Composition of planets and properties of protoplanetary disks

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Planetary Compositions depend on:

Elemental composition and stability of their phases in the accretion disk
silicates, metal, sulfides, ices…

At a given location, condensation/evaporation chemistry depends
on P-T structure of accretion disk

Are there any compositional gradients from the disk preserved in planets?

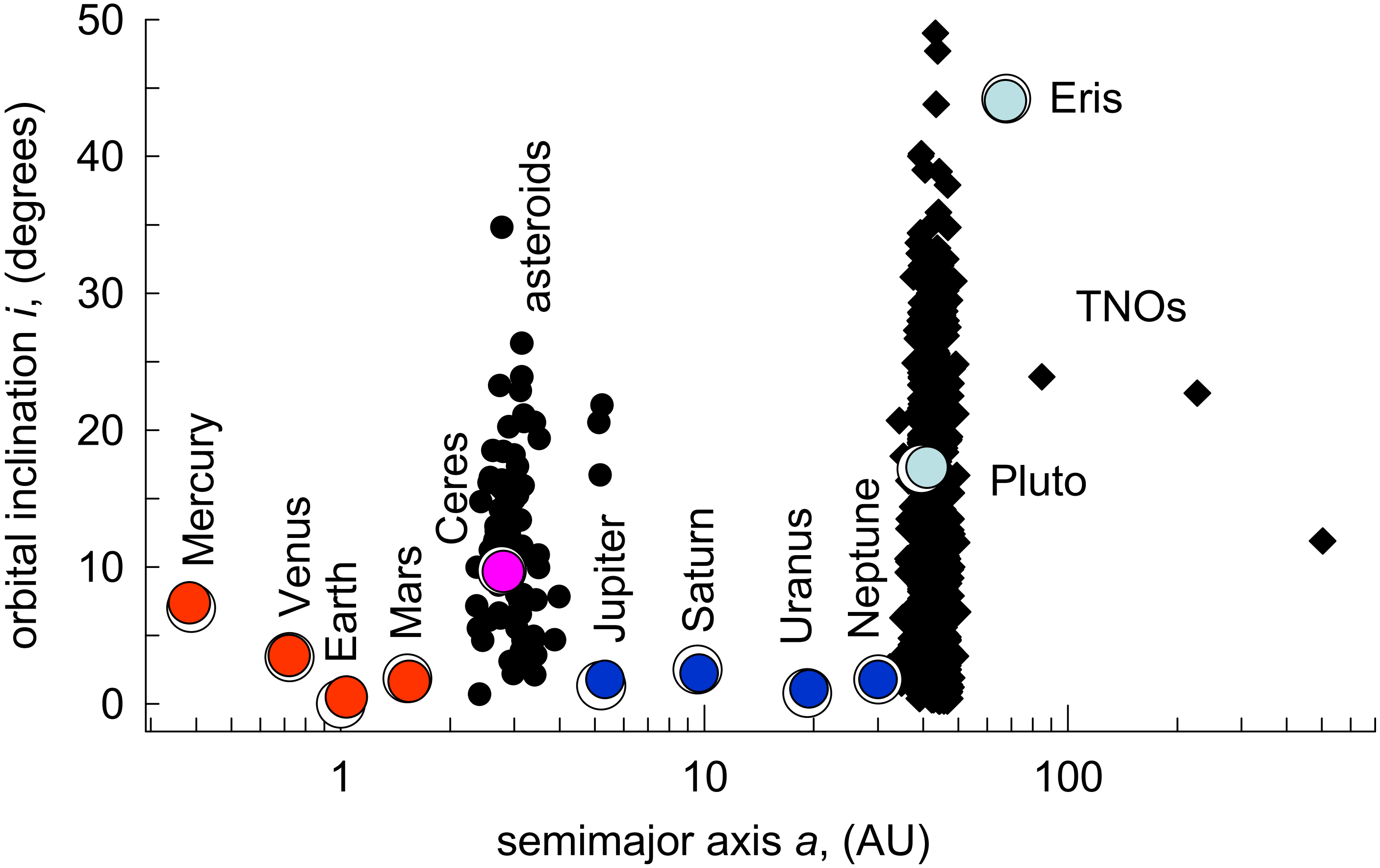
Rocky (terrestrial) planets

Gas giant planets

All That is in the Planets was in the Disk,

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

What's left of the disk: Planets, Dwarf Planets, Many Small Objects



4 rocky terrestrial planets

+ 1 rocky dwarf planet

+ >10^4 rocky asteroids

4 gas giant planets

+ 2(3) icy dwarf planets

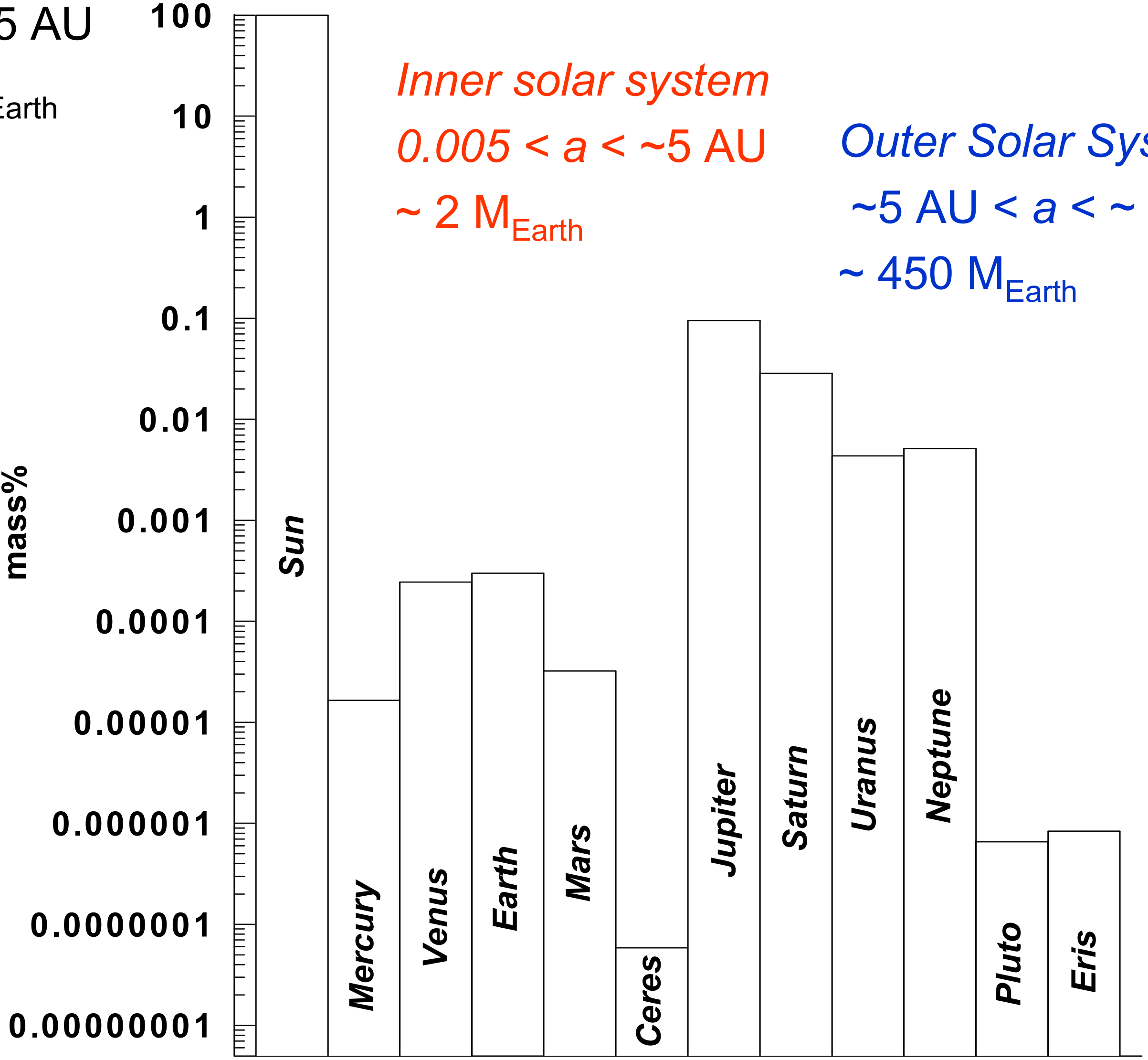
+ >10^4 icy comets

objects shown have
diameters >100 km

Sun

$R_{sun} = 0.005$ AU

333,000 M_{Earth}



Inner solar system

0.005 < a < ~5 AU

~ 2 M_{Earth}

Outer Solar System

~5 AU < *a* < ~ 500 AU (Sedna)

~ 450 M_{Earth}

Inputs to Planetary Compositions

Solar system elemental abundances

→ see Lodders, Palme, & Gail 2009, Landolt Boernstein; on astroph.

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-solid equilibria at low temperatures
  - (e.g., sulfide content, hydrated silicate formation)

for gas giant planets also:

- H_2 & He gas accretion efficiencies

Chemical fractionations *after* dissipation of the gaseous disk

- impact processing; Moon

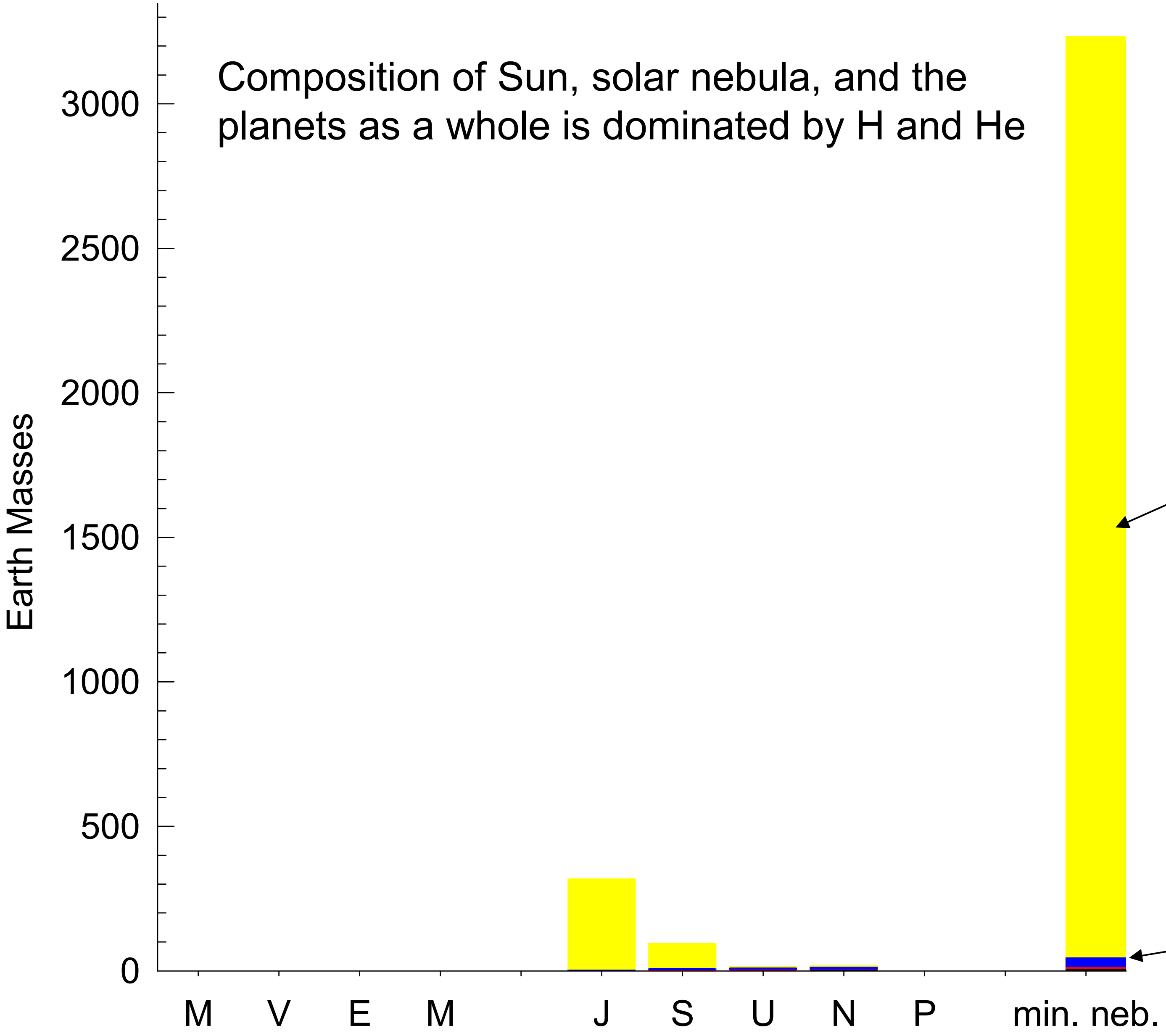
Major components

Rock (Metal, Silicate, Sulfide)

Ices (H_2O; CO, CH_4, CO_2, NH_3, N_2, and/or clathrates or hydrates thereof)

Gas (H_2, He)

Composition of Sun, solar nebula, and the planets as a whole is dominated by H and He



minimum mass nebula

~0.01 M_{sun}

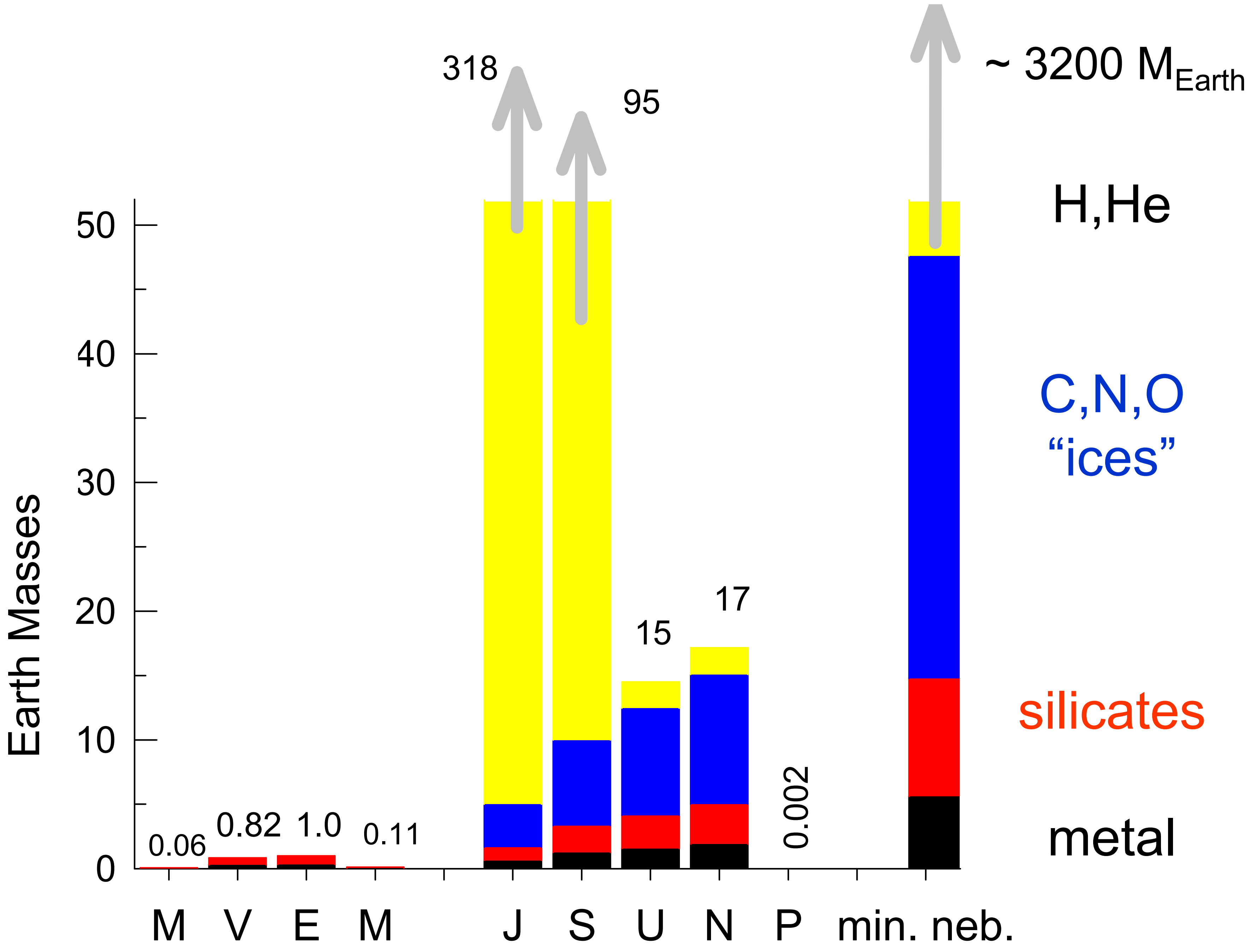
~10 M_{jup}

~3200 M_{Earth}

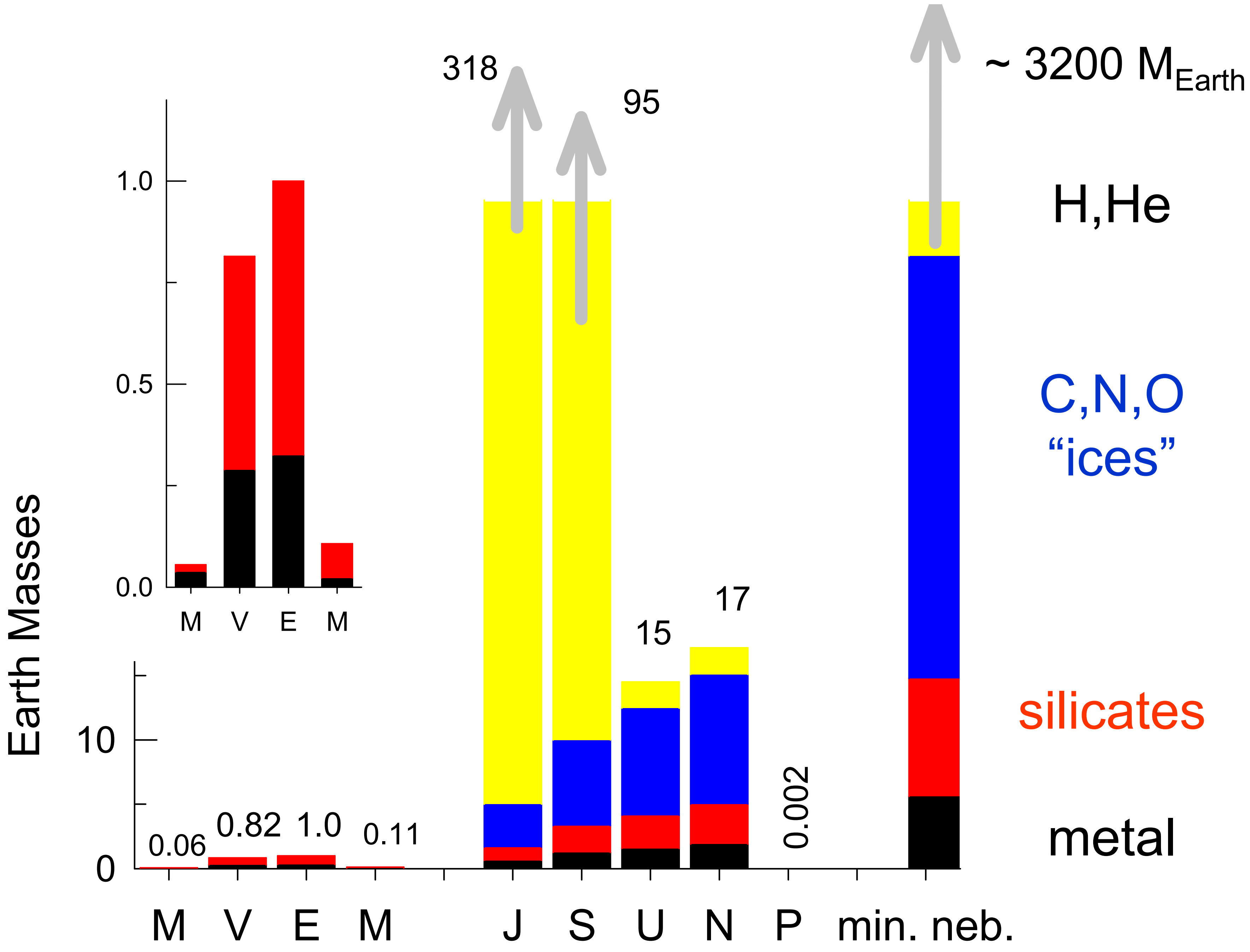
H,He

All other elements

(1.5% of total)



318
95
~ 3200 M_{Earth}
H,He
C,N,O
"ices"
silicates
metal
Earth Masses
50
40
30
20
10
0
0.06
0.82
1.0
0.11
15
17
0.002
M
V
E
M
J
S
U
N
P
min. neb.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Overall planet densities depend on relative amounts and individual densities of accreted components

Zero-pressure Densities
g/cm^3

FeNi metal alloys: 8.1 – 8.9

refractory

FeNi alloy + 10% S: 5.7
Eutectic Fe-FeS: 5.15
Troilite (FeS): 4.7

volatiles

Silicate phases
Mg-rich silicates (forsterite, enstatite): 3.2 – 3.6
Fe-rich silicates (fayalite, ferrosilite): 4.4 – 4.0

refractory

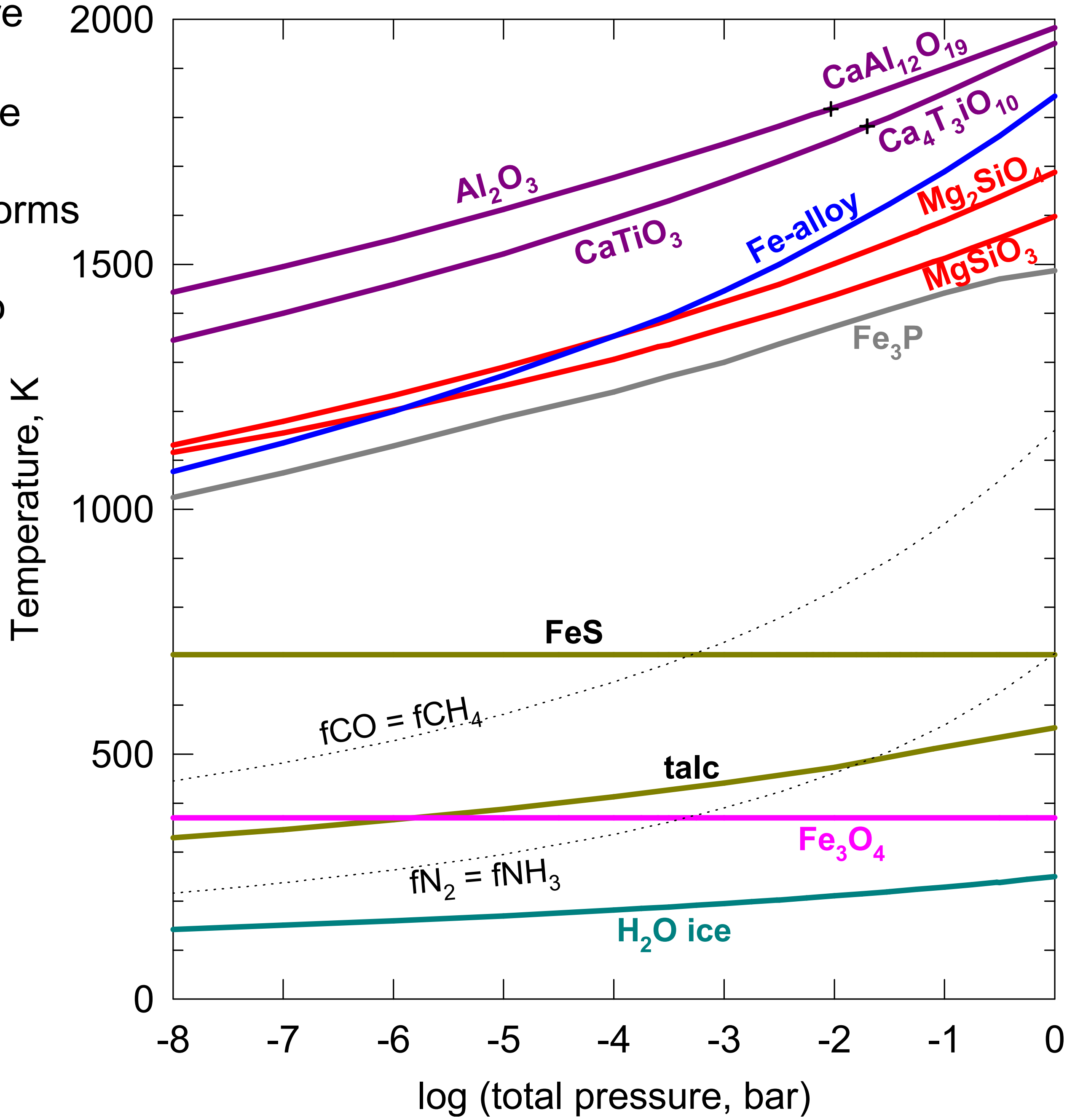
Organics: 1.2 – 1.5
Water ice: 1.0
Methane clathrate: 0.9
Ammonia ice: 0.82
NH_3 hydrate: 0.96

highly volatiles

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

Major change in sequence

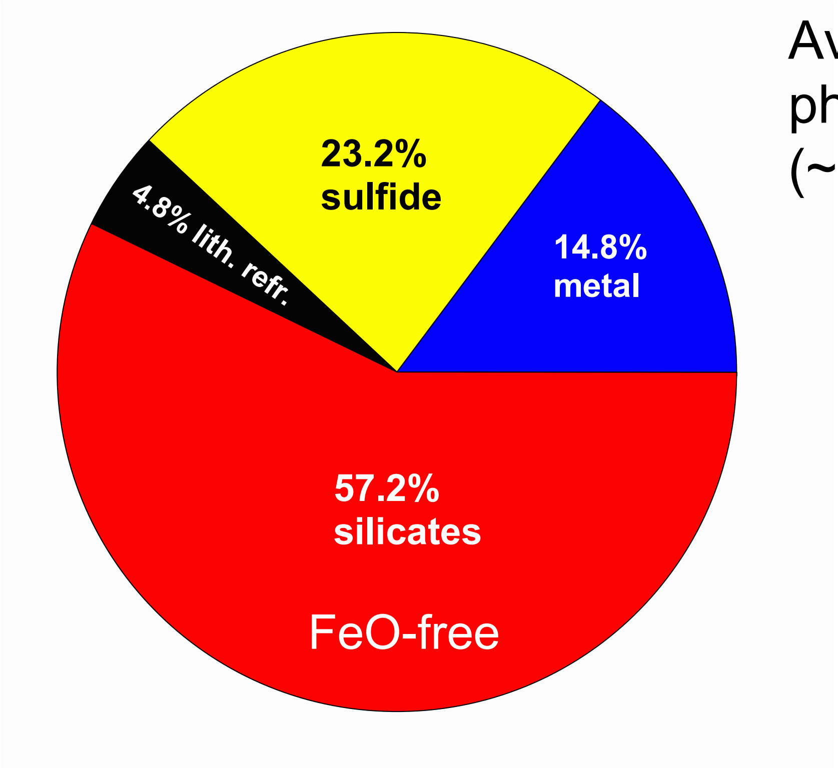
Above ~ 10^{-5} bar, metal forms before Mg-silicates both major contributors to condensed mass



Troilite (FeS)

Water ice

Terrestrial Planets



Available high-temperature (> 600 K) phases in a solar composition system (~0.5% of total mass in solar composition)

<< Assuming all Fe distributed between metal and sulfide; no FeO in silicates.

Oxidation of metallic Fe to FeO increases mass fraction of silicates and reduces metal + sulfide fractions

Influences metal content in chondritic meteorites, planetary cores

Incorporation of FeO into silicates below ~ 600 K in solar gas

Fe (**metal**) + H_2O (gas) + Mg-silicates = “FeO” (in silicates) + H_2 (gas) *SLOW!*

Reaction of

Fe (**gas**) + H_2O (gas) + Mg-silicates = “FeO” (in silicates) + H_2 (gas)

faster at higher temperature, needs higher H_2O/H_2 ratio or at higher dust: gas ratios

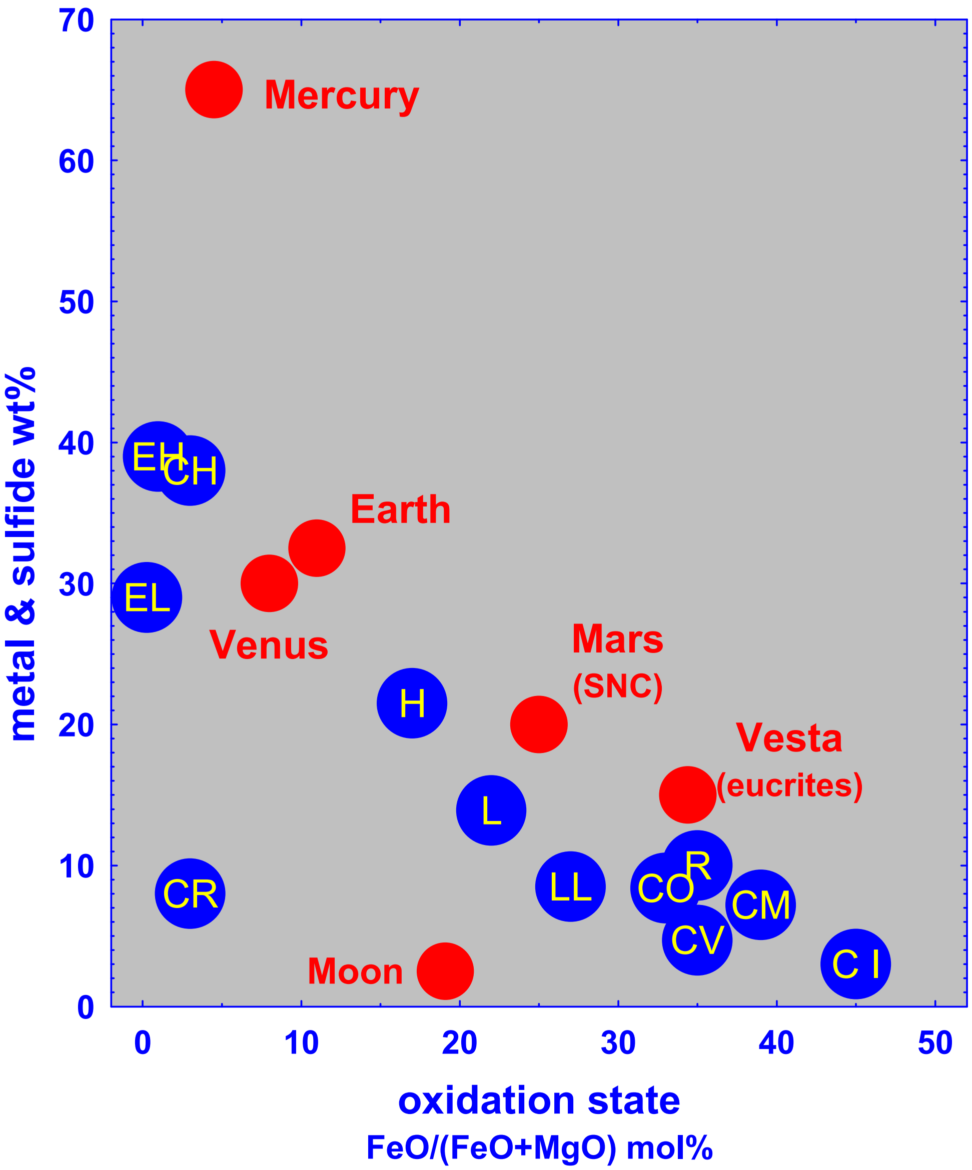
Very, very broadly,
the rocky planets are similar in composition to chondrites for the more refractory elements

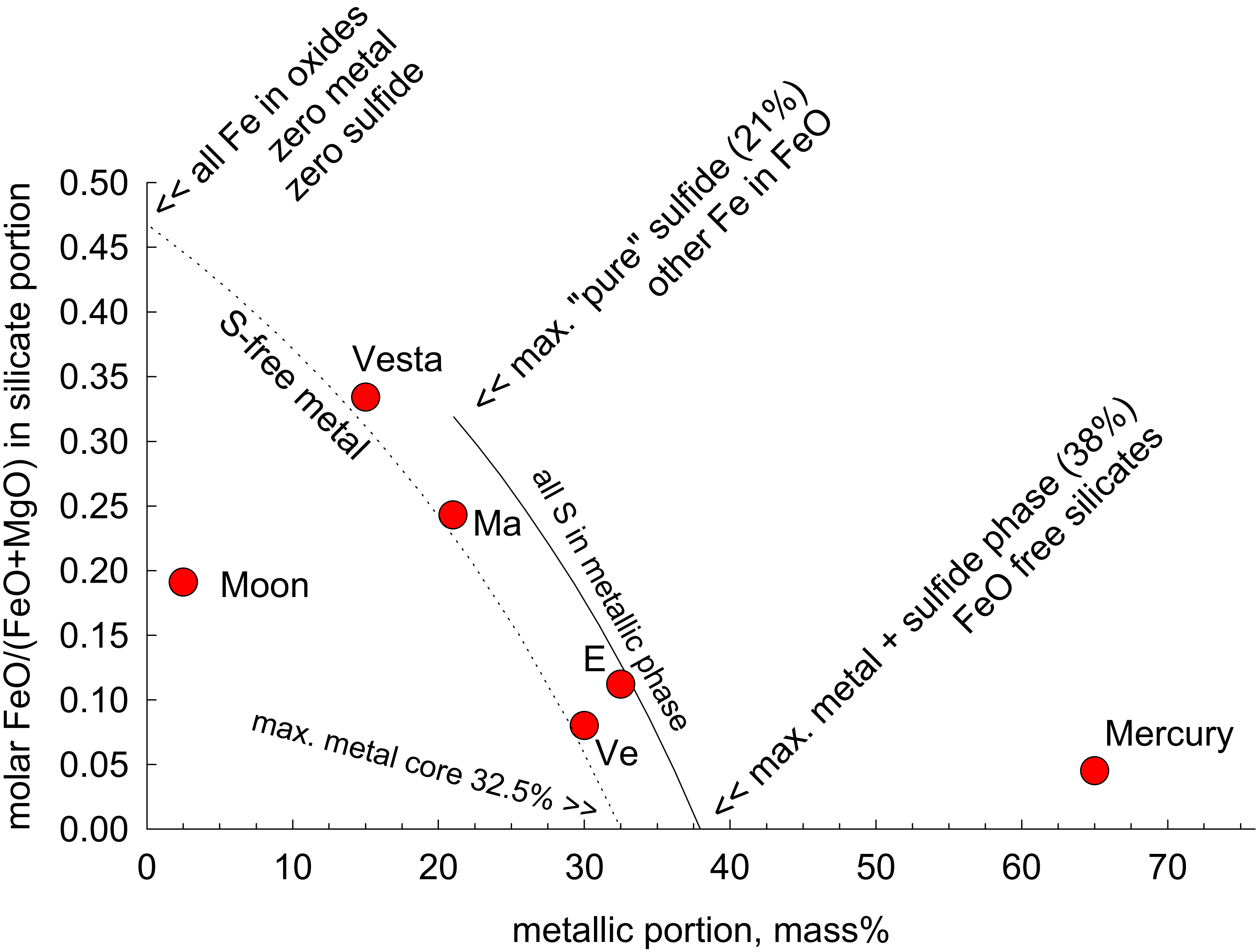
(e.g., Ca, Al, Ti, Mg, Si, Fe)

Oxidation state varies:
Silicate FeO content up,
Metal content down

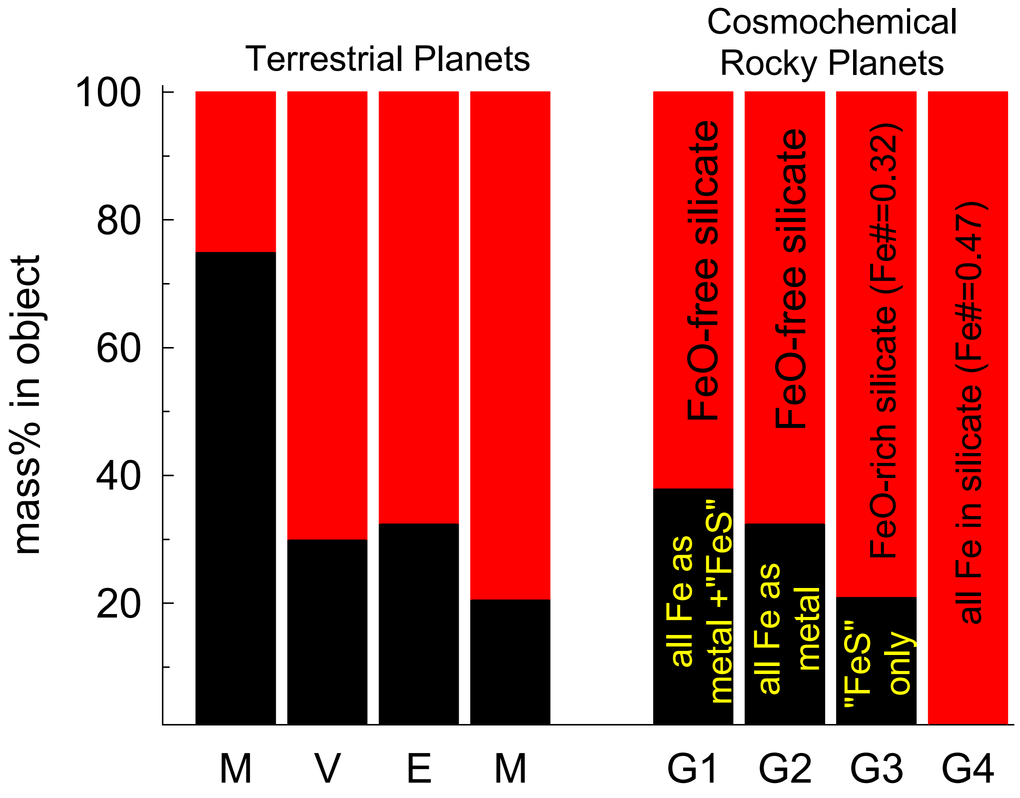
Sulfur content varies in chondrites and planets
S is moderately volatile
(FeS stable below 700K)

Size of metallic core
(FeNi metal+sulfide)





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

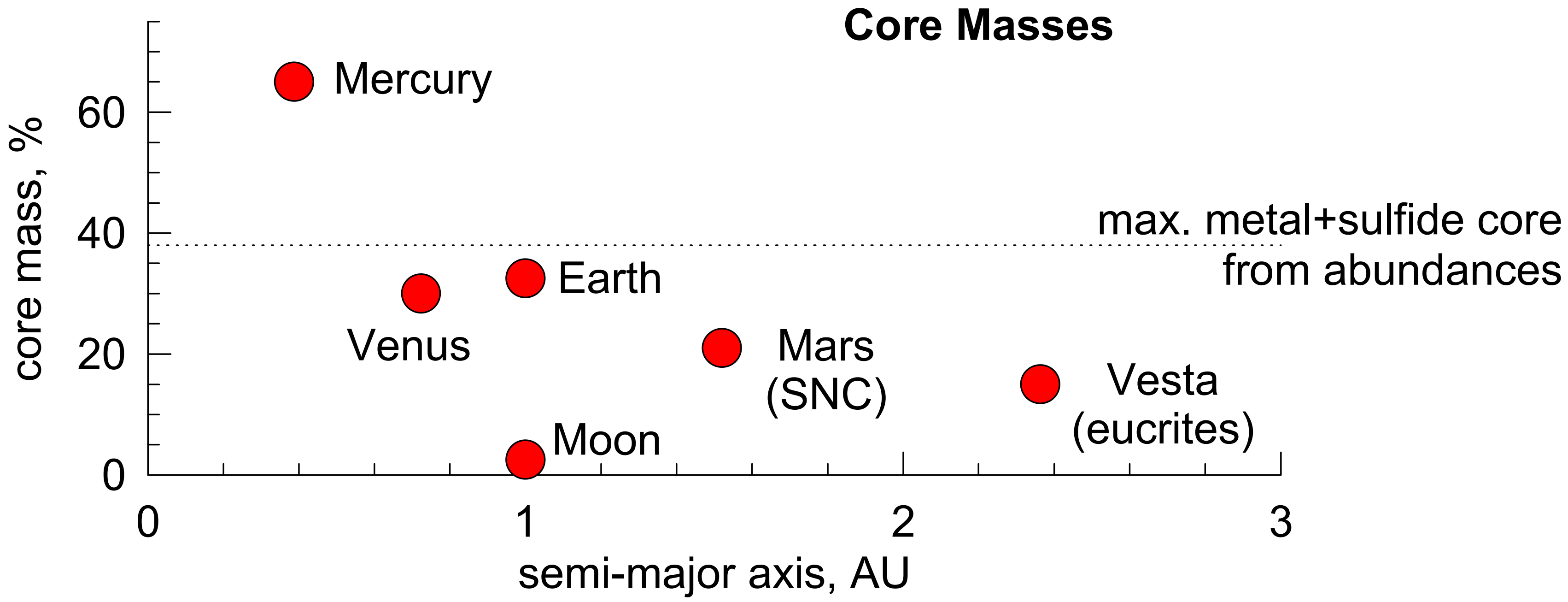


End members
FeO-free silic. + metal+sulfide
FeO-free silic. + metal
FeO-rich silic. + FeS; no metal
FeO-rich silic. no metal, no sulfide

Cores of Venus, Earth, Mars, (& Vesta) within range of plausible cosmochemical models

Mercury: additional metal – silicate fractionation is needed.

Suggestions:
preferred metal retention or preferred condensation over Mg-silicates in solar nebula at higher total pressure (> 10^{-5} bar)
Loss of silicate mantle by boil-off after a massive impact (*i*)
Magnetic metal-silicate separation in disk and selective accretion?

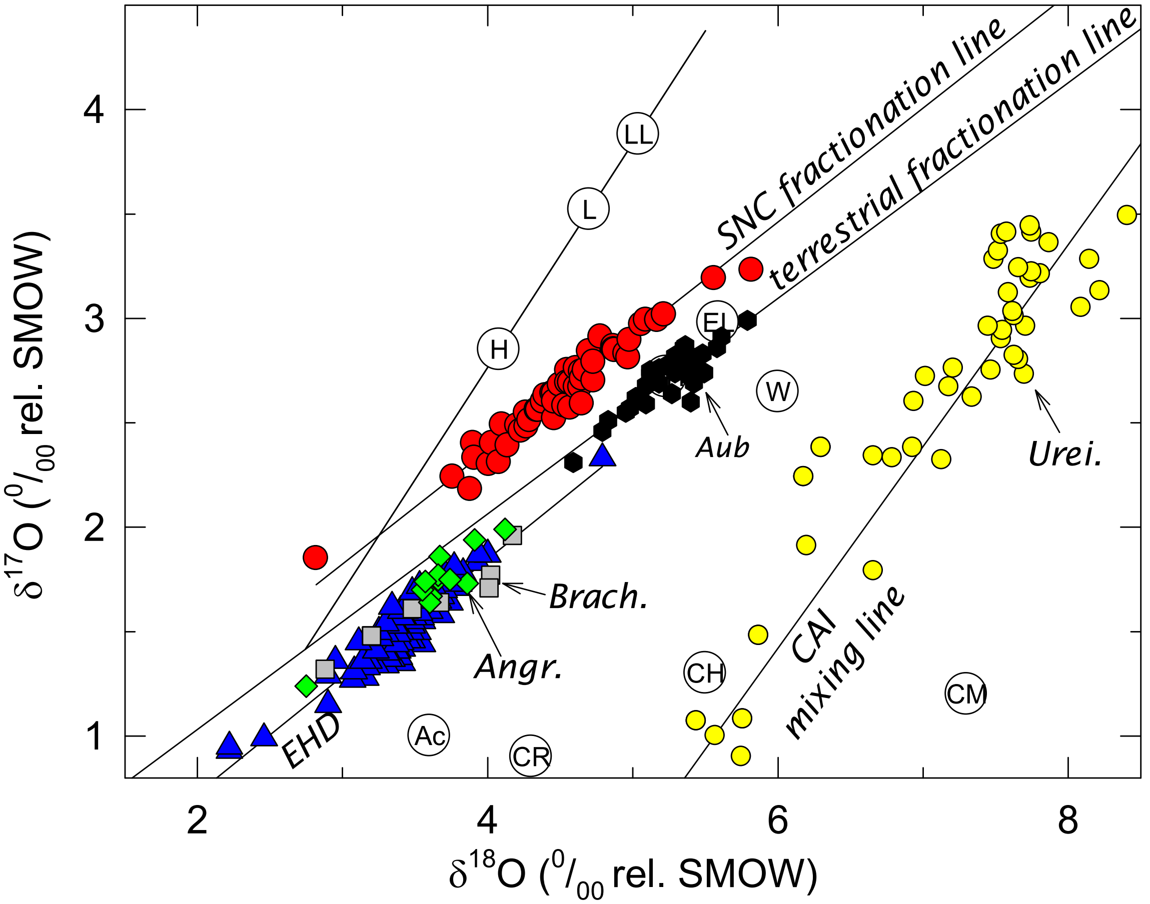


Core masses decrease with increasing radial distance from the Sun (excluding special cases of Mercury, Moon)

Change in Fe oxidation state:
metal to “FeO” in silicate at lower T; higher H_2O/H_2 in disk?

Amount of volatile S for sulfide higher from Mercury < Earth < Mars;
Vesta?

Mars (SNC)
Earth & Moon
Vesta (EHD)

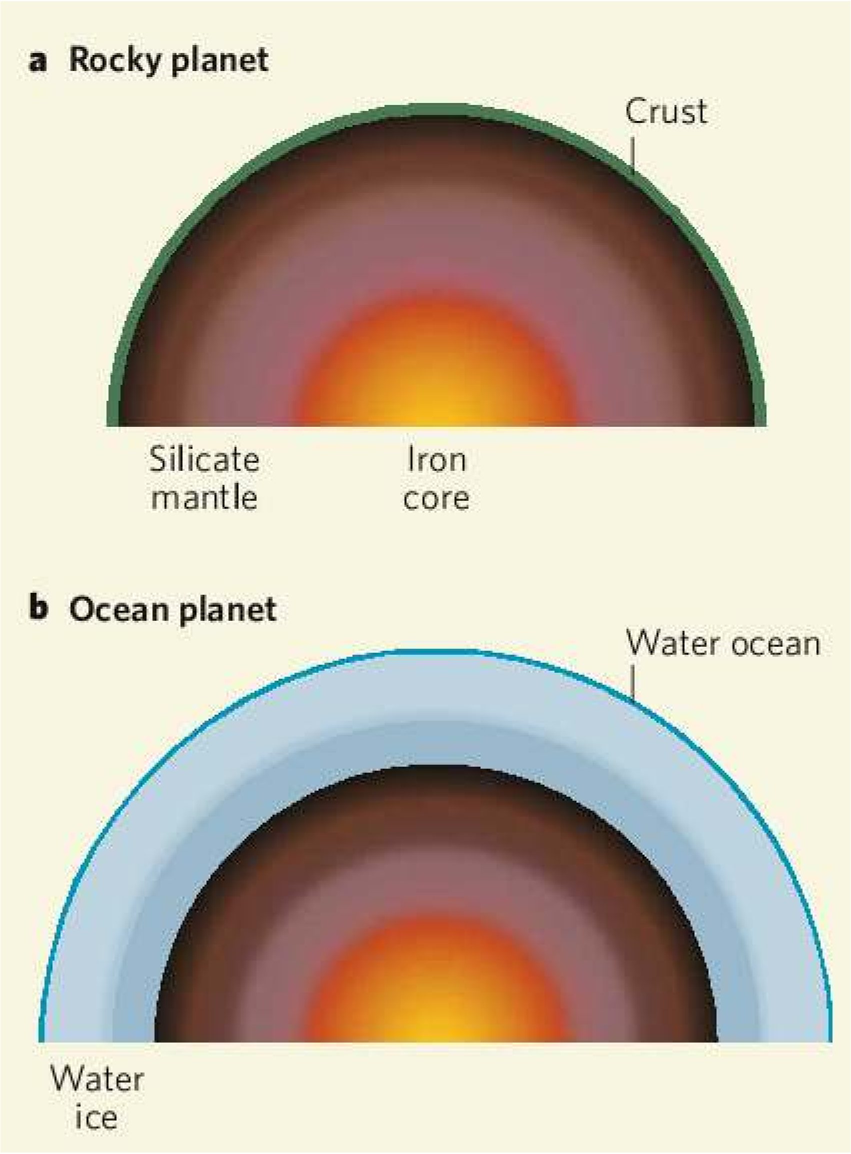


No systematic variation in O-isotopic composition with radial distance

M – E – V E –M – V

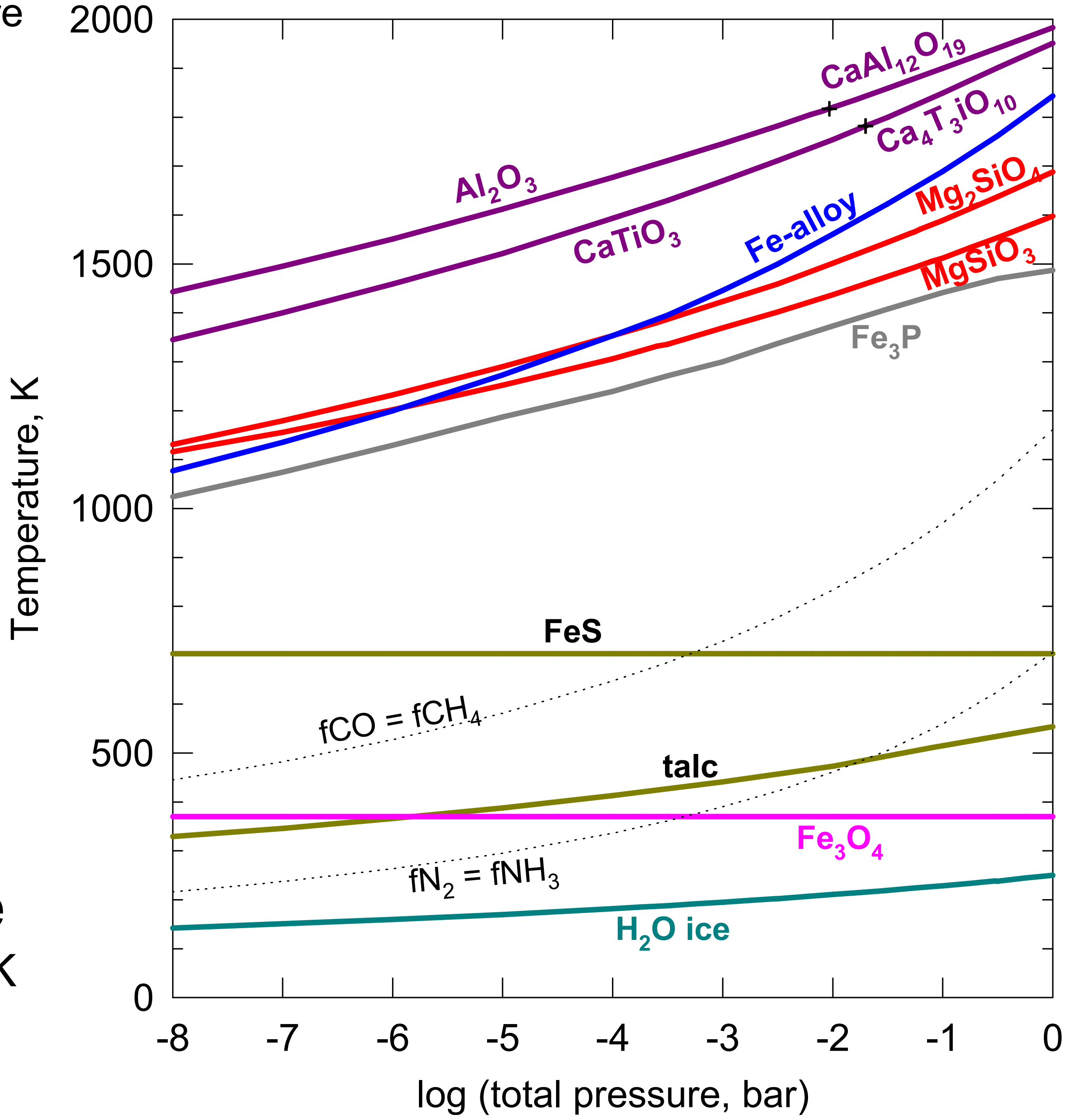
Planets made of high and low temperature phases

Rock & Ocean
and
Rock &Ice Planets



Sasselov 2008

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



Troilite (FeS)

Water Ice

~ 130 – 180 K

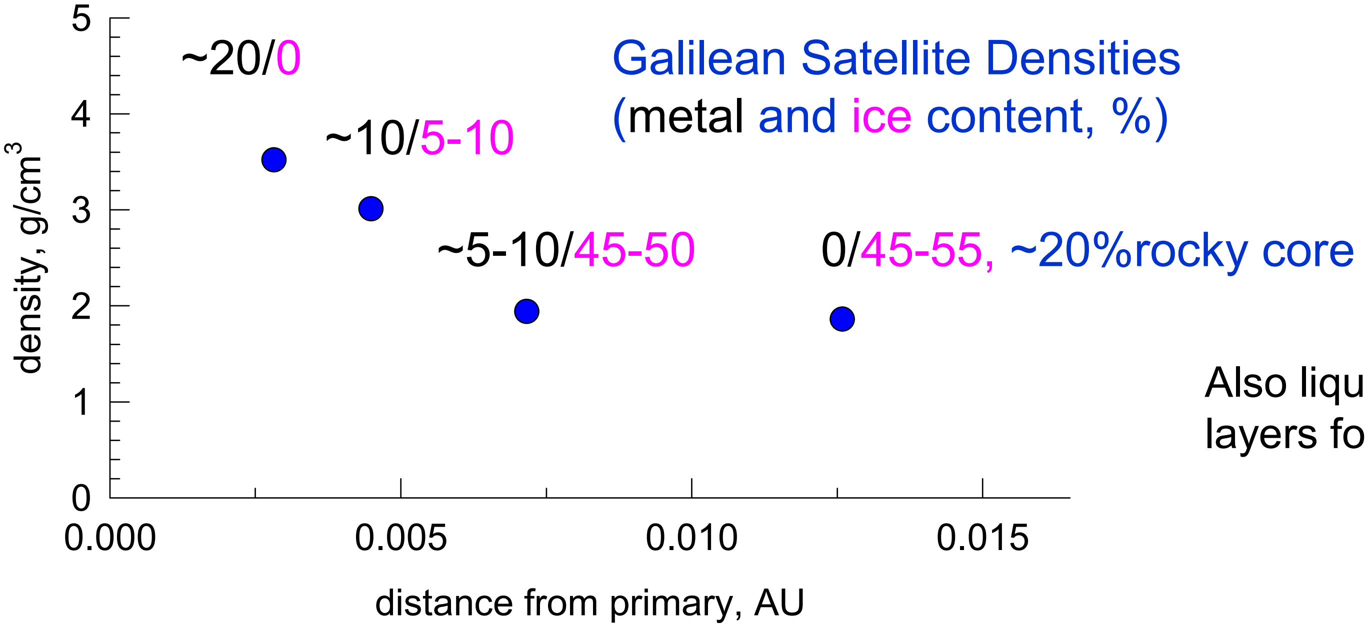
The Snowline

Water ice condensation/evaporation front

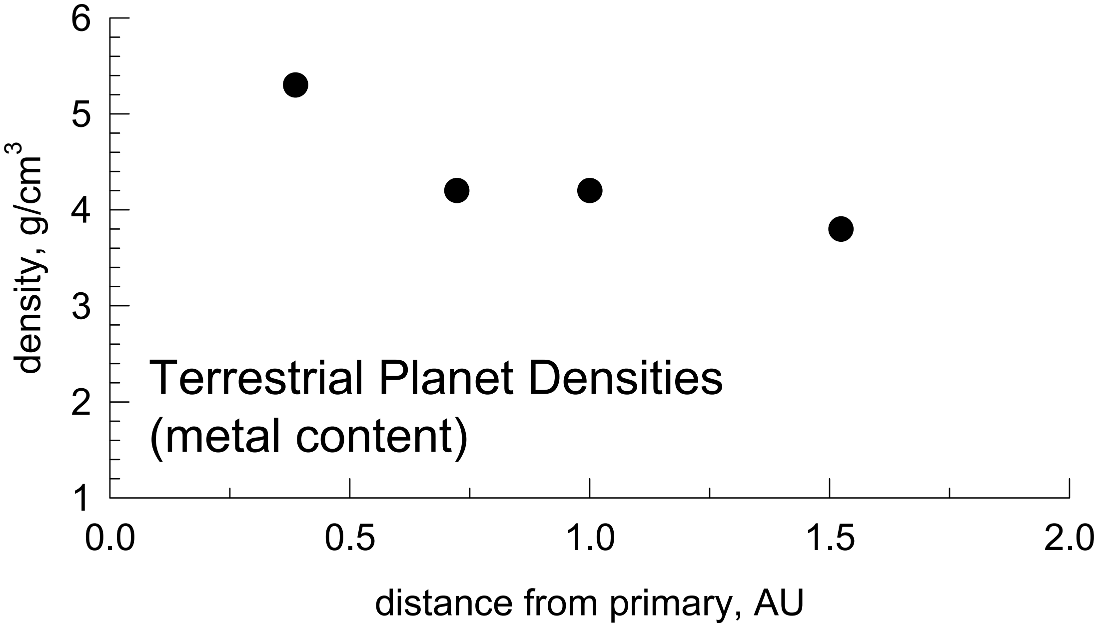
as close to the Sun as:

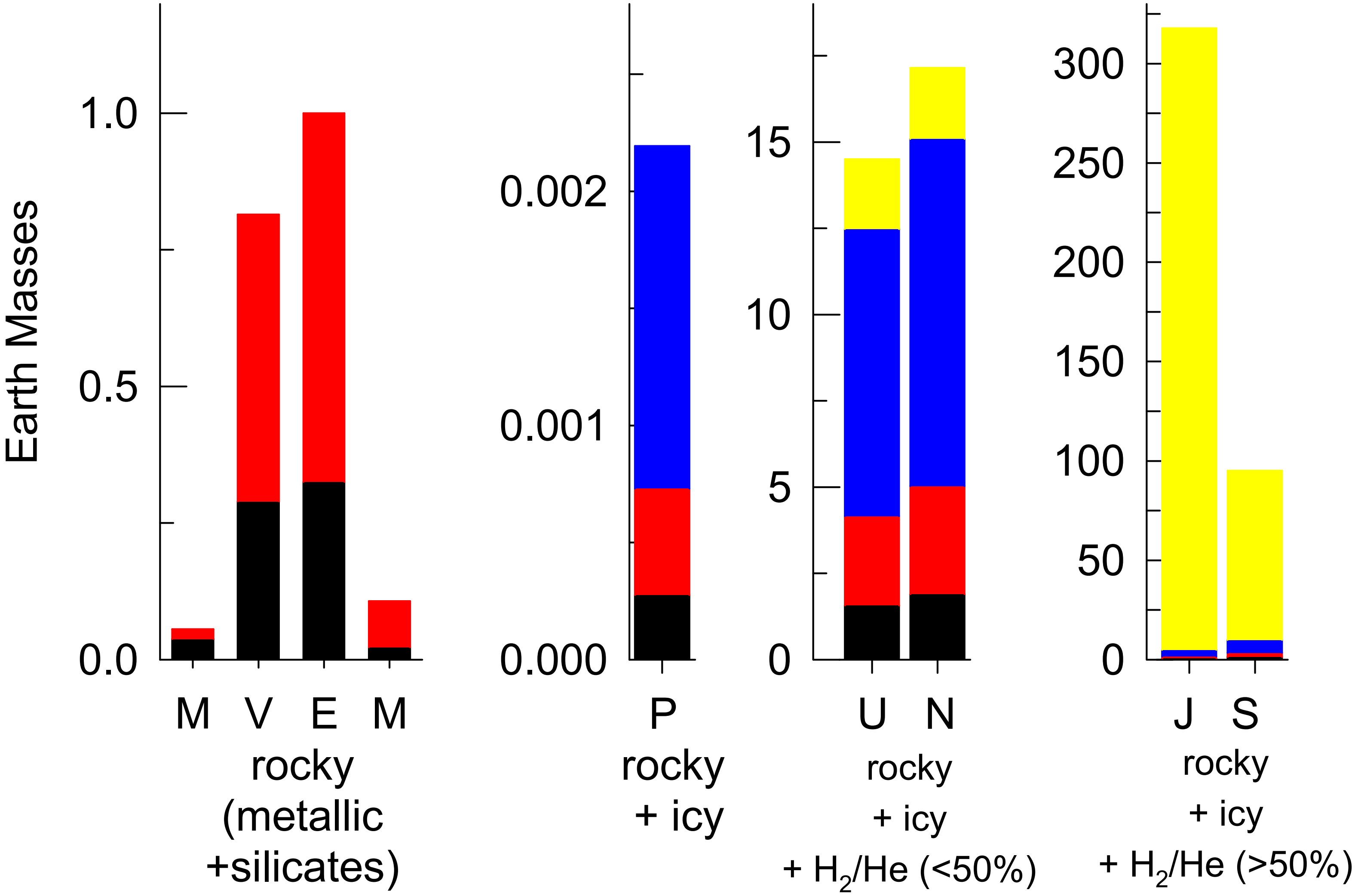
2.8 AU if ice-bearing objects in the outer asteroid belt formed there from disk material
Caveat: ice evaporation during the past ~4.5 Ga?

5.2 AU if Jupiter and the ice-bearing Galilean Satellites formed there
Caveat: Did Jupiter & Co. accrete at 5.2 AU?


Galilean Satellite Densities
(metal and ice content, %)

Also liquid “oceans”
layers for E,G,C


Terrestrial Planet Densities
(metal content)


Earth Masses
0.0
0.5
1.0
M
V
E
M
rocky
(metallic
+silicates)
0.000
0.001
0.002
P
rocky
+ icy
0
5
10
15
U
N
rocky
+ icy
+ H2/He (<50%)
0
50
100
150
200
250
300
J
S
rocky
+ icy
+ H2/He (>50%)

Exoplanet compositions: Ideas from densities

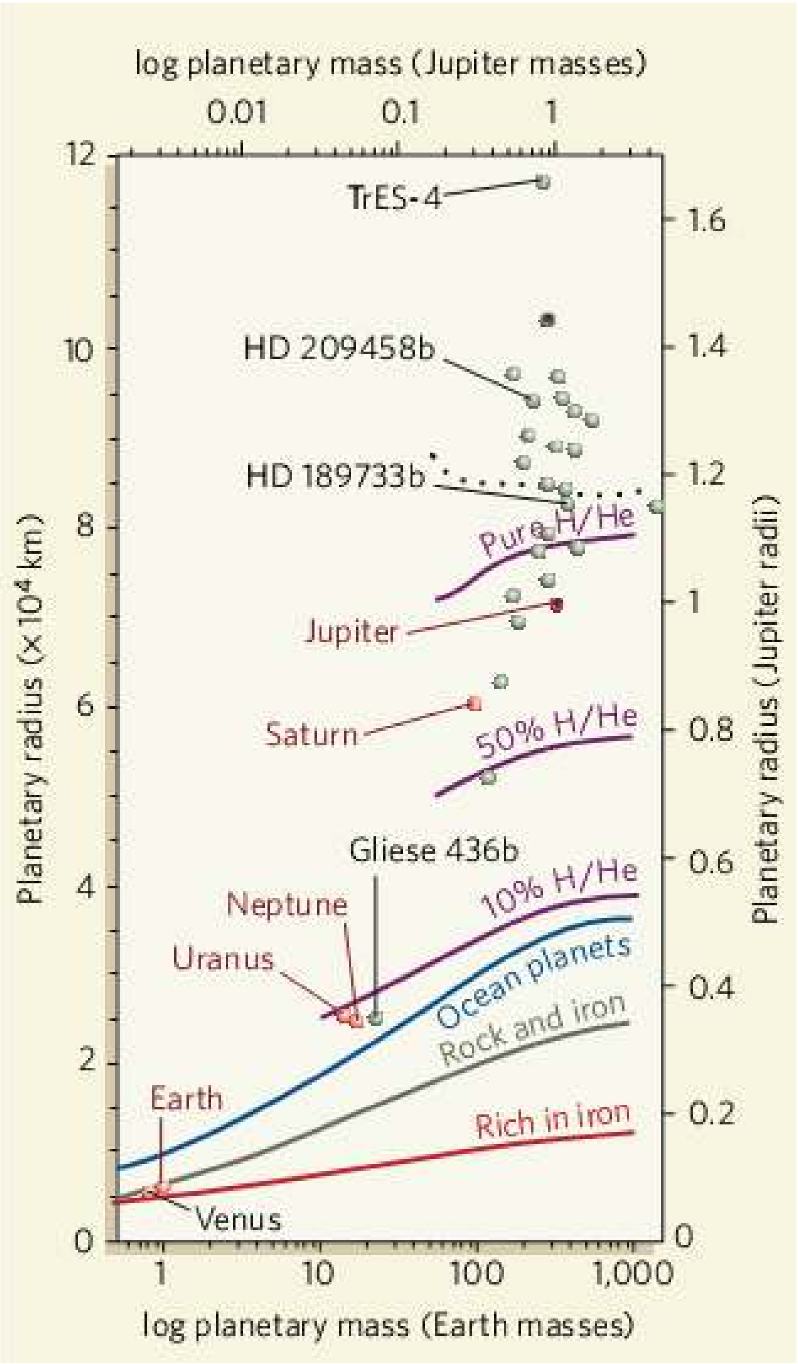
Some planets have larger radii than other planets of the same mass

→Lower density

Different compositions?

Extra heat sources for volume increase?

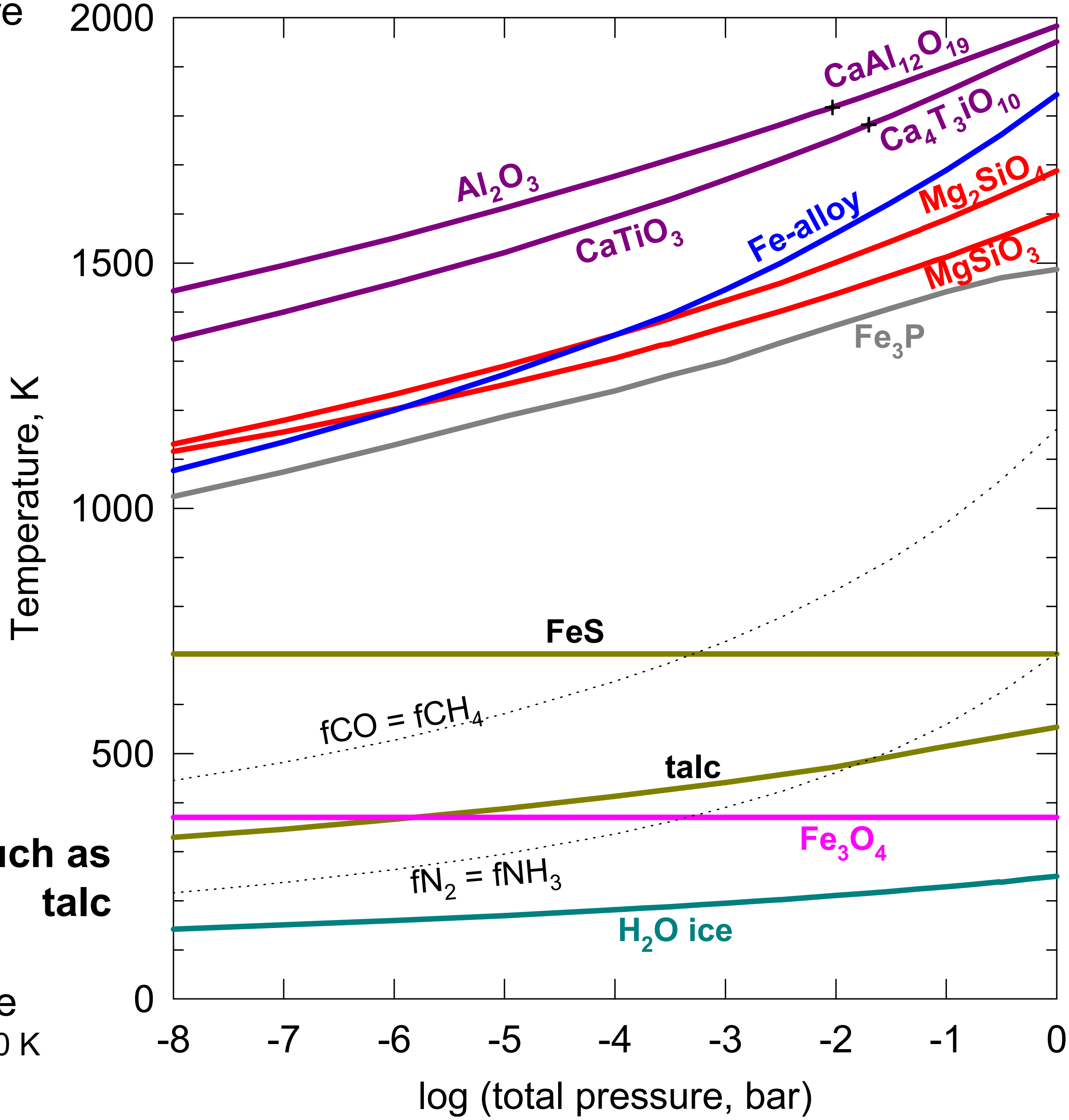
Measurement uncertain?



Sasselov 2008

More on condensation chemistry

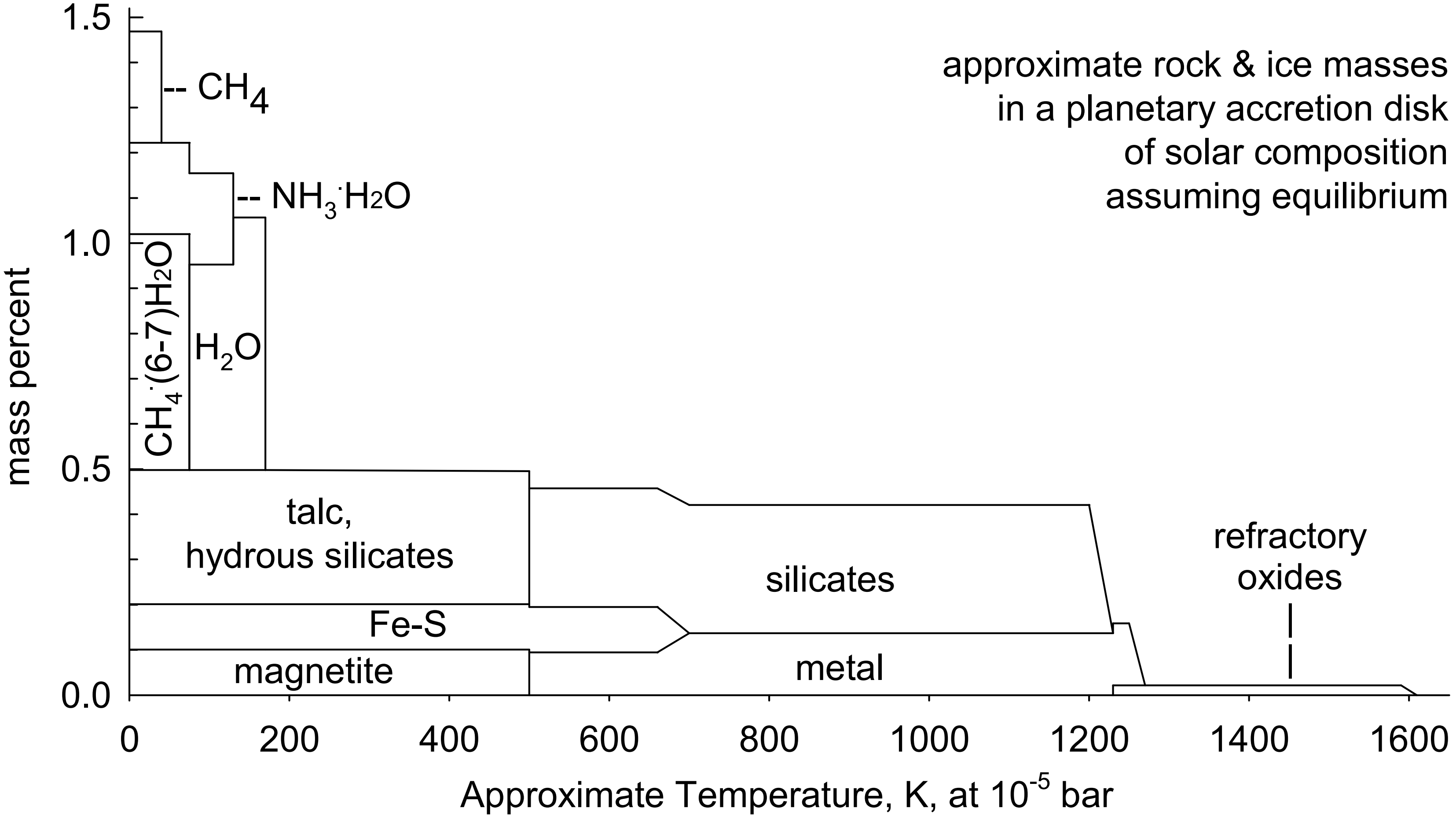
Solar composition system: Condensation/evaporation *sequence* is not very dependent on total pressure



Troilite (FeS)

Hydrated silicates such as talc

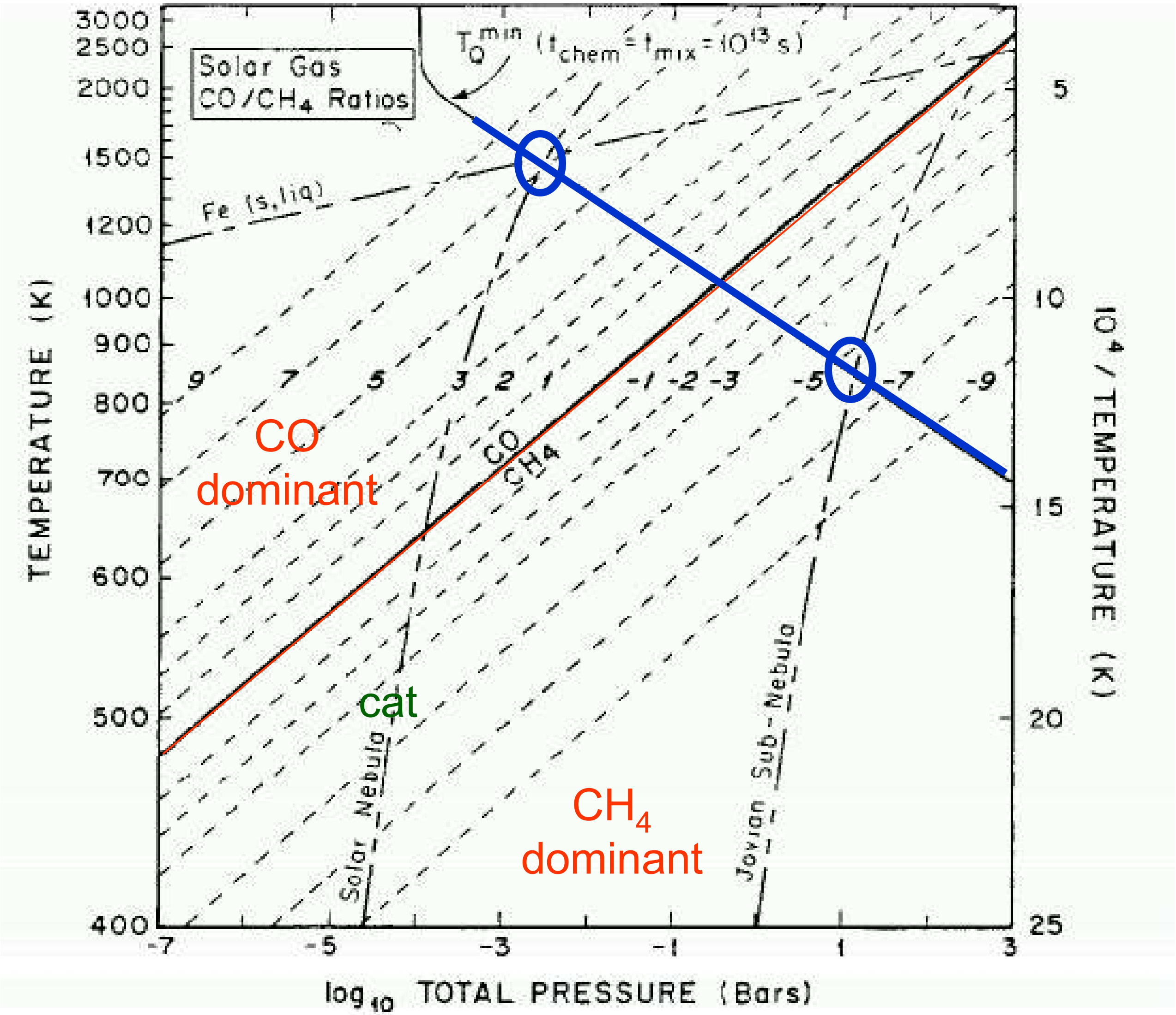
Water Ice
~ 130 – 180 K



equilibrium condensate mass distribution

But: not all low-T phases can form within the solar nebula lifetime

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



$CO + 3\ H_2 = CH_4 + H_2O$

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

CO abundances become “frozen in”

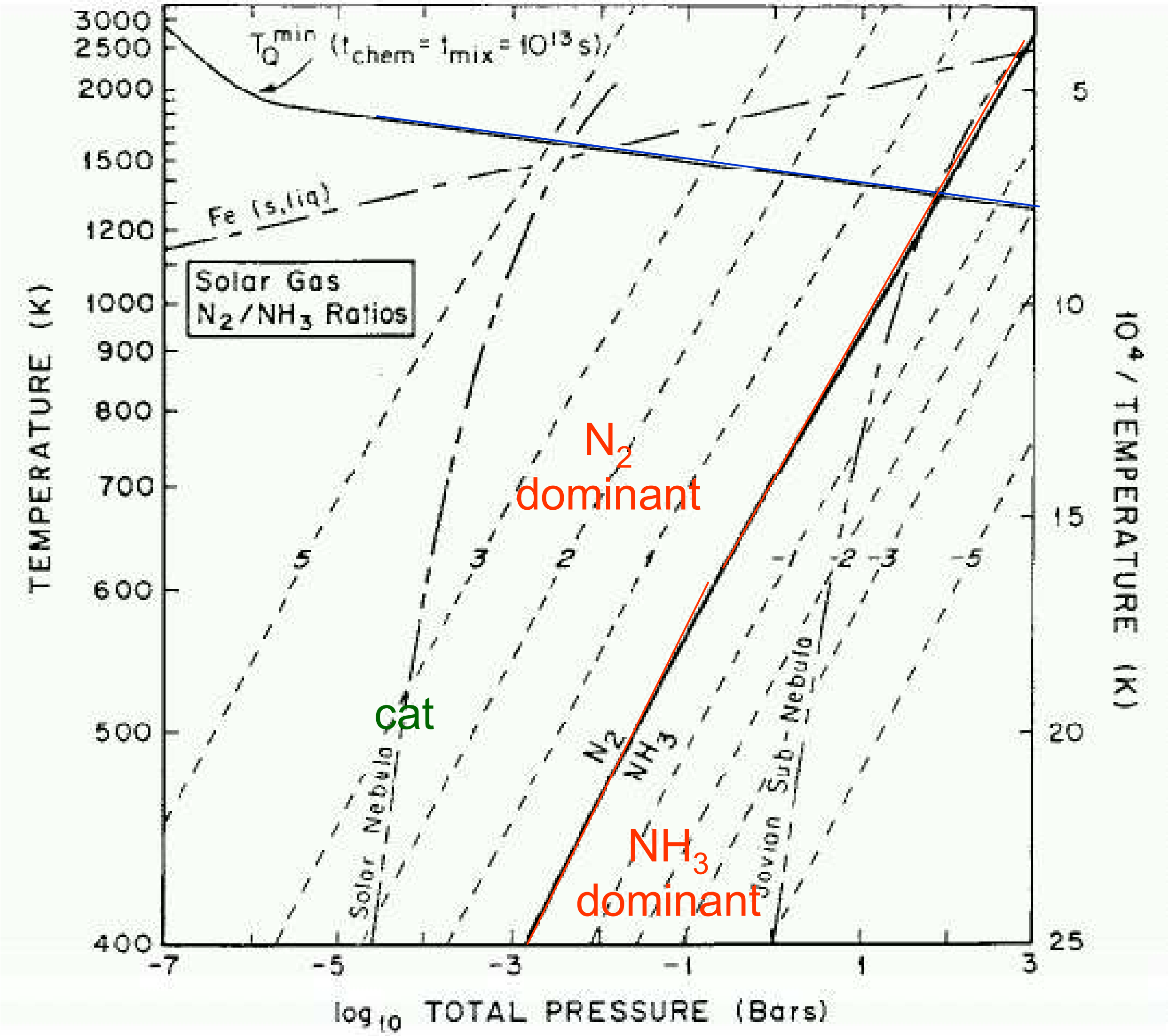
below ~ 1470 K in solar nebula
CO remains the major C gas

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

Contours: log CO/CH_4 ratios

From Prinn & Fegley 1989

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



$N_2 + 3 H_2 = 2 NH_3$

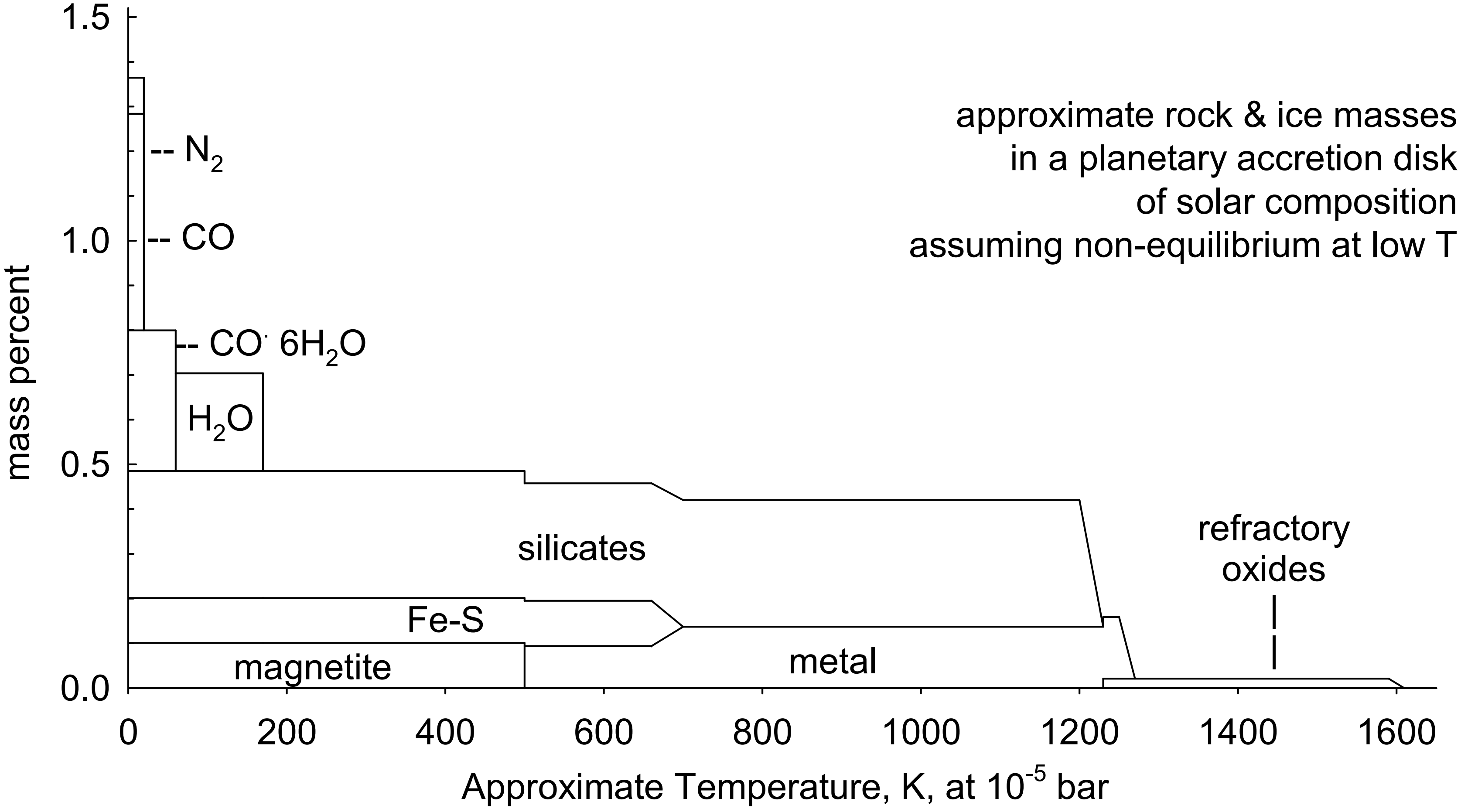
N_2 to NH_3 conversion kinetically inhibited at low T and low P

N_2 abundances become “frozen in”

below ~ 1600 K in solar nebula
N_2 remains the major N gas

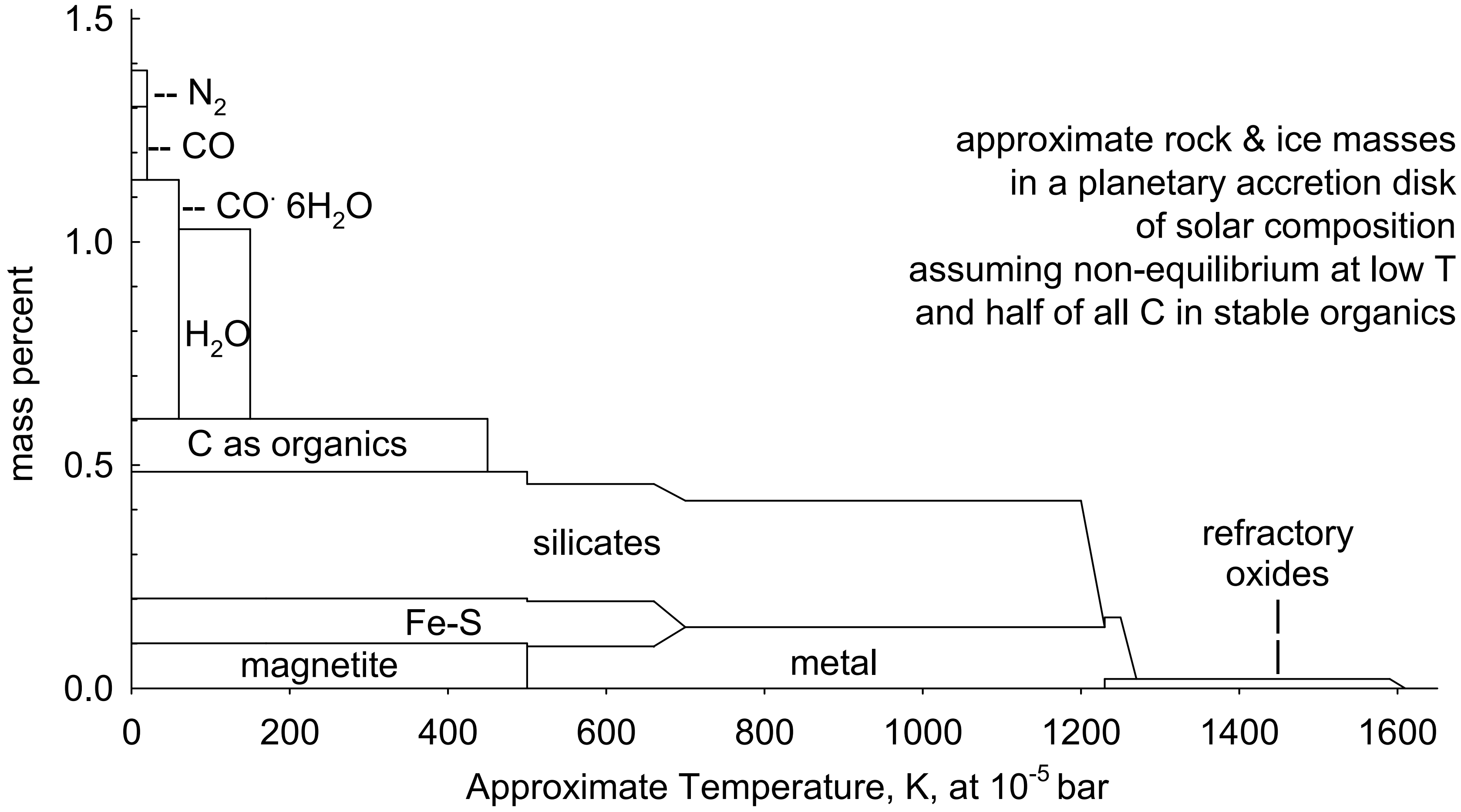
below ~1370 K in Jovian sub-nebula
NH_3 and N_2 about equal

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



Non-equilibrium condensate mass distribution
all C as CO

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

Non-equilibrium condensate mass distribution
Half of all C in condensed organics

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

No hydrous silicates, no methane and ammonia bearing ices

Solid organics could be important for core accretion model

Core – accretion model

Fast build-up of protocore facilitated if surface mass density is increased

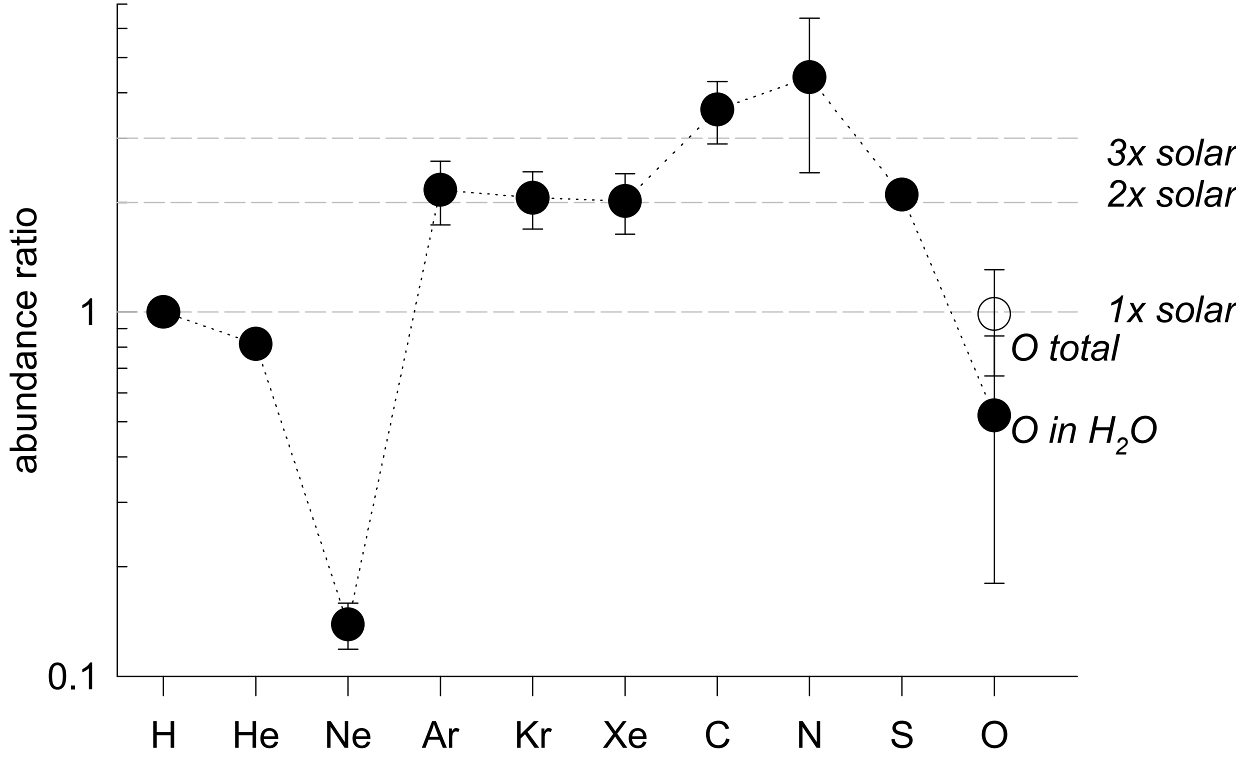
Mass density of solids is higher at the snowline and beyond from stability of water ice:

solar abundances 2009: rock ~ 0.5% and *water* ice ~ 0.6% of all mass
solar abundances AG89: rock ~ 0.5% and *water* ice ~ 0.9% of all mass
abundances allow for factor 2-3 mass increase

an increase of up to 5-10 times the rock surface density is required (Lissauer, 1987, Pollack et l 1996, Hueso & Guillot 2003)

Diffusive redistribution of water from the inner solar system and ice cold-trapping at the snow line and beyond can increase mass density (Stevenson & Lunine 1988, Cyr et al. 1998)

Jupiter/solar system, H = 1



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

The Tar-line
Carbonaceous condensation/evaporation front

Stability of organic solids during condensation and against evaporation

Carbonaceous matter more refractory than water
Gooey sticky properties

Jupiter's observed envelope composition
high carbon abundance: C/H ~ 3-4x solar
low-solar oxygen O/H 0.5 – 1 x solar

Plentiful Evidence for Solid Organics

CH_4/H_2	
Jupiter	0.0021(±0.0004)
Saturn	0.0051(±0.0010)
Uranus	0.016±0.007
Neptune	0.022±0.006

Carbonaceous matter abundant in outer solar system CH_4/H_2 (e.g., Pollack et al. 1986)
Outer planet satellites, KBOs (rock, ices, & organics)
"Kerogen" observed in carbonaceous chondrites, cometary organics

On Jupiter, C/S ratio is *larger* than solar ratio; C is enriched over more refractory S

Sources of Carbonaceous Material
Non-vaporized organics
 up to 50% of all C in the ISM is tied to organic solids (Ehrenfreund et al. 1991)
Organics produced in the (outer) solar system
 Non-equilibrium carbonaceous dust production (at <530K at 10^{-6} bar)
 Fischer-Tropsch type catalyzed reactions,
 ion-molecule & photochemical reactions
 (e.g, Prinn & Fegley 1989, Aikawa et al. 1999)

C and O in Giant Planets relative to solar

	C/H_2	O/H_2
Jupiter	3 – 4	0.5 – 1
Saturn	7.4 (±2.4)	3.7 – 6.4
Uranus	32	≤ 260
Neptune	41	440

Non-uniform C and O abundance variation relative to solar:

Jupiter & Saturn more enriched in C than O

Uranus & Neptune more enriched in O than C, very high H_2O enrichments
“Neptune, the God of the Seas…”

If the abundance variations are inherited from the solar nebula, there should be
Regions dominated by silicates, (water) ice and solid *organics* in accretion disks

See Lodders & Fegley 1994, Lodders 2004, Visscher et al. 2005 (CO, PH_3, SiH_4)

Conclusions

The terrestrial planet compositions *may* record trends in oxidation state

The C and O abundances in gas giant planets likely preserve a memory of the position of major low-temperature condensation/evaporation fronts:
a snow-line and a tar-line

If present, a tar-line of refractory organics is positioned closer to the star than the snow-line

Likely positions in the solar nebula: tarline ~ 5.2 AU, snow-line
Compared to methane, water abundances increase more strongly from Jupiter to Uranus suggesting water ice pile-up in the outer solar system