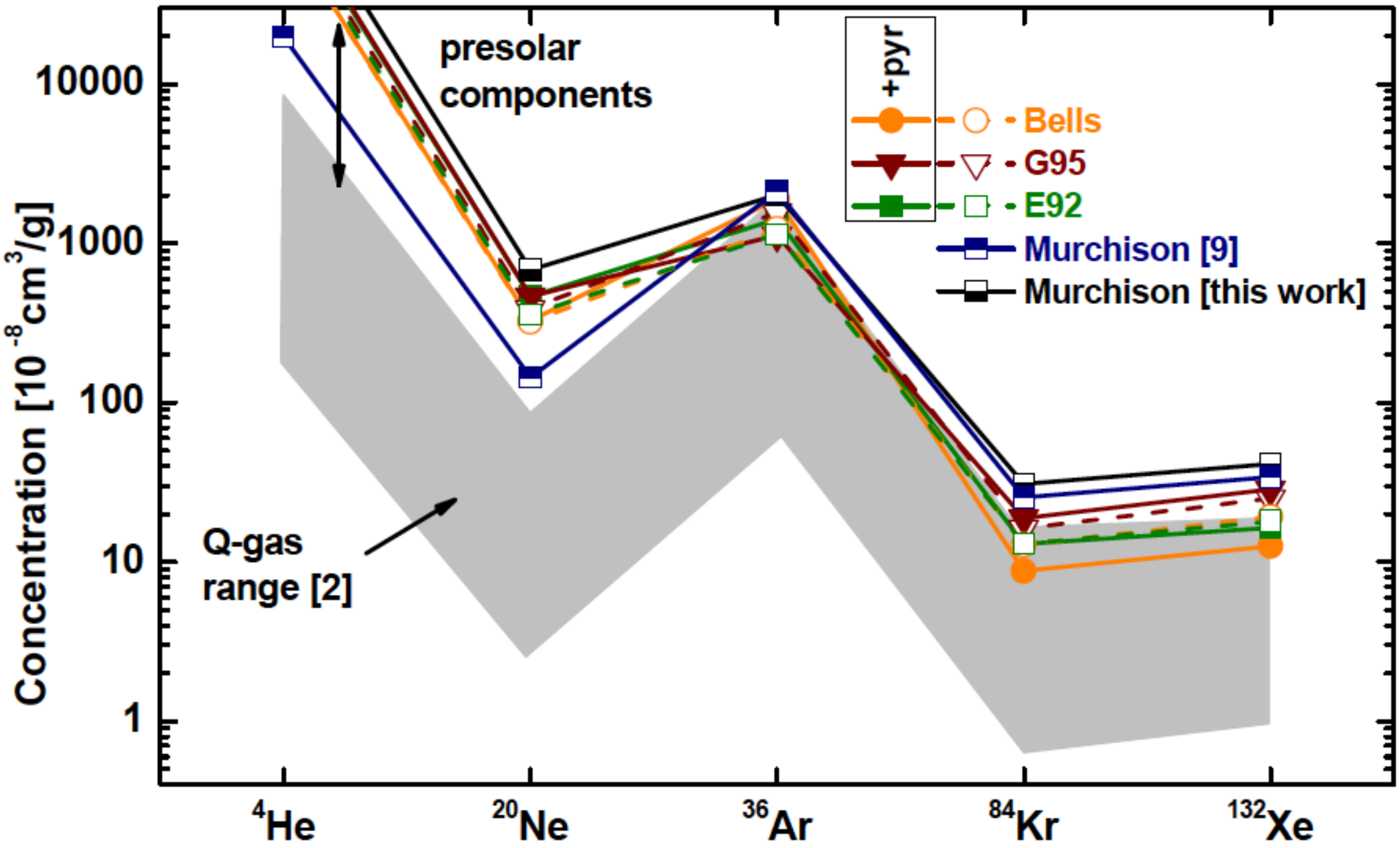


Fig. 1: Gas concentrations in E92, G95, Bells and Murchison IOM before and after pyridine treatment.

Busemann et al (2008)

I-Pu-Xe Systematics and Missing Xe

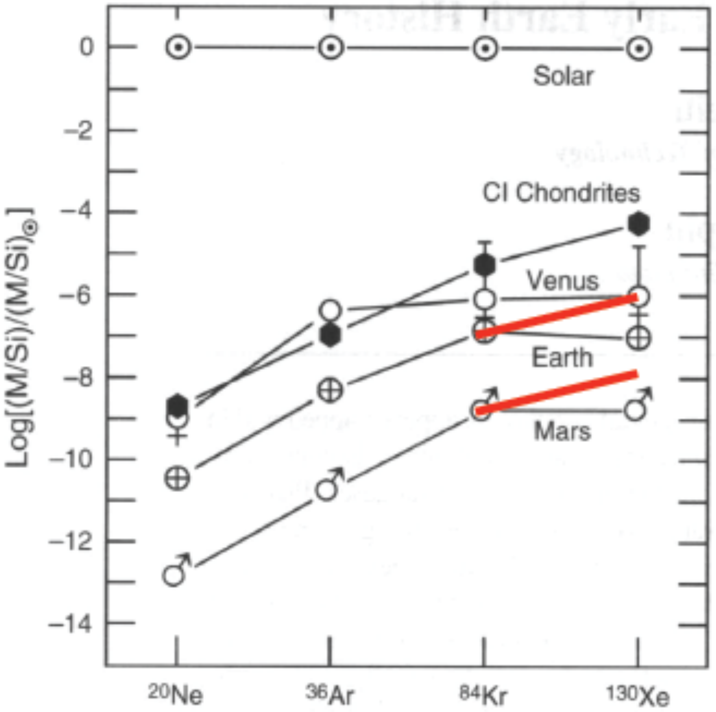
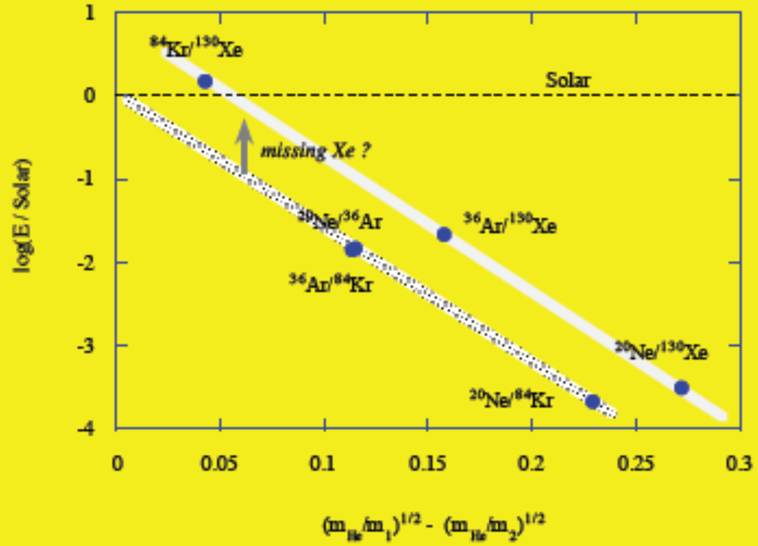
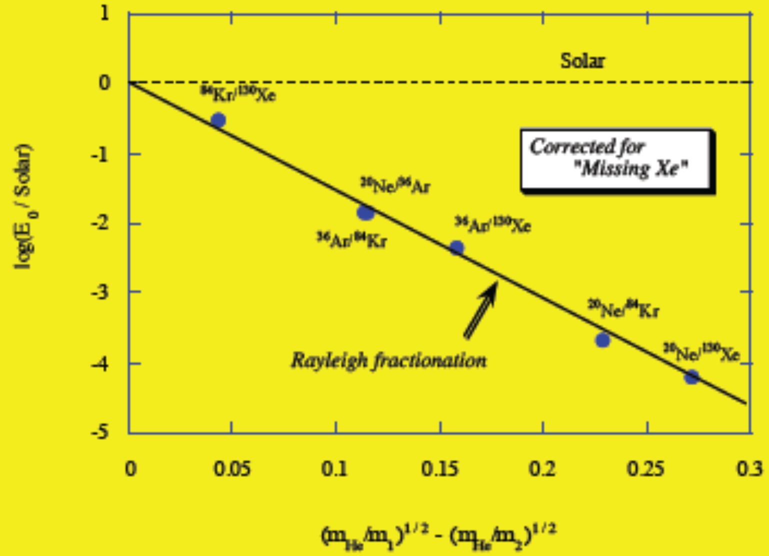


Fig. 1. Noble gas abundances in planetary atmospheres and CI chondrites, plotted as the atom concentration relative to Si divided by the corresponding solar ratio. Data are from a compilation by *Pepin* (1991). Note that ranges of Kr and Xe values are shown for Venus.

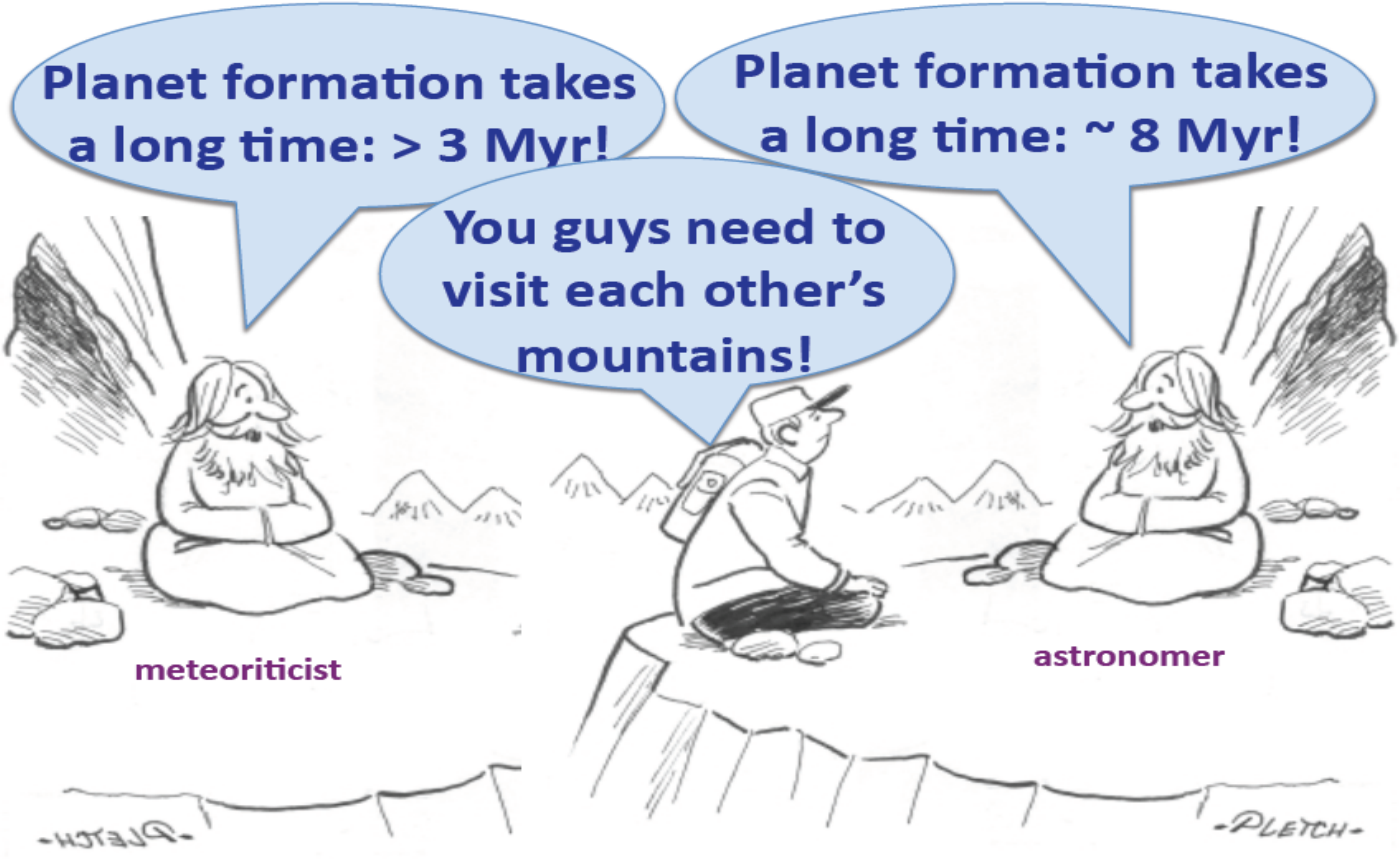




Qualitatively, missing Xe of about one log unit is discernible. ca. 90%

For mass-dependent Rayleigh distillation, all the points should fall on a straight line through the origin.
Ozima and Podosek (1999): First quantitatively derived the missing Xe amount to be 86% based on the least square fit.

Conclusions



Courtesy of S. Desch via S. Stewart