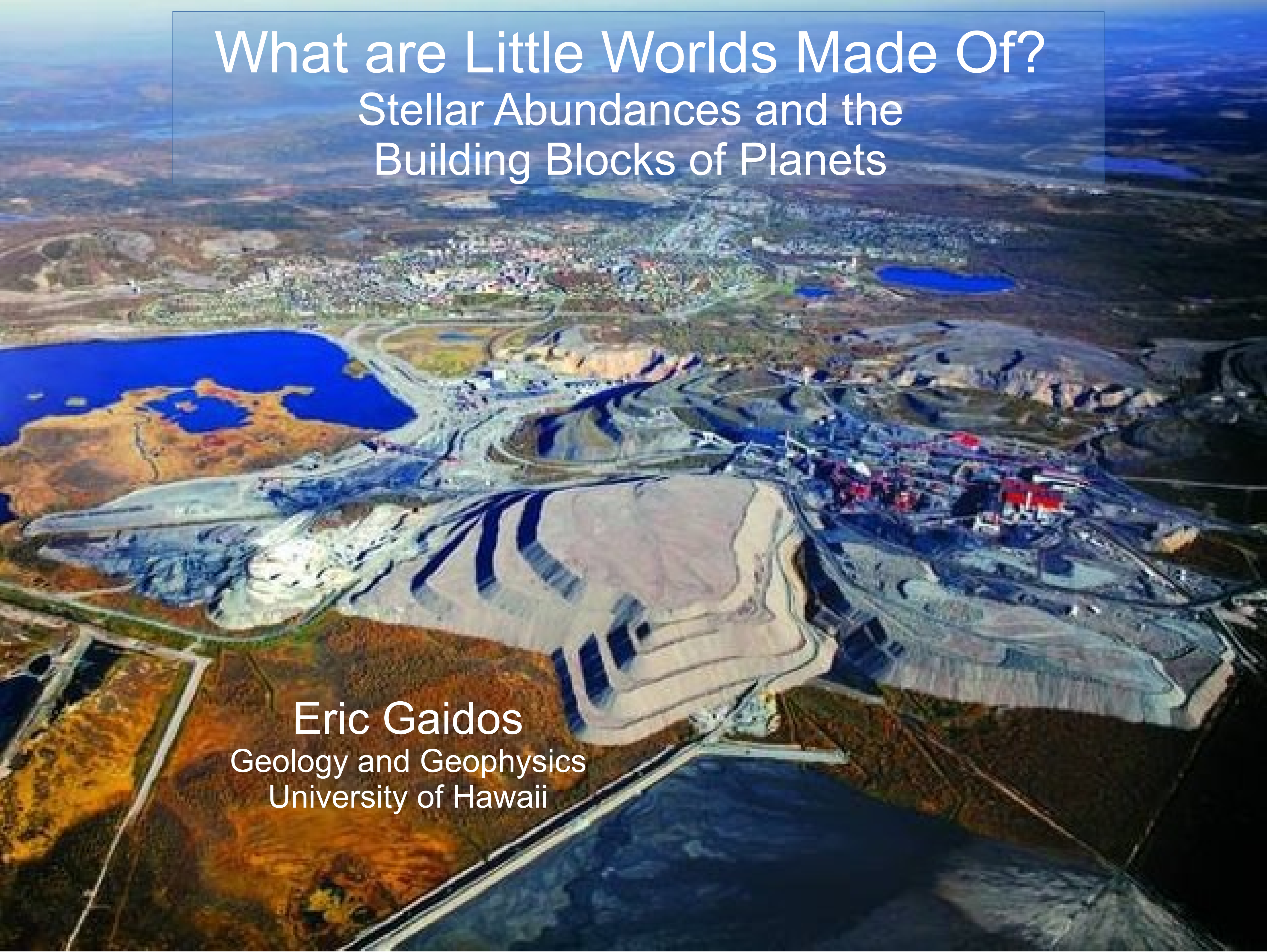
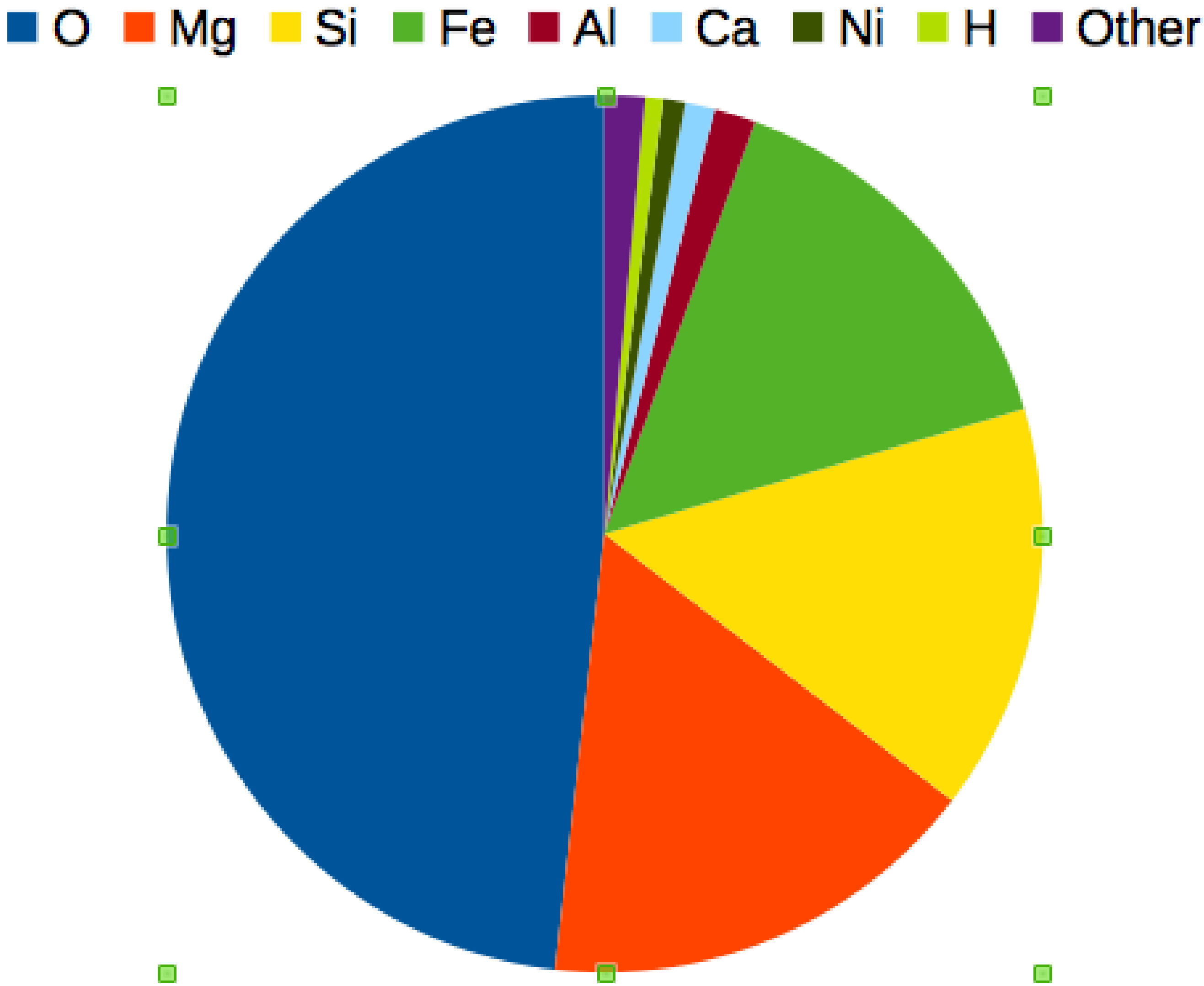
What are Little Worlds Made Of?

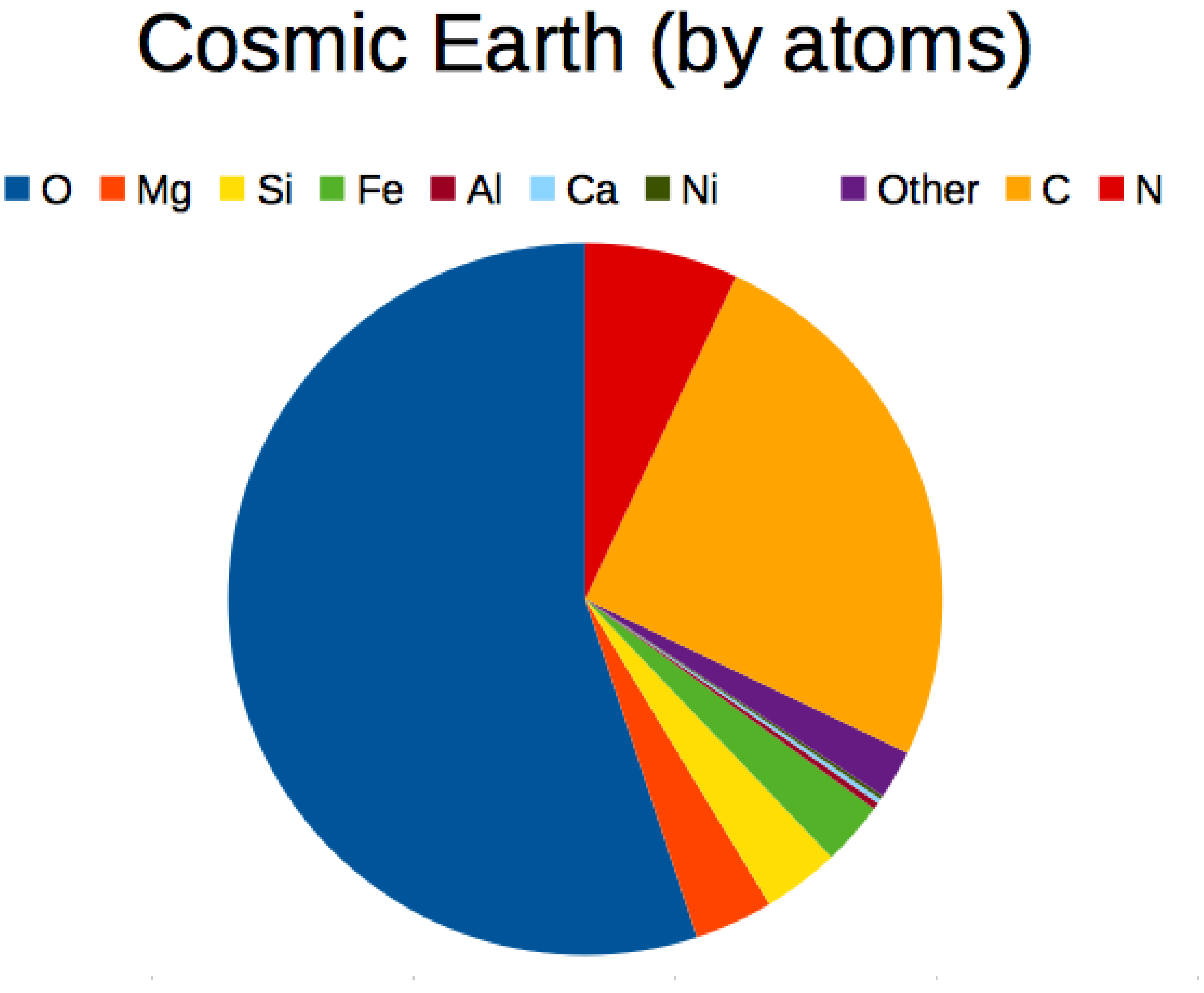
Stellar Abundances and the Building Blocks of Planets



Eric Gaidos
Geology and Geophysics
University of Hawaii

Bulk Earth (by atoms)




Cosmic Earth (by atoms)
O
Mg
Si
Fe
Al
Ca
Ni
Other
C
N

The Carbon to Oxygen Ratio (C/O)

Solar C/O = 0.55 ± 0.12 (Caffau et al. 2010)

$$C + O \rightarrow CO$$

Condensation temperature ~ 50 K

C/O < 1 (excess O)

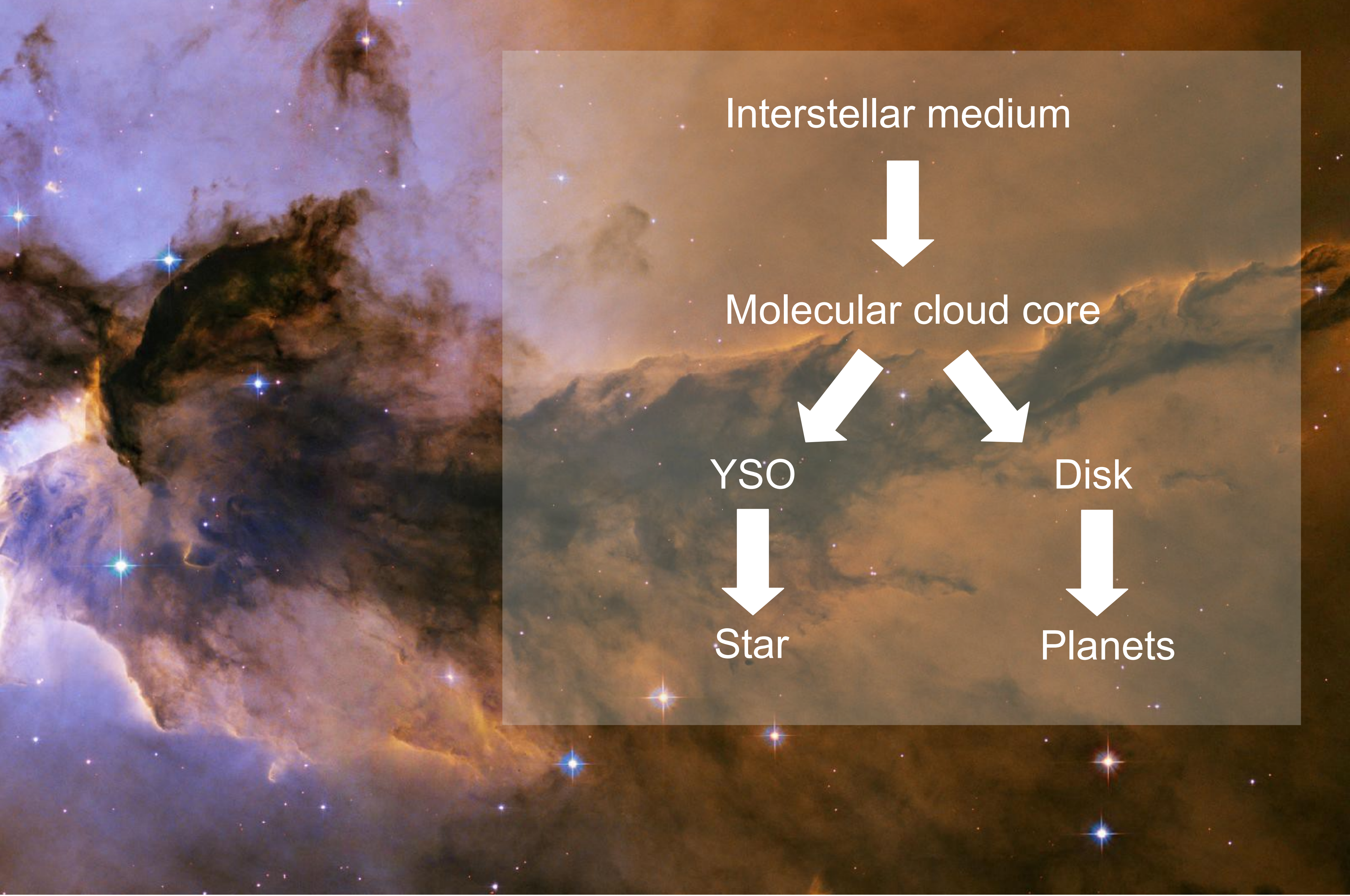
- Carbon is depleted
- Silicates condense at high T
- Most excess O condenses as H_2O

C/O > 1 (excess C)

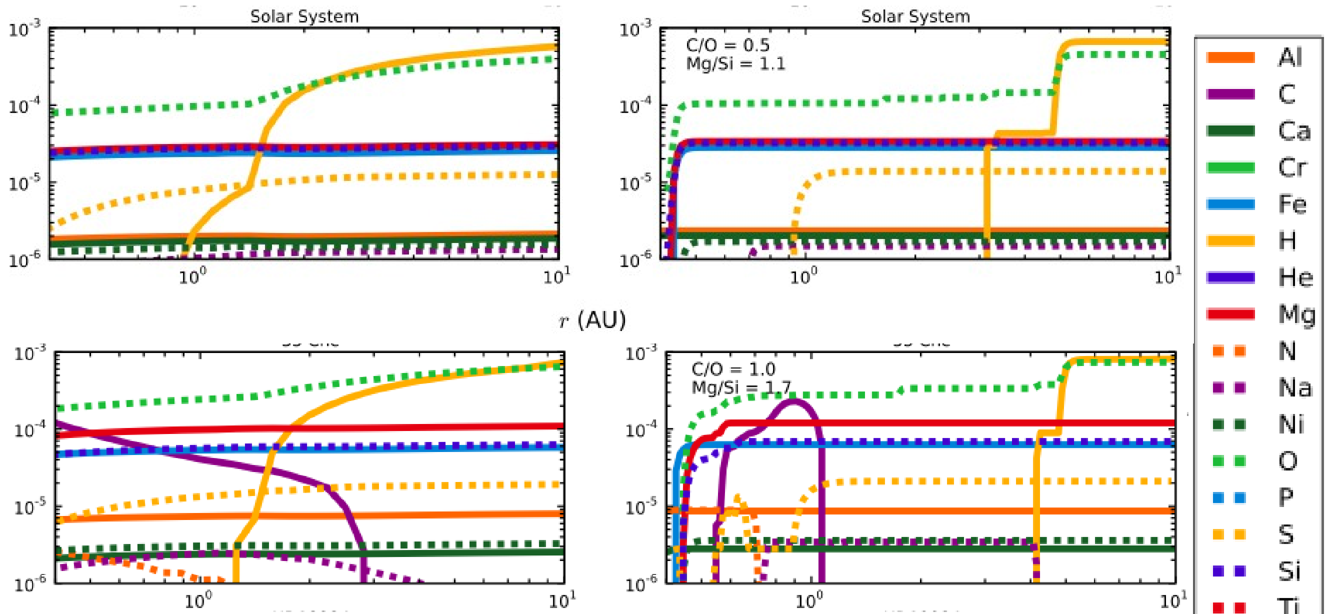
Oxygen is depleted
Silicon carbides condense at high T
Most excess C condenses as graphite or hydrocarbons

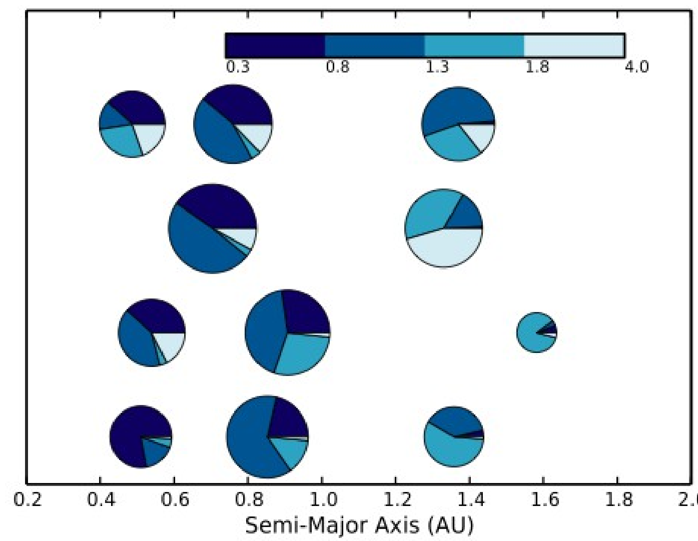
$$\frac{water}{rock} = 2.23 \frac{0.88 - C/O}{1 + C/O}$$

Stars and Planets: A Common Chemical Inheritance



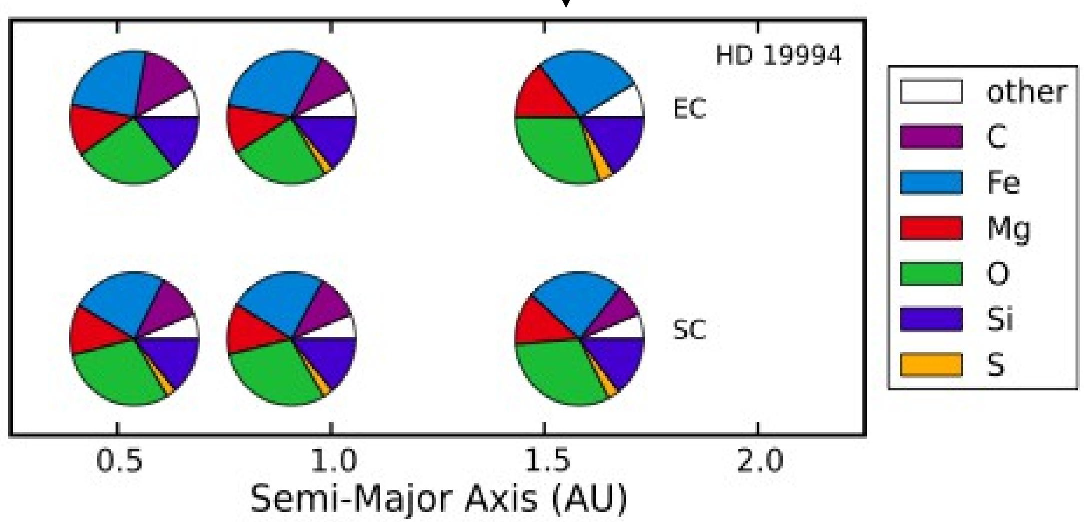
Solar System (C/O=0.55)



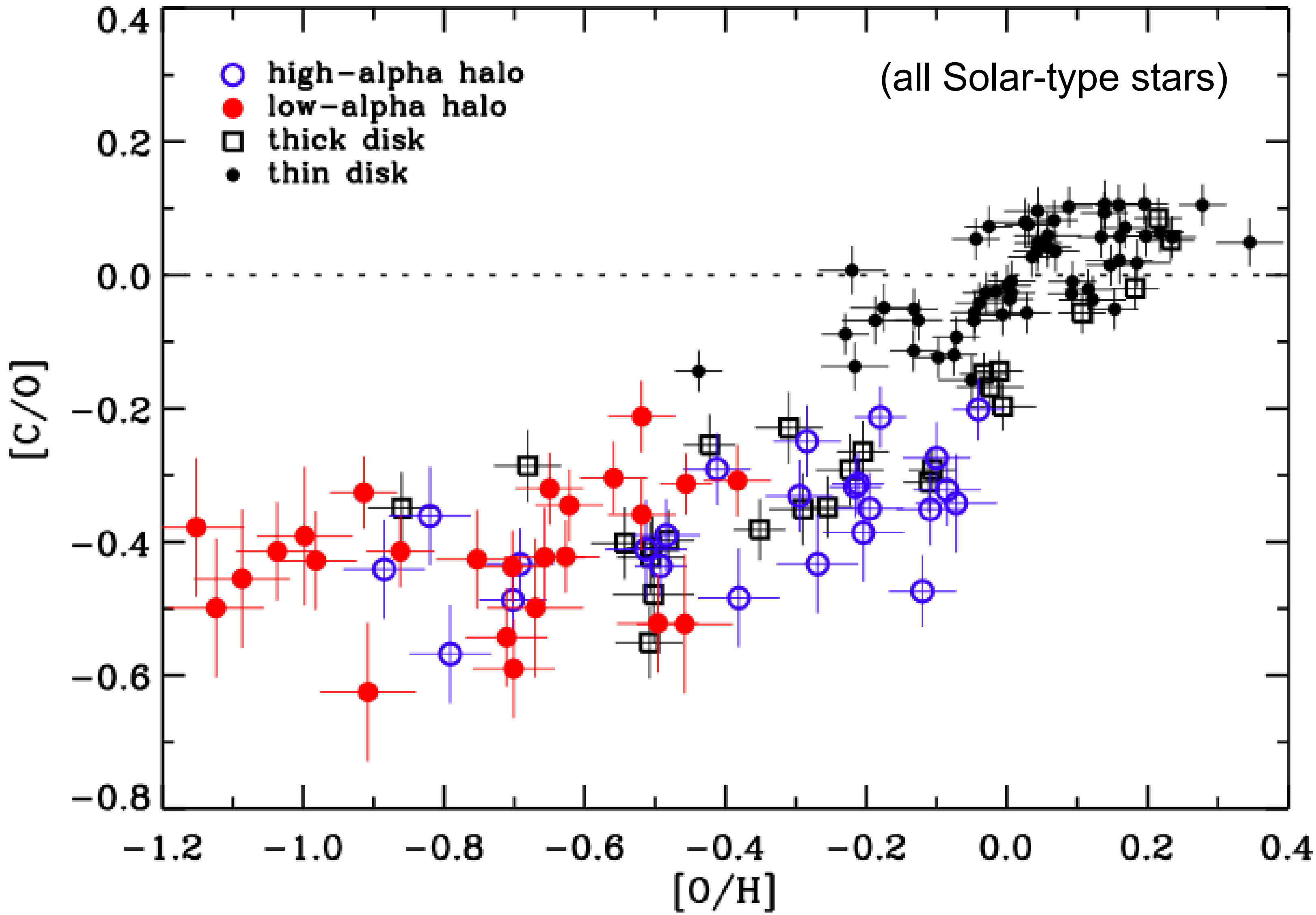


55 Cnc (C/O = 1.12?)

Moriarty et al. (2014)

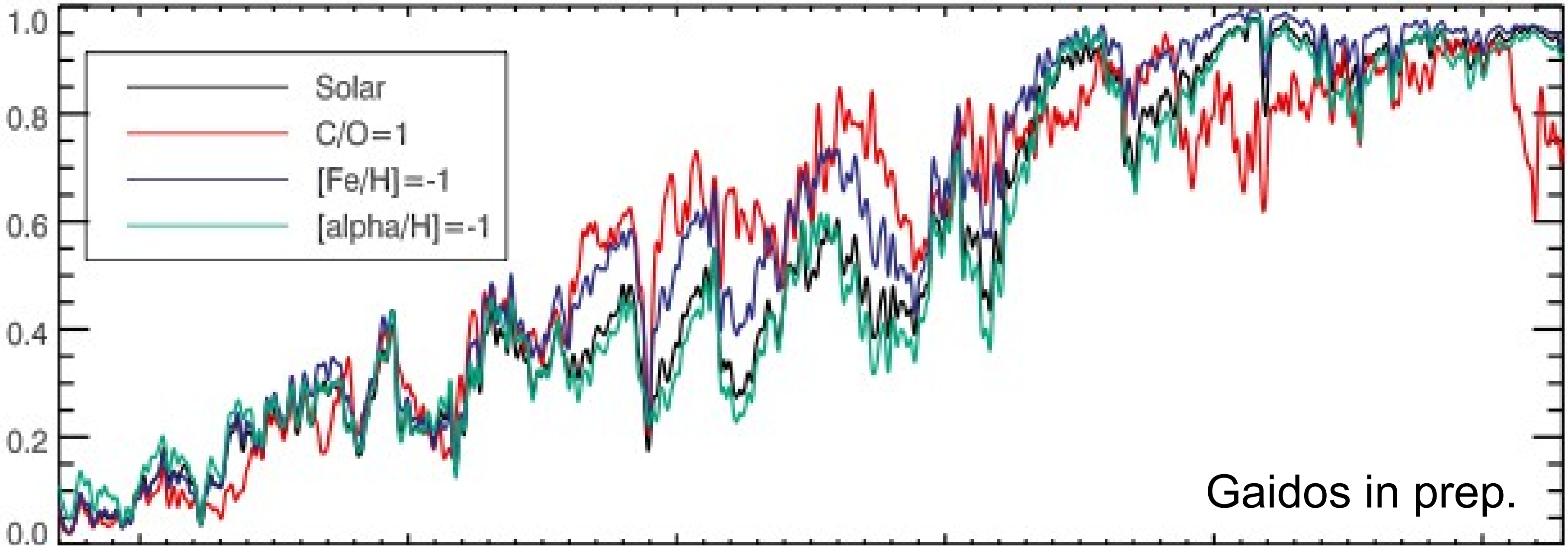


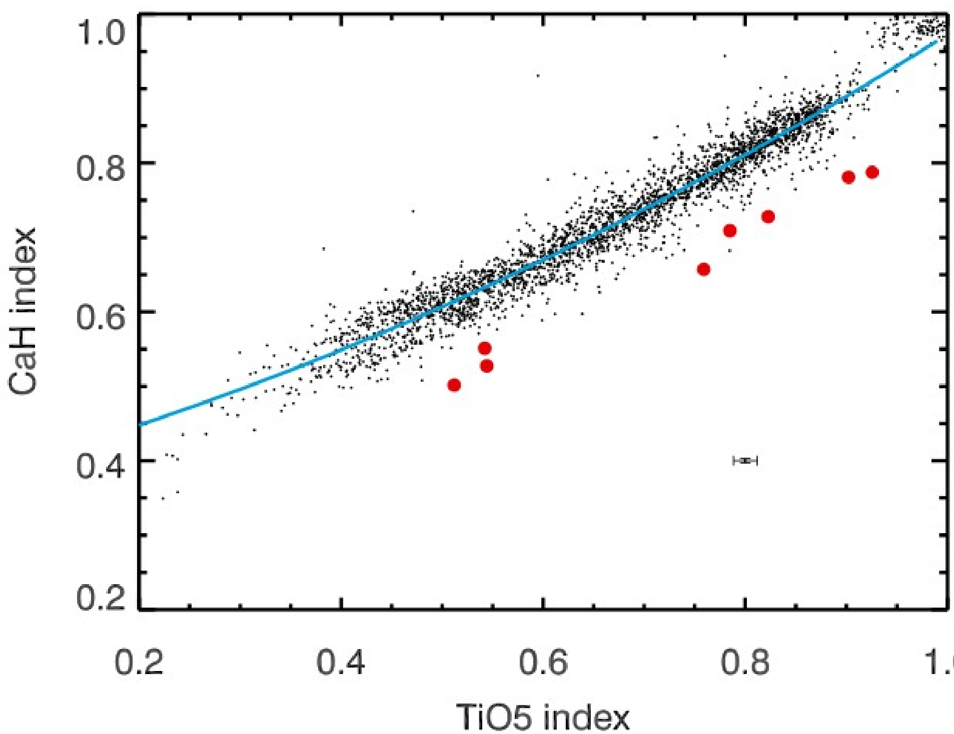
Problem 1: Most/all Stars Have Solar or Lower C/O

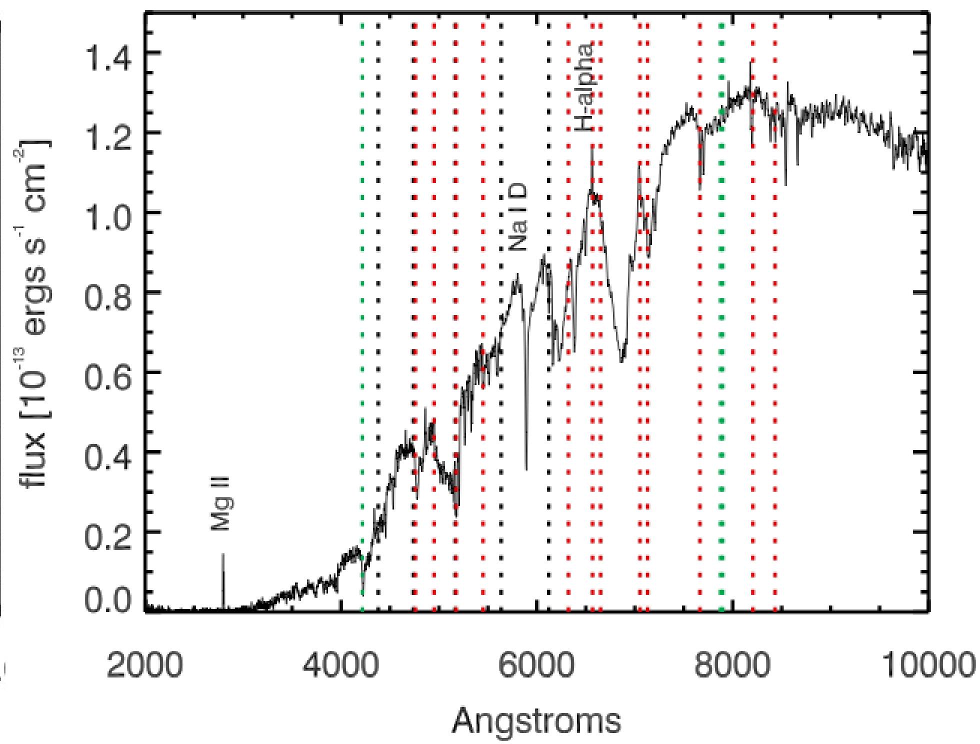


Nissen et al. 2014

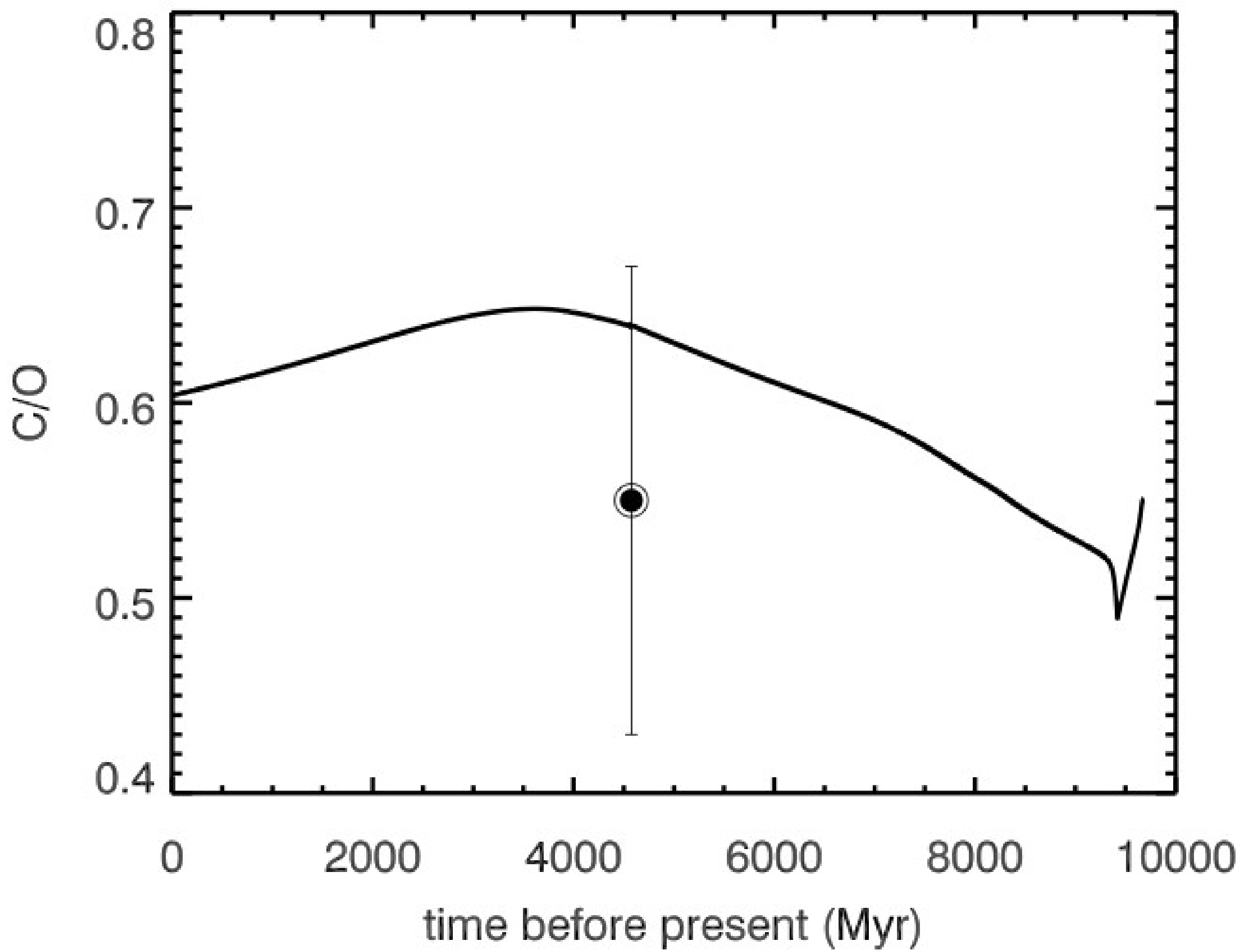
Fewer than < 1 in 10^4 M Dwarfs have C/O ~ 1





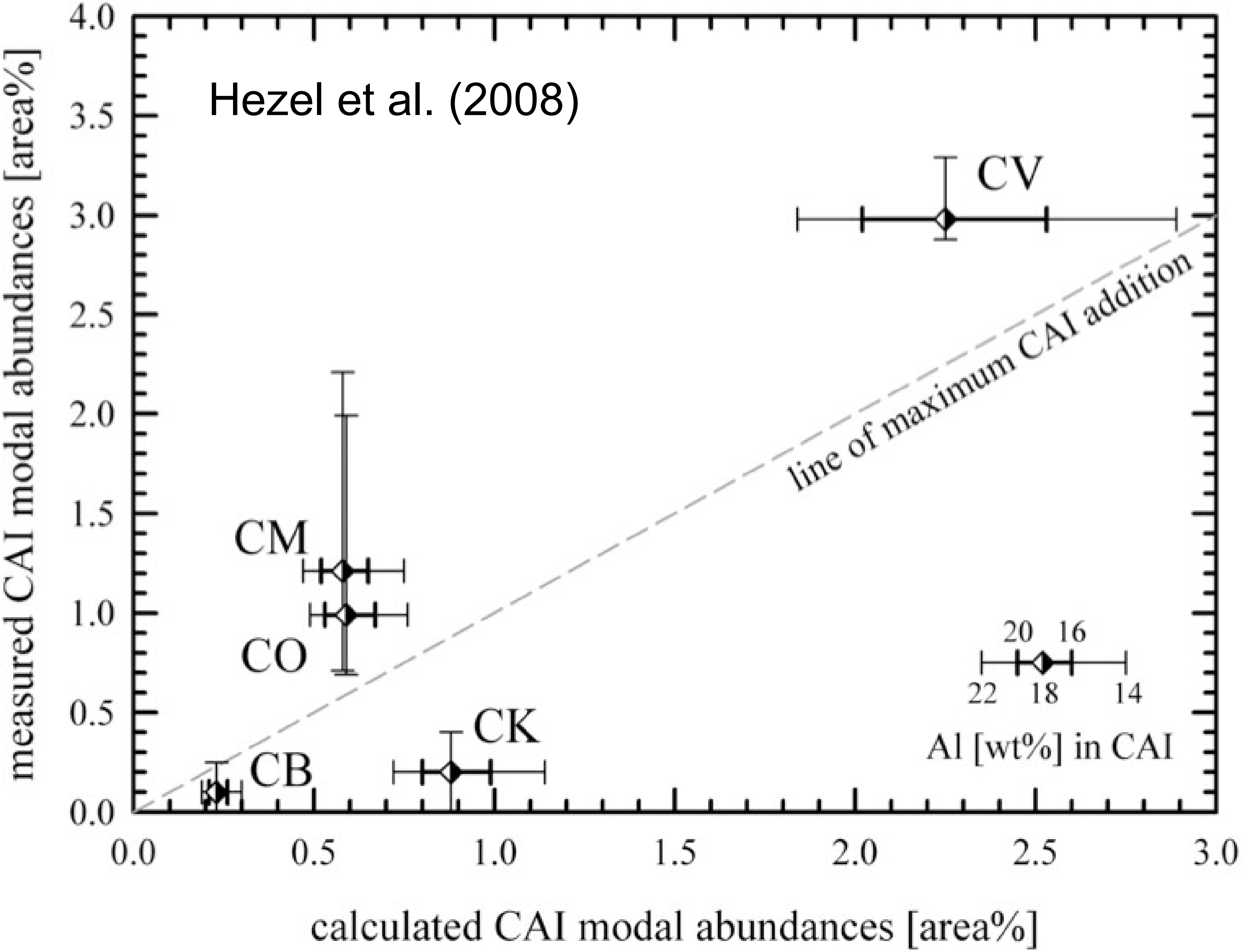


Problem 2: Galactic Chemical Evolution Models do not Predict C/O ~ 1

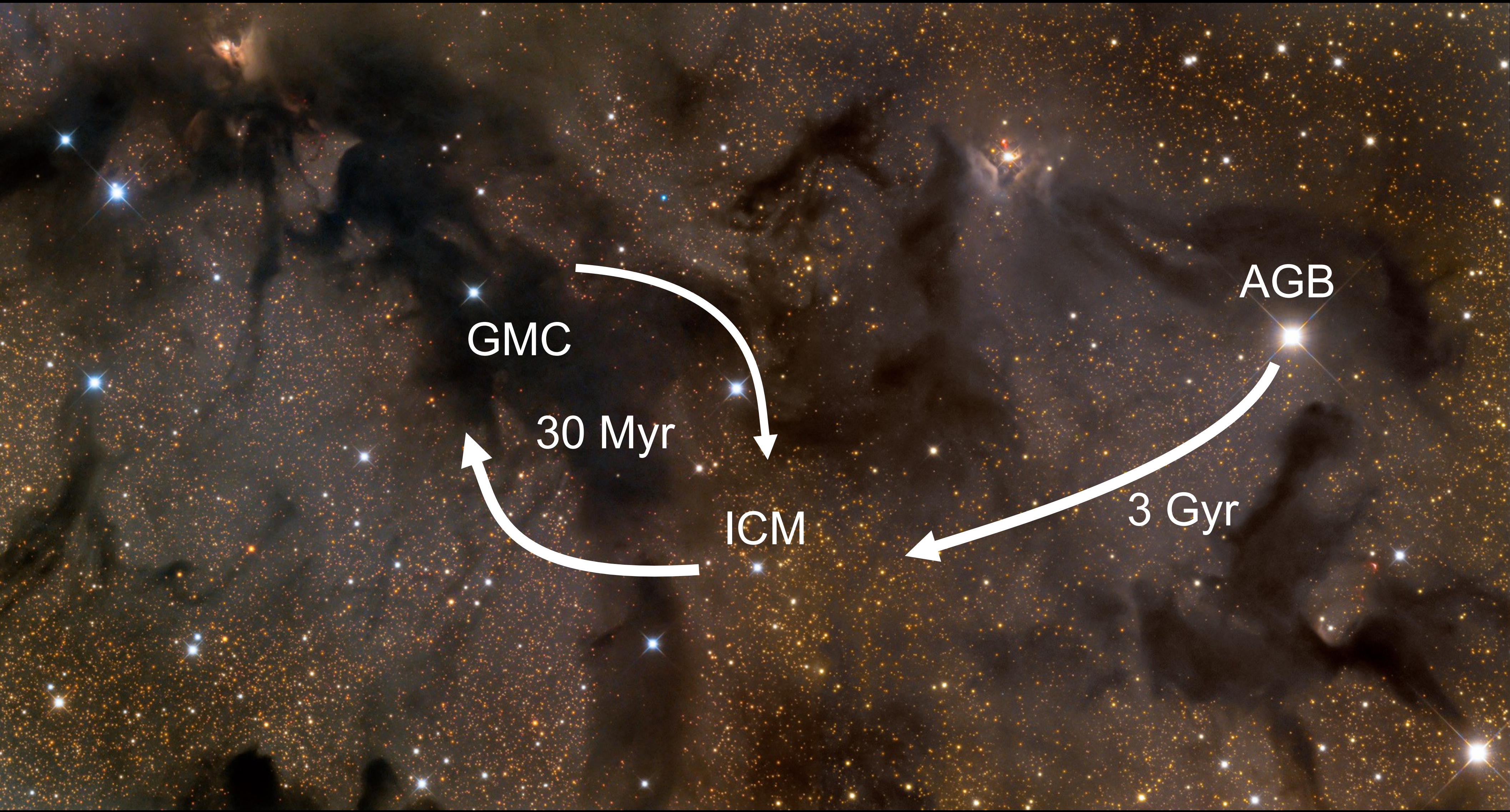


Gaidos in prep.

Problem 3. Solar System Planets did not Condense from Hot Disk Gas but mostly Processed Interstellar Dust

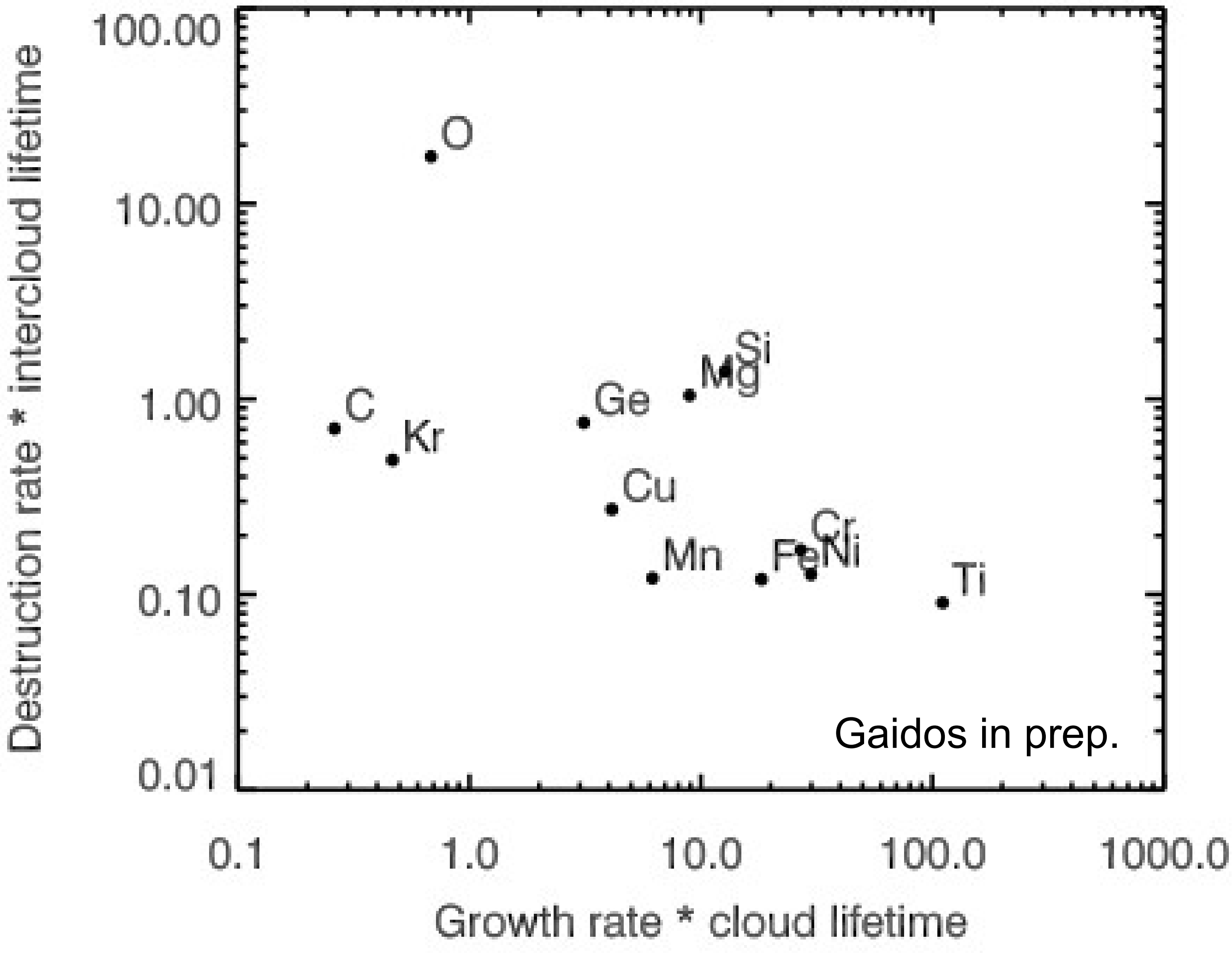


What is the C/O of Interstellar Dust?

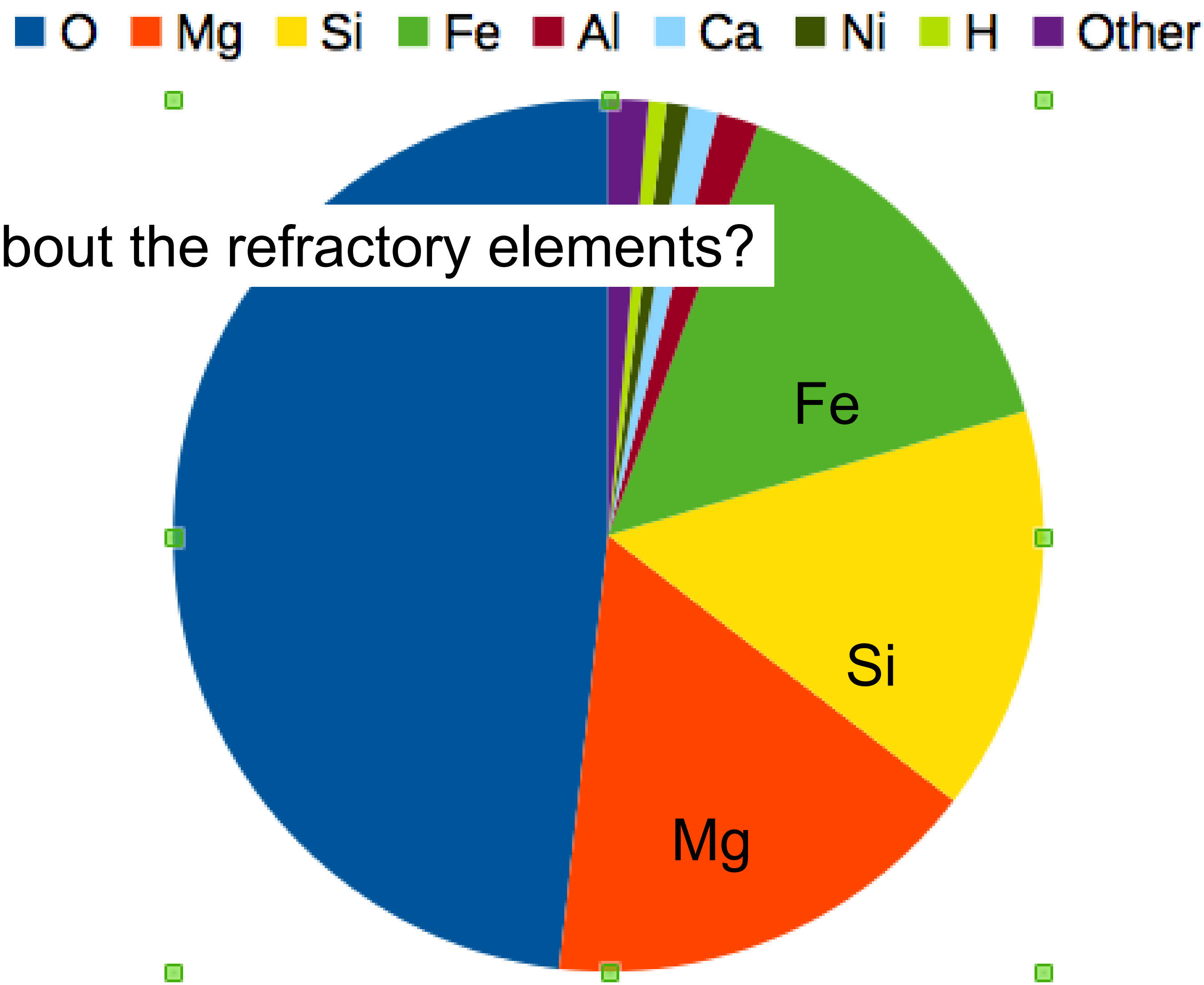


Controlled by rates of growth and destruction of grains in the ISM

Inferred Elemental Growth and Destruction Rates in Dust

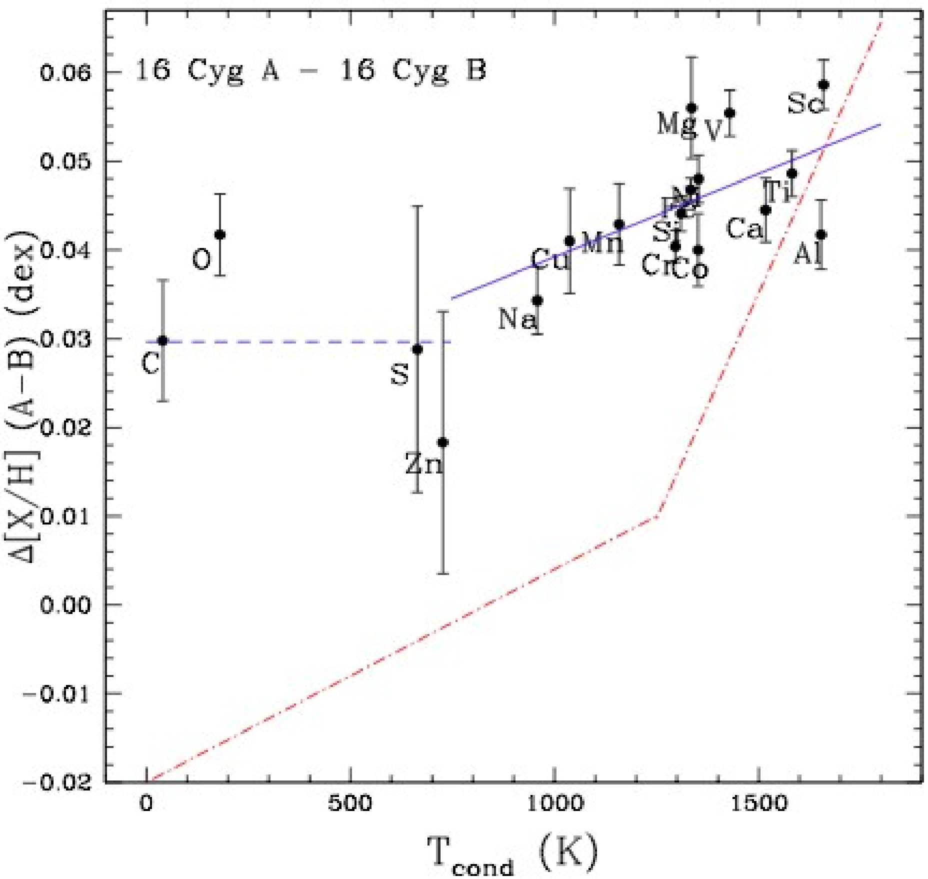


Bulk Earth (by atoms)

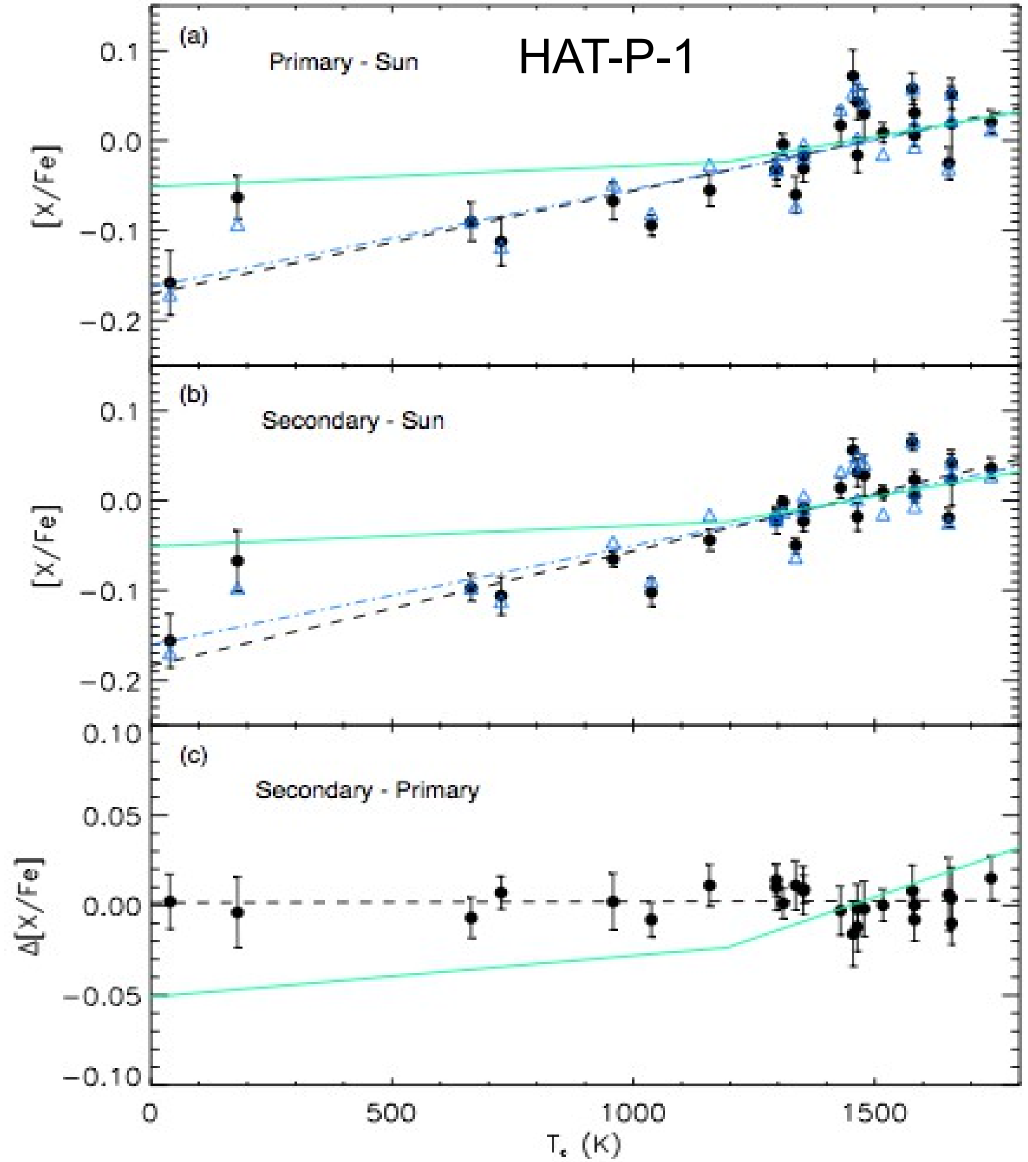


What about the refractory elements?

A Signature of Planets?

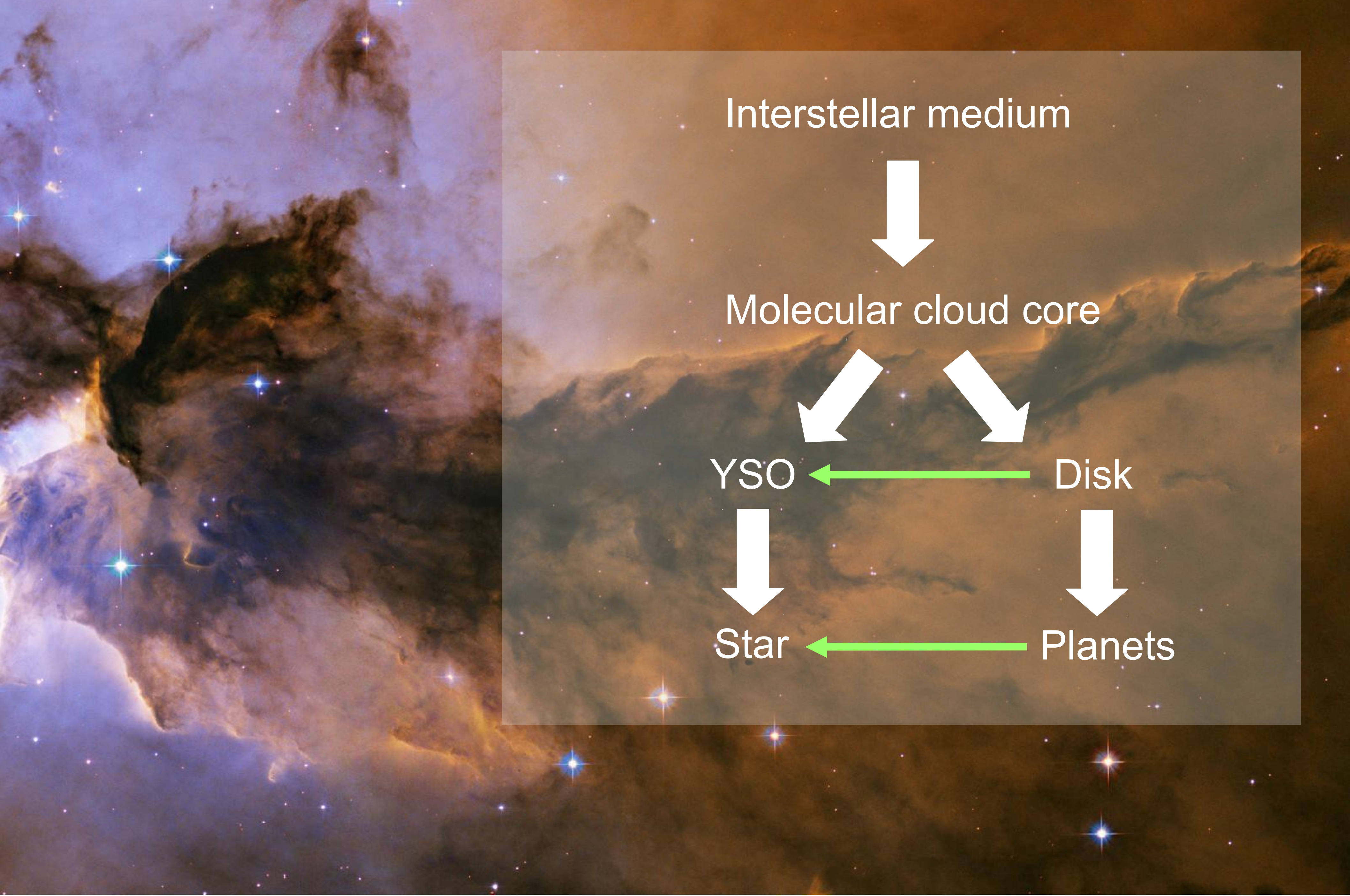


Maia et al. (2014)

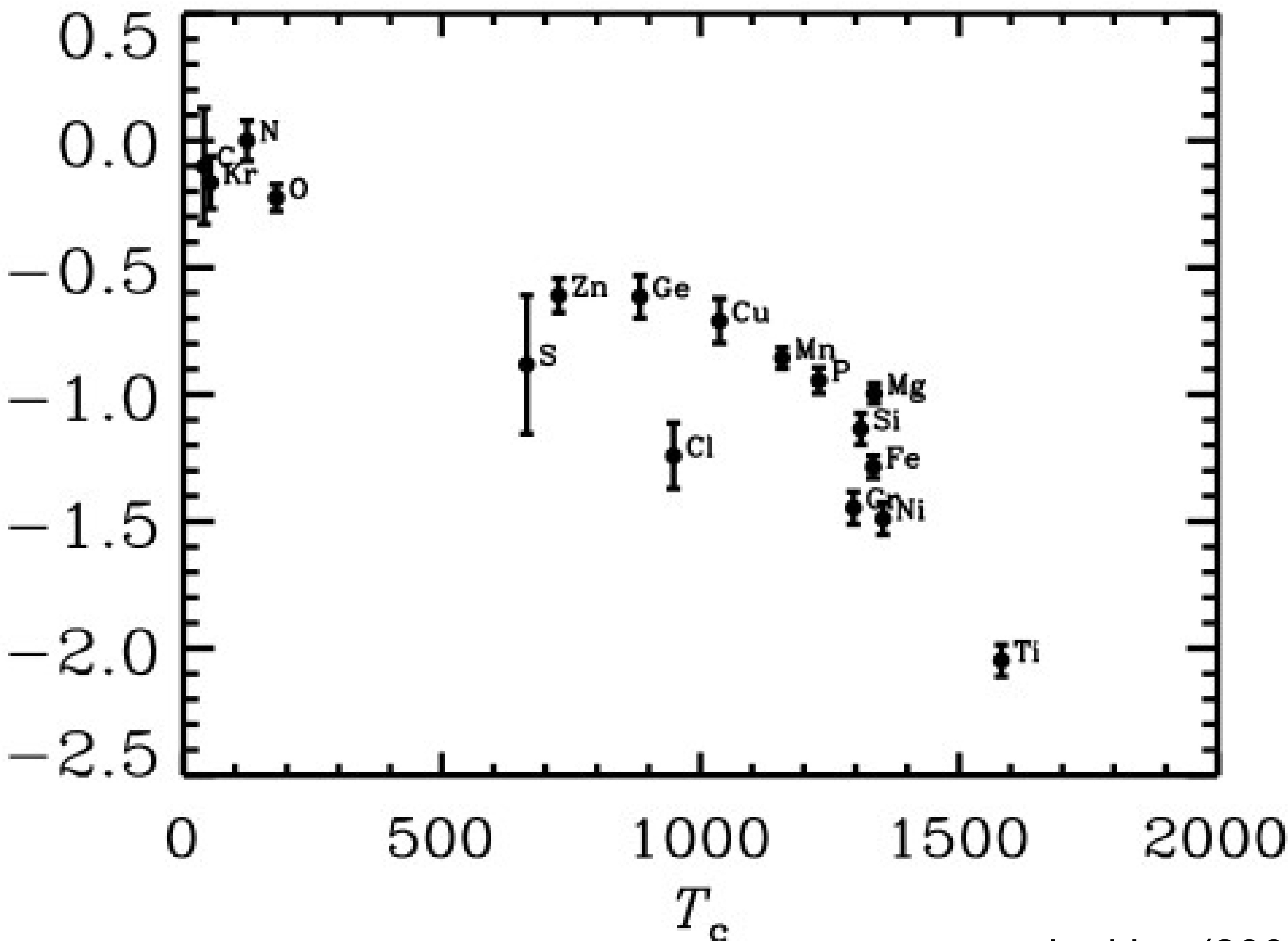


Liu et al. (2014)

Stars and Planets: A Common Chemical Inheritance



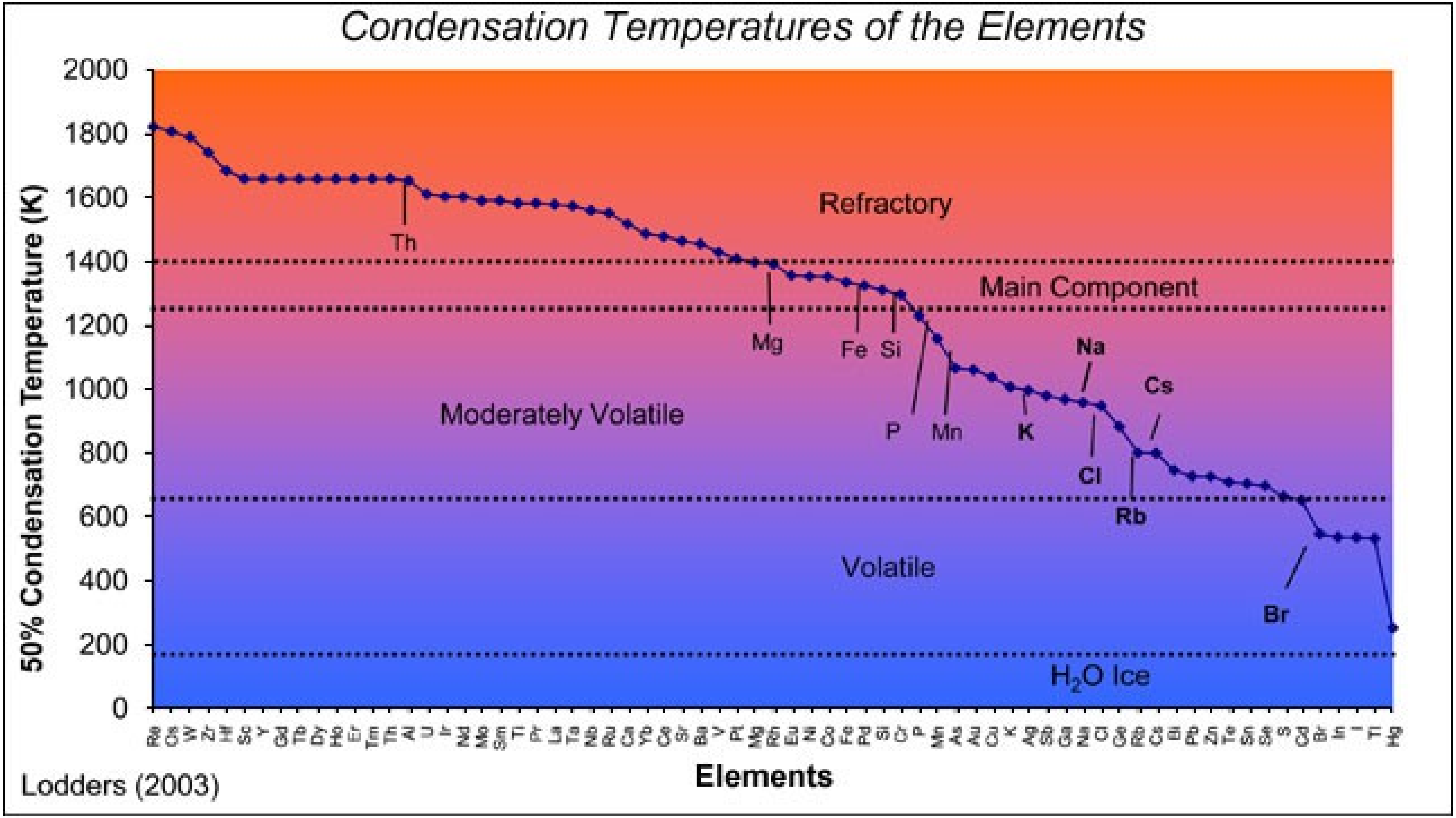
ISM Gas Depletion Imitates Condensation Temperature: "Planet Signature" may be Gas-Dust Segregation



Jenkins (2009)

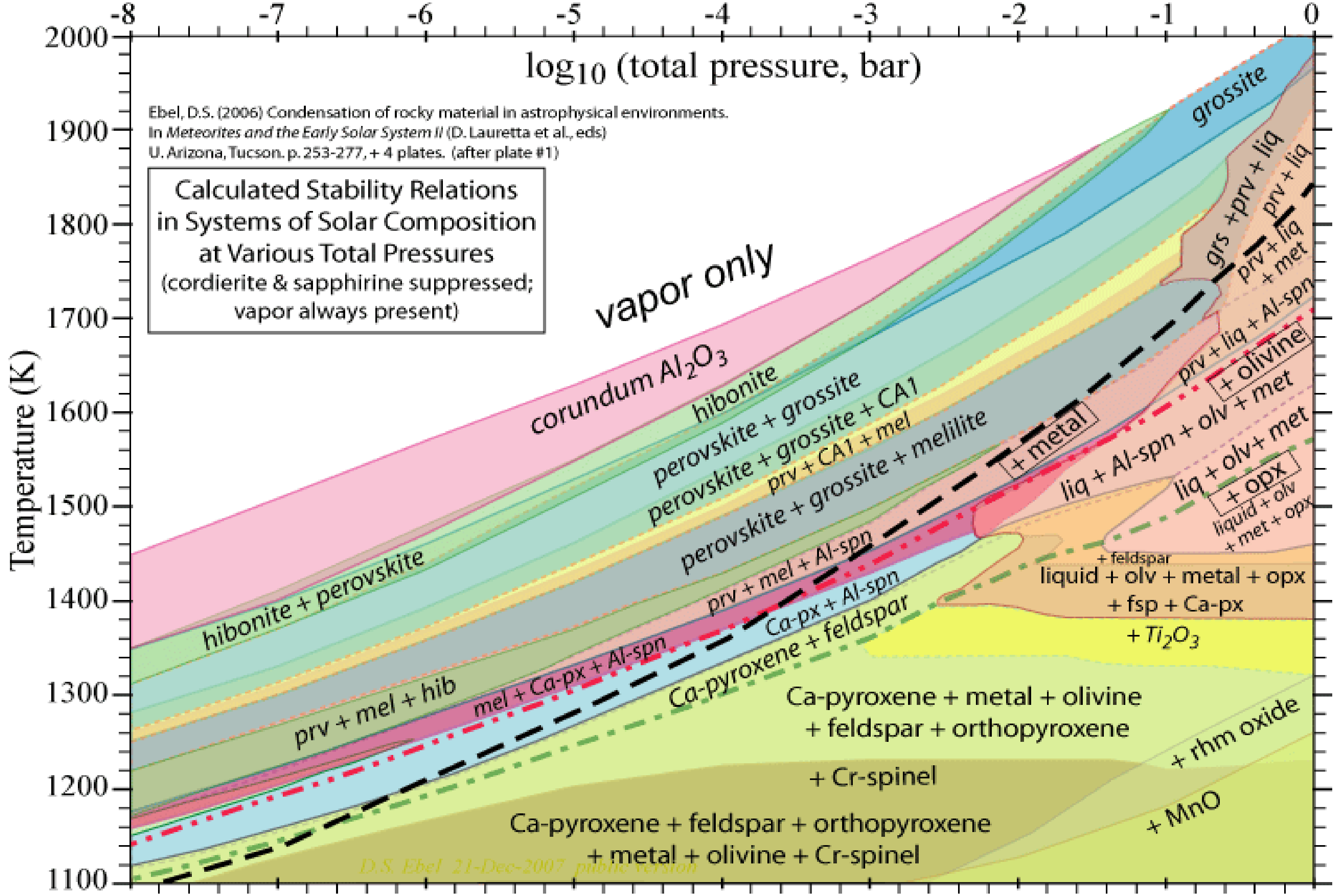
Summary

- Stars with primordial C/O ~ 1 are rare, if they exist at all, and are not predicted by GCE models
- Building blocks of Solar System planets were formed from processed interstellar dust, with little condensates from disk gas
- ISM dust is likely to be as oxidized or more oxidized than the bulk ISM
- Variation in the abundances of the refractory elements in stars may be a signature of gas- dust segregation, not planet formation
- Exoplanet scientists need to talk to cosmochemists and ISM researches more



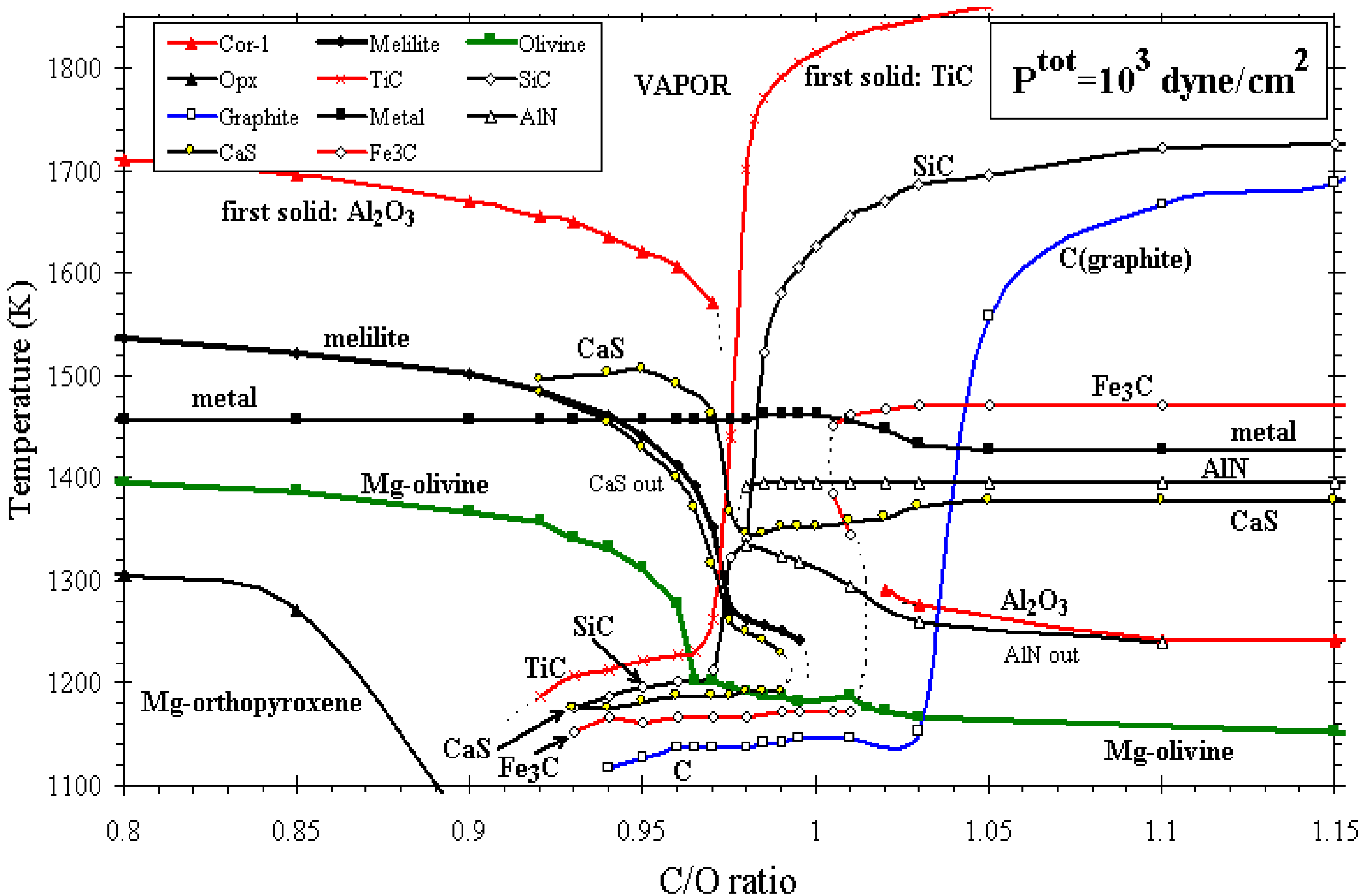
(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)

Condensation Sequence for Gas of Solar Composition



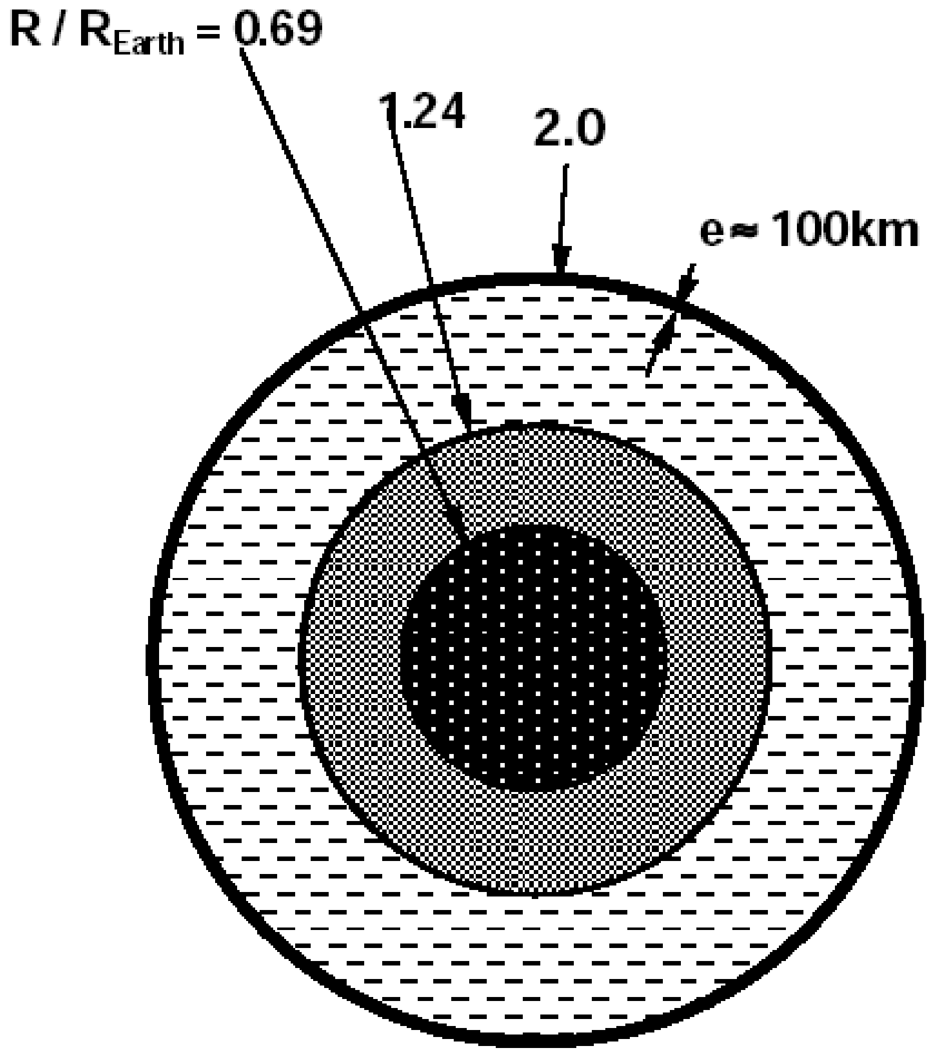
Ebel (2006)

Variation of Condensation Sequence with C/O



Ebel (1999)

Low C/O: Water Worlds?

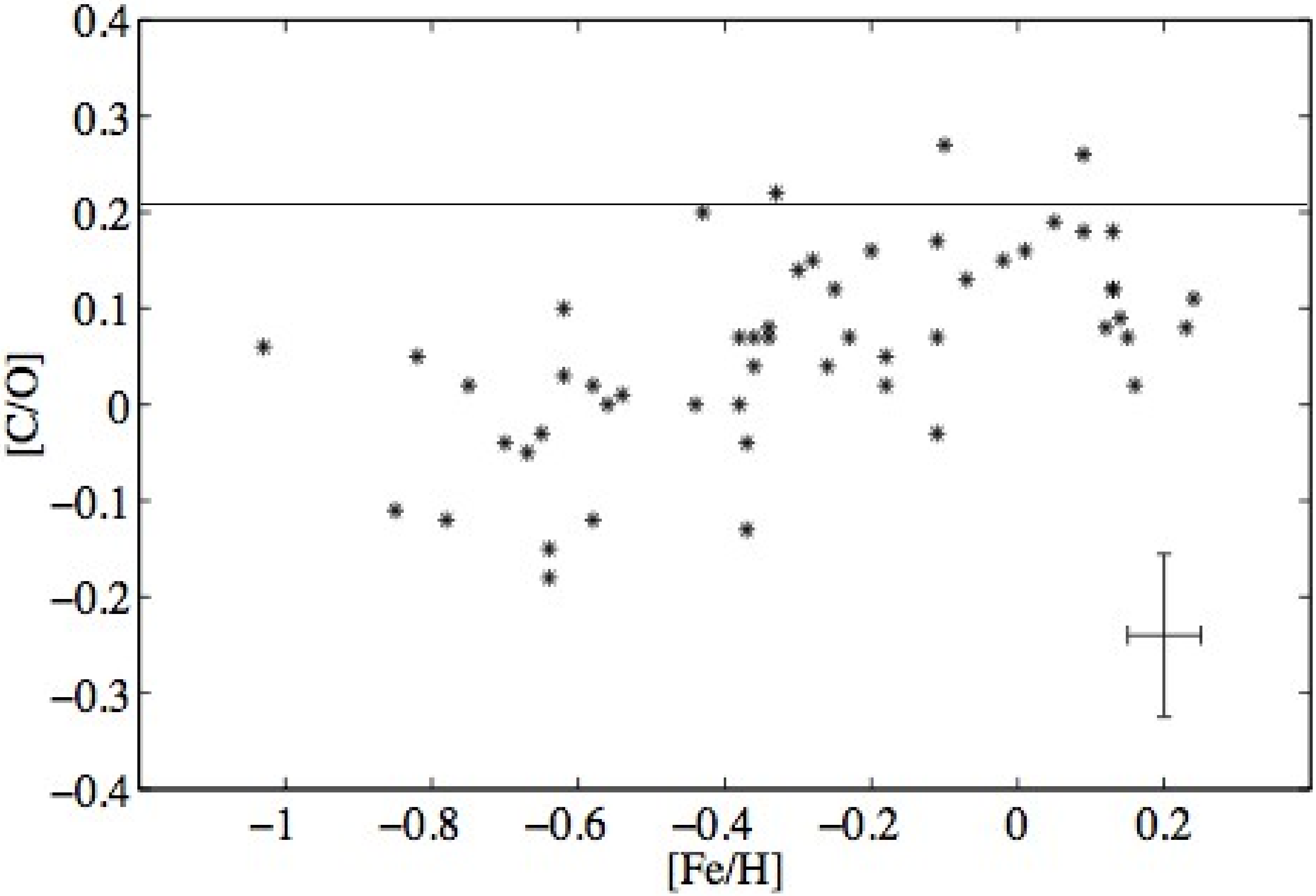


Leger et al. (2004)

Variation of C/O Between Stars?

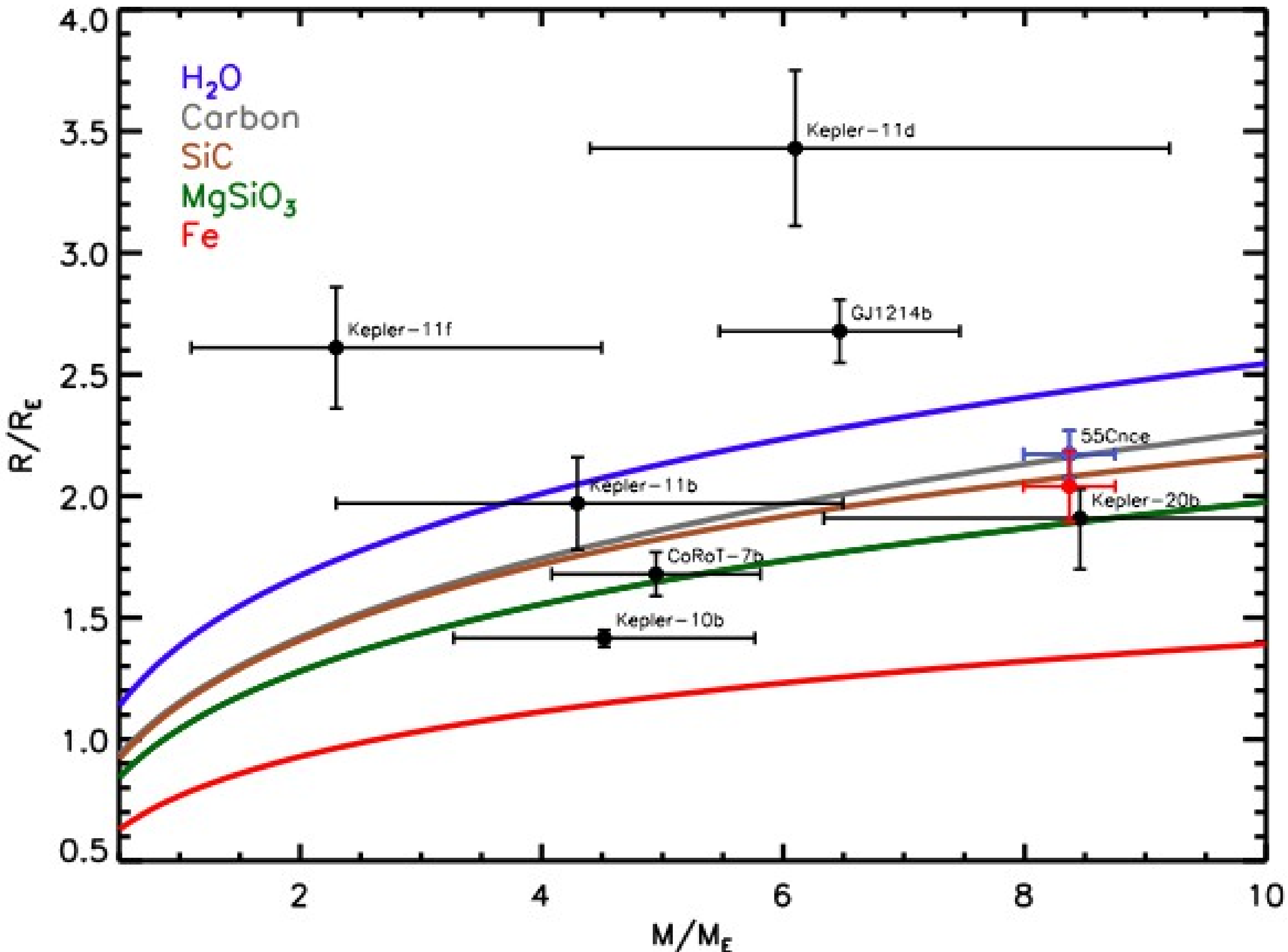
C/O = 0.88

C/O ~ 0.55



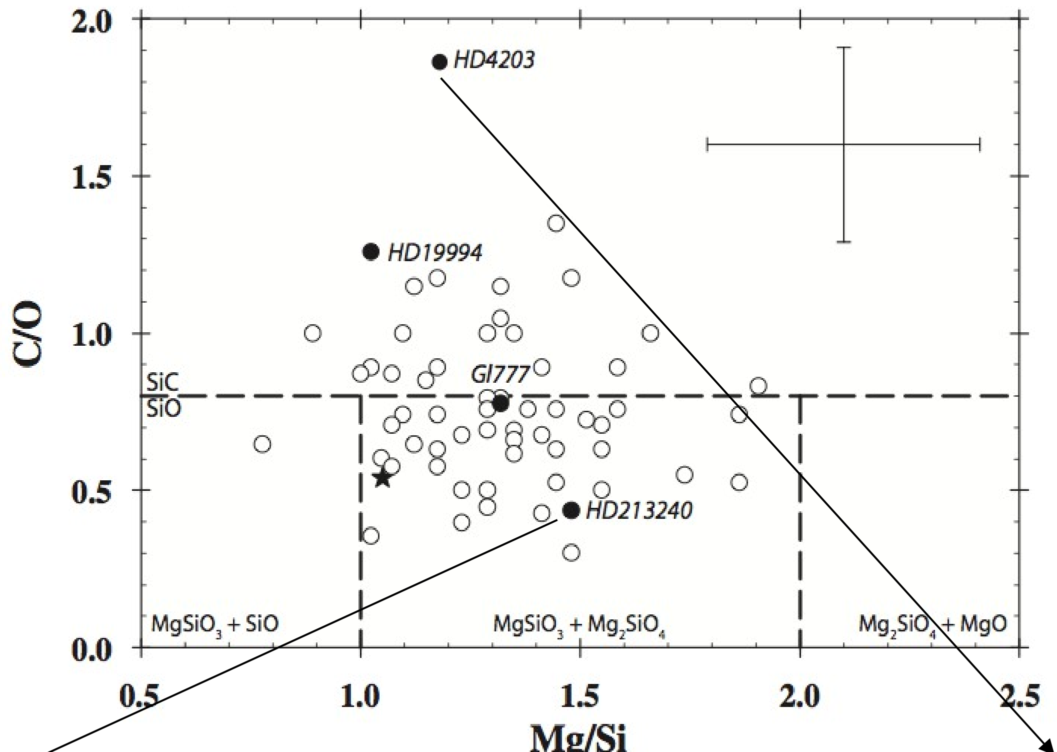
Gustafsson et al. (1999)

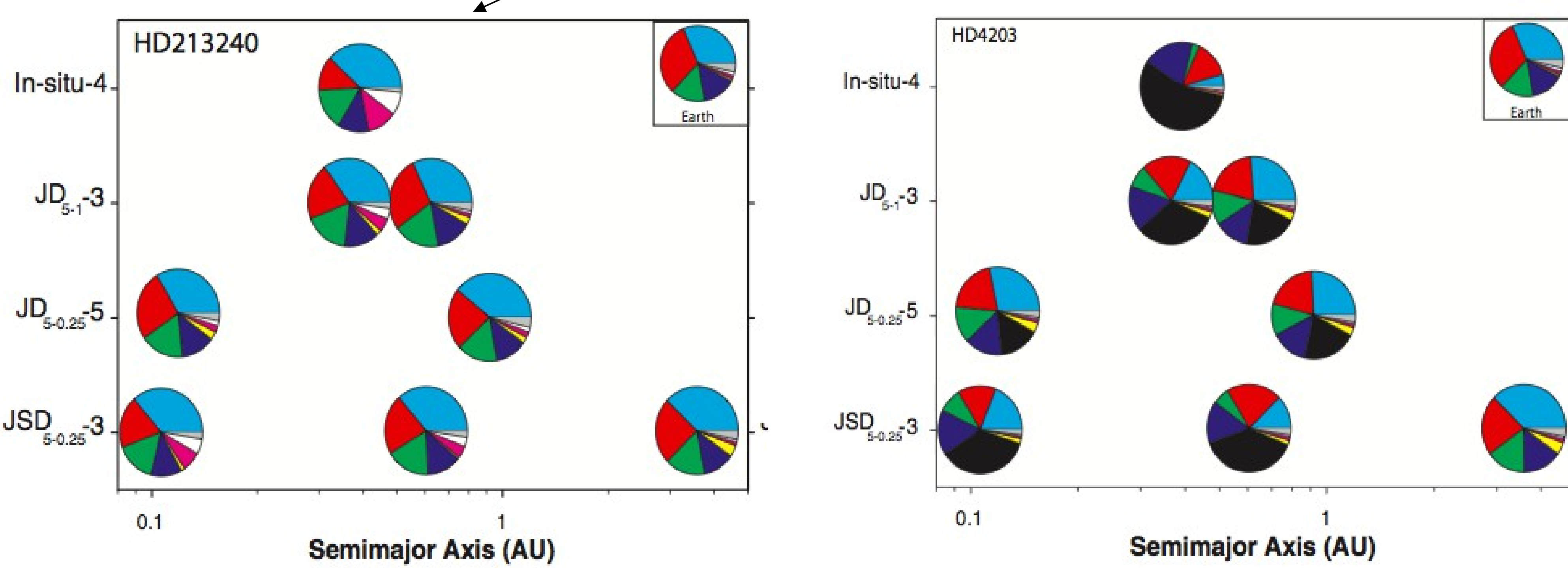
55 Cnc: A C/O=1.12 Star with a Carbide Planet?



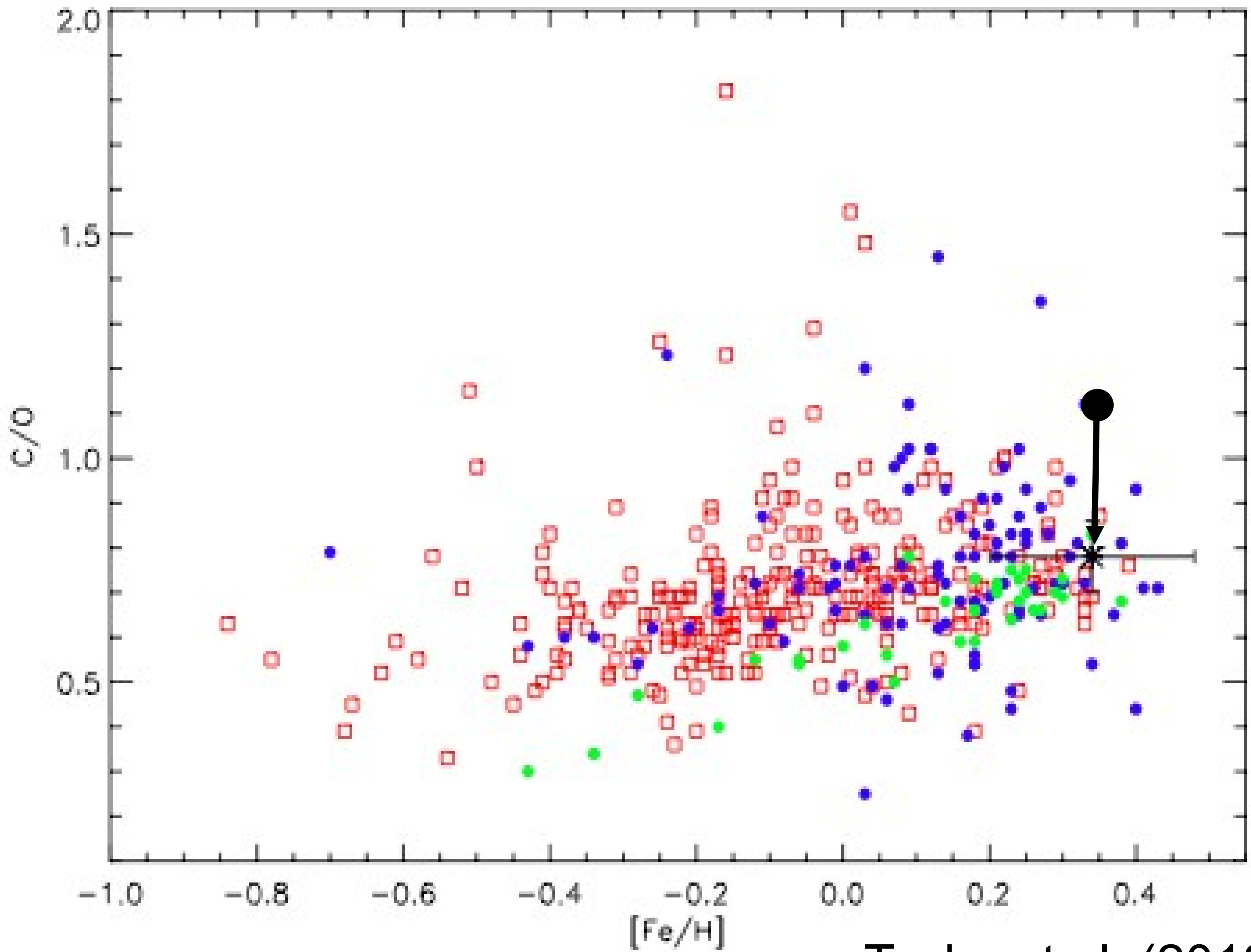
Medhuseden et al. (2012)

Carter-Bond et al. (2013)



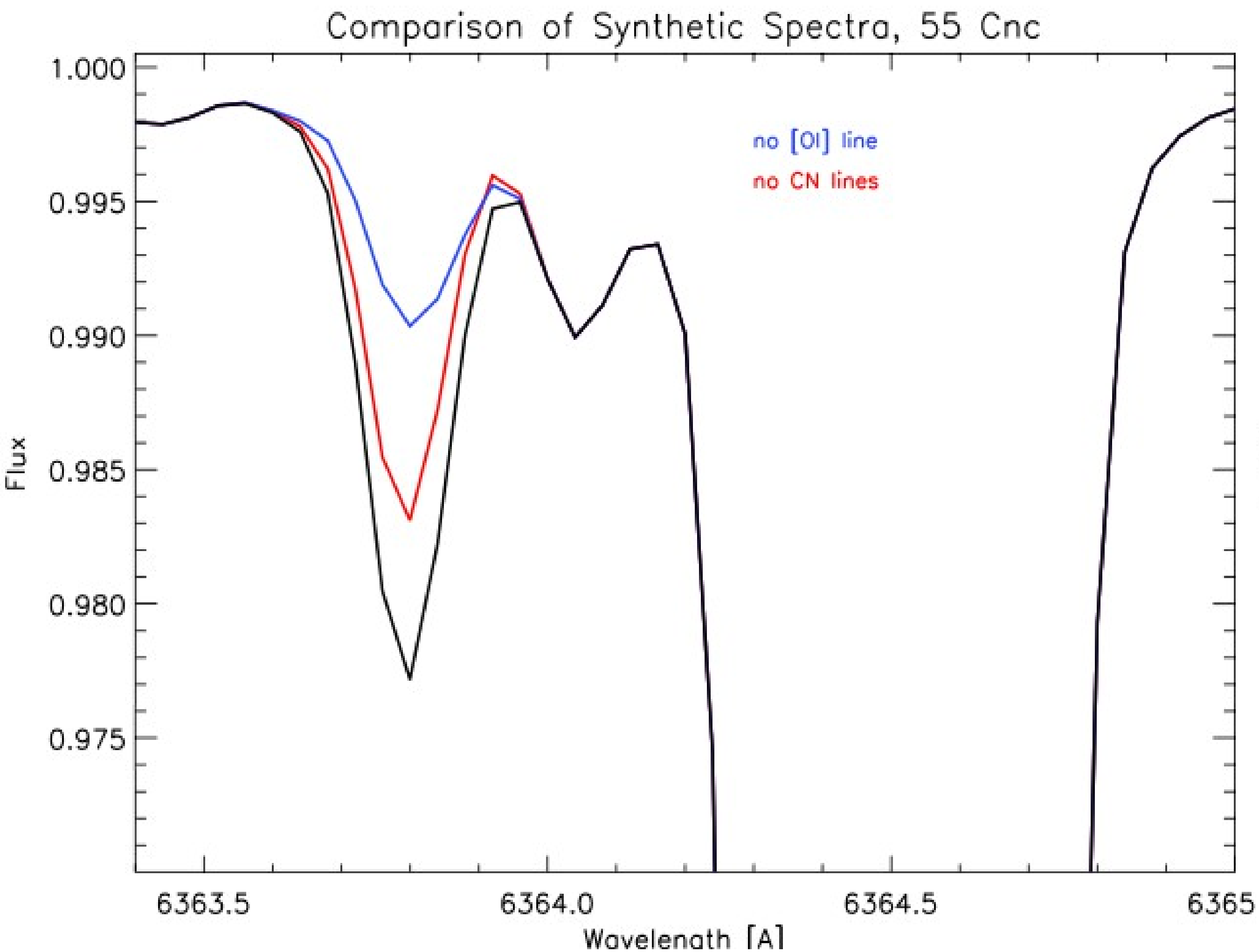


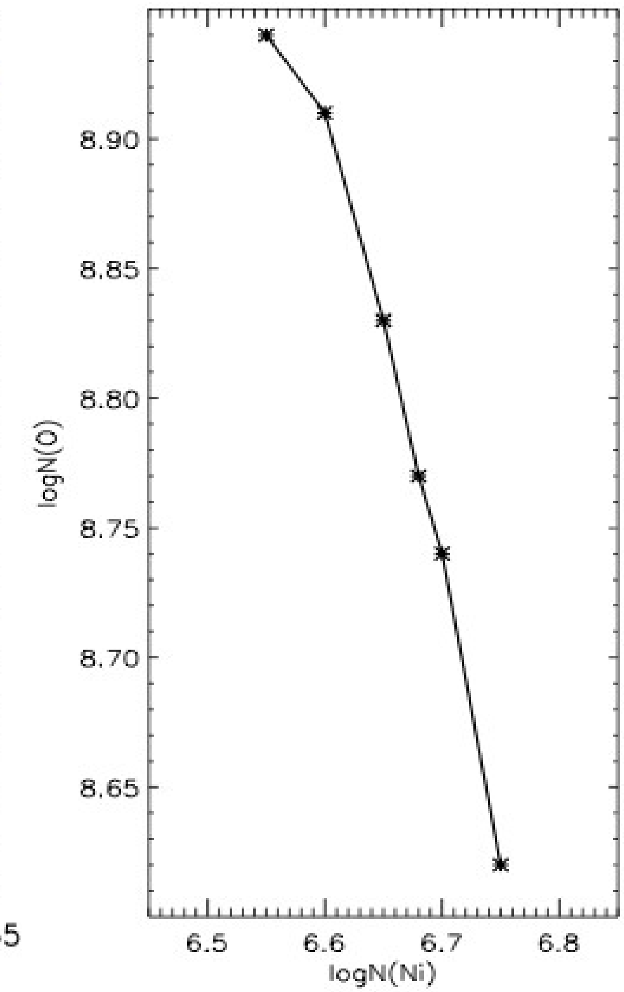
Downward Revision of 55 Cnc C/O



Teske et al. (2013)

Measuring [C] and [O] is difficult for solar-type stars

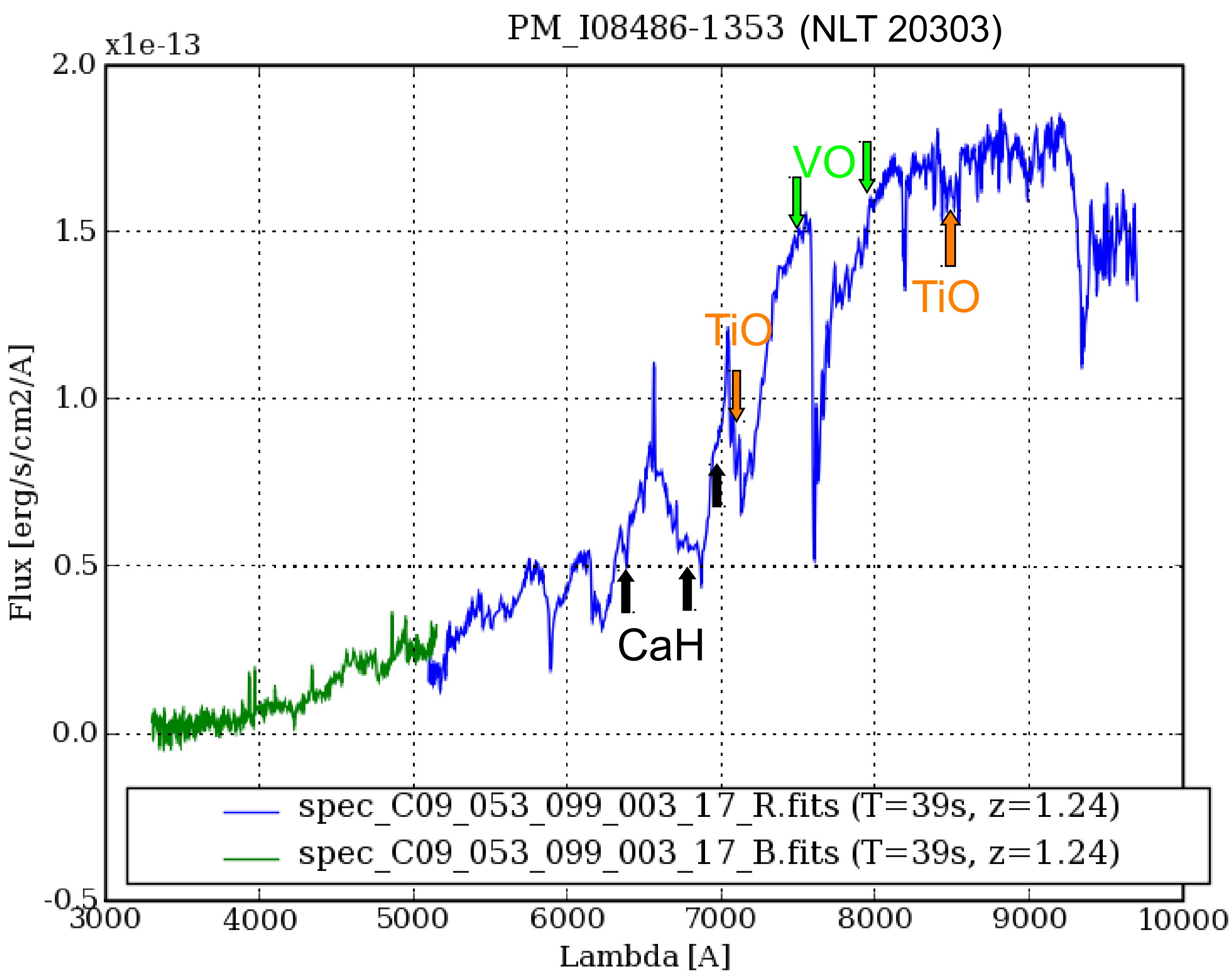




Measuring C/O of the Sun also difficult!

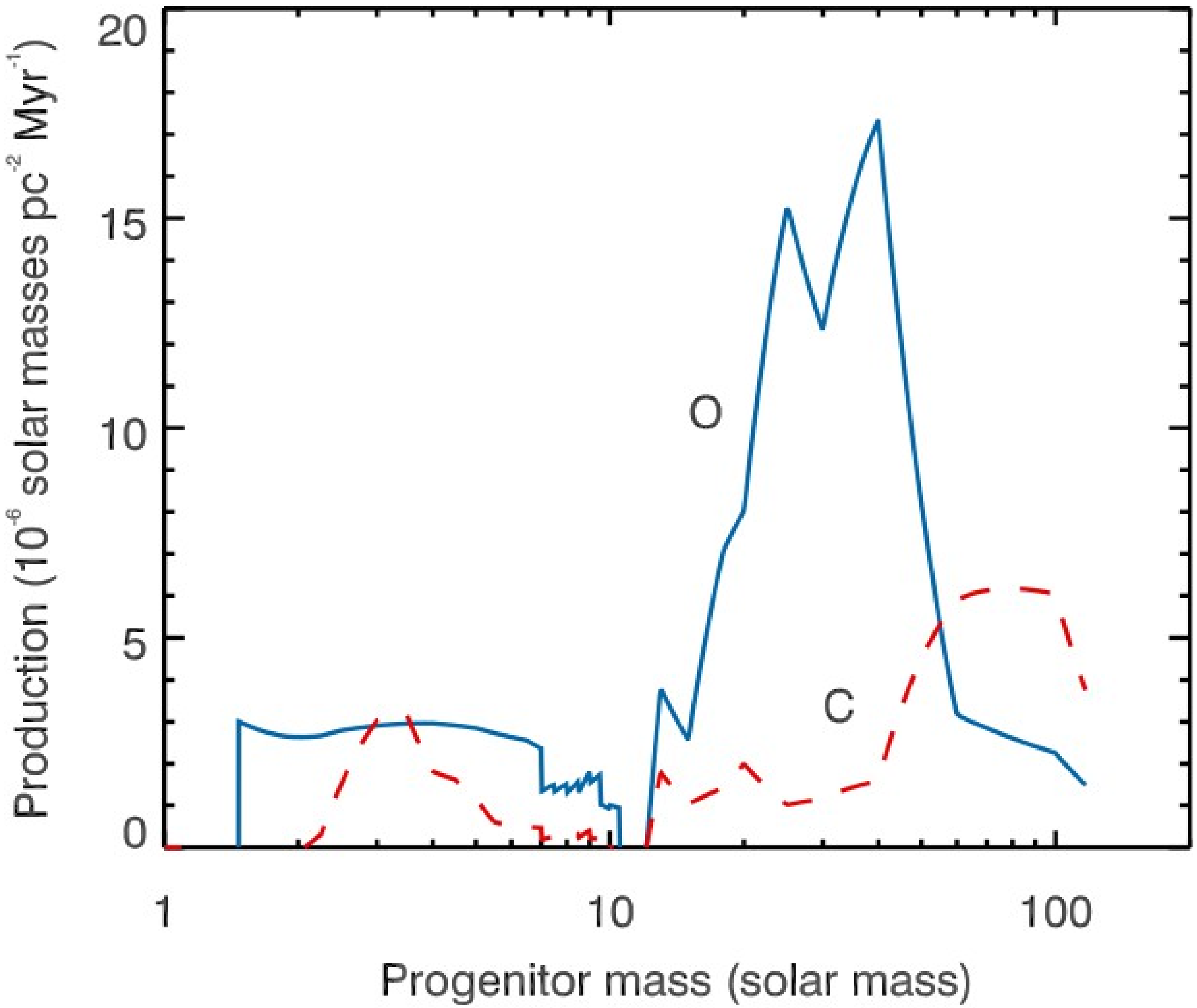
Teske et al. (2013)

Oxygen-bearing molecules have prominent absorption features s in M dwarf spectra

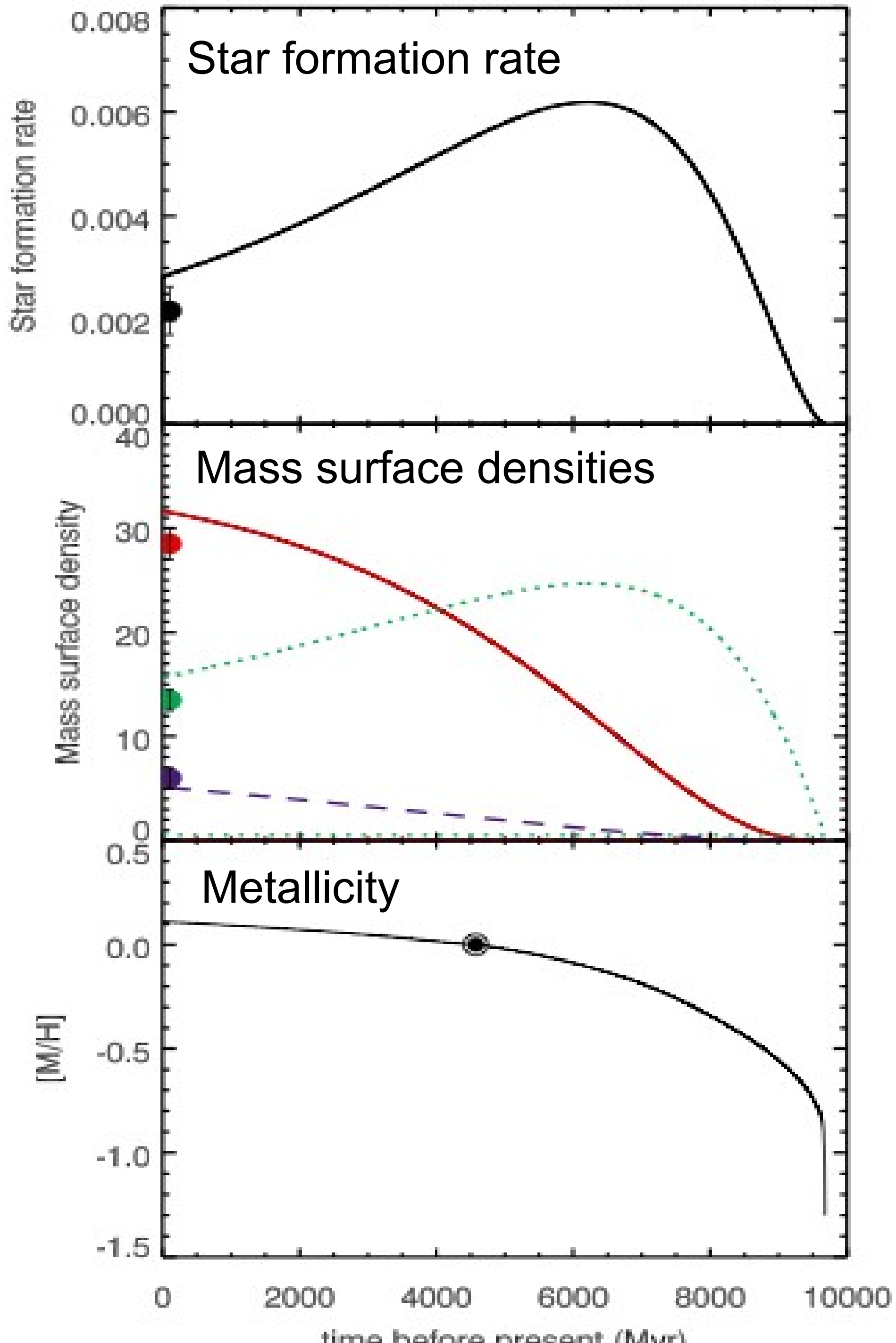


Reason 2:
Galactic Chemical Evolution Models do not Predict C/O > 1

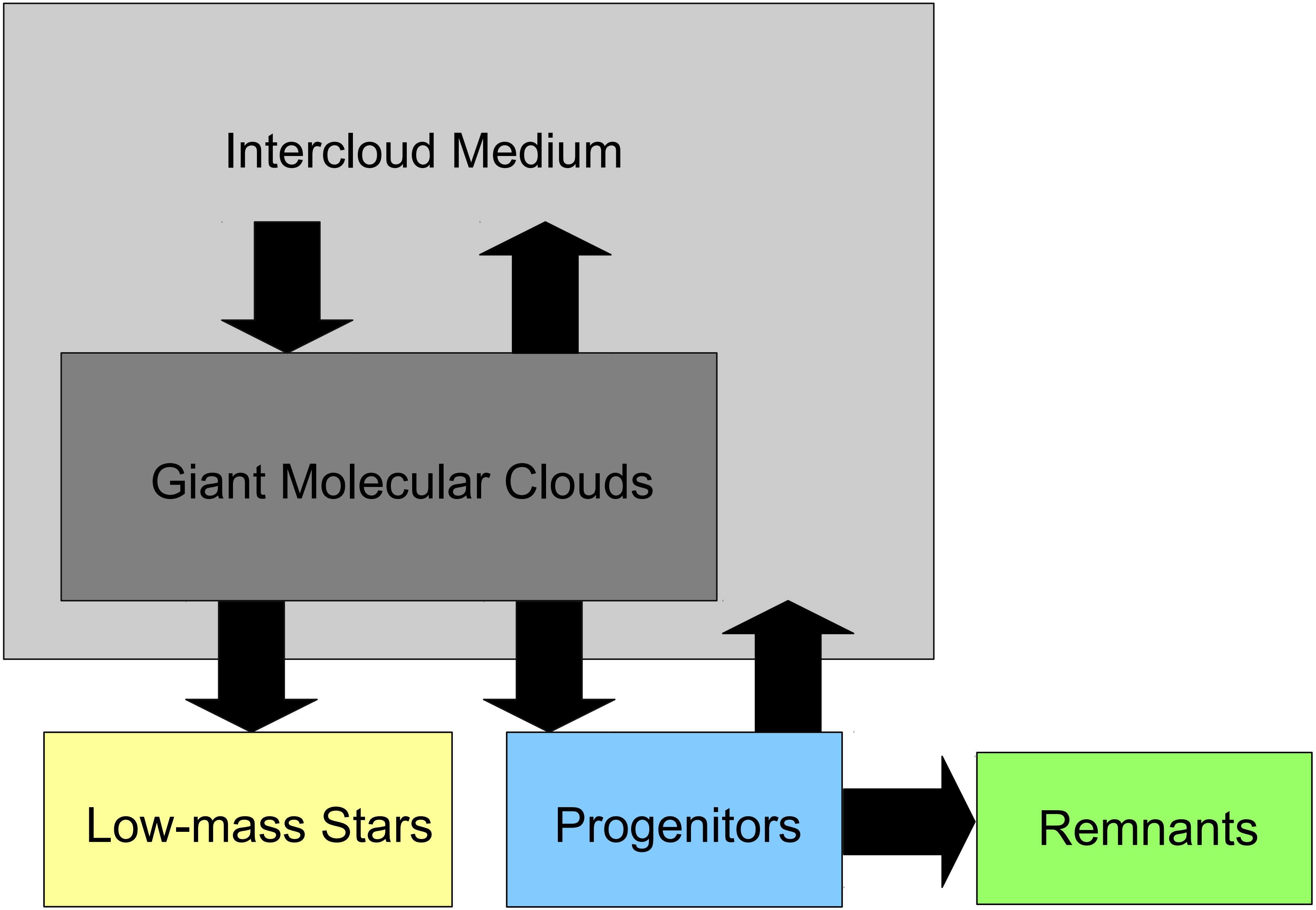
IMF-Weighted Production of C and O



Model Tuned to Reproduce Observables of Milky Way (solar galactocentric radius)



Box Model of Galactic Chemical Evolution



Barnard 68

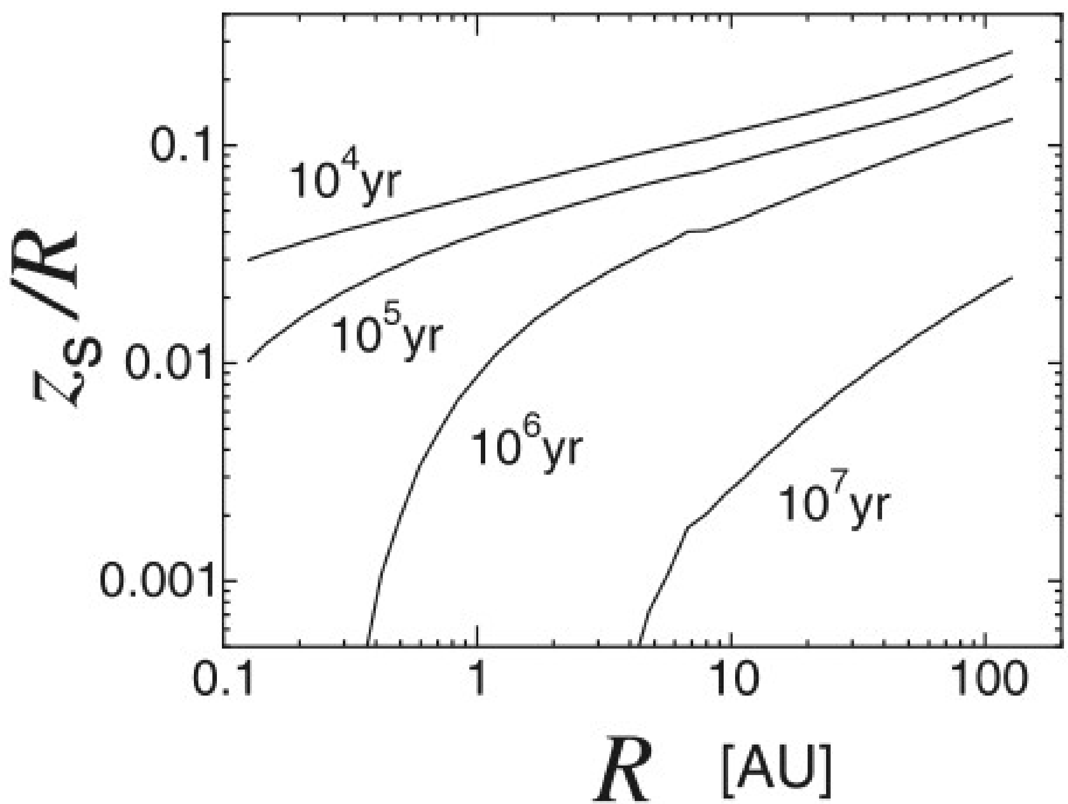
Primitive Solar System Objects contain Relict Material

Table 1. Types and properties of pre-solar materials identified in meteorites and IDPs

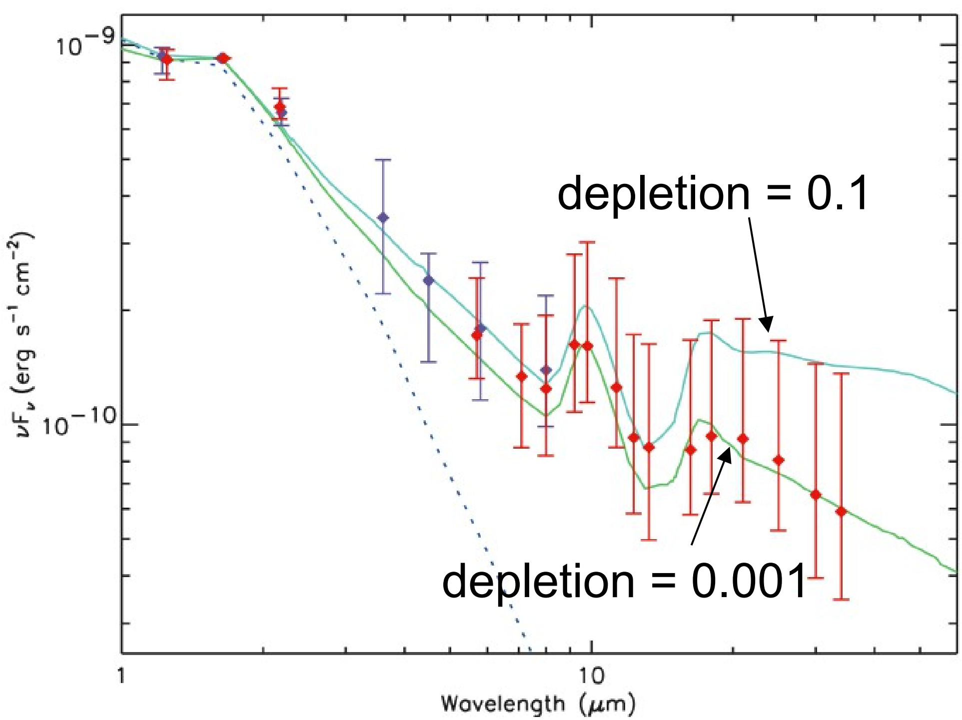
Material	Source	Grain Size (μm)	Abundance (ppm)†	Chemical resistance	Thermal resistance
Diamond		~0.002	~1400		
P3 fraction	?			high	low
HL fraction	circumstellar			very high	high
Silicon carbide	circumstellar	0.1-20	13-14	high	high
Graphite	circumstellar	0.1-10	7-10	moderate	low
D-rich organics	interstellar			low to mod.	low to mod.
P1 noble gas carrier	interstellar	*	*	moderate	high
Corundum (Al_2O_3)	circumstellar	0.5-3	0.01	high	very high
Spinel ($MgAl_2O_4$)	circumstellar	0.1-3	1.2	high	very high
Hibonite ($CaAl_{12}O_{19}$)	circumstellar	1-2	0.02	high	very high
Forsterite (Mg_2SiO_4) } Enstatite ($MgSiO_3$)	circumstellar	0.2-0.5	10-1800	low to mod.	high
Amorphous silicates	circumstellar	0.2-0.5	20-3600	low	moderate

Huss & Draine (2006)

Grain settling produces high dust/gas ratio and non solar-composition at the disk mid-plane

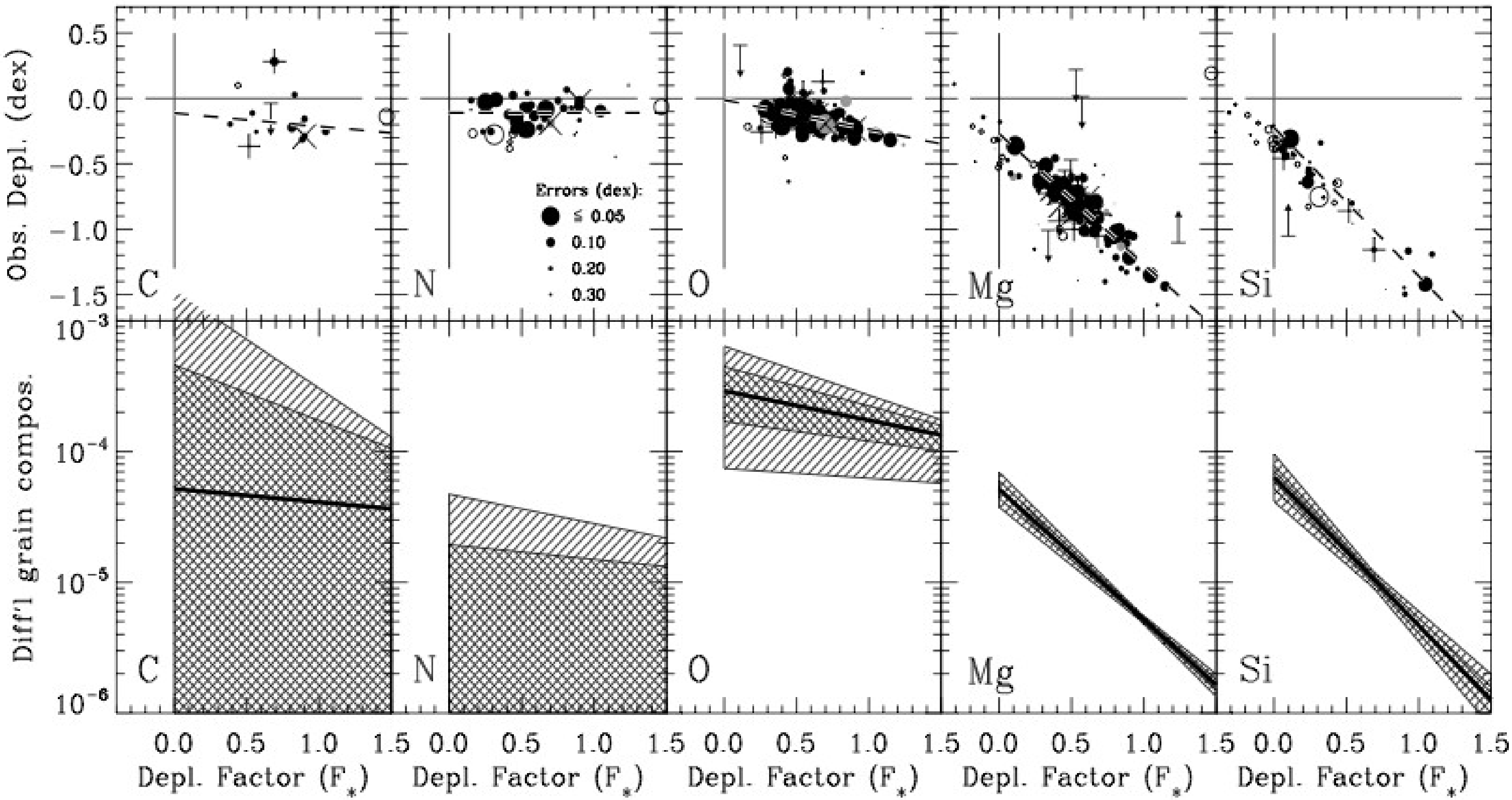


Tanaka et al. (2005)

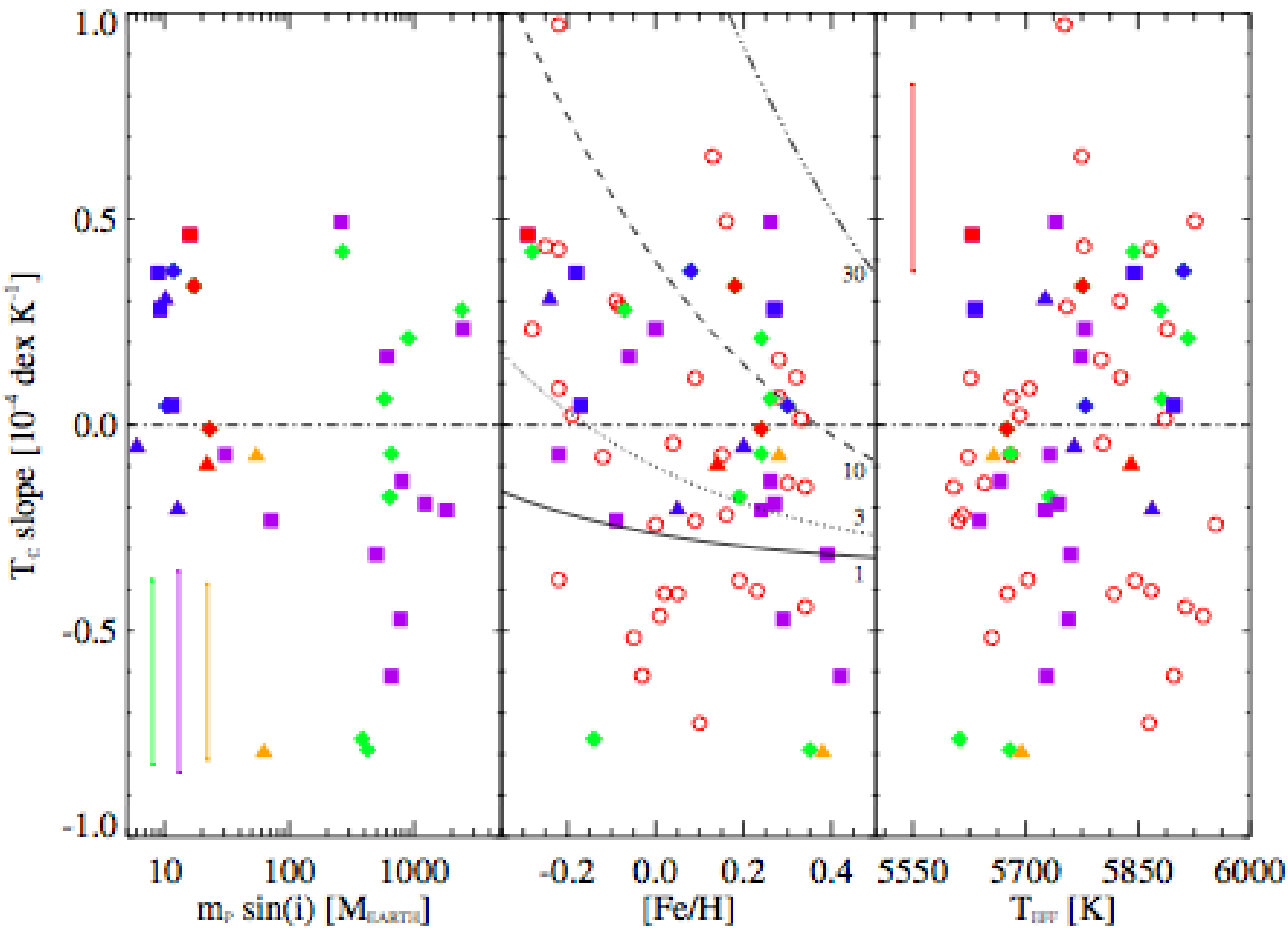


Furlan et al. (2006)

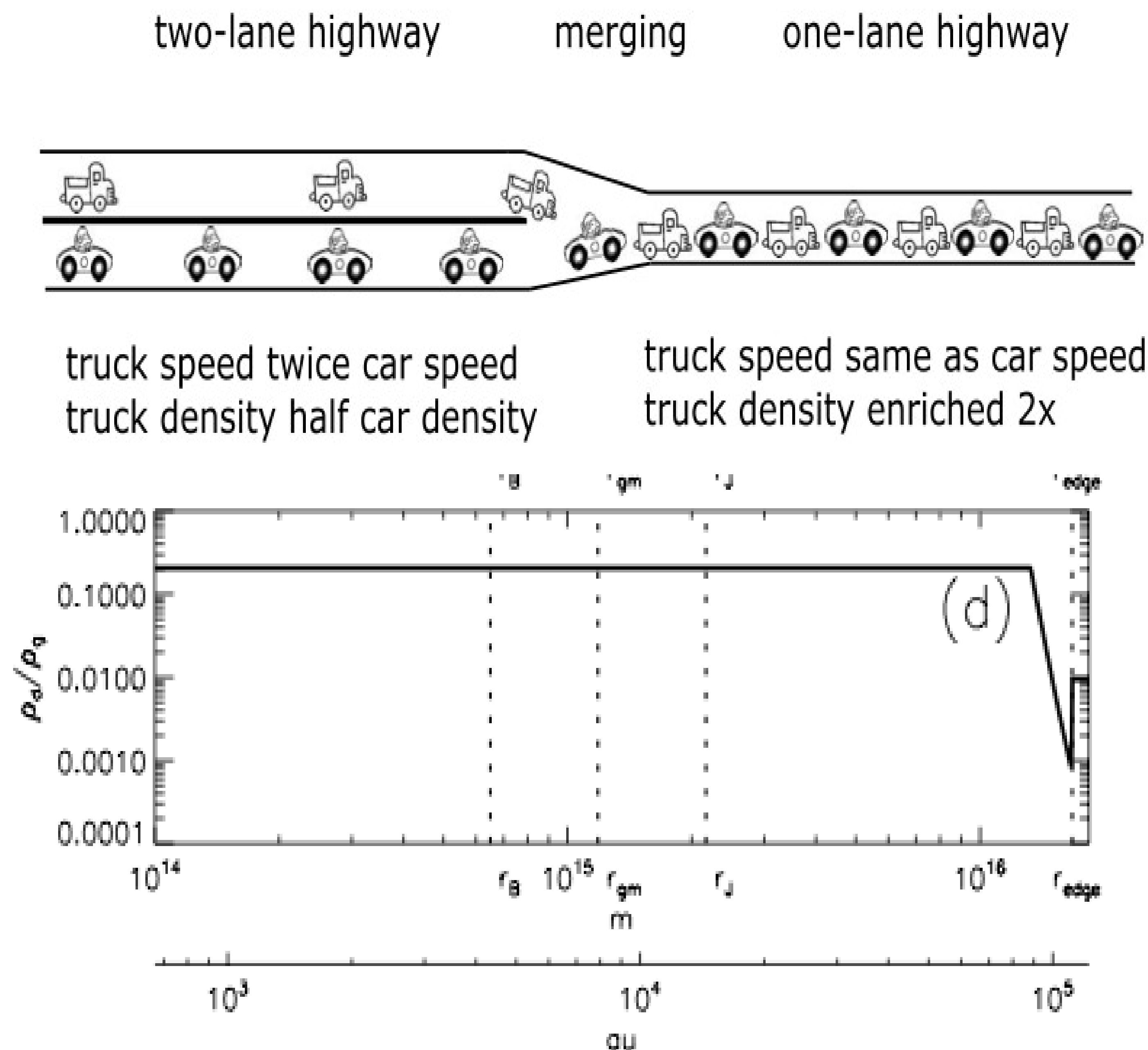
Dust Abundances from Measurements of Depletion in the Gas Phase



Jenkins (2009)

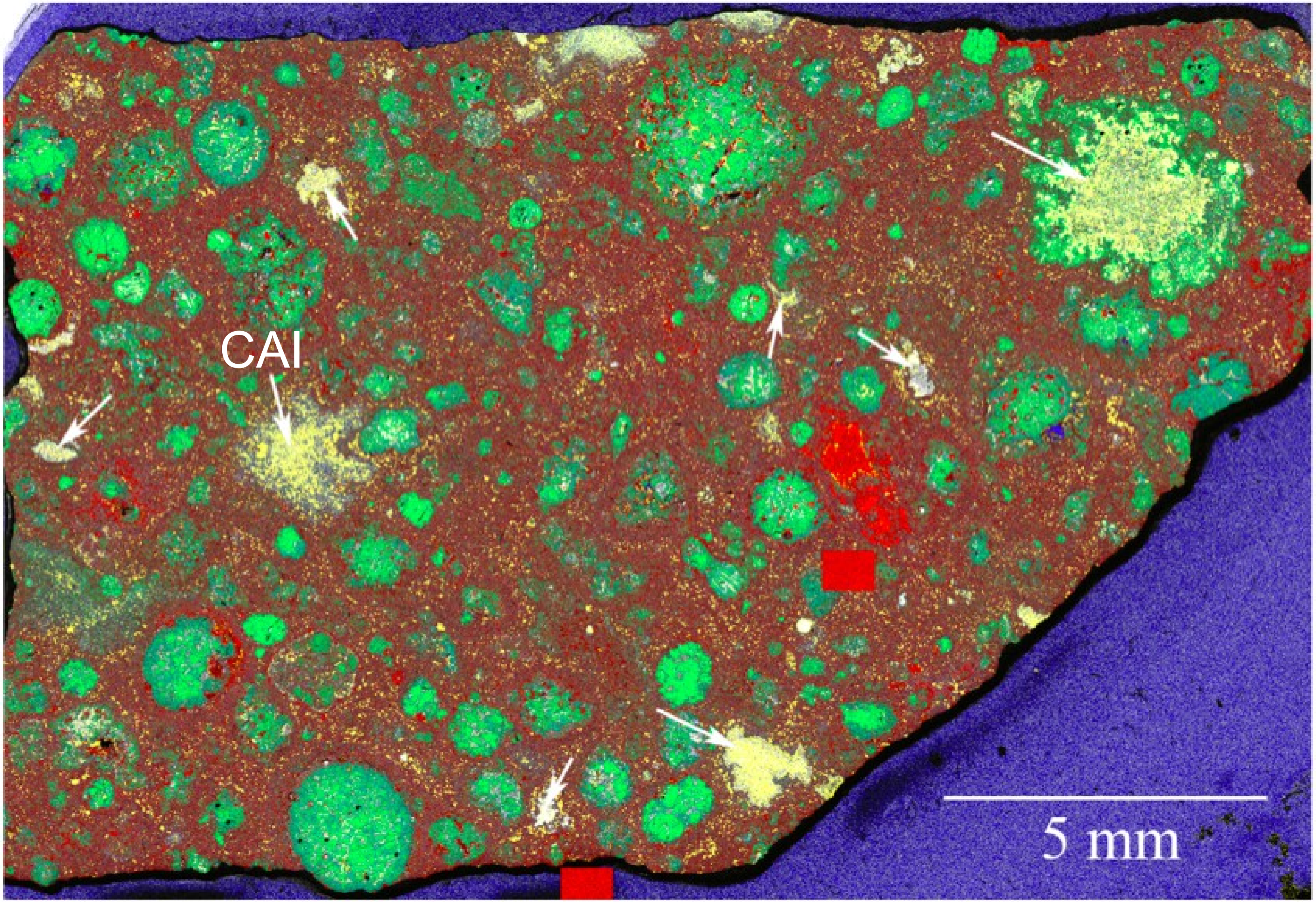


Gonzalez-Hernandez et al. (2013)


two-lane highway
merging
one-lane highway
truck speed twice car speed
truck density half car density
truck speed same as car speed
truck density enriched 2x
1.0000
0.1000
0.0100
0.0010
0.0001
ρd/ρg
(d)
10^14
r_B
10^15
r_gm
r_J
10^16
r_edge
m
10^3
10^4
10^5
au

Bellan (2008)

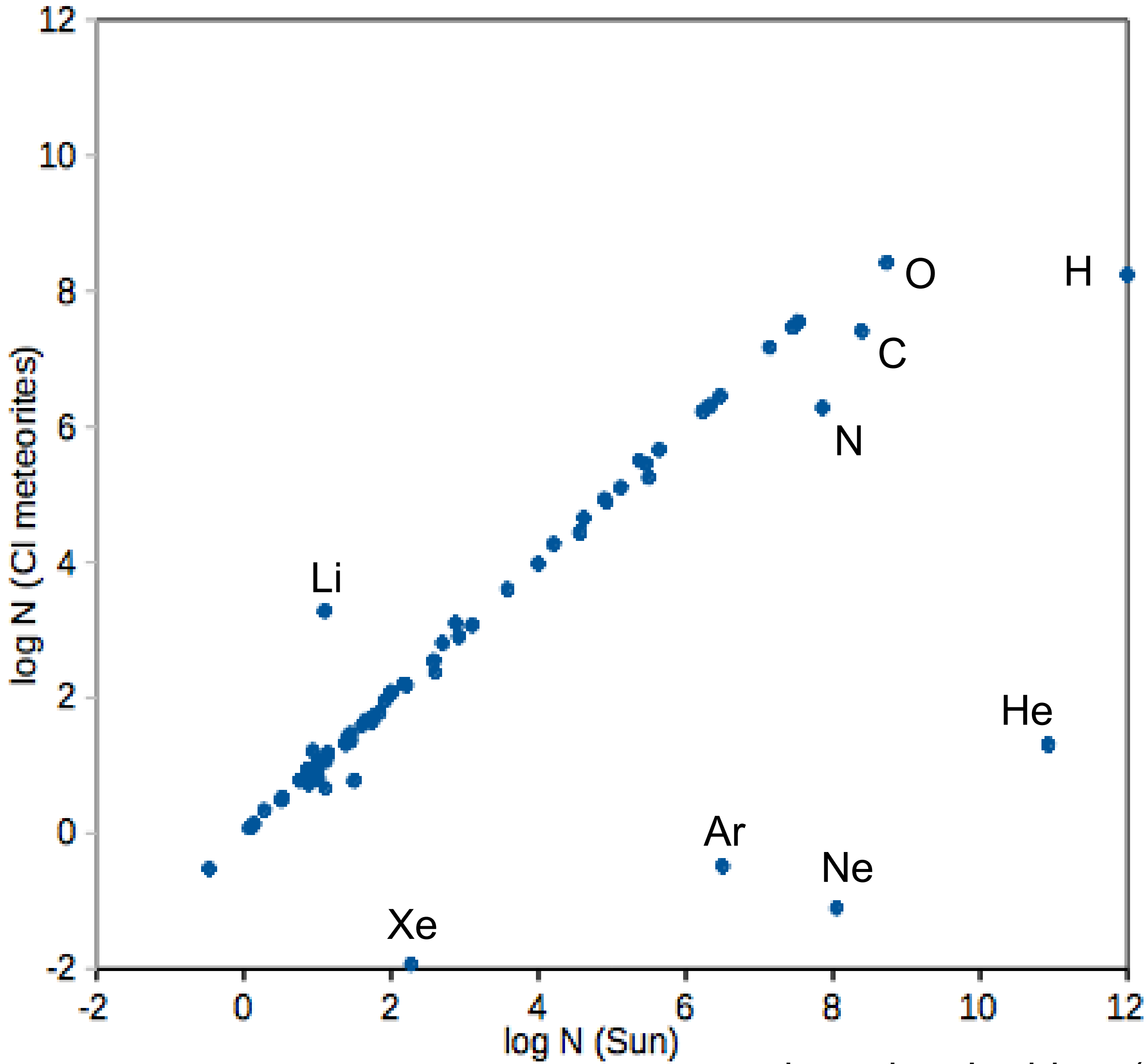
Reason 3: Most Primitive Material is not a Condensate!



Yellow = Ca, Green = Mg, Blue = Si, Red = Fe

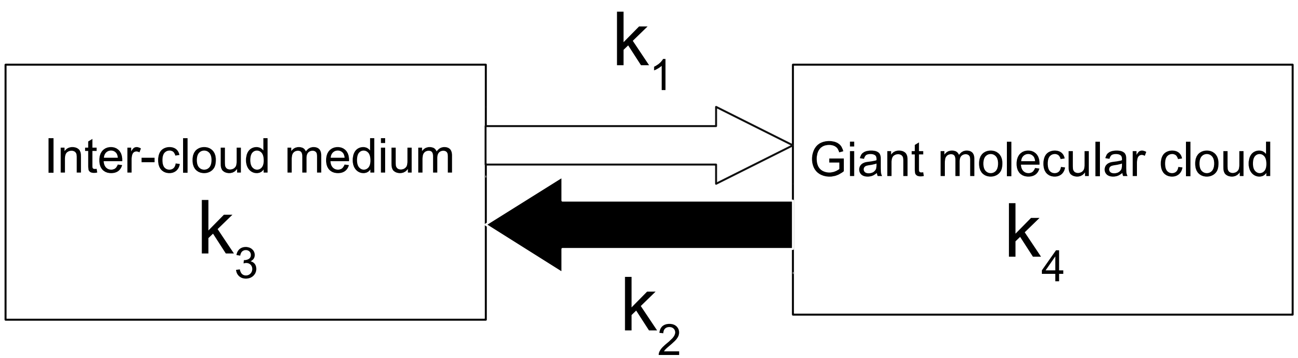
Hezel et al. (2008)

The Solar Photosphere vs. Primitive Meteorites



based on Lodders (2010)

Thielens et al. Model of ISM Grain Evolution

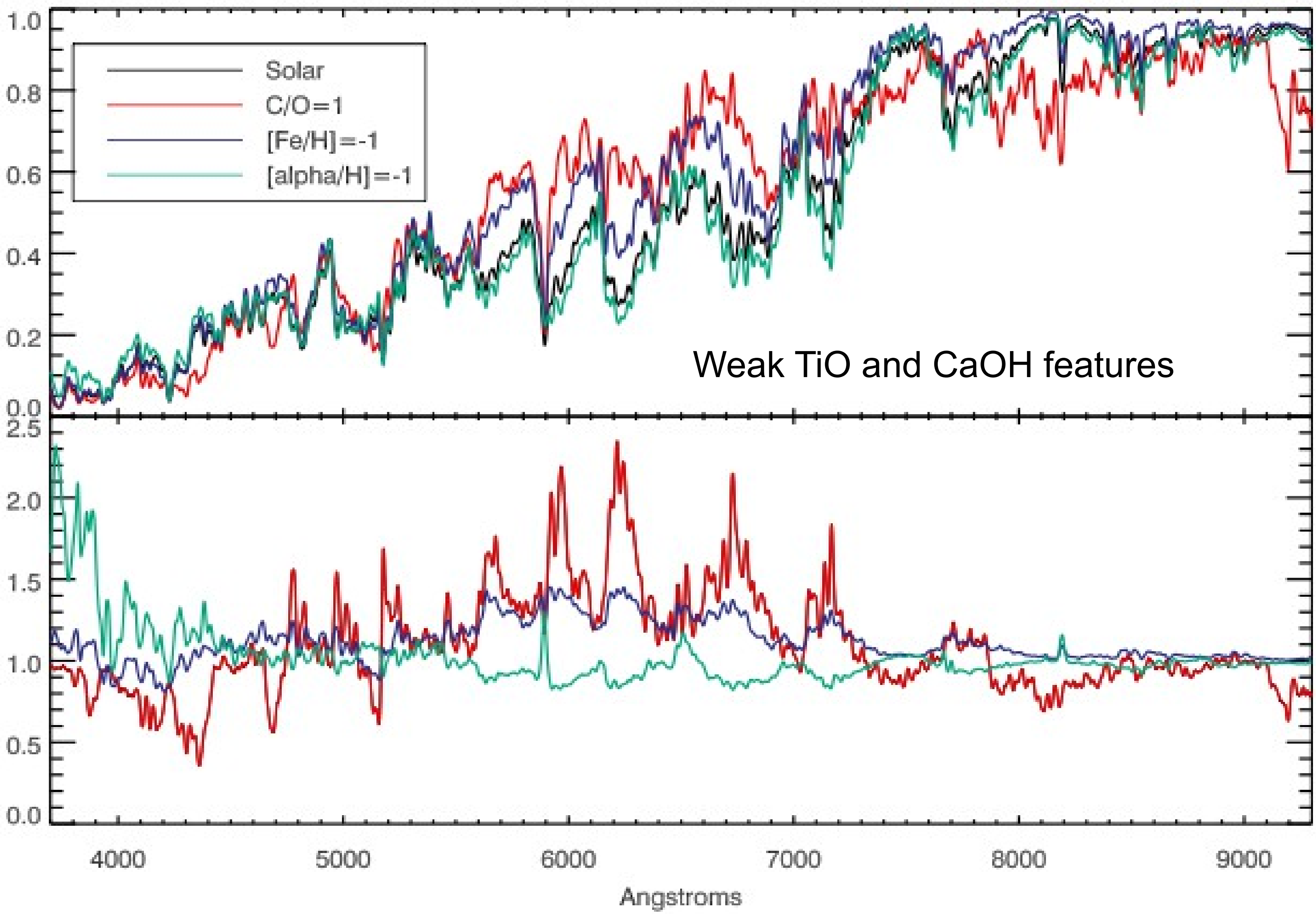


Equations of motion of depletion:

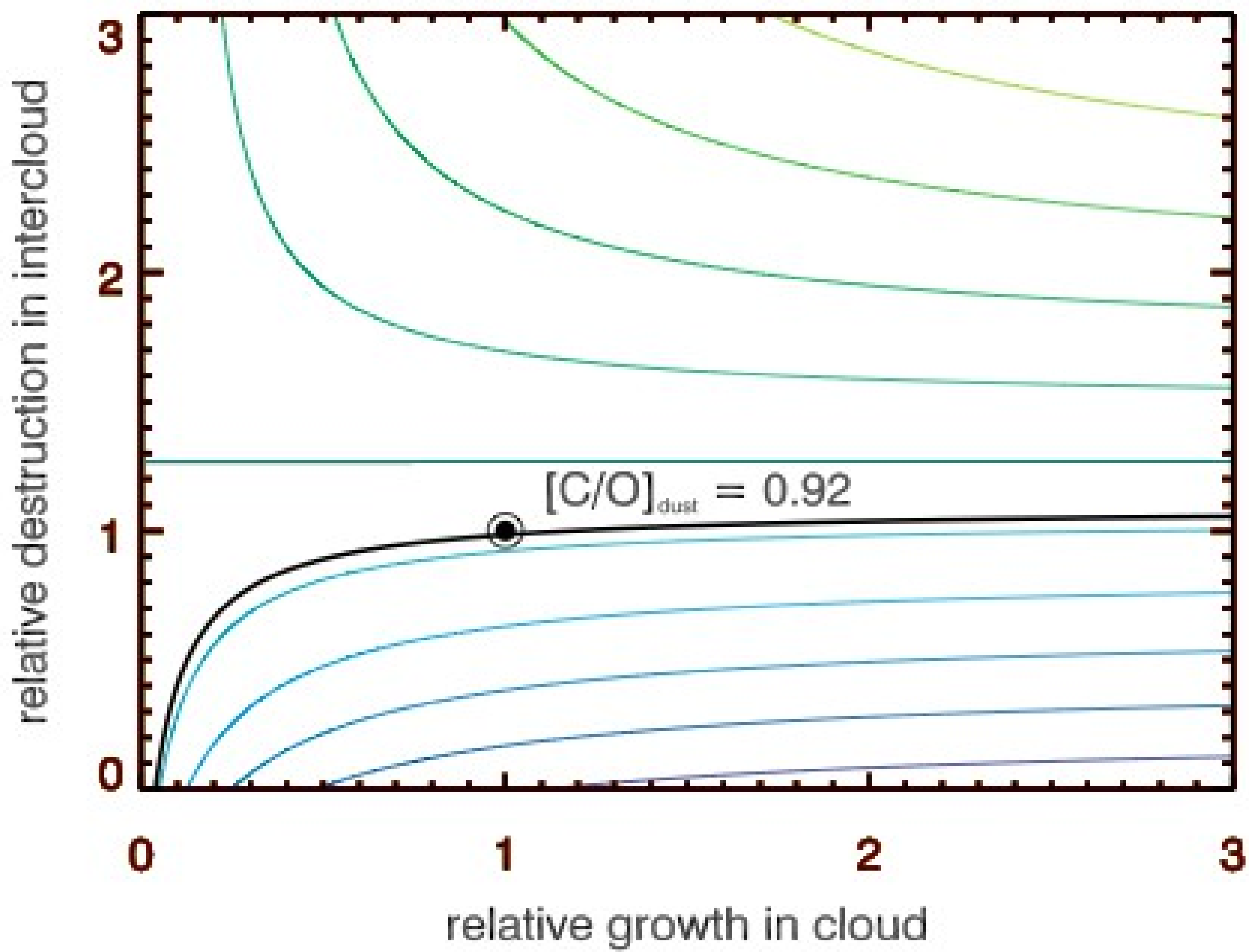
$$\frac{\delta_c}{dt} = -k_2\left(\delta_c - \delta_i\right) + k_4\left(1 - \delta_c\right) \qquad \delta_c = \frac{1 + k_1/k_3}{1 + k_1/k_3 + k_2/k_4};$$

$$\frac{\delta_i}{dt} = -k_1\left(\delta_i - \delta_c\right) + k_3\delta_i, \qquad \delta_i = \frac{k_1/k_3}{1 + k_1/k_3 + k_2/k_4}.$$

Effect of C/O on the Spectra of M Dwarf Stars



Interstellar dust has similar C/O of bulk ISM



Gaidos in prep.