Constraints on the Solar Oxygen Abundance From Meteorites, Planets, and Other Planetary Objects

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Can solar-system objects other than the Sun be used to estimate the solar system oxygen abundance?

Meteorites

Planets

Planetary Satellites

All That is in the Planets was in the Disk,

But Not All That was in the Disk is in the Planets

Understand constitution of planets and how they formed

Chemical fractionations of the elements *in* the accretion disk
formation location in disk, chemistry depends on T, P, ρ
→ chemistry feed-back into disk structure

Chemical & physical fractionations of planet-building blocks
Thermal stabilities of solids (and liquids)
Iron oxidation/reduction reactions (metal content)

Extent of gas equilibria at low temperatures (CO/methane, N_2/ammonia)
Extent of gas-solid equilibria at low temperatures
(e.g., sulfide content, formation of magnetite, hydrated silicates)

for gas giant planets also:
H_2 & He gas accretion efficiencies

Chemical fractionations *after* dissipation of the gaseous disk
thermal metamorphism, aqueous alterations, impact processing; moon

Overall elemental composition of object depends on available condensing phases:

Major Condensed Components

Refractory “Rock”: Metal, Oxides, Silicate, Sulfides, Salts

Volatile Ices: H_2O;
CO, CH_4, CO_2, NH_3, N_2,
and/or clathrates or hydrates thereof

Problem:
Oxygen present in several phases and many compounds ranging from highly refractory to highly volatile: silicates, oxides, ices

Conditions for using planetary or meteoritic compositions as a proxy for solar system elemental abundances:

Full Condensation of a given element

- Stability of oxygen-bearing phases in the accretion disk
- No partial gas/solid fractionation in disk – need full condensation
- Thermal and density structure in the accretion disk – location

No major re-distribution/fractionation of phases in the disk

- metal/silicate (e.g., ordinary chondrites), rock/ice (snowline, water redistribution)

Full Retention on solid object

- closed system metamorphism or aqueous mineral alterations
- No volatile loss after accretion (ice evaporation)

Need representative sampling

- No large scale differentiation of object into core, silicate mantle, crust
- Water loss from meteorites after fall(?); contamination

Meteorites best samples of more or less unfractionated material from the early solar system

Ernst Chladni, 1756–1827

1794: Meteorites are extraterrestrial
"On the Origin of the Pallas Iron and Other Similar to it, and on Some Associated Natural Phenomena"

French Academy response:
"rocks don't fall from the sky"

L'Aigle meteorite fall in 1803
Academy sent Biot to investigate

CI CHONDRITES: Best choice for Solar System Proxy of refractory to volatile elements

NOT a good choice for highly volatile H, C, N, O, noble gases

- good agreement with photospheric abundances
- good agreement with nucleosynthetic constraints
- Other meteorite types: similar refractory element RATIOS, but depleted in more volatile elements
  → incomplete low T condensation

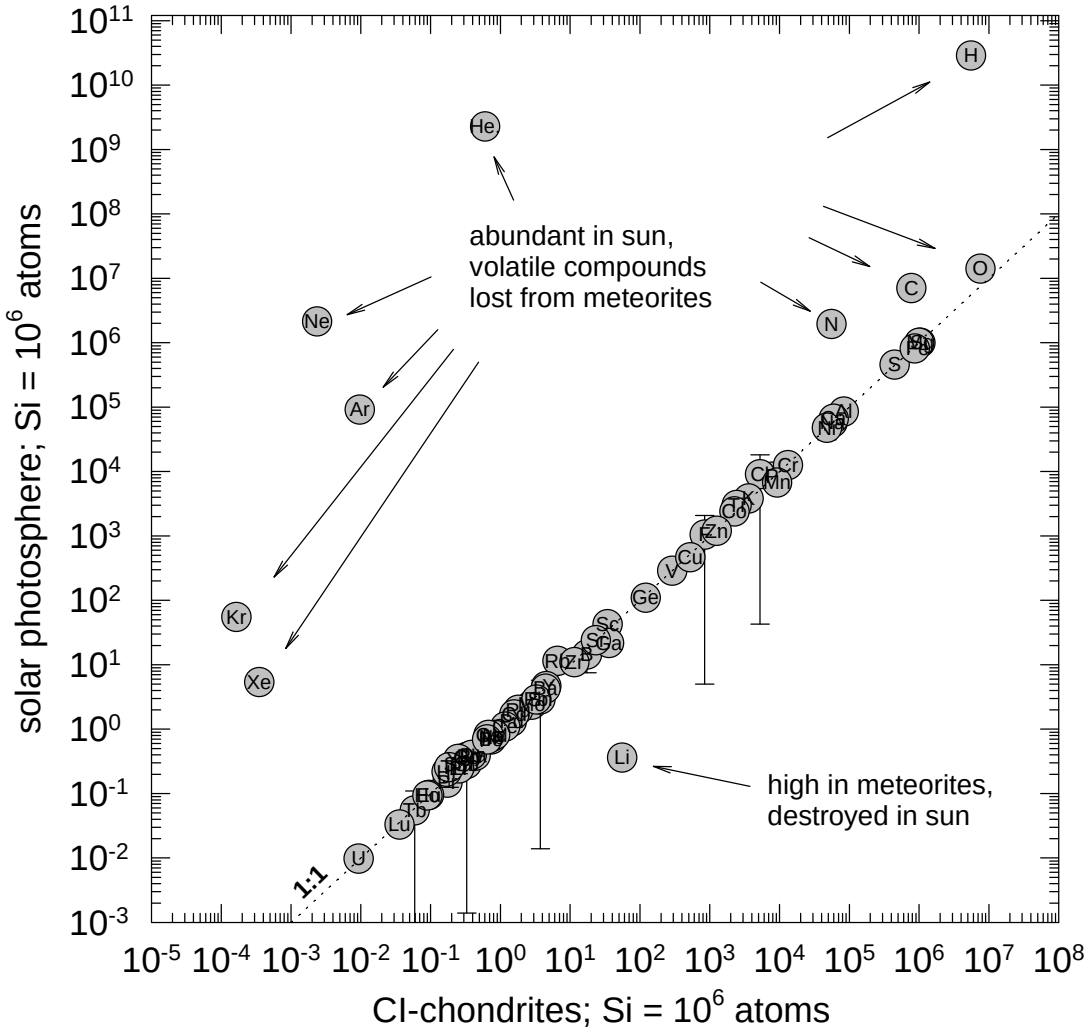
Orgueil meteorite

Observed Falls of CI-Chondrites			
Meteorite	Date of Fall	Country	**Preserved Mass**
Alais	15 March 1806	France	**6 kg**
Ivuna	16 Dec. 1938	Tanzania	**0.7 kg**
Orgueil	14 May 1868	France	**14 kg**
Revelstoke	31 March 1965	Canada	**<1 g**
Tonk	22 Jan. 1911	India	**10 g**

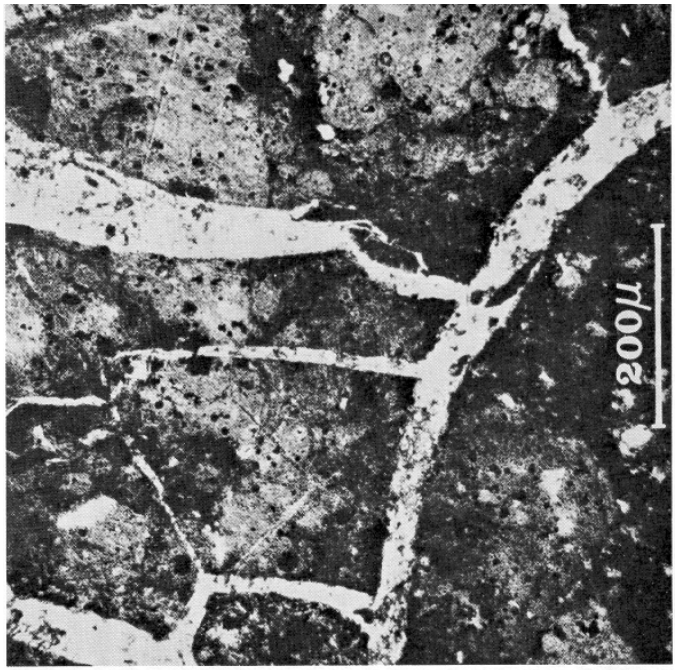
Photos: Le Muséum National d'Histoire Naturelle, Paris

CI CHONDRITES as solar system abundance proxy

- good agreement with refractory to volatile elements determined in photosphere
- NOT good for highly volatile elements H, C, N, O, noble gases
- Abundance curve good agreement w. nucleosynthetic constraints (Suess, Urey, Cameron, Anders …)



Data on CI-chondrites for Solar system abundances: Lodders 2003; Lodders, Palme & Gail 2009; Palme, Lodders & Jones 2013



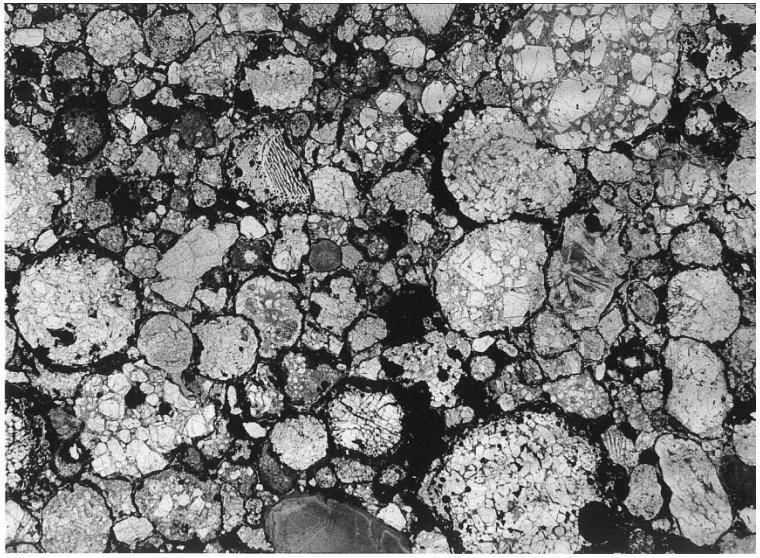
CI chondrites
- do not contain chondrules
- their minerals are aqueously altered hydrous silicates, salts
- metal and sulfide are oxidized, magnetite

Secondary mineral alterations did not change overall elemental composition. CI chondrites contain the highest amount of volatile elements when compared to other chondrites

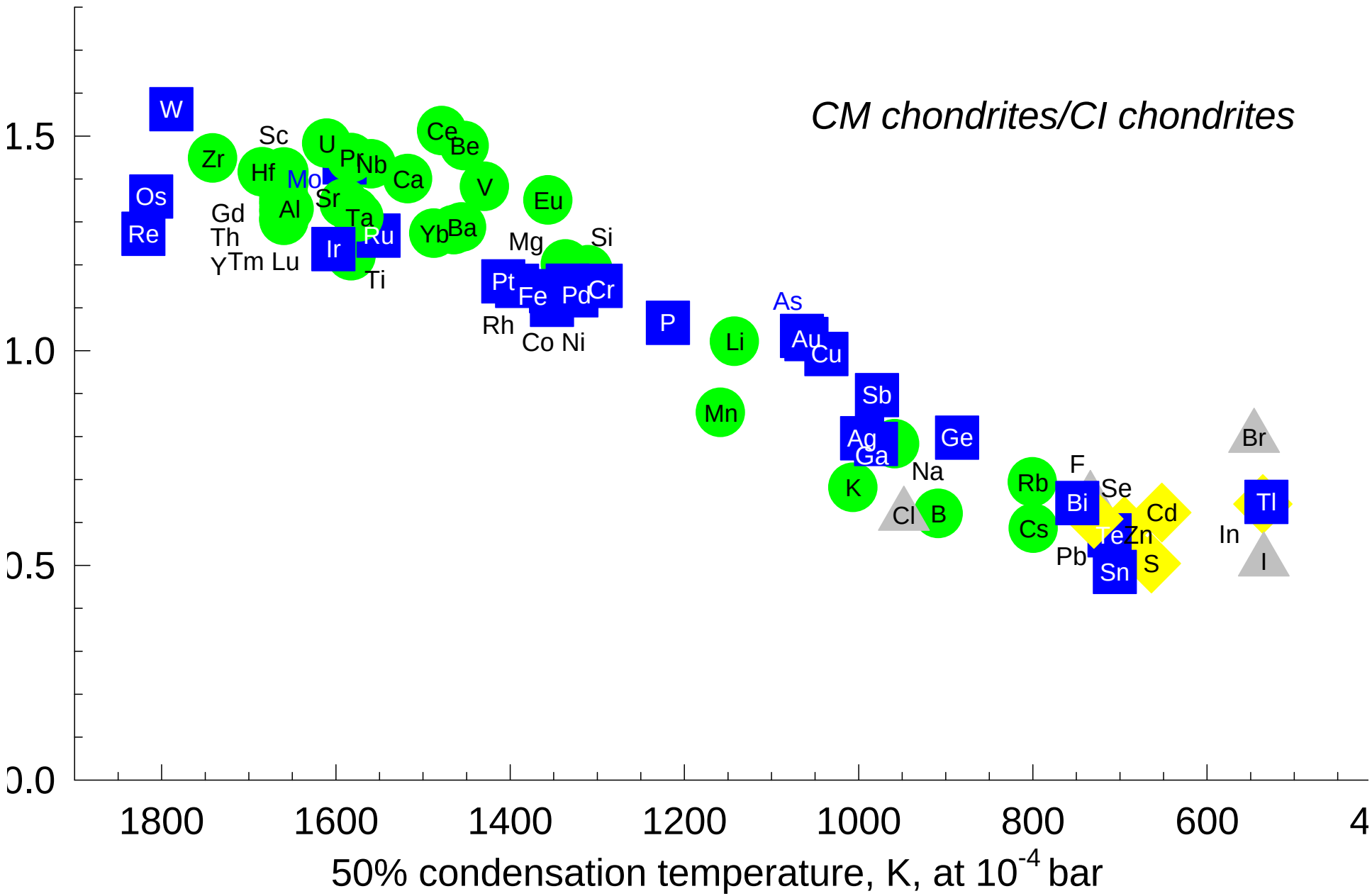
CV chondrite:

ca. 3.5 cm tall

Ordinary chondrite:



Field of view 5-6 mm wide


CM chondrites/CI chondrites
1.5
1.0
0.5
0.0
1800
1600
1400
1200
1000
800
600
4
50% condensation temperature, K, at 10-4 bar
W
Os
Re
Zr
Sc
Hf
Gd
Th
Y
Tm
Lu
Mo
Al
U
Pr
Nb
Sr
Ta
Ir
Ru
Ti
Ca
Ce
Be
V
Yb
Ba
Eu
Mg
Si
Pt
Fe
Pd
Cr
Rh
Co
Ni
P
Li
Mn
As
Au
Cu
Sb
Ag
Ga
Ge
Na
K
Cl
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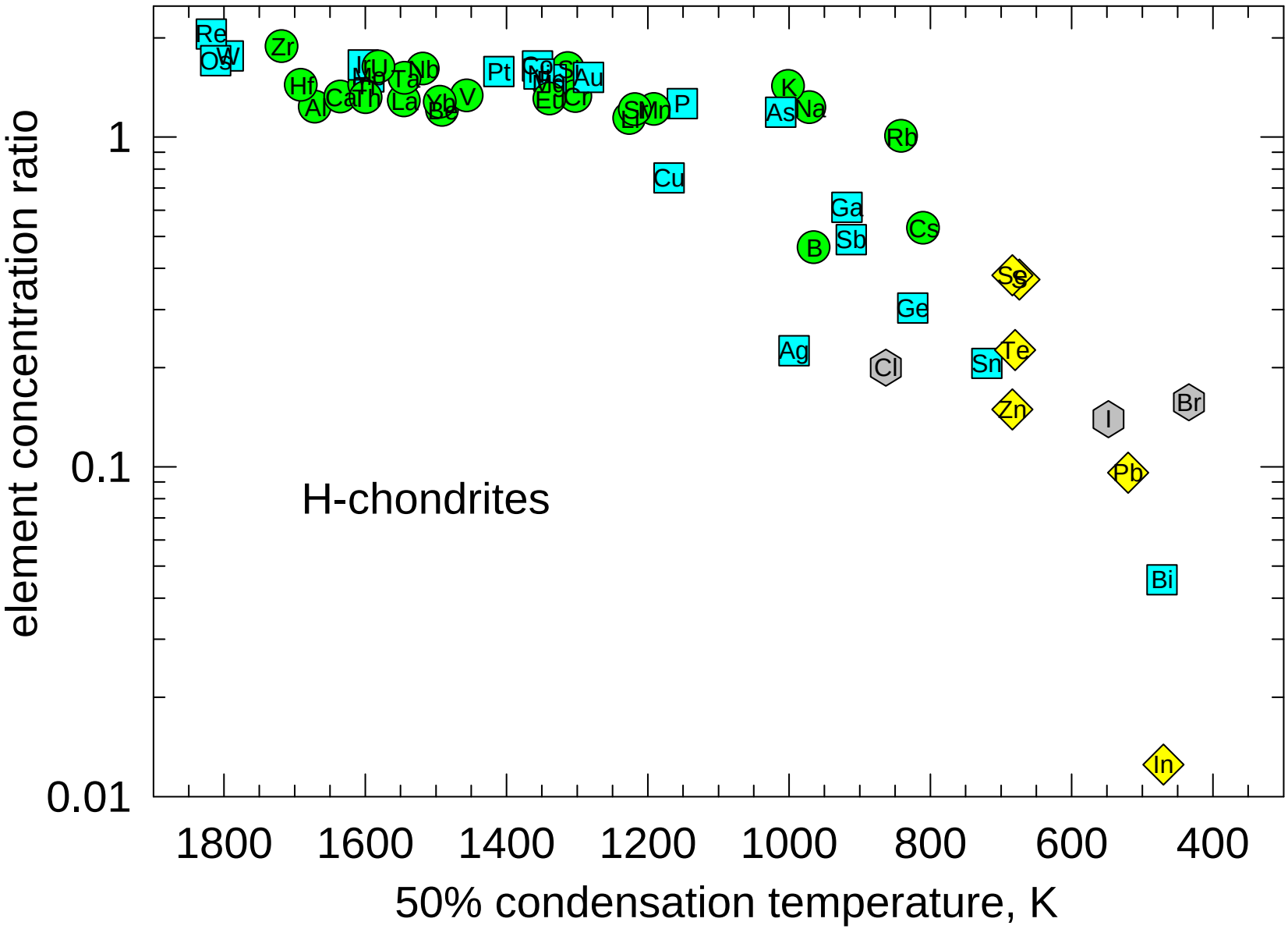
Rb
Cs
F
Bi
Se
Cd
Zn
Pb
Sn
S
Br
Tl
In
I


element concentration ratio
1
0.1
0.01
1800
1600
1400
1200
1000
800
600
400
50% condensation temperature, K
H-chondrites
Re
Os
W
Zr
Hf
Al
Ca
Th
La
Ta
Nb
Yb
Be
V
Pt
Au
Cr
Eu
Sm
Mn
P
Cu
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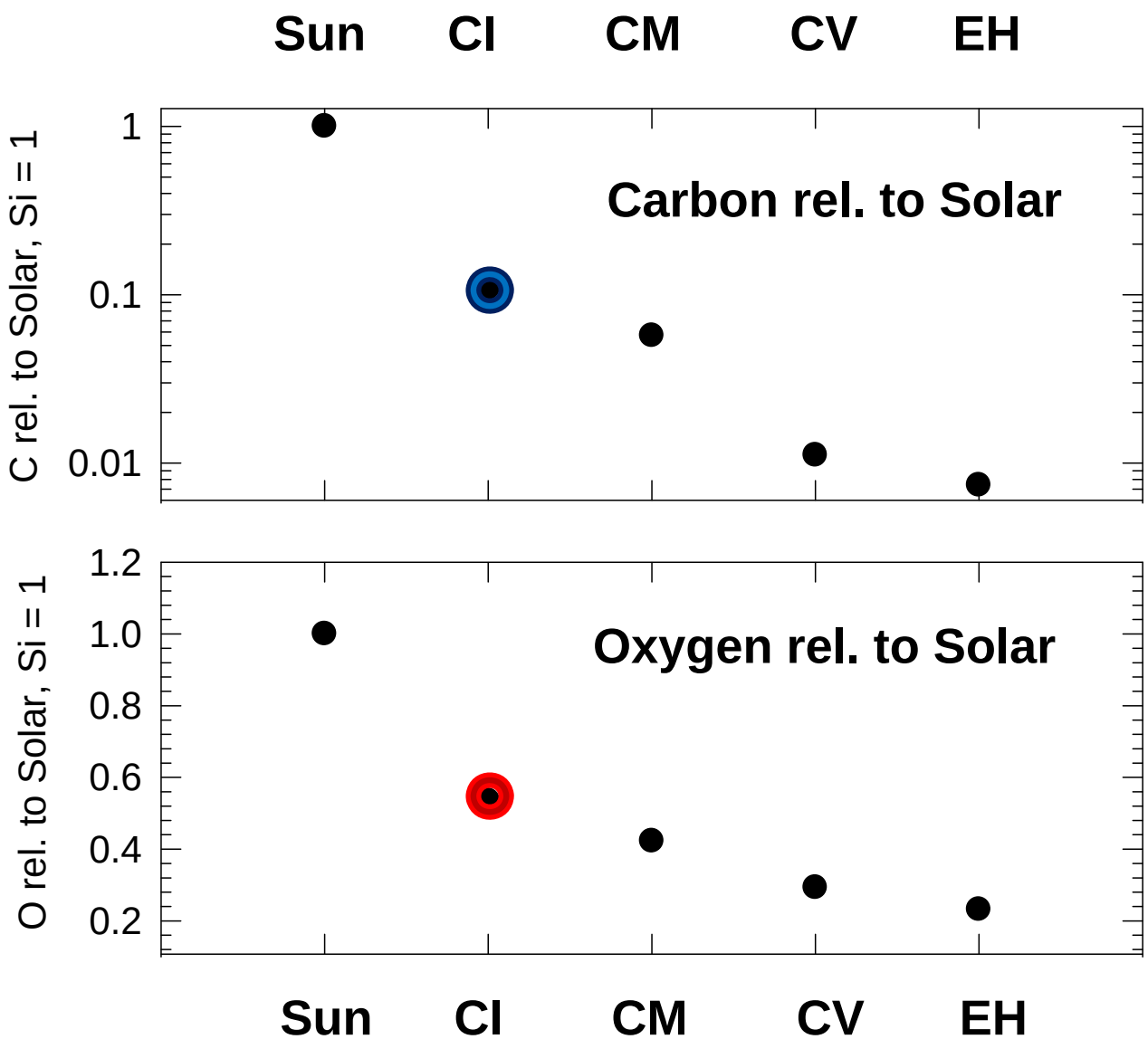


CI chondrites Contain about 10% of solar carbon ($(A(C)_{sun}$=8.50)

CI chondrites contain about half of solar oxygen, ($(A(O)_{sun}$=8.73)

Chondrites are depleted in elements forming highly volatile compounds
Shown here only some carbonaceous chondrites - more oxidized (FeO-bearing) and the highly reduced enstatite Fe rich chondrites

Solar composition system: Condensation/evaporation *sequence* is not very dependent on total pressure

Oxides,
Silicates (FeO-free)
Fe-metal alloy

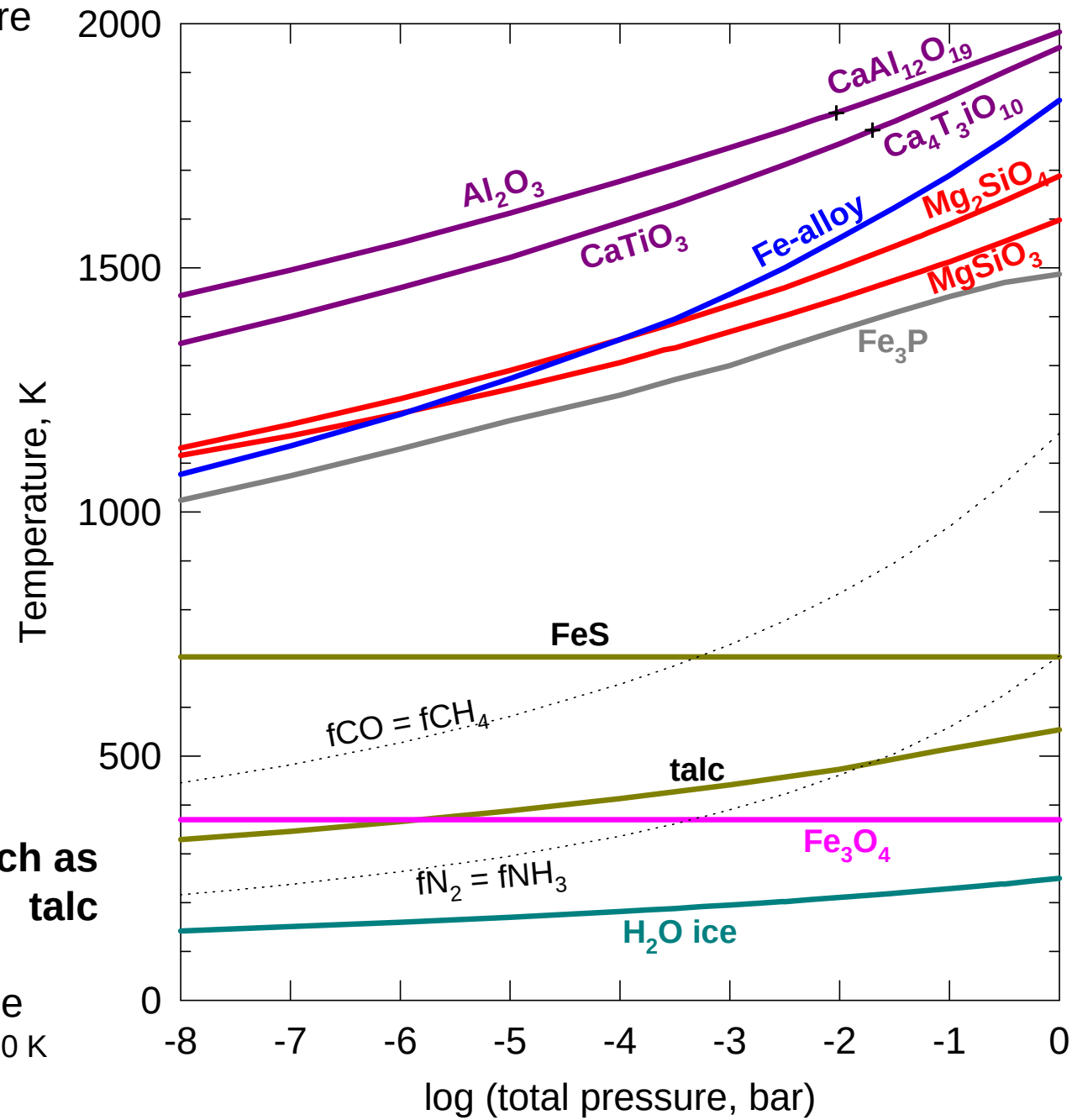
Troilite (FeS)

FeO into silicates

Magnetite

Hydrated silicates such as talc

Water Ice
~ 130 – 180 K



Rock: High-temperature Condensates, >600 K
about 0.5% of solar system mass

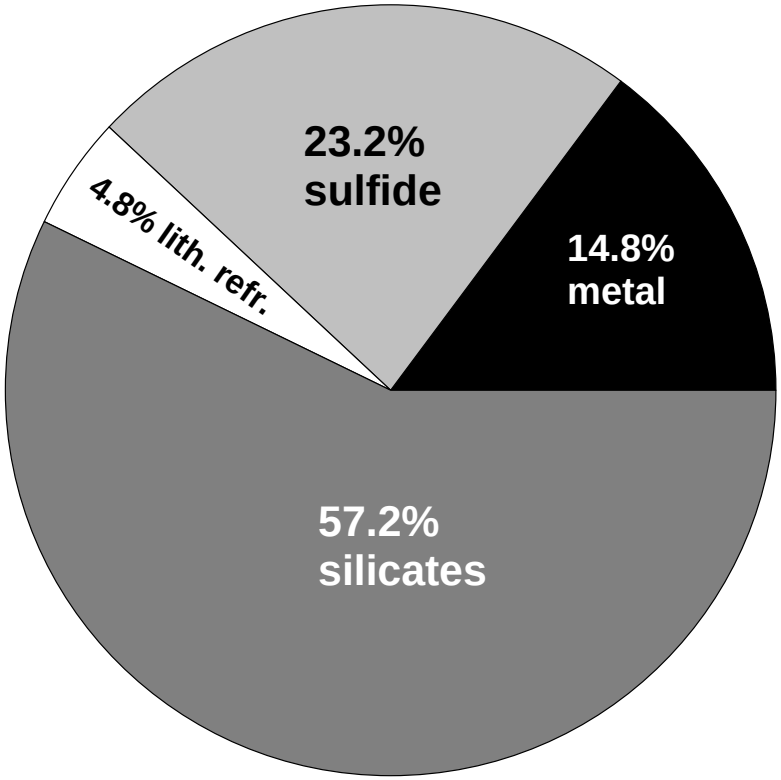
All Fe distributed between metal and sulfide, no ‘FeO’ in silicates

No magnetite Fe_3O_4, no hydrates silicates, sulfates, phosphates…

No ices

Mass Distribution

"solar condensates"



Without “FeO’ and ices, this takes 20.8% of all solar O (using log O/H = 8.73)

Incorporation of more oxygen into silicates as ‘FeO’ affects size of planetary cores

How to get ‘FeO’-bearing silicates and magnetite?

‘FeO’-bearing silicates & magnetite only stable low T=400-600 K

- slow solid-state diffusion at low temperatures (<600 K)
- inhibits equilibration of gas-solid and solid-solid reactions
- cannot form magnetite and FeO-rich silicates within estimated 1-10 Ma lifetime of the solar nebula.

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- High-temperature condensation under more oxidizing conditions
  e.g.; higher dust/gas regions, O release from dust causes higher O/H

- Oxidation reactions on the meteorite parent body
  e.g., during metamorphism (‘FeO’ into silicates)
  aqueous alteration (magnetite)

How to get ‘FeO’-bearing silicates?

$2MgSiO_3$ (enstatite) + 2Fe (metal) + 2 H_2O
= Mg_2SiO_4 (forsterite) + Fe_2SiO_4 (fayalite) + 2 H_2

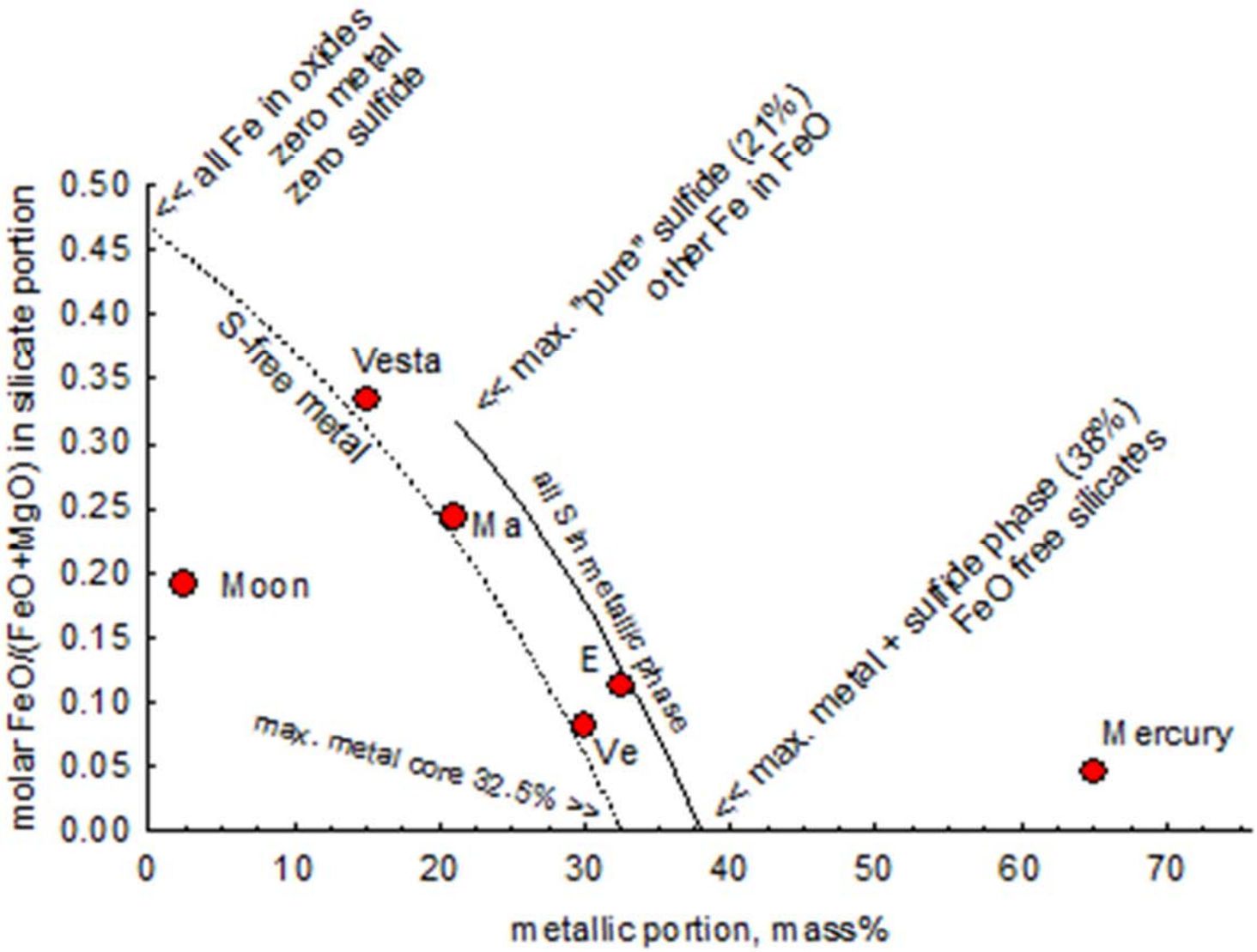
Fe_2SiO_4 (fayalite) + 2 $MgSiO_3$ (enstatite)
= Mg_2SiO_4 (forsterite) + 2 $FeSiO_3$ (ferrosilite)

3Fe (metal) + $4H_2O$ = Fe_3O_4 (magnetite) + $4H_2$

‘FeO’-bearing silicates & magnetite only stable low T=400-600 K

BUT: KINETICS, very slow under solar nebula conditions

Incorporation of oxygen into silicates affects amount of metal left; size of planetary cores

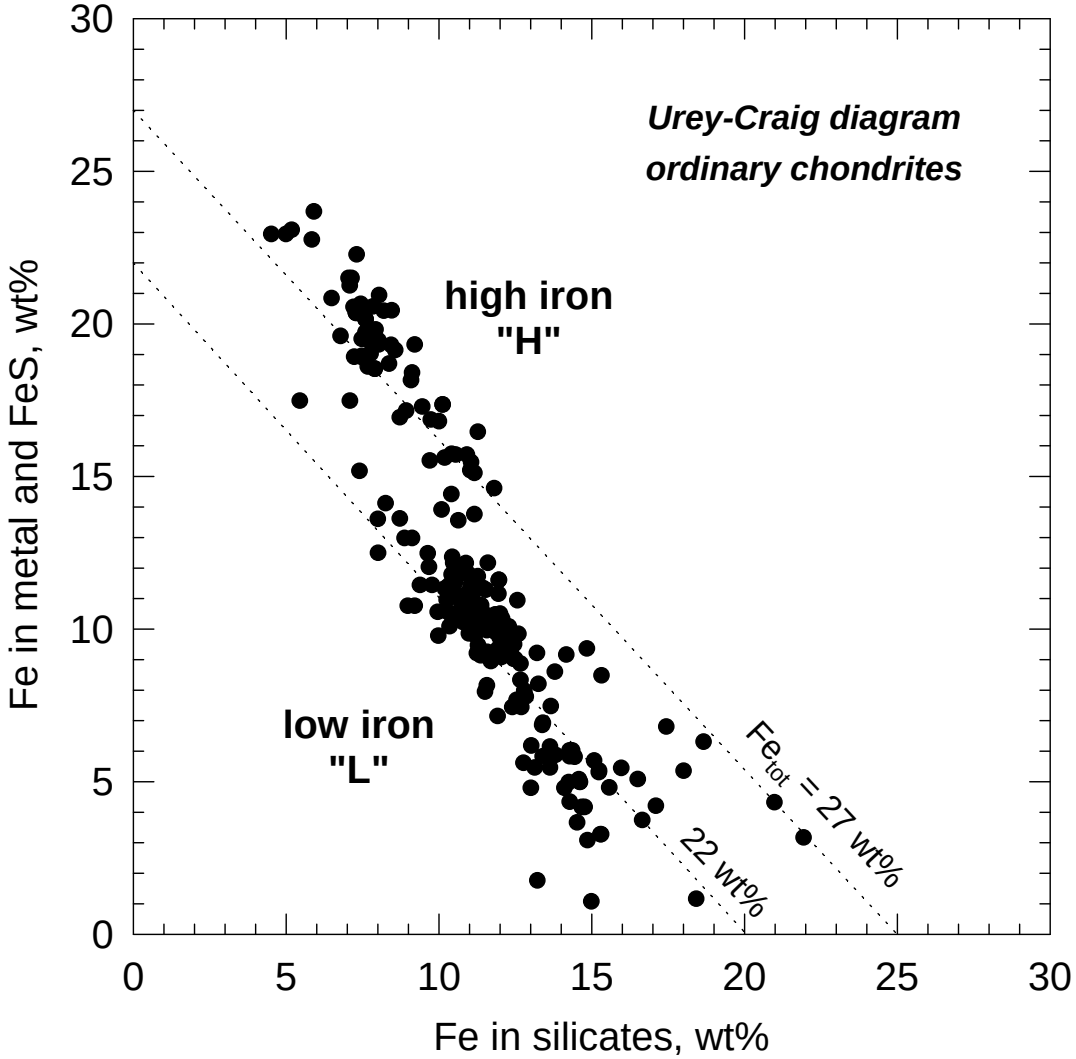


Elemental abundances limit plausible terrestrial planet compositions that can be obtained without additional metal-silicate fractionations (as needed for Mercury, Moon)

$$2MgSiO_3 \text{ (enstatite)} + 2Fe \text{ (metal)} + 2H_2O = Mg_2SiO_4 \text{ (forsterite)} + Fe_2SiO_4 \text{ (fayalite)} + 2\,H_2$$

Olivine-pyroxene exchange:

$$Fe_2SiO_4 \text{ (fayalite)} + 2\,MgSiO_3 \text{ (enstatite)} = Mg_2SiO_4 \text{ (forsterite)} + 2\,FeSiO_3 \text{ (ferrosilite)}$$



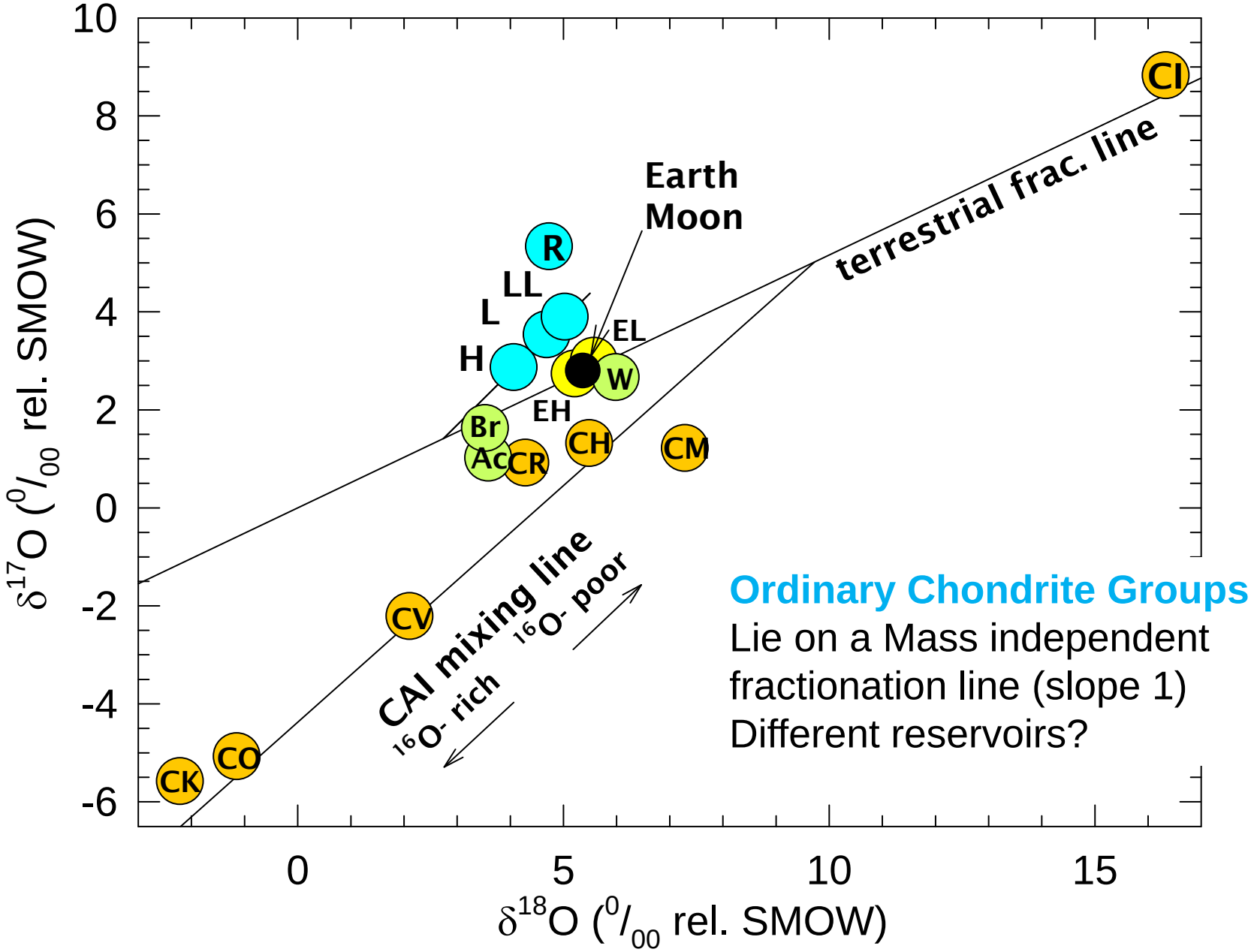
Ordinary Chondrites:

Metal and “FeO” contents roughly follow “mixing line” along constant total Fe content.
Indicates oxidation of metal.

‘FeO’ content not same for groups

One group of chondrites was <u>not</u> derived from the other by adding/losing losing total Fe!

Oxygen Isotopes!



Ordinary Chondrite Groups

Lie on a Mass independent fractionation line (slope 1)

Different reservoirs?

Hydrated silicates such as serpentine and talc are stable below 300 K at 10^{-4} bar in solar nebula

$$2Mg_2SiO_4 \text{ (forsterite)} + 3H_2O \text{ (gas)} = Mg_3Si_2O_5(OH)_4 \text{ (serpentine)} + Mg(OH)_2 \text{ (brucite)}$$

$$4MgSiO_3 \text{ (enstatite)} + 2H_2O \text{ (gas)} = Mg_3Si_4O_{10}(OH)_2 \text{ (talc)} + Mg(OH)_2 \text{ (brucite)}$$

Problem: vapor phase hydration of rock in a near vacuum is very slow

More likely process on meteorite parent bodies

Requires accretion of water – how much water is there?

$$CO\ (gas) + 3H_2\ (gas) = CH_4\ (gas) + H_2O\ (gas).$$

High T, low P favors CO

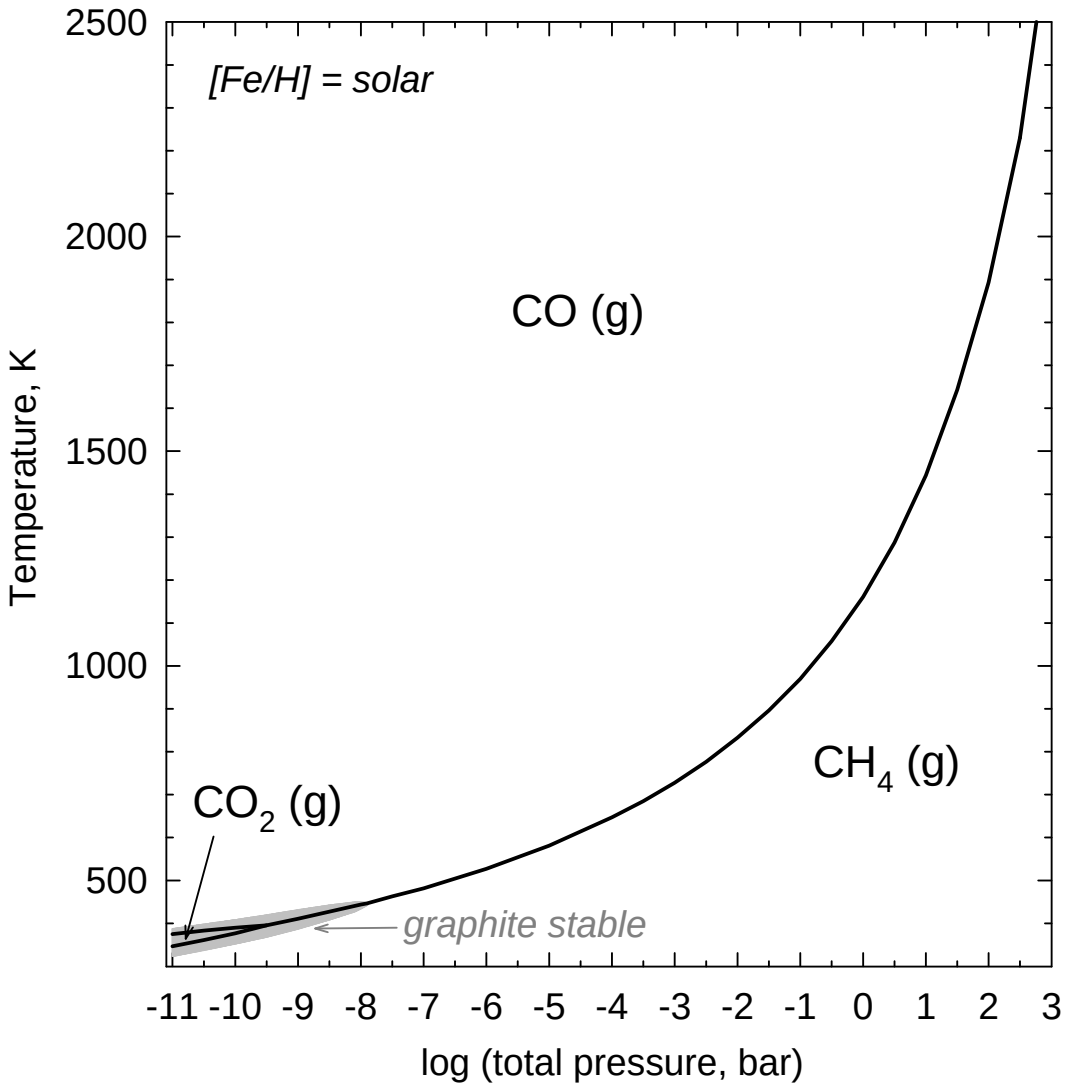
Low T, high P favors CH_4

In solar nebula, equal CO and methane abundances around 600 K, if the CO to methane conversion were fast enough

CO remains the dominant C-bearing gas below ~1470 k

CO to methane conversion important for amount of water ice

$$CO\ (gas) + 3H_2\ (gas) = CH_4\ (gas) + H_2O\ (gas).$$



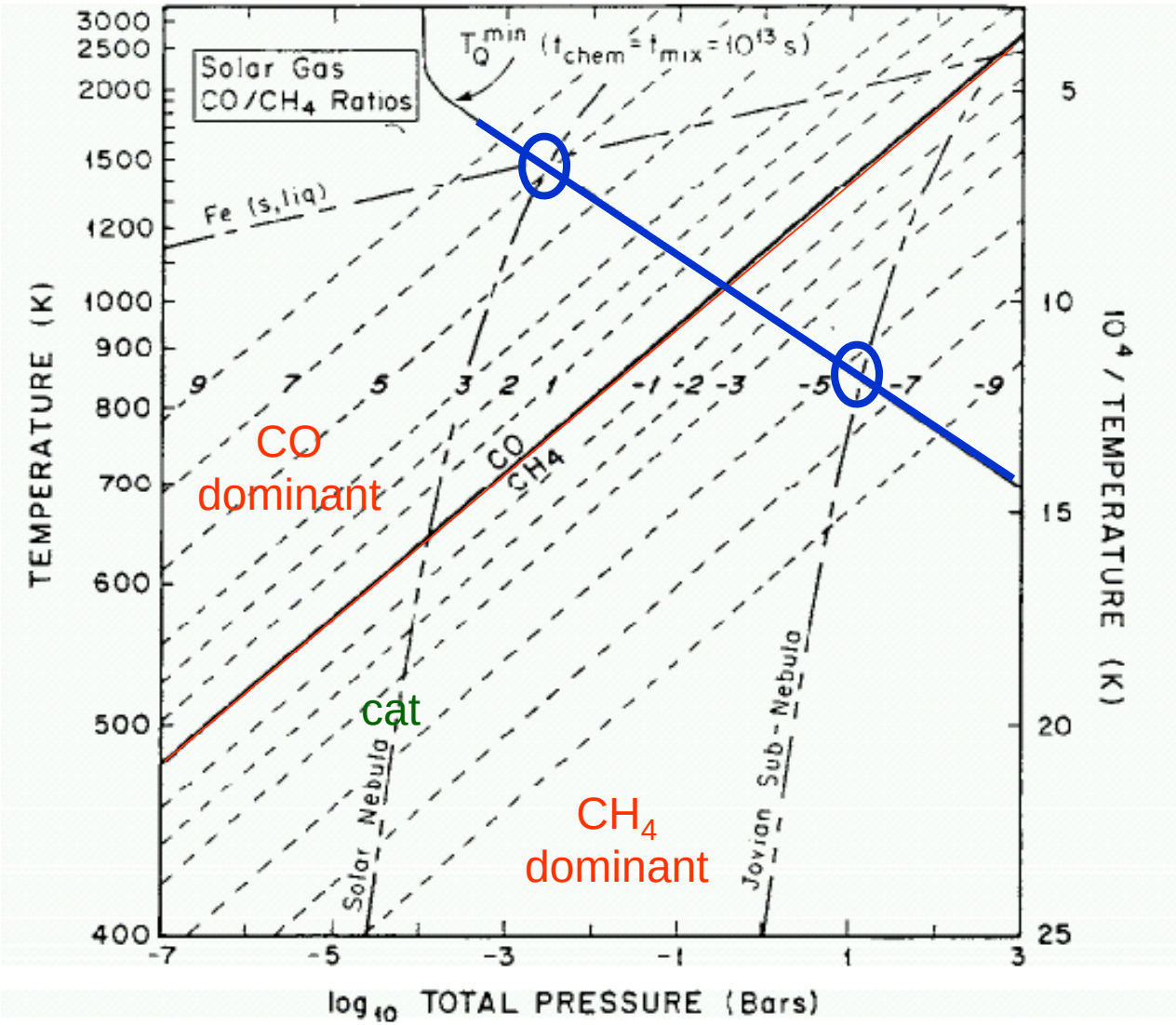
At very low pressures, CO and CH_4 decompose

$$CO + CH_4 = H_2O + H_2 + 2C\ (graphite).$$

At very low T and low P CO disproportionates to CO_2

$$2\ CO = CO_2 + C(gr)$$

$CO + 3\,H_2 = CH_4 + H_2O$



CO to CH_4 conversion kinetically inhibited at low T and low P

CO abundances become “frozen in”

below ~ 1470 K in solar nebula CO remains the major C gas

below ~840 K in Jovian sub-nebula
CH_4 is the major C gas

Contours: log CO/CH_4 ratios

Minimum quench temperatures
assuming maximum mixing times
(1x gas turn-over over nebular life time)

From Prinn & Fegley 1989

$$CO\ (gas) + 3H_2\ (gas) = CH_4\ (gas) + H_2O\ (gas).$$

High T, low P favors CO

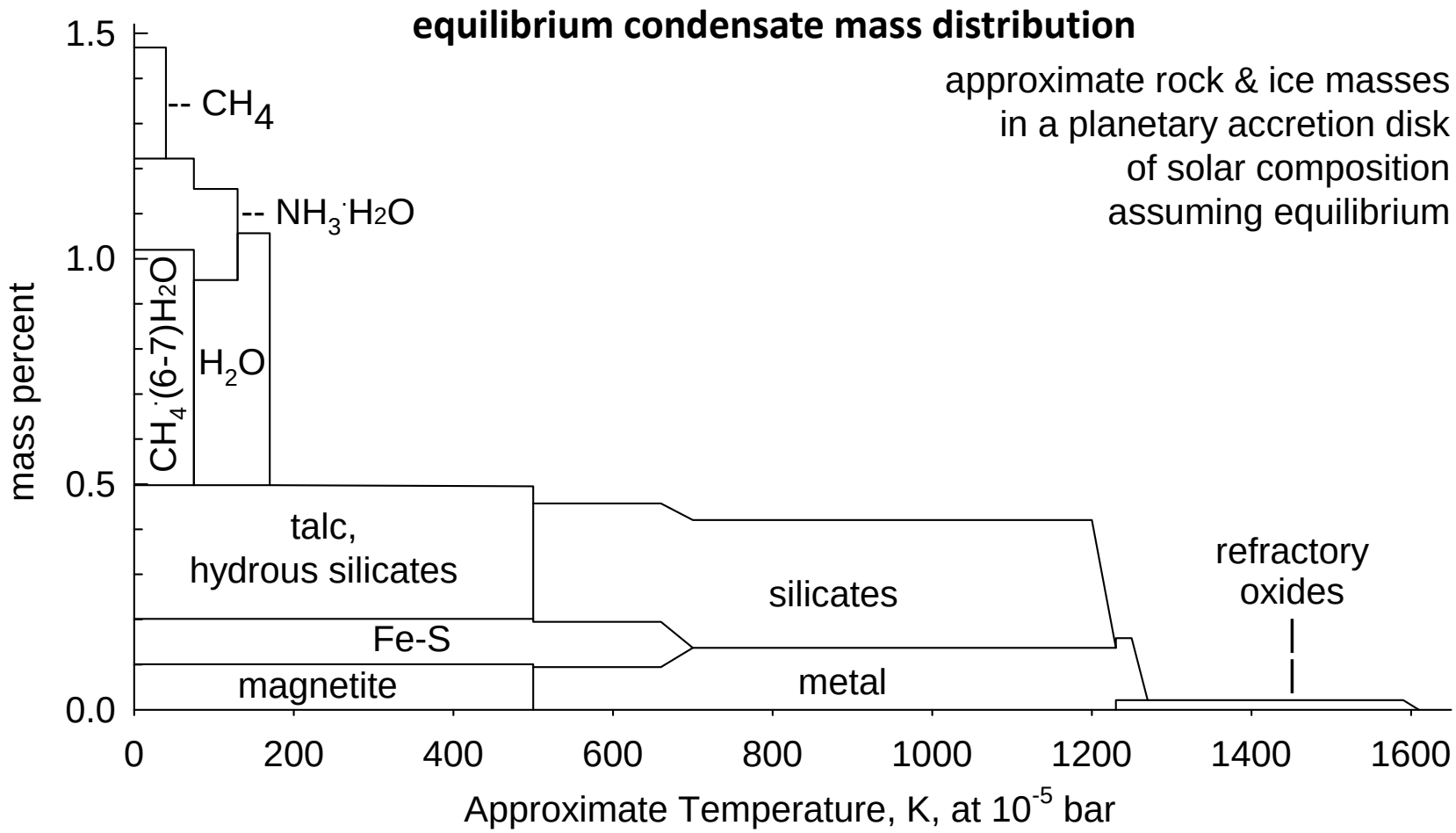
Low T, high P favors CH_4

CO cannot be converted to CH_4 within the lifetime of the solar nebula.

Oxygen remains tied to CO gas – less water ice available!
→ Less ice for objects → higher density objects
higher rock:ice

But CO can be converted to CH_4 within the lifetime of the Jovian Subnebula

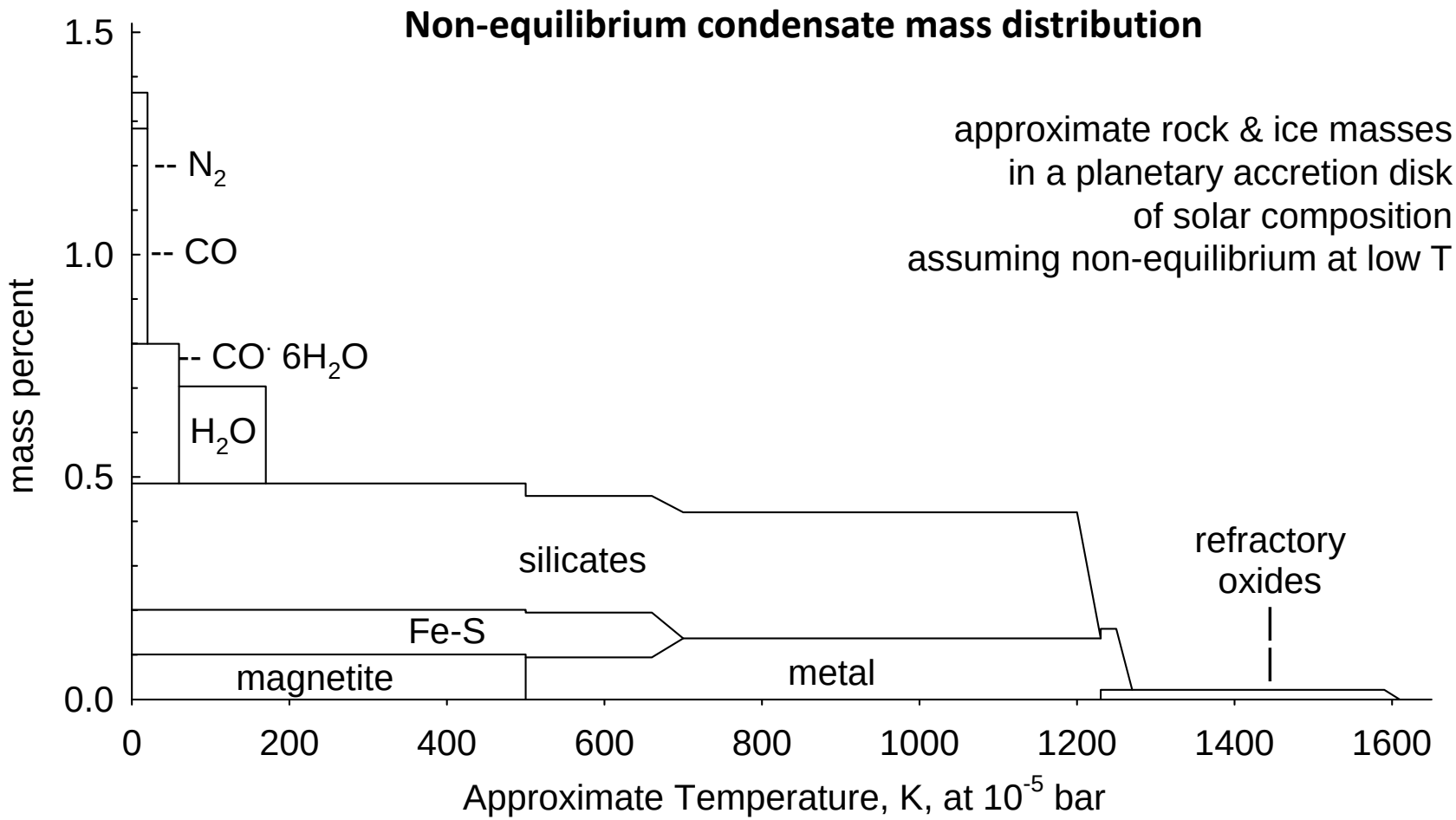
Oxygen goes into H_2O gas – more water ice available!
→ More ice for objects → lower density objects,
lower rock:ice



Percent of all solar O:
20.8% in rock, 4.3% in magnetite
75% H_2O (all ices, hydrous sil.)

Requires complete CO to methane + water conversion; not all low-T phases can form within the solar nebula lifetime

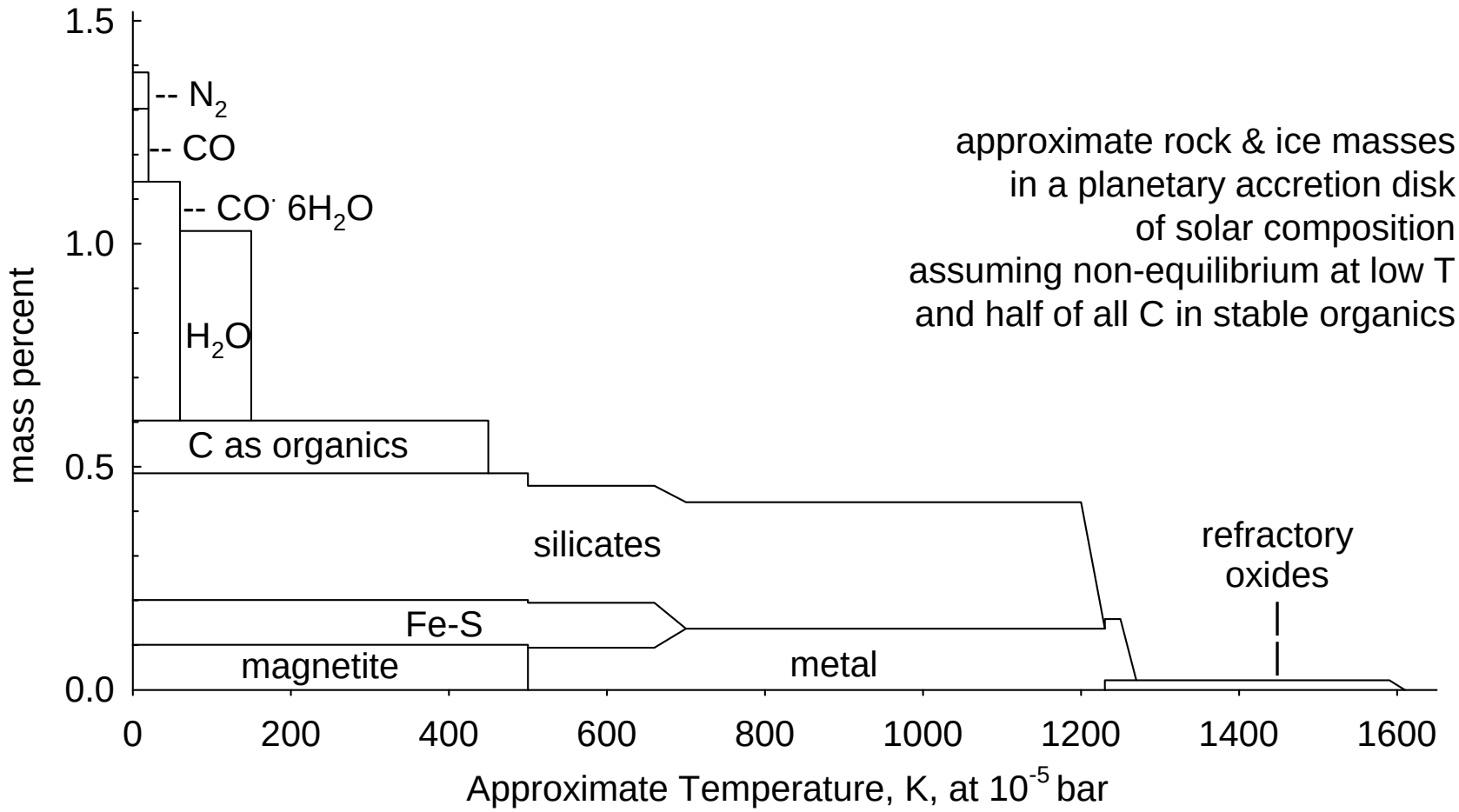
But: No hydration of silicates in “vacuum”; only little methane gas, little ammonia gas



Percent of all solar O:
20.8% in rock, 4.3% in magnetite
16% in H2O ice
59% in CO ices

all C as CO
No methane means NO more H_2O from CO to methane conversion

No hydrous silicates, no methane and ammonia bearing ices



approximate rock & ice masses
in a planetary accretion disk
of solar composition
assuming non-equilibrium at low T
and half of all C in stable organics

Percent of total solar O:
20.8% in rock, 4.3% in magnetite
65% H2O ice
20% in CO ices

ISM-organics require 350-450 K for complete evaporation, Nakano et al. 2003

Solid organics could be important for core accretion model

No hydrous silicates, no methane and ammonia bearing ices

Distribution of Solar O
(percent of total O)

Oxides and Silicate "Rock", (FeO-free) 20.8%

Low temperature and likely oxidation by water **on parent body**:

Magnetite (FeS present) 4.3%

Magnetite (no FeS) 7.9%

Hydrous Silicates 2.2%

Sulfates 8.2%

Phosphates 0.1%
carbonates possible

Fraction of O in various ices depends on CO to methane conversion:

"Equilibrium"

O in H2O	**after rock**	**79.2%**
	after mag	**74.9%**
	after hydr. Sil	**72.7%**
	after FeS oxid.	**60.9%**

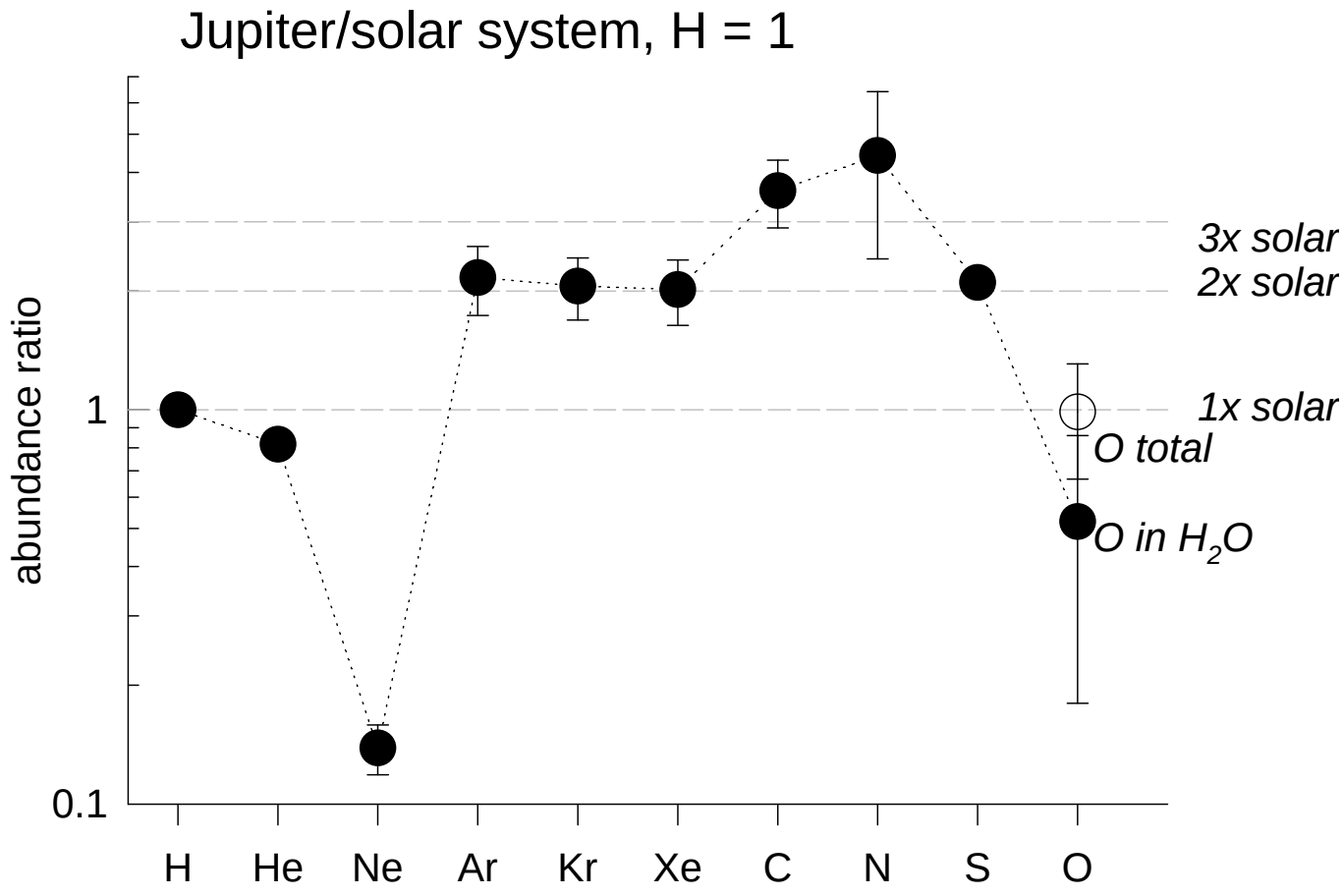
No CO → CH4 + H2O conversion

O in CO		**58.9%**
O in H2O	**after rock**	**20.3%**
	after mag	**16.0%**
	after hydr. sil	**13.8%**
	after FeS oxid/.	**2.0%**

Can accrete more water ice:
lower mass fraction of rock 0.3-0.43

Object with less water ice:
higher mass fraction of rock: 0.75

O-abundance from Giant planet atmospheres?



Galileo probe measurements relative to H:
2x solar: Ar, Kr, Xe, S
3-4x solar: C, N
0.4 – 1x solar: O

Essential all measurements for H_2O yield solar to subsolar O values

If Jupiter formed with a lot of water ice: Where is the water now?

Also limits on H_2O abundance from CO, SiH_4; Visscher et al. 2006, ApJ

Conclusions:

Compositions of meteorites, planets and other planetary objects cannot be used to get a direct measurement of the solar system O abundance (taken here as A(O) = 8.73)

CI chondrites indicate a lower limit: A(O) $\geq$ 8.42
(about half photospheric)

C and O are fractionated from solar in Jupiter's atmosphere,
Jupiter atm: A(O) = 8.39, O/H = 0.4x solar, C is 3-4x solar

Compositions and inferred rock:ice ratios of planetary objects in the outer solar systems could be used to obtain limits on C and O abundances, depends also on what types of ices other than water are present and amount of organics too.