Volatiles: Constraints on disk evolution, and planetesimal/planets accretion

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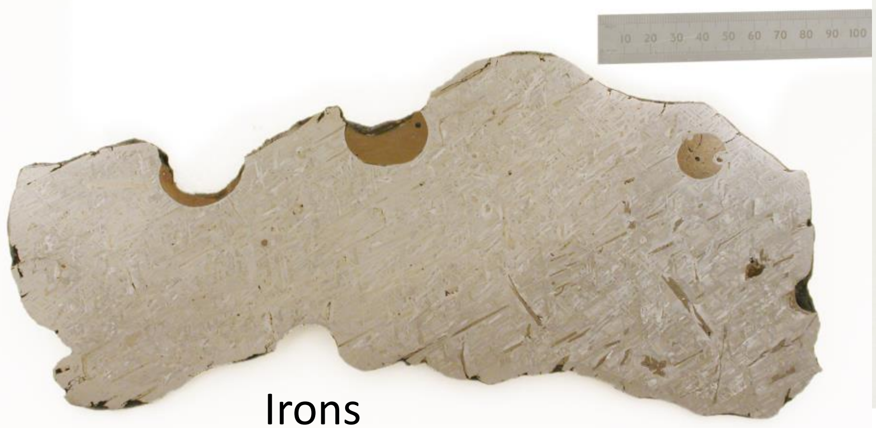
Meteorites

Recorders of first few million years (Ma)

Achondrites



Irons

Formed in <2 Ma

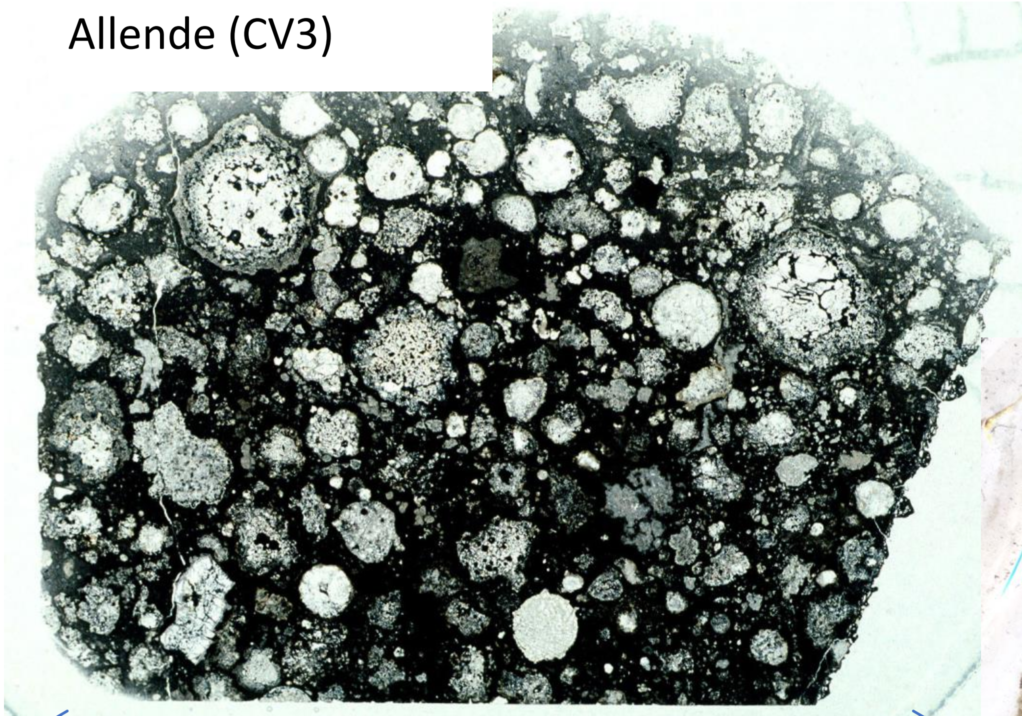
Chondrites

1 cm

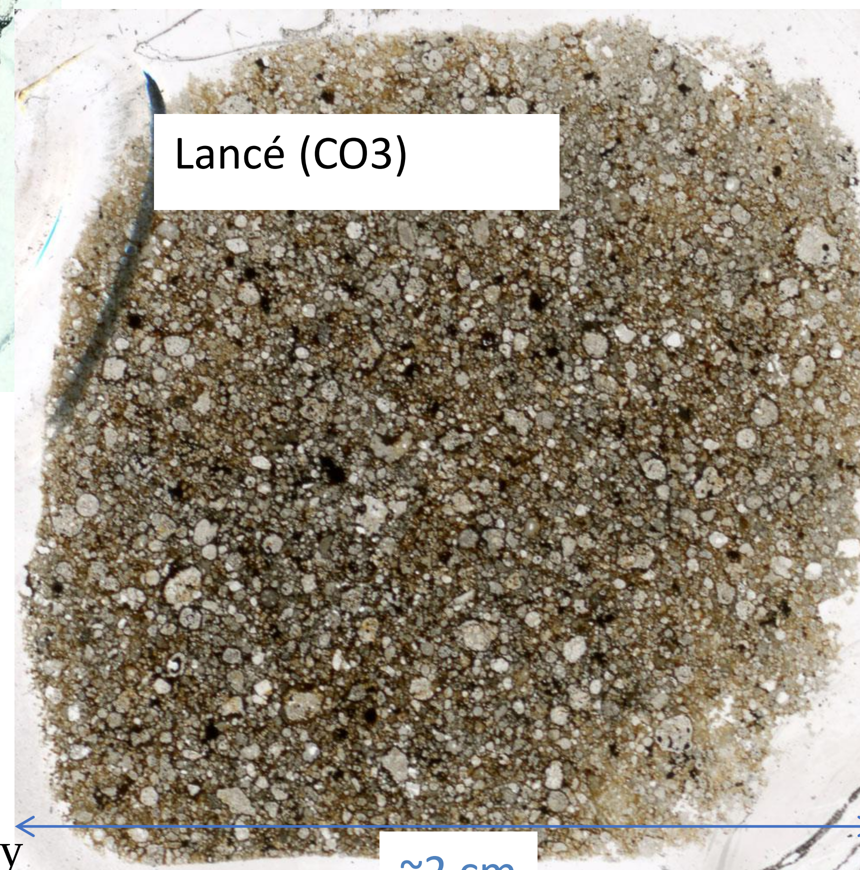
4,567.3±0.2 million years old

Formed in ~2-4 Ma

Chondrites – ‘cosmic’ sediments



Three basic components:
Chondrules, CAIs, Matrix.

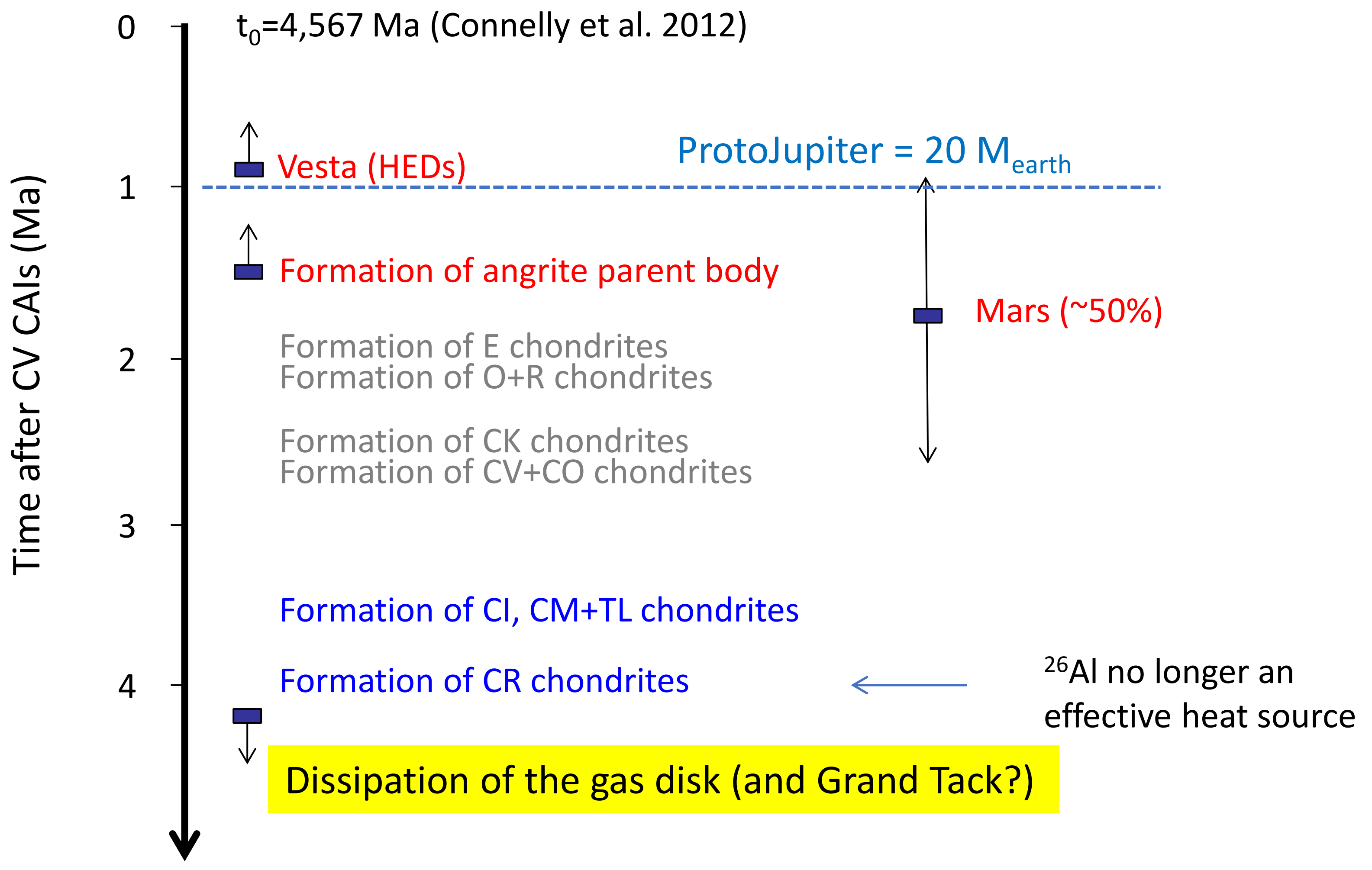


Enstatite – EH, EL
Ordinary – H, L, LL (and R)

Carbonaceous – CI, CM, CR, CV, CO, CK

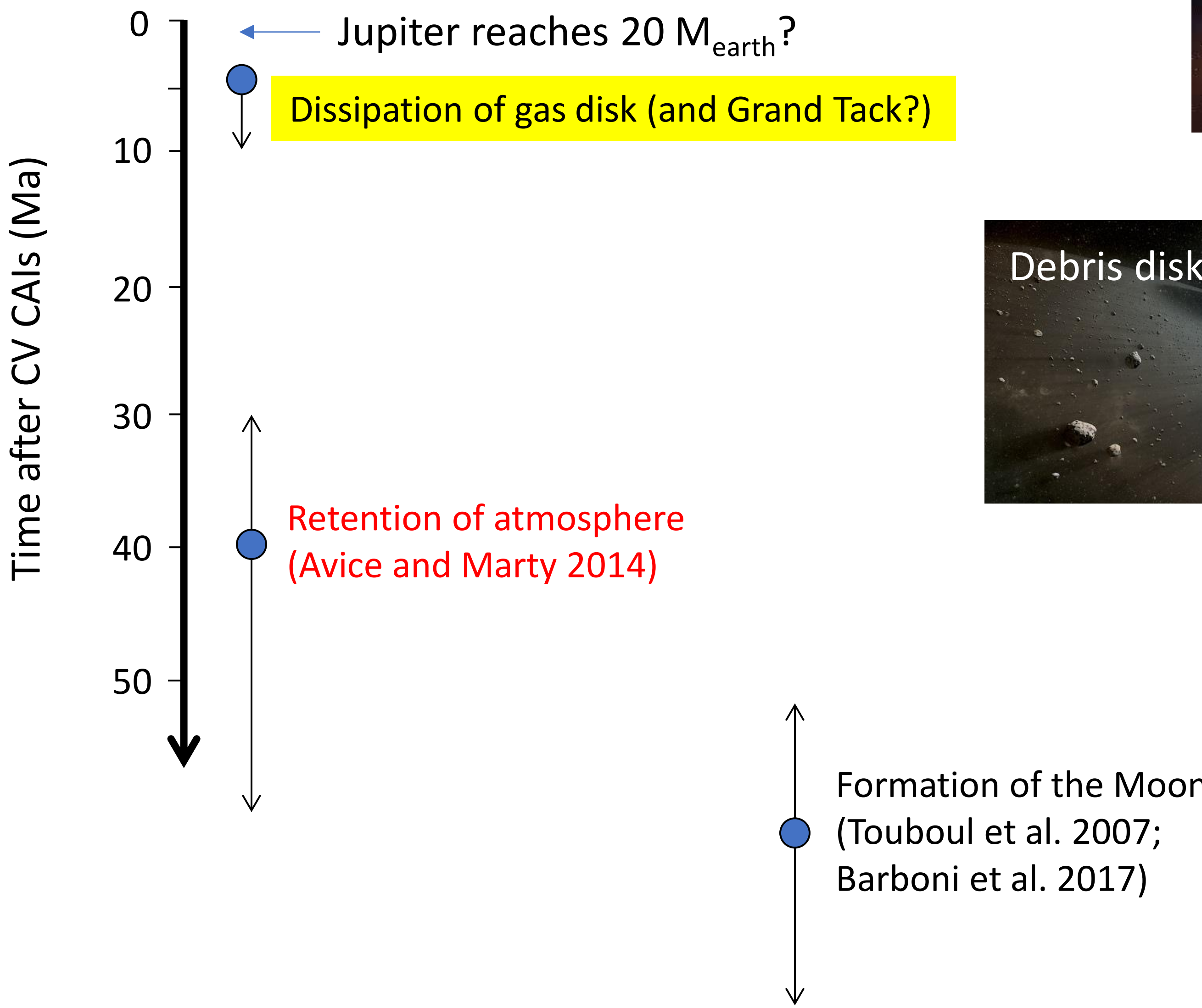
Photomicrographs Courtesy Adrian Brearley

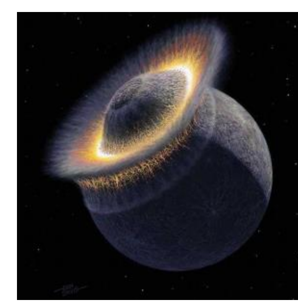
Time constraints – Asteroids-Mars



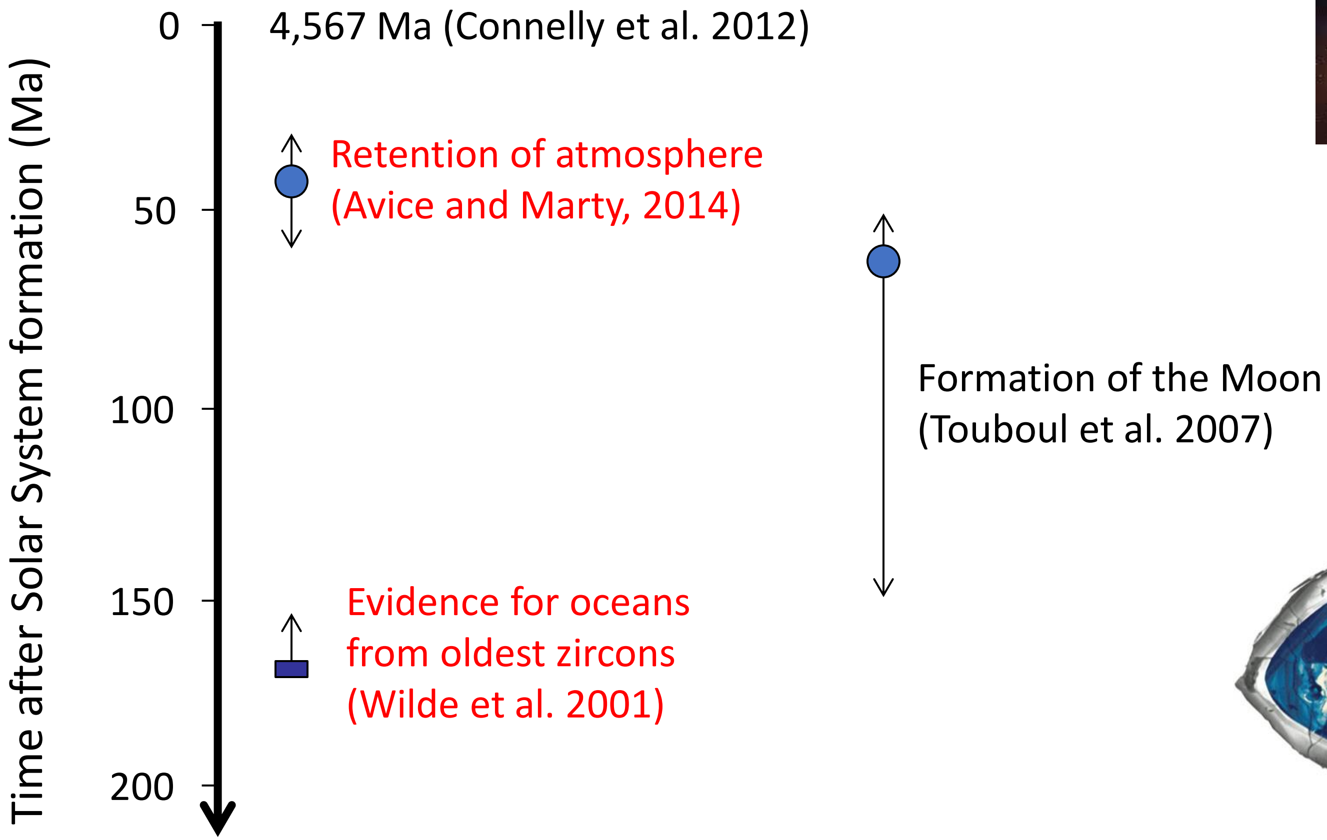
Time constraints - Earth

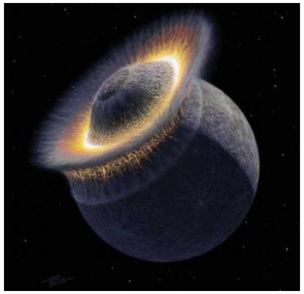
t_0=4,567 Myr (Connelly et al. 2012)

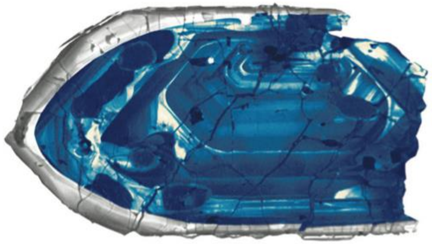




Time constraints - Earth

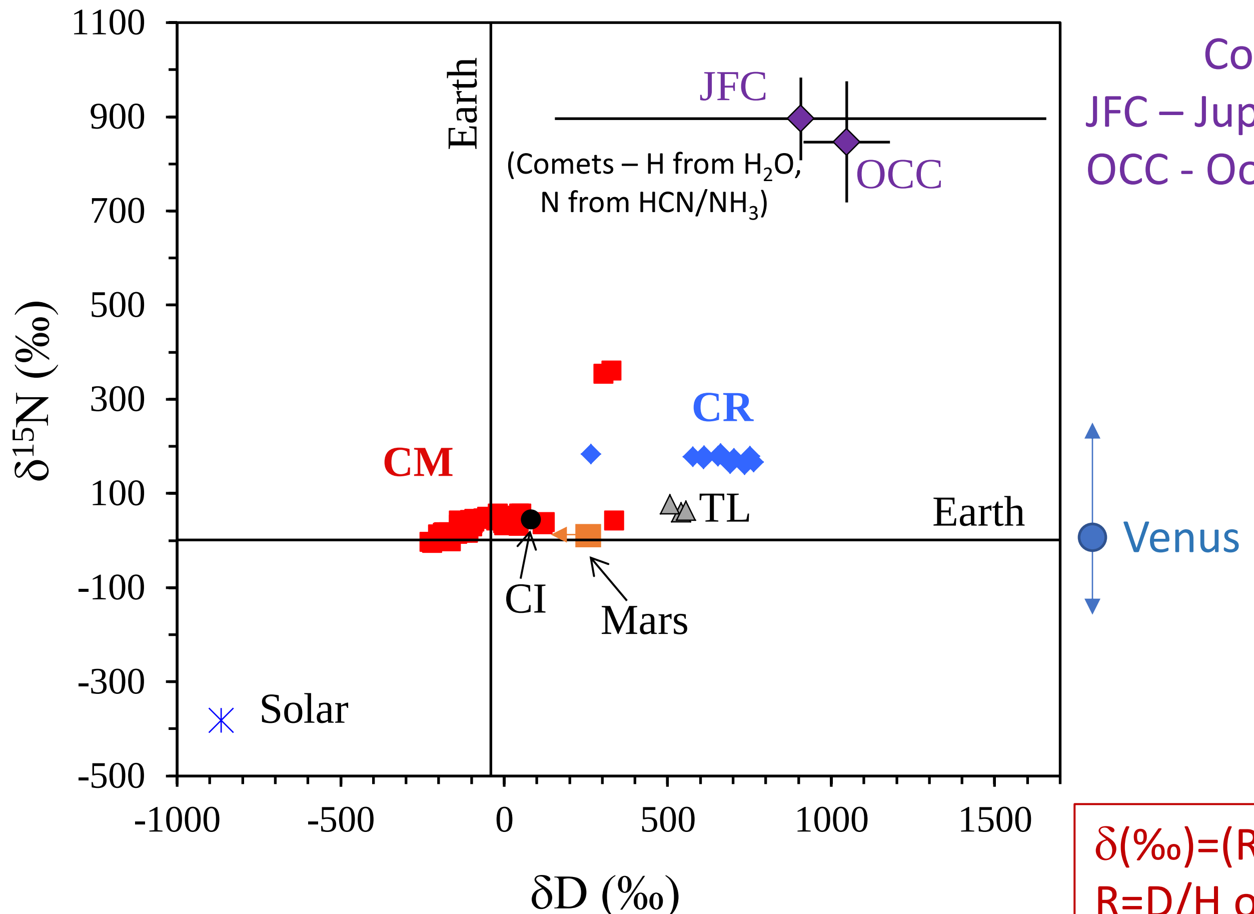






What did the Earth accrete and when was it accreted?

Asteroids and Comets



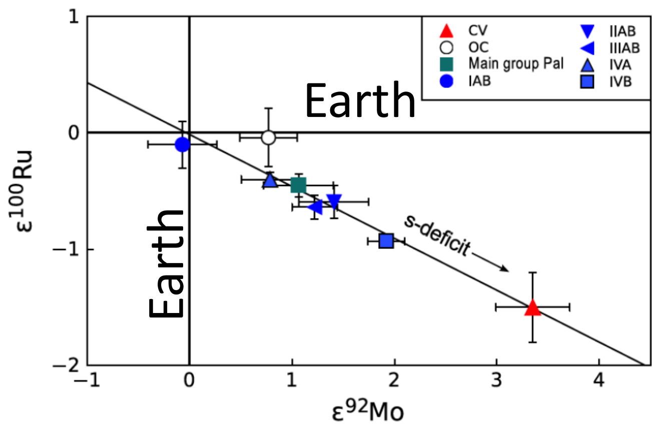
Comets
JFC – Jupiter Family
OCC - Oort Cloud

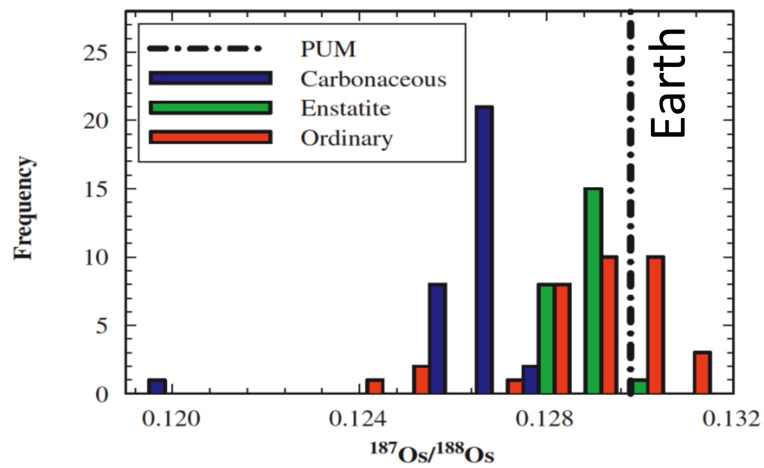
$\delta(‰)=(R/R_{std}-1)x1000$
$R=D/H$ or $^{15}N/^{14}N$

Marty et al. (2016) – cometary contributions to H-C-N were minor, but may have been important for noble gases.

Earth's siderophile isotopes

All inconsistent with carbonaceous chondrites



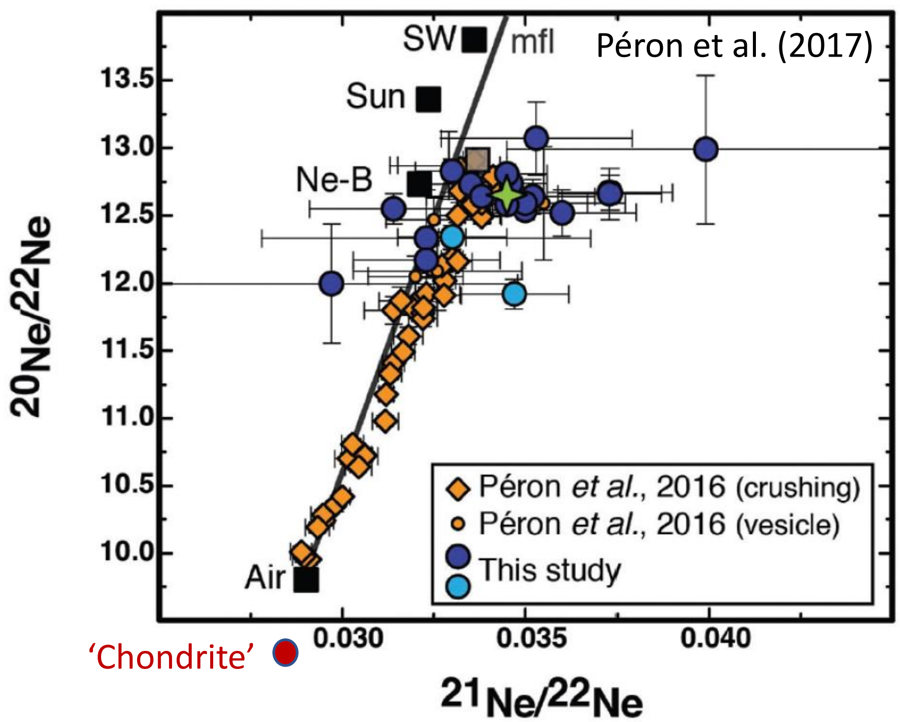


Of the carbonaceous chondrites, the CIs are closest to the Earth's composition.

Nevertheless, if CI-like material was the source of the volatiles, it must have accreted before the end of core formation – assumed to be Moon-formation.

The late veneer after Moon-formation was too little and too dry.

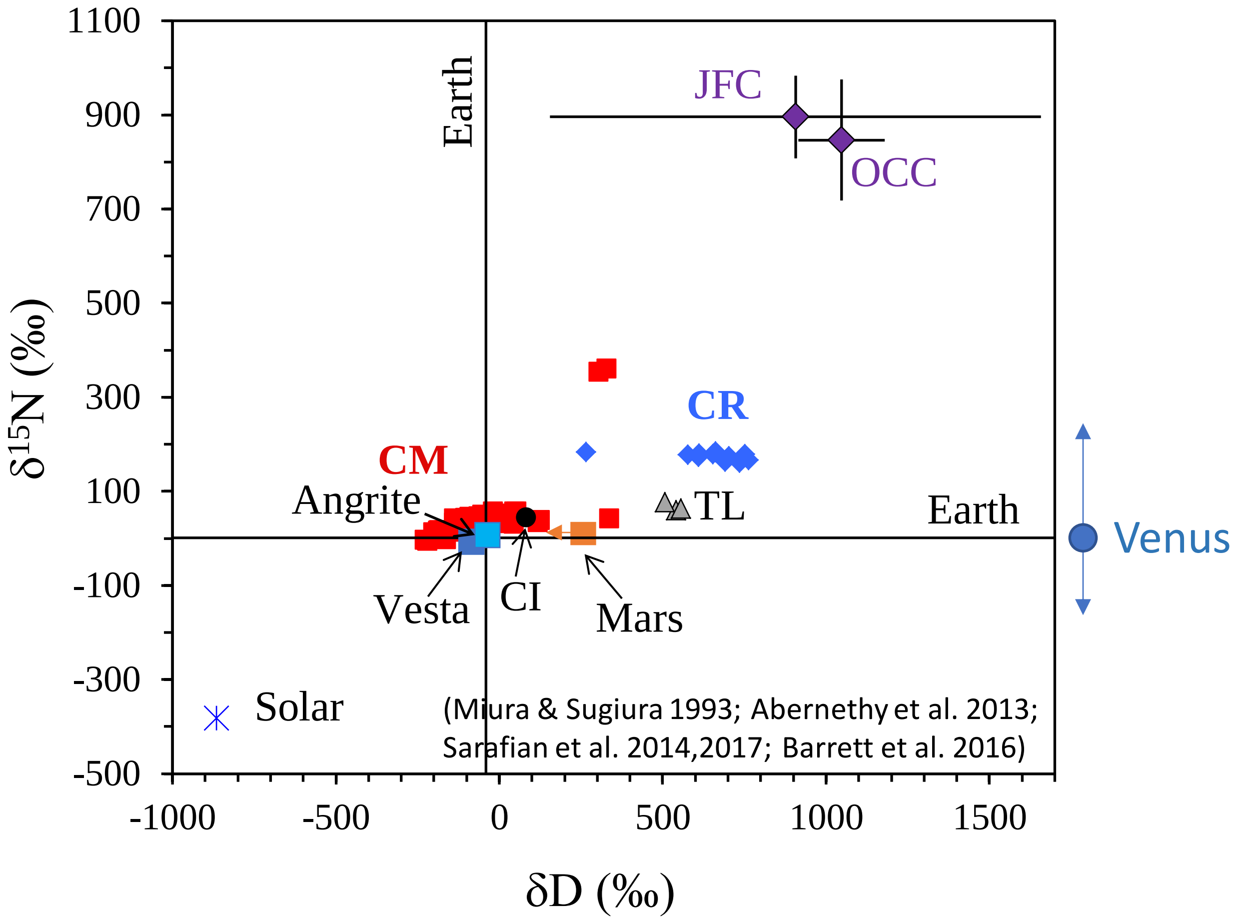
Atmosphere ≠ interior



Mantle Ne – Solar or implanted solar wind (and H & He?)

Either the atmosphere was not degassed from the interior, or the interior/atmosphere compositions have change after degassing?

Did early planetesimals fully degas?



Crystallization ages

Angrite D'Orbigny ~3.5 Ma after CAIs

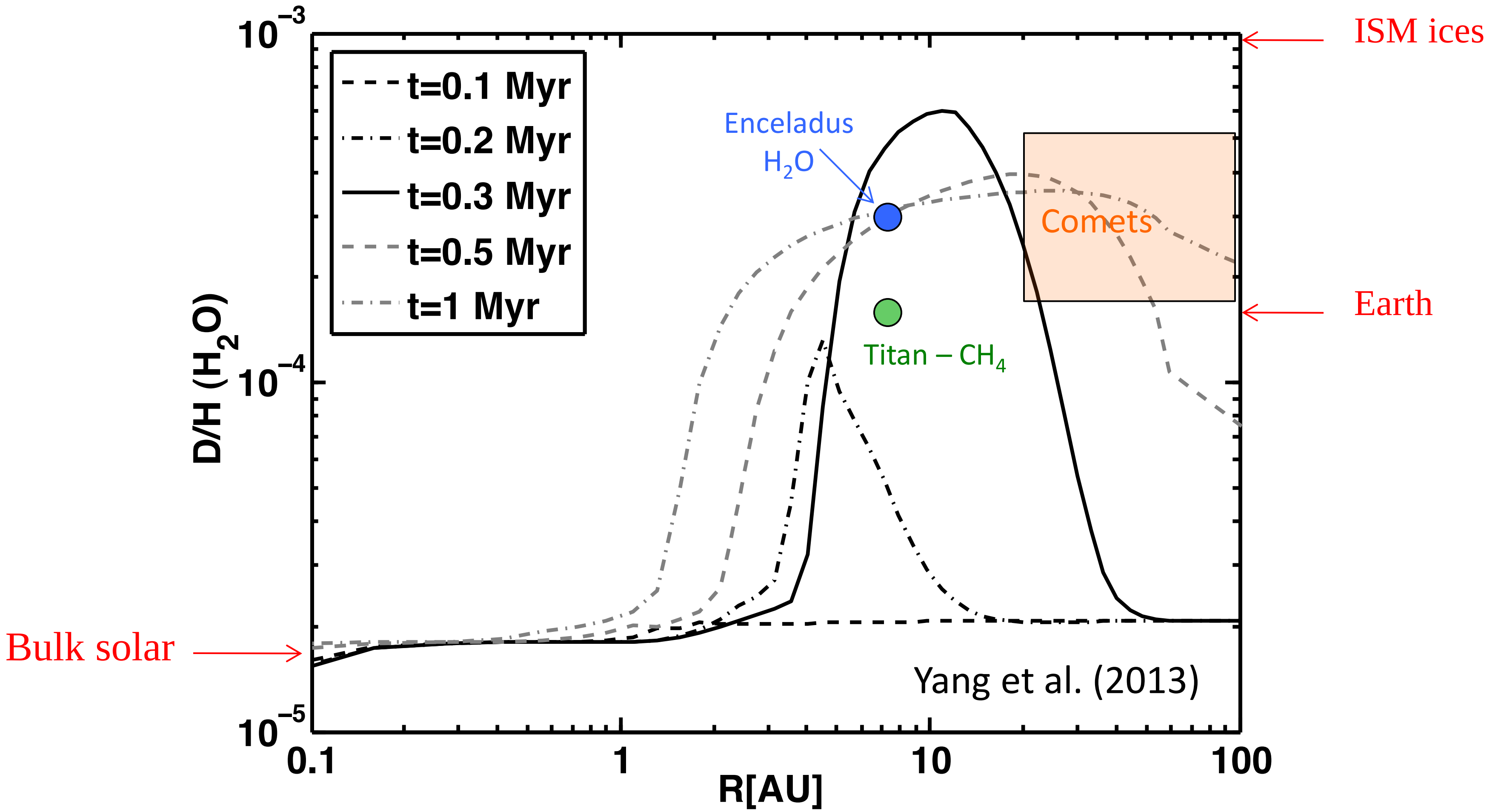
HED Stannern ~3.6 Ma after CAIs

Accretion ages of CIs and CMs

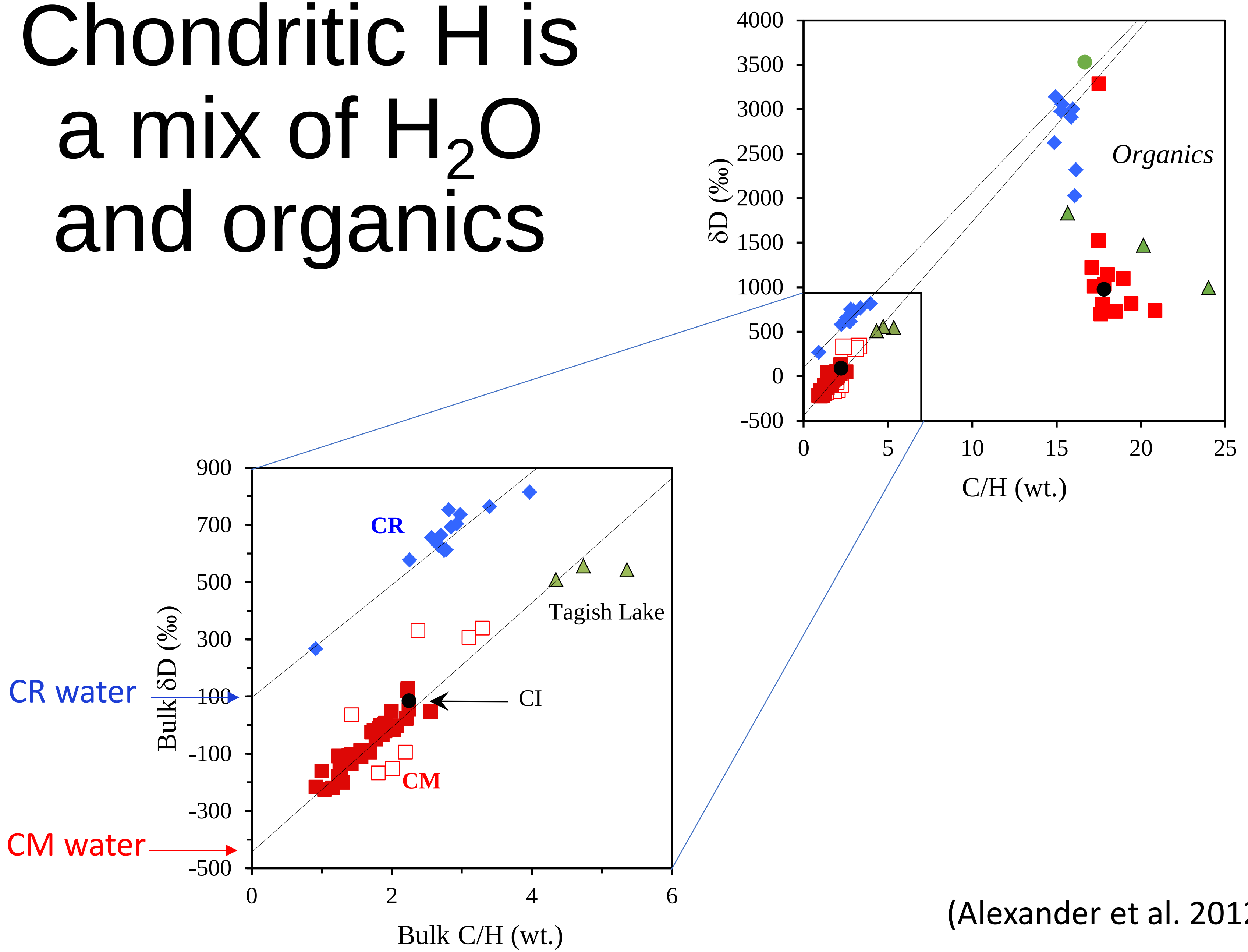
~3.5 Ma after CAIs (Fujiya et al. 2013)

Where did the carbonaceous chondrites form?

Trouble with Saturn's moons

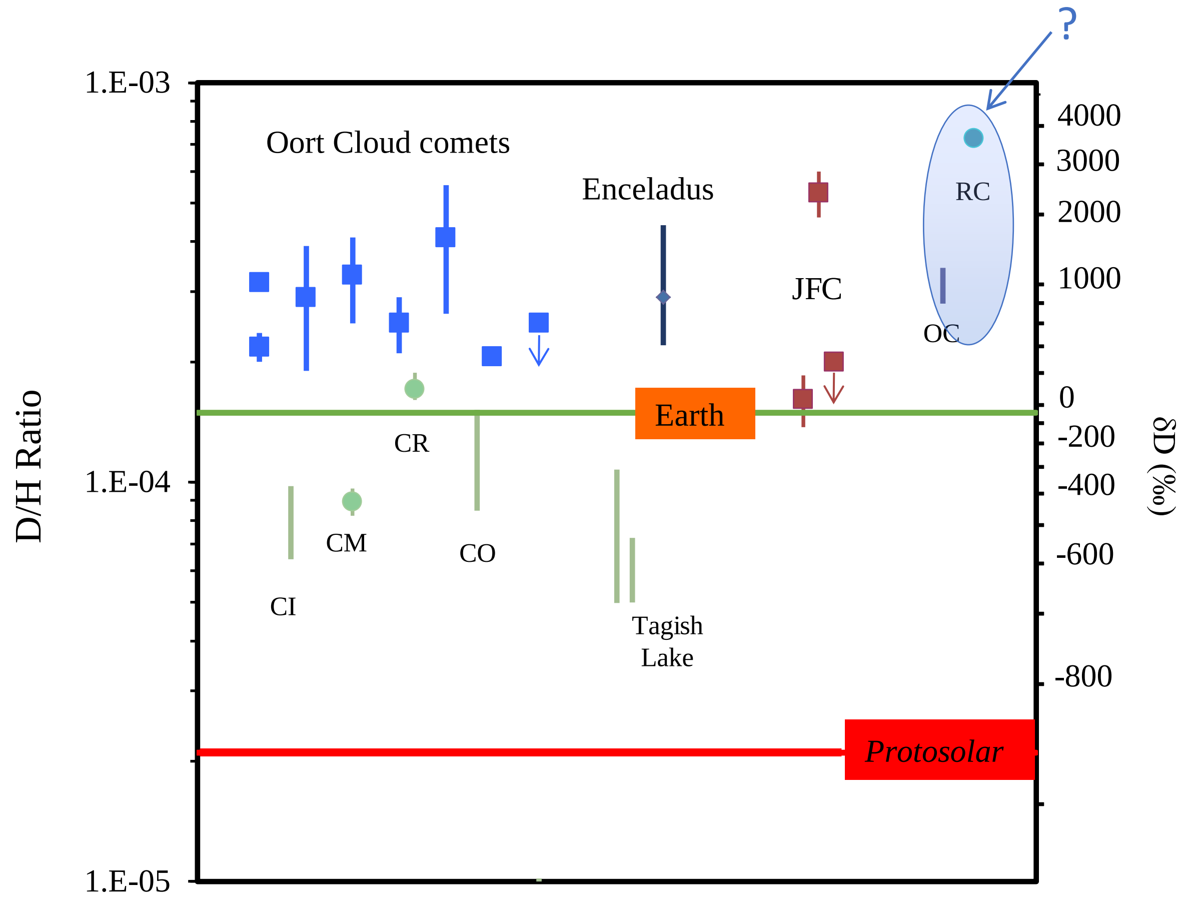


Chondritic H is a mix of H_2O and organics



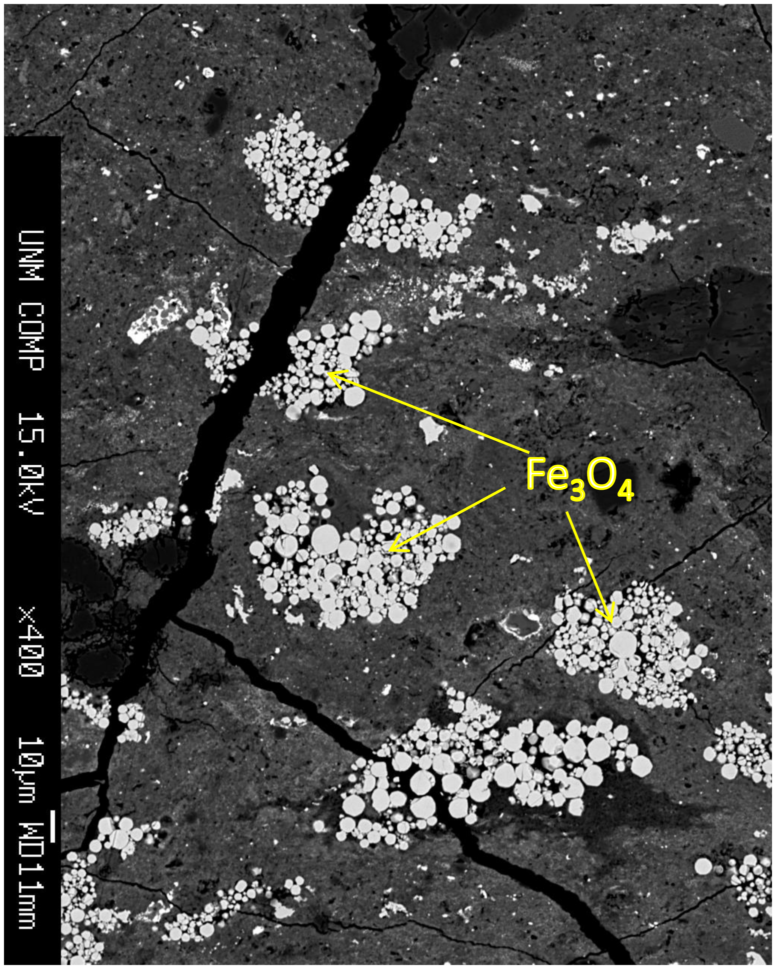
(Alexander et al. 2012)

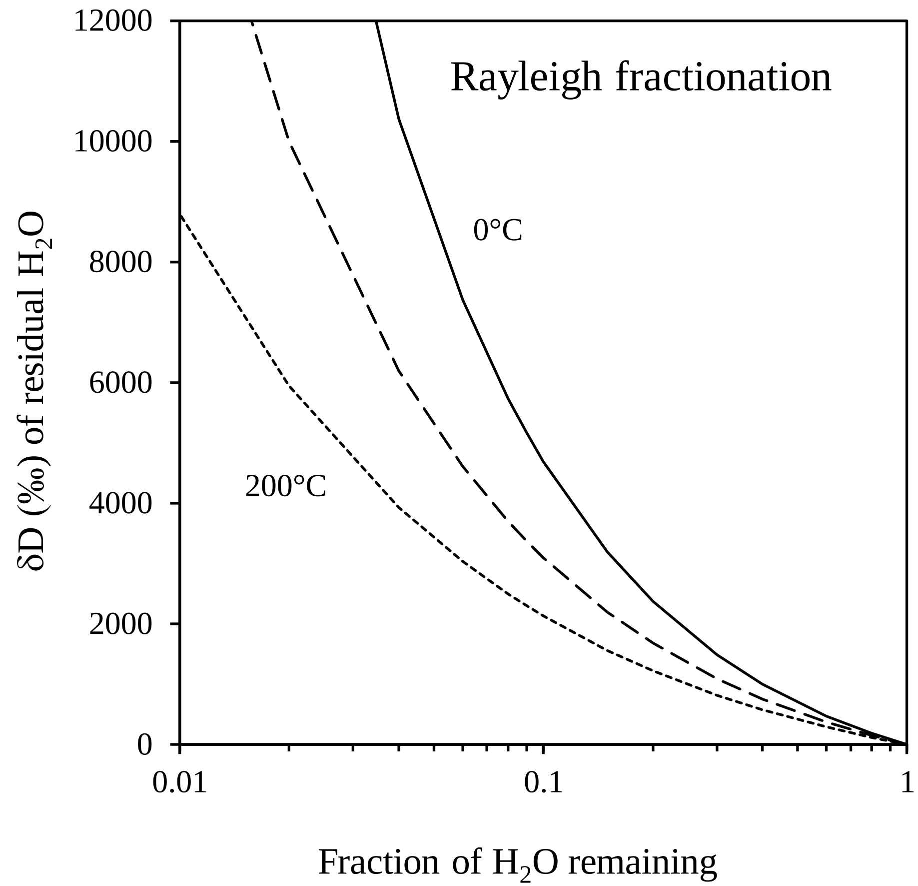
Chondritic water was not from the outer Solar System



After Alexander et al. (2012)

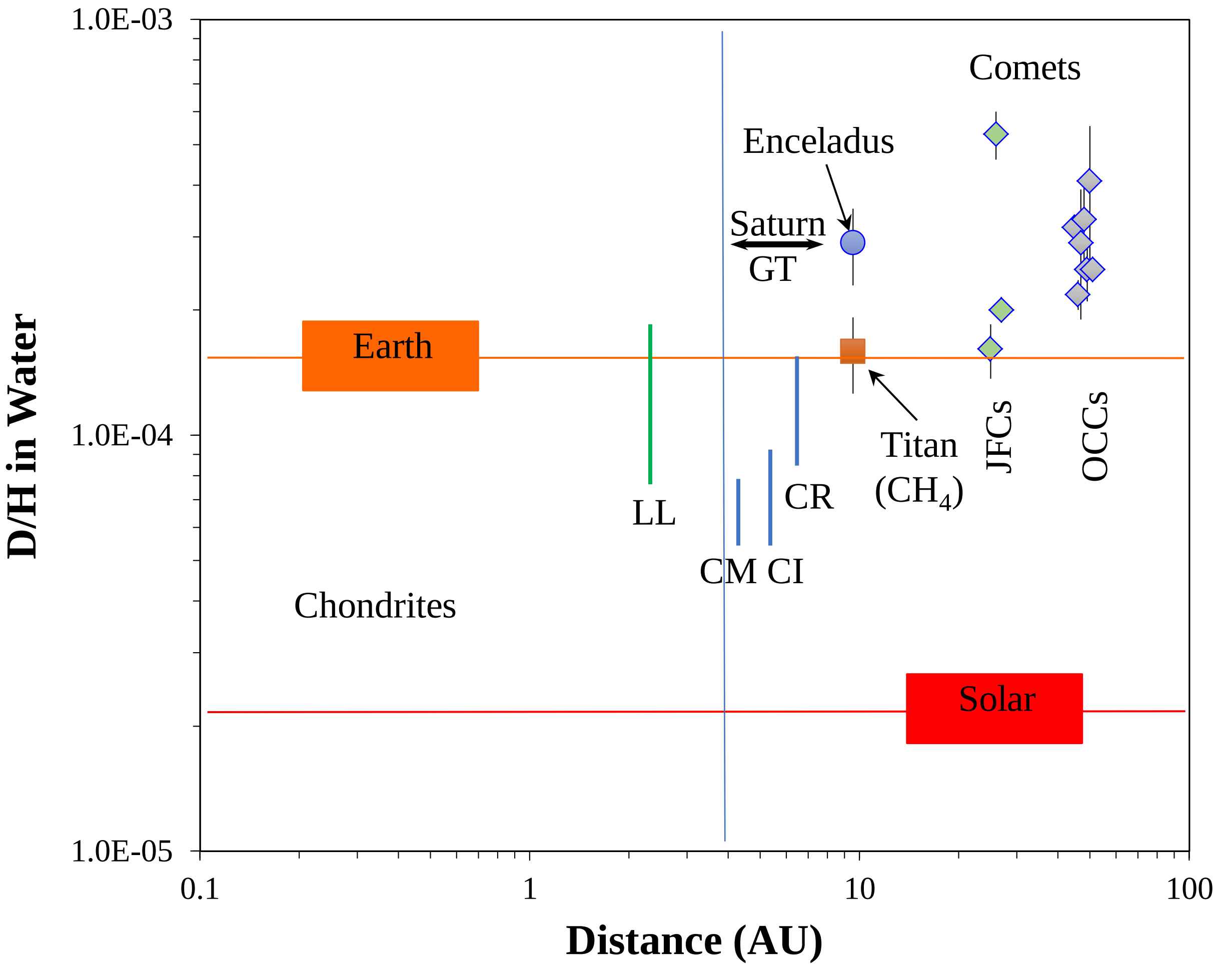
$3Fe + 4H_2O = Fe_3O_4 + 4H_2$





(Alexander et al. 2010)

H isotopes: Indicators of formation distance?



Summary

- All chondrites accreted their volatiles in a ~CI-like matrix. C, N, noble gases and some H was in a macromolecular organic matter. H_2O was accreted as ice that also included CO_2 and HCN/NH_3. No chondrite seems to have accreted their full solar H_2O complement.

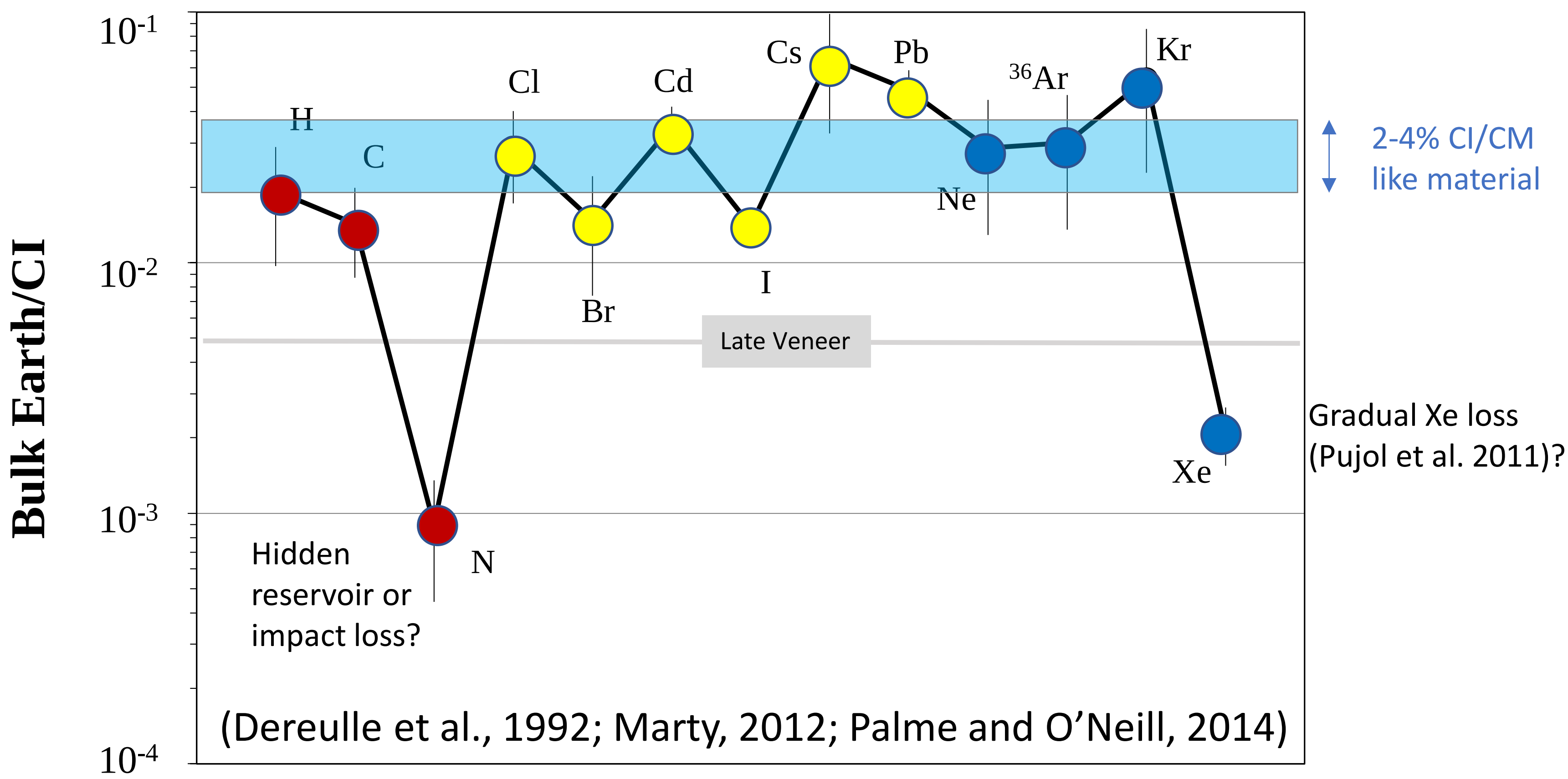
- The initial D/H of water in CCs and non-CCs were not very different, contrary to model expectations, and less than Enceladus or even Titan.

- From these perspectives, there are no compelling reasons for the CCs to have formed in outer Solar System, or at least not beyond the location of Saturn when its moons formed (3-7 AU in the Grand Tack).

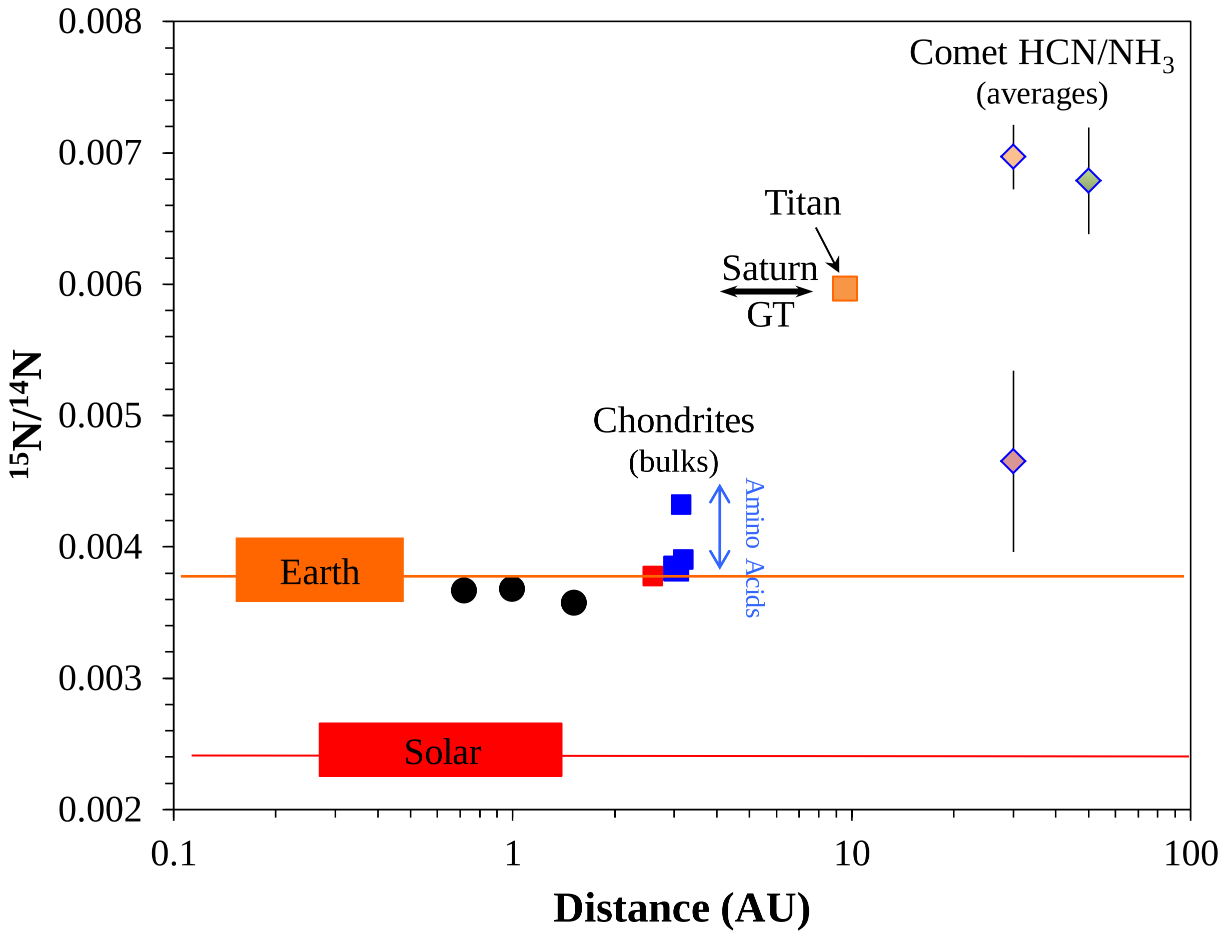
- CI/CM-like material was the major source of terrestrial planet H+N+C, perhaps with some solar input, but comets may have been much more important for noble gases.

- Atmospheric volatiles were accreted before Moon-formation and may not have been initially stored in the Earth's interior, yet somehow they survived impacts large and small.

Roughly chondritic volatiles

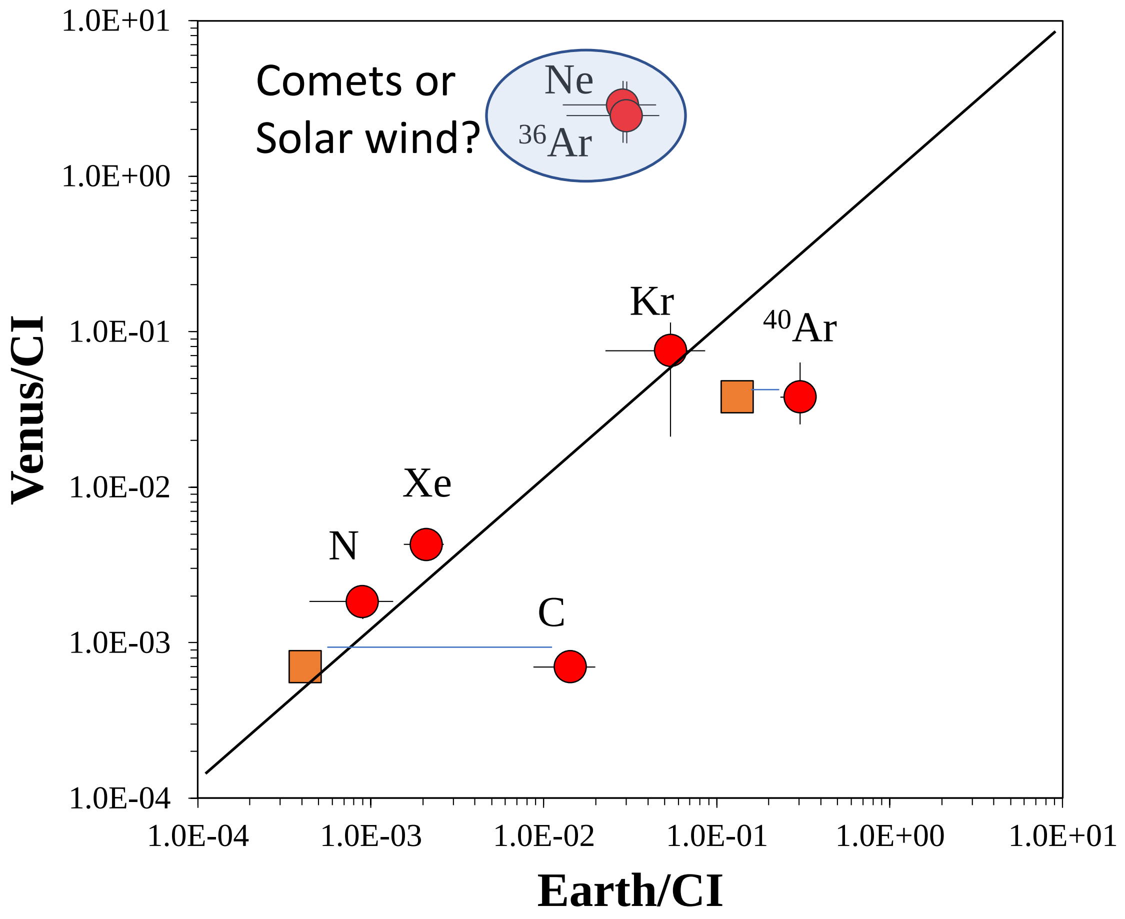


N isotopes:
Indicators of formation distance?



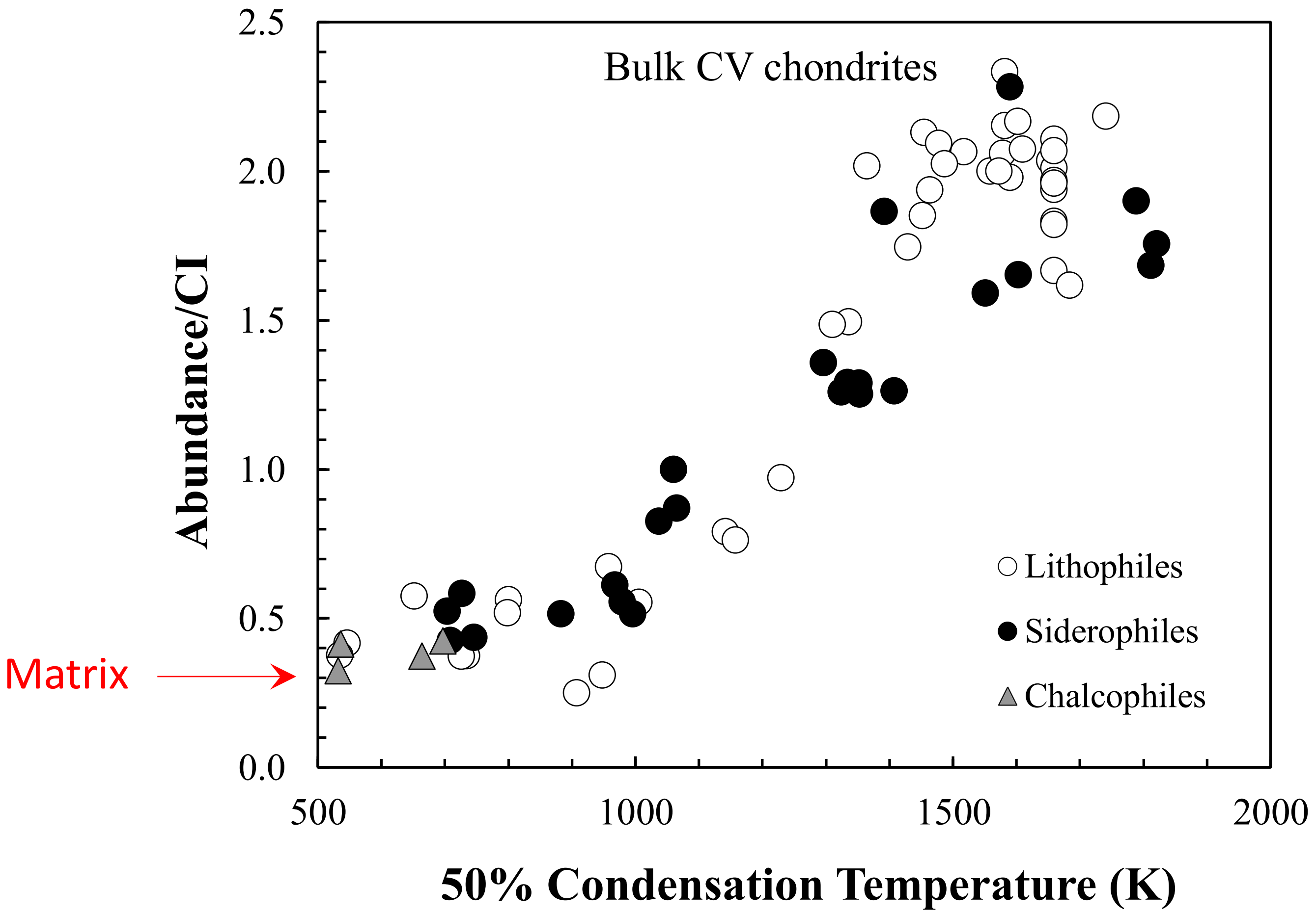
Strecker-cyano synthesis R-C=O + HCN + NH_3 + H_2O = R-CNH_2-COOH

’Twin’ planets are not identical



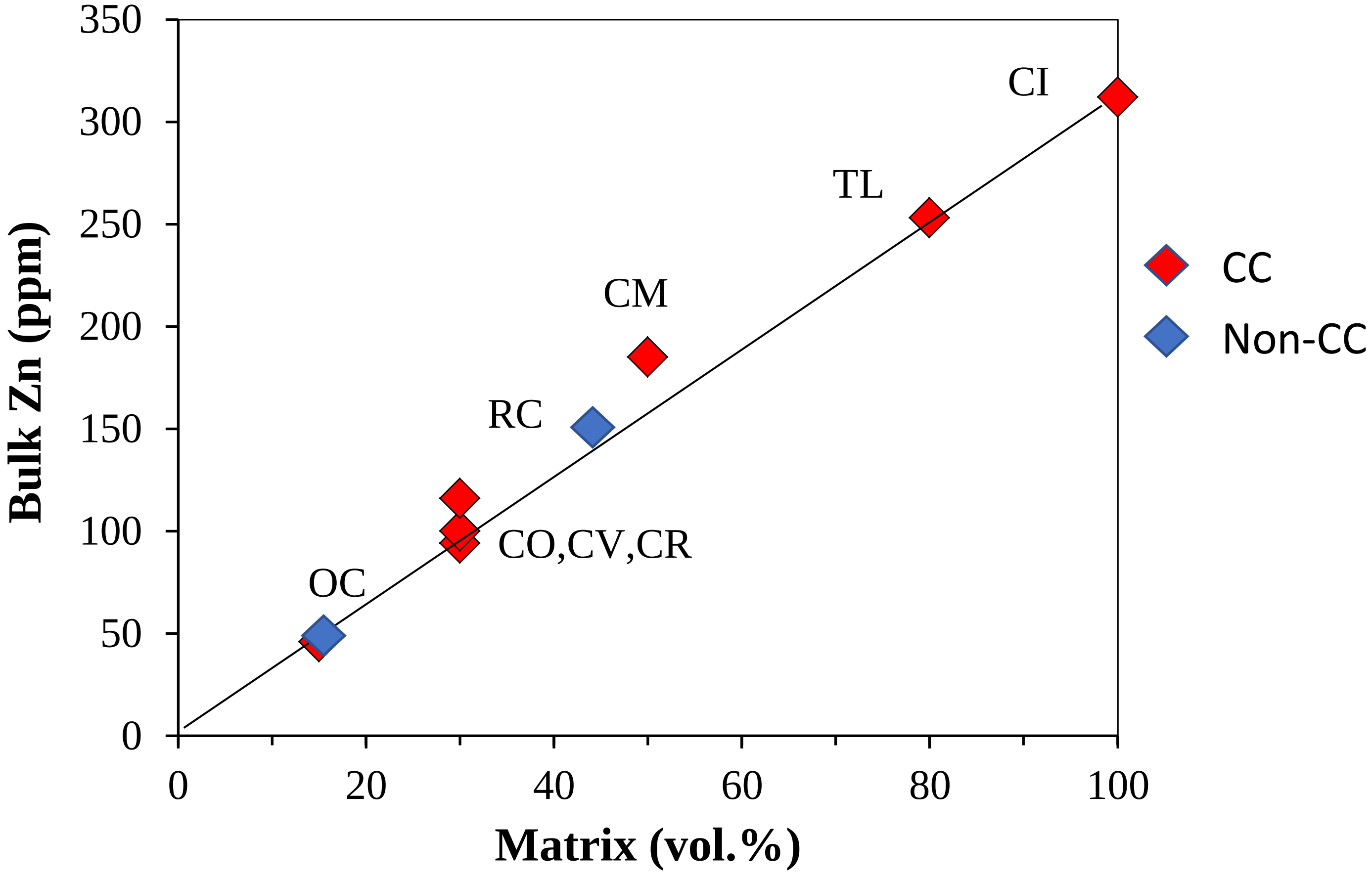
Venus abundances just for atmosphere

Volatiles in matrix



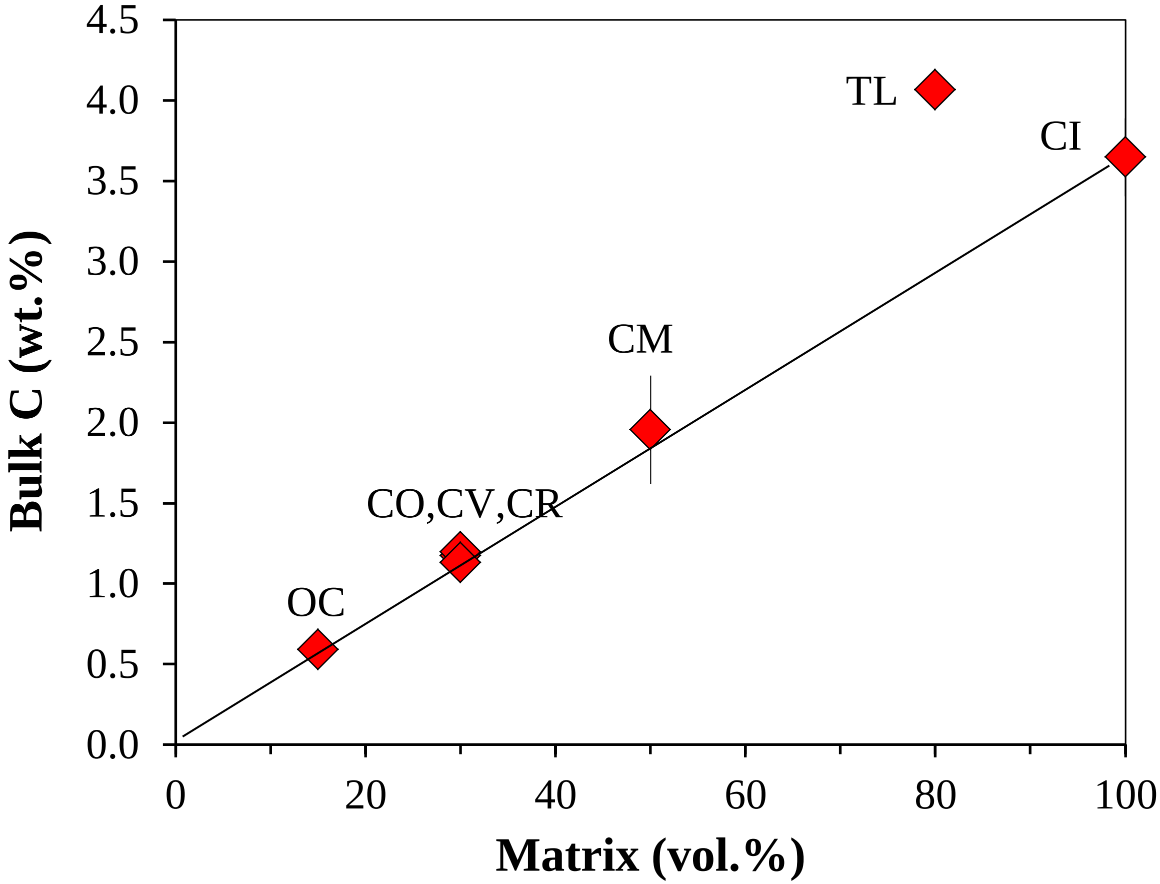
(Wasson and Kallemeyn, 1988)

Volatiles in matrix



(Wasson and Kallemeyn, 1988; Rubin and Wasson 1993: Brown et al. 2000)

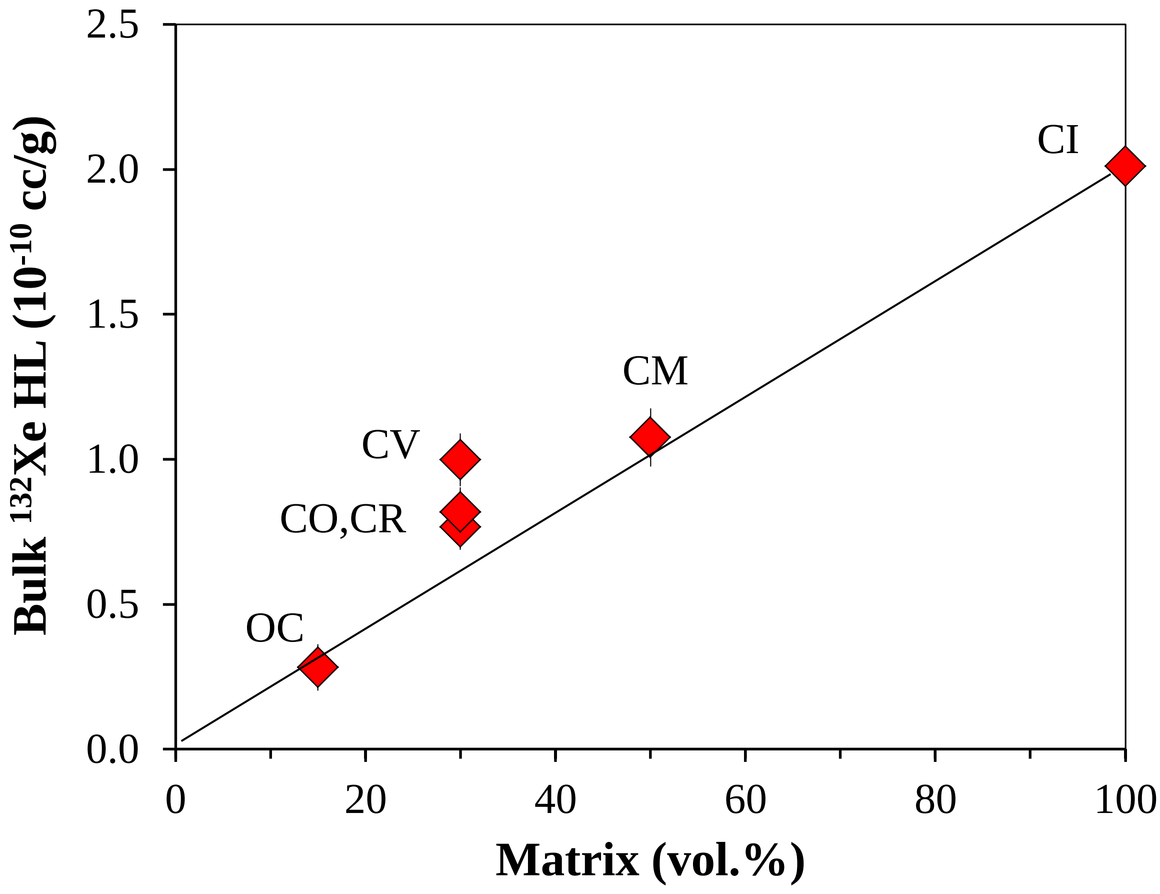
Volatiles in matrix



(Alexander et al. 2012,2014)

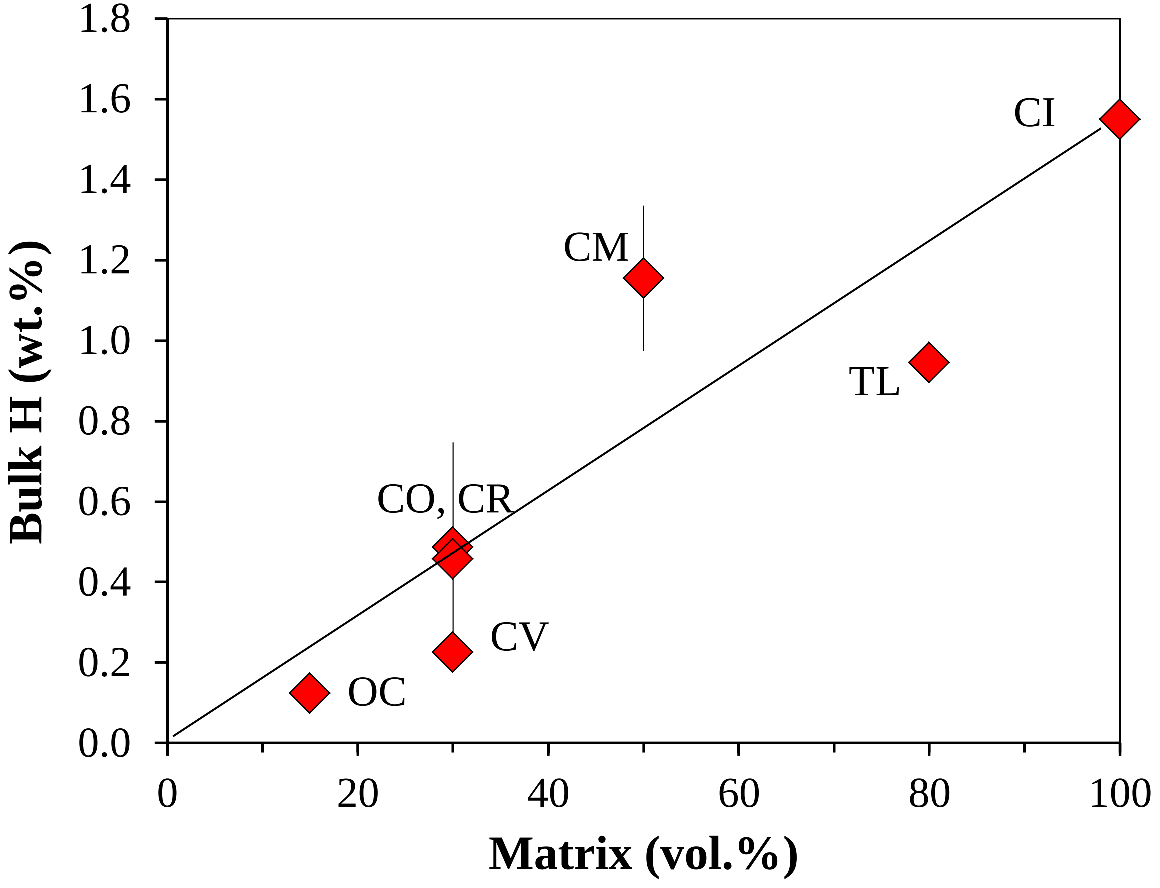
Presolar grains in matrix

(Xe-HL carried by supernova nanodiamonds)



(Huss and Lewis 1995; Huss et al. 2003)

Volatiles in matrix



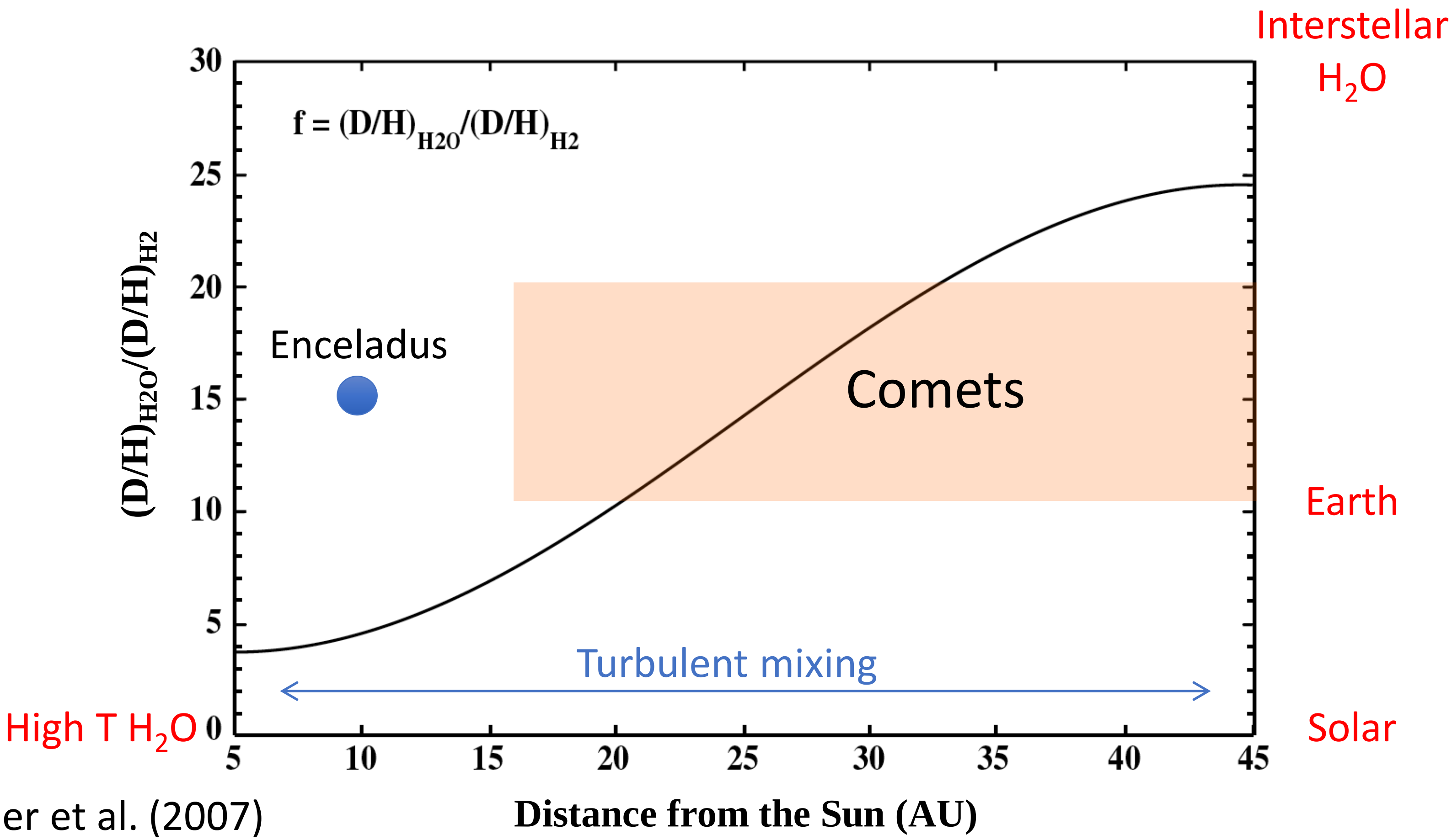
(Alexander et al. 2012)

Story so far

- The abundances of highly volatile elements, organic C, presolar circumstellar grains and water suggest that matrices in ALL chondrites are dominated by ~CI-like material.

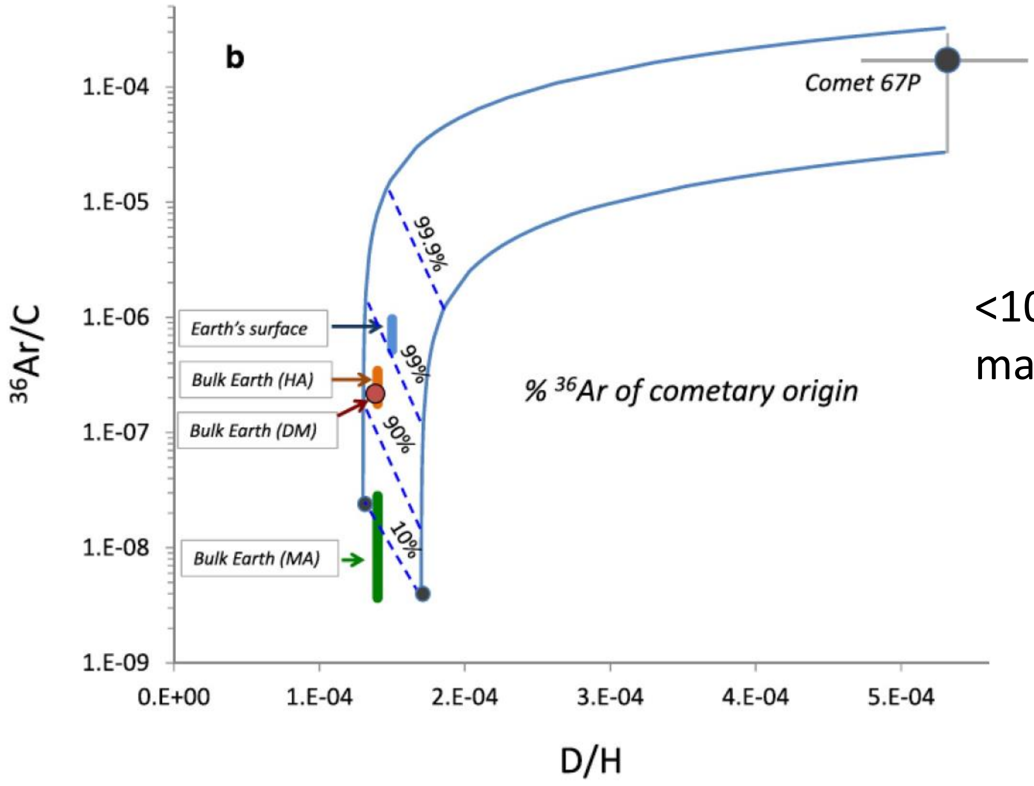
- If correct, since the ECs, OCs & RCs all formed ~2 Ma after CAIs:
  (1) CI-like material was present in the inner Solar System >2 Ma before a possible Grand Tack, and ~1 Ma after the inner Solar System was possibly sealed off by a growing Jupiter.
  (2) The snowline was already in the inner Solar System by 2 Ma. The main building blocks of the terrestrial planets may not have been initially volatile-free, but if formed <3-3.5 Ma after CAIs they were heavily modified by internal heating due to ^{26}Al.

D/H in H_2O: an indicator of formation distance from the Sun?



Horner et al. (2007)

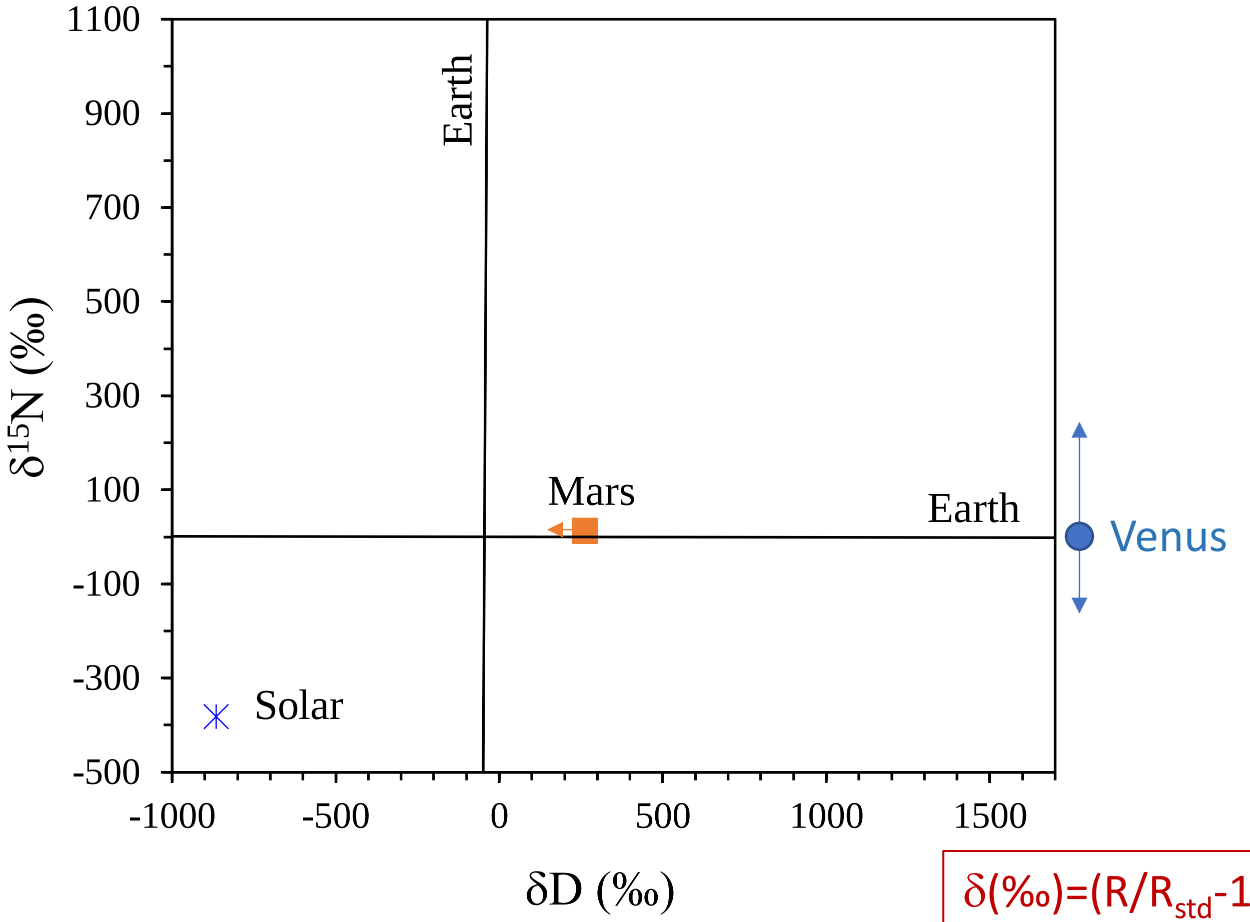
Rosetta results



<10% to >90% of terrestrial ^{36}Ar may be cometary (Marty et al. 2016)

22±5% of Xe from comets (Marty et al. 2017)

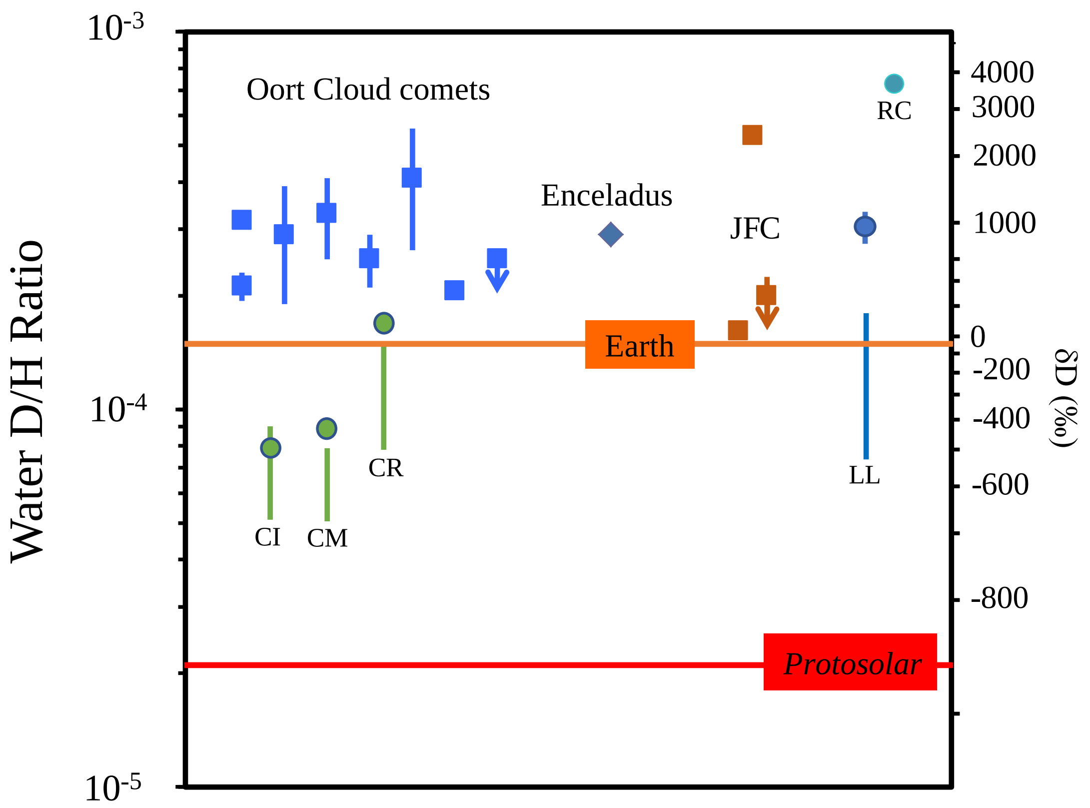
Not primordial atmospheres



$\delta(‰)=(R/R_{std}-1)\times1000$
$R=D/H$ or $^{15}N/^{14}N$

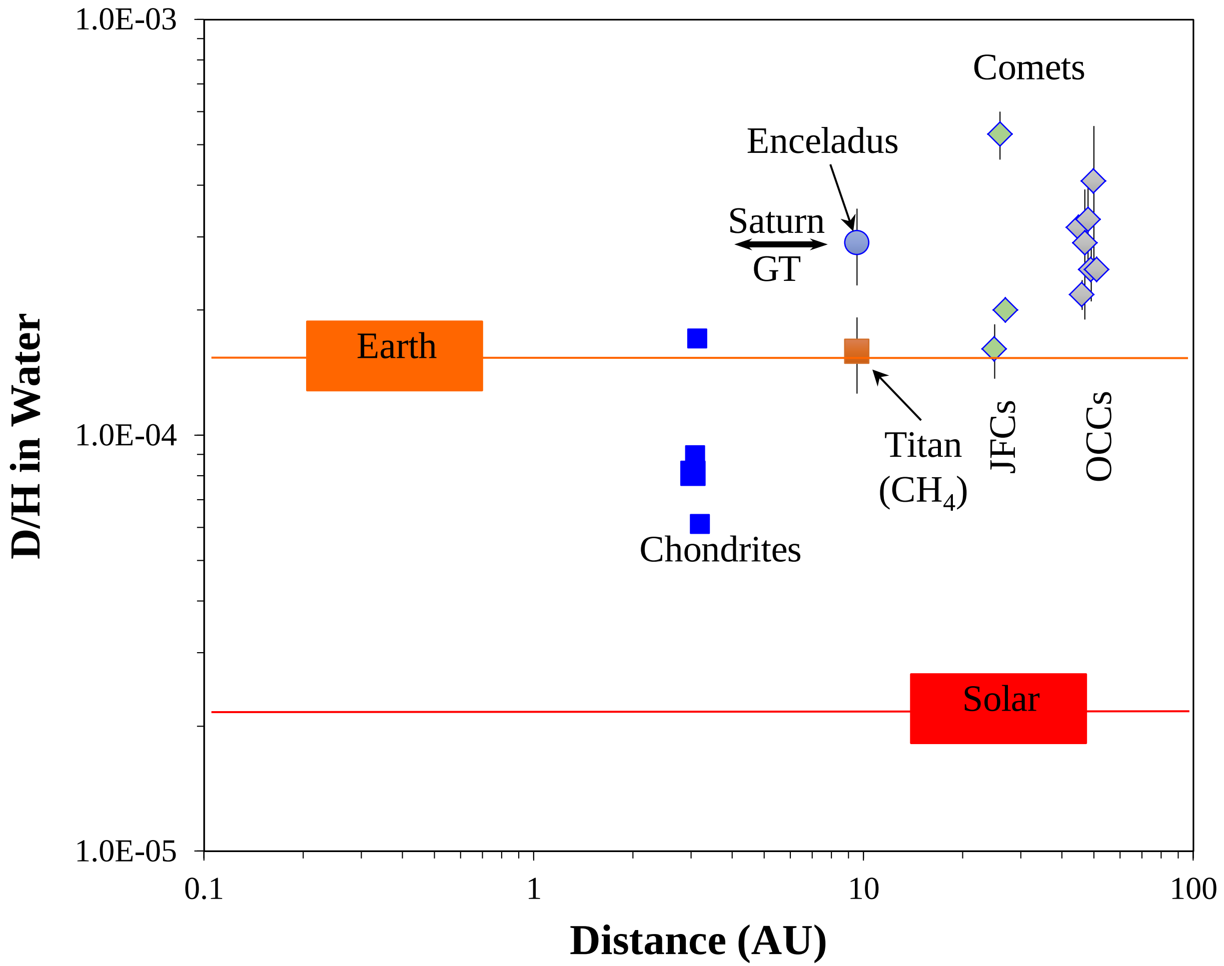
Jaupart et al. (2017) – Ne, at least, in embryos not from primordial atmospheres.

Corrected water H isotopes



(Sutton et al. 2017)

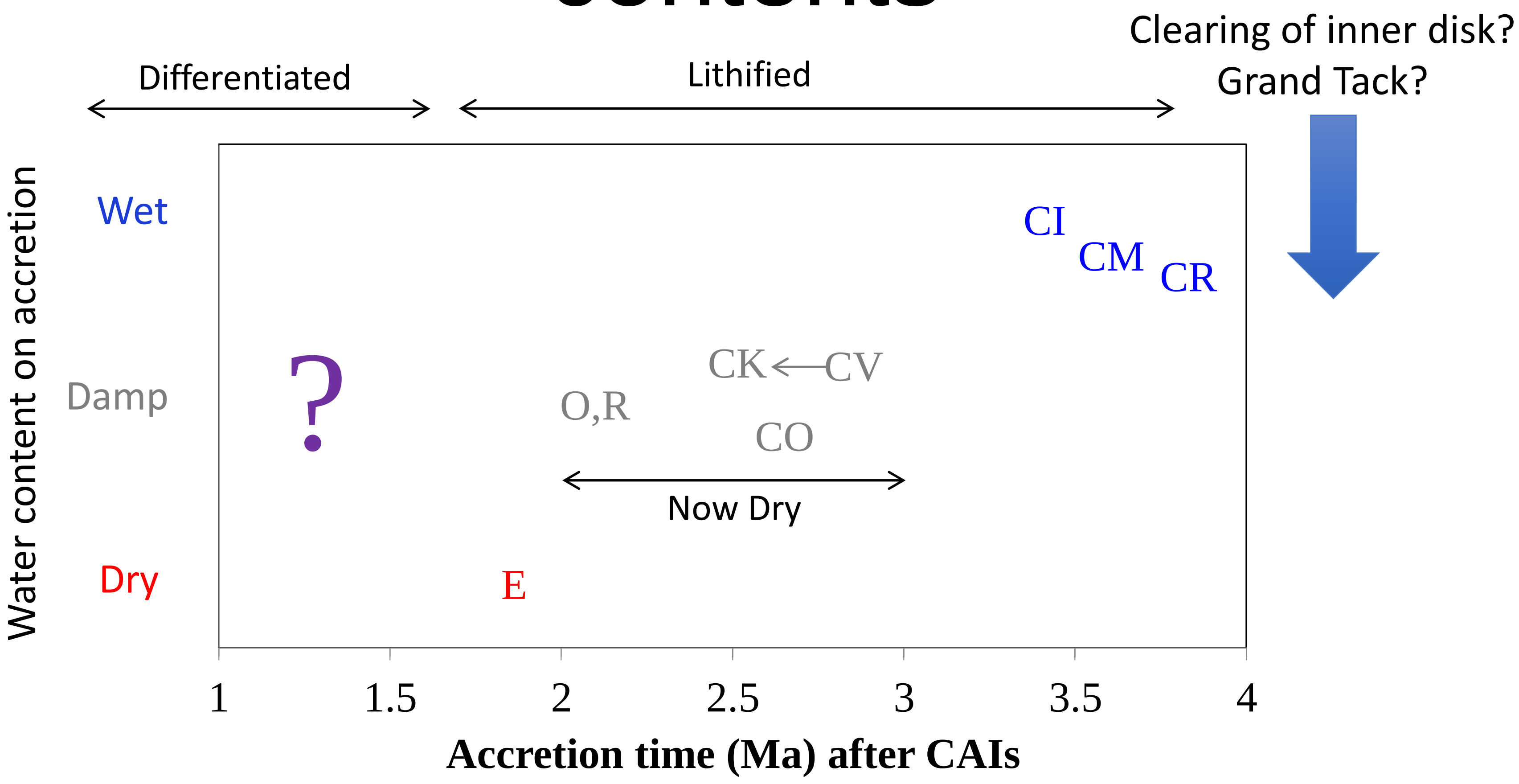
H isotopes:
Indicators of formation distance?



A possible alternative?

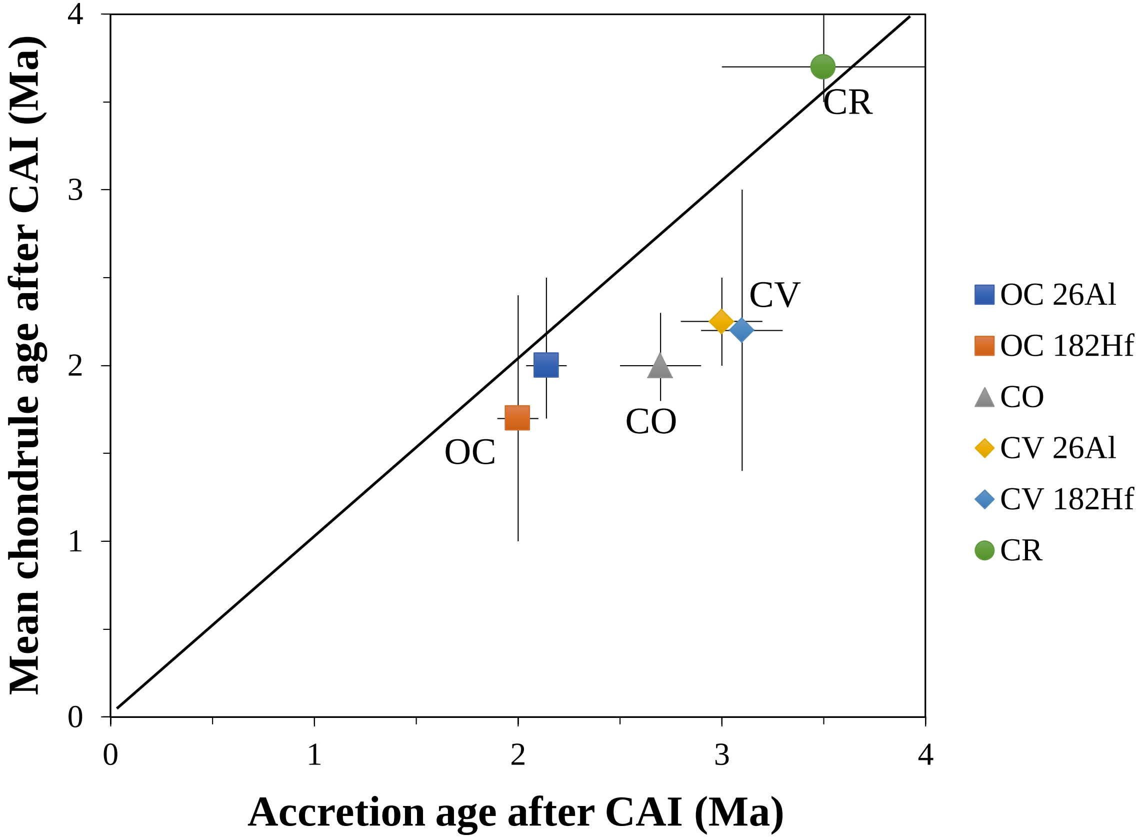
- There was a burst of early planetesimal formation involving material that had been thermally processed by FU Orionis outbursts and from which CAI material was extracted.
- By 2 Ma this material was nearly exhausted and material from the outer Solar System (matrix) began diffusing in and dominated later formed planetesimals. This material included refractory inclusions (CAIs and AOAs).

Accretion times and water contents



Accretion times modified after Sugiura and Fujiya (2014)

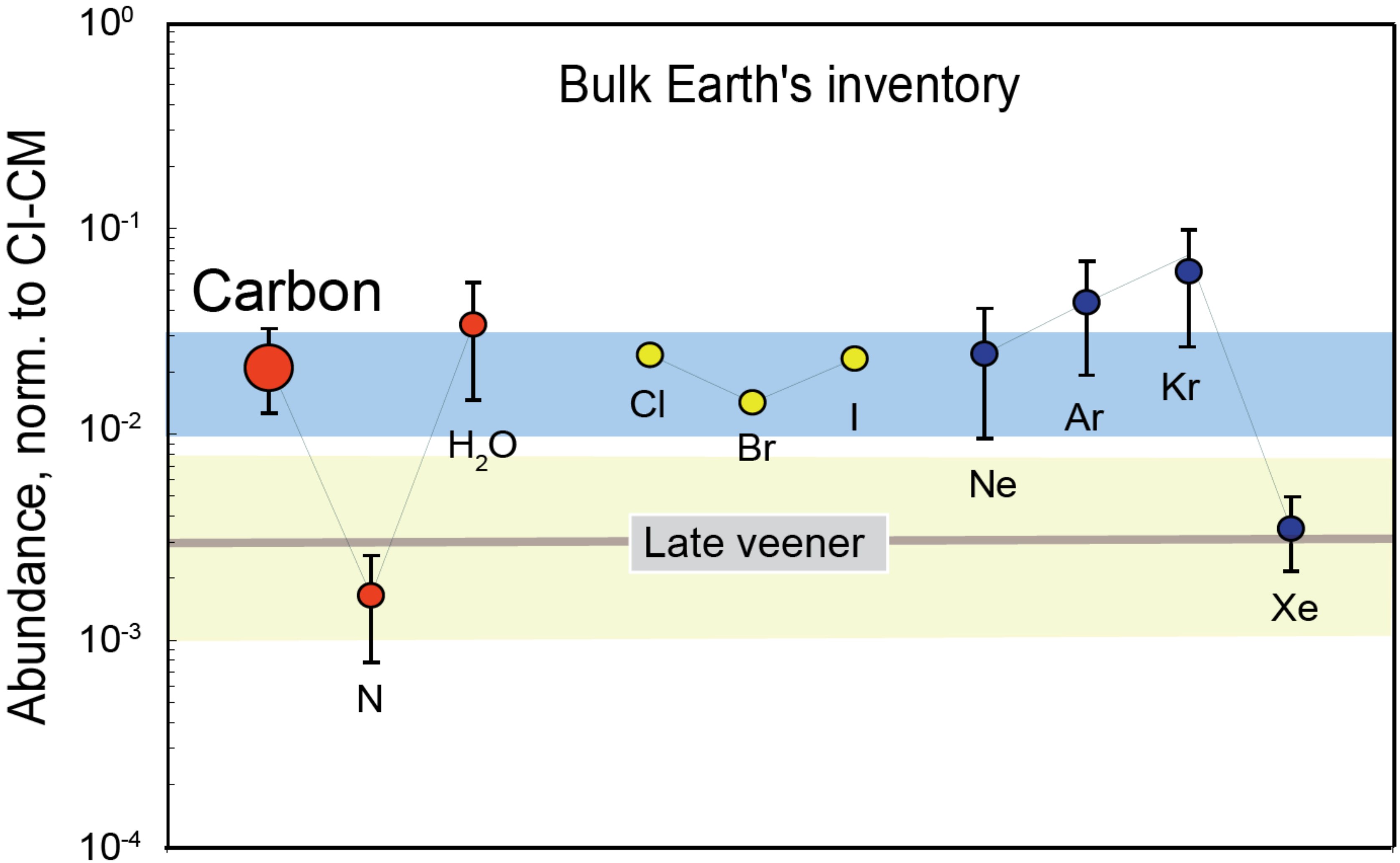
Summary



Accretion ages: Sugiura and Fujiya (2014)

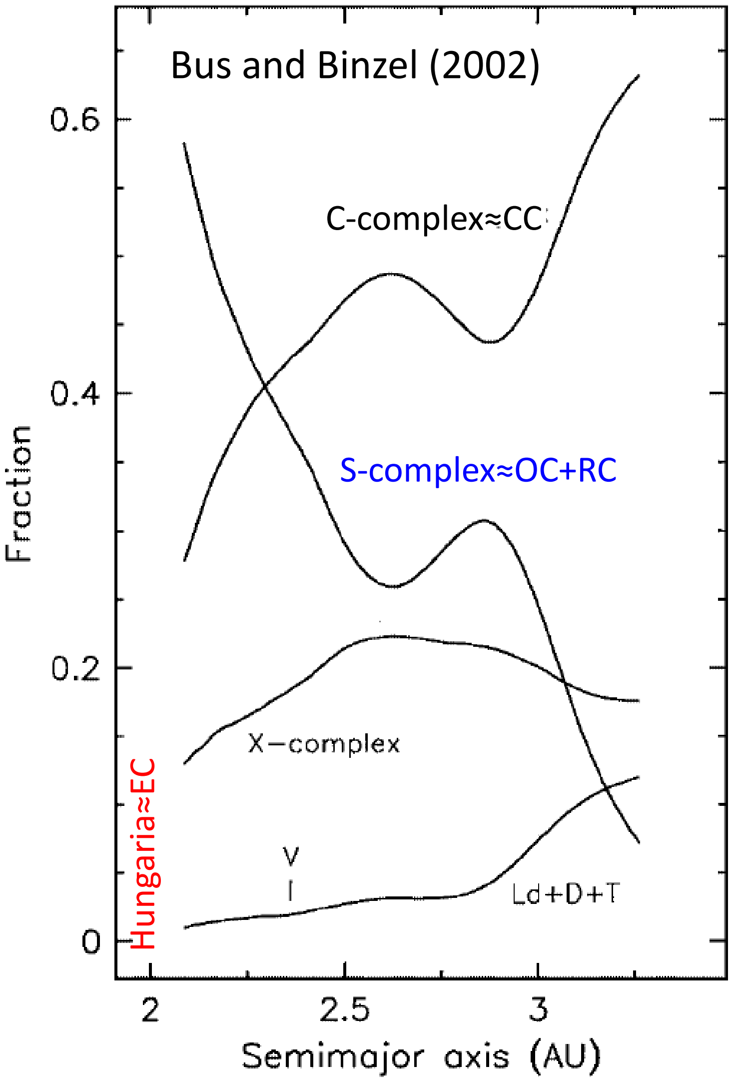
Chondrule ages: OC Al-Mg, Kita et al. 2008, Villeneuve et al. 2009; OC Hf-W, Kleine et al. 2008; CO Al-Mg, Kurahashi et al. 2008; CV Al-Mg (Kaba) Nagashima et al. 2015; CV Hf-W Budde et al. 2016; CR Al-Mg Schrader et al. 2017.

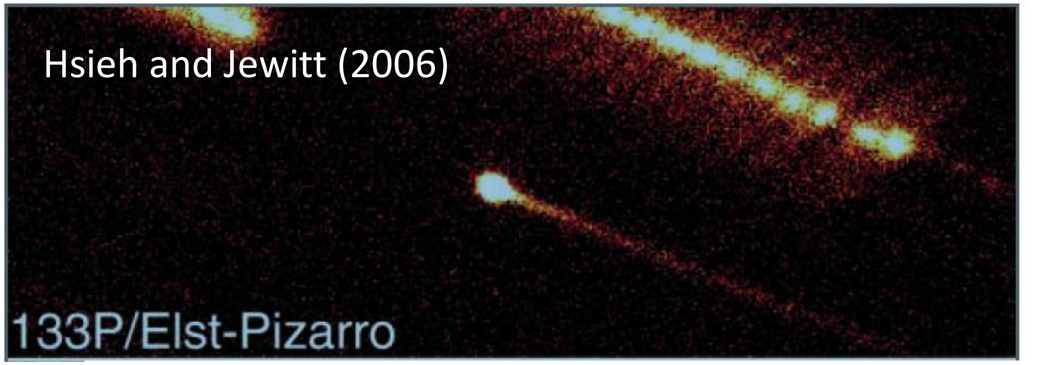
Volatiles from primitive meteorites

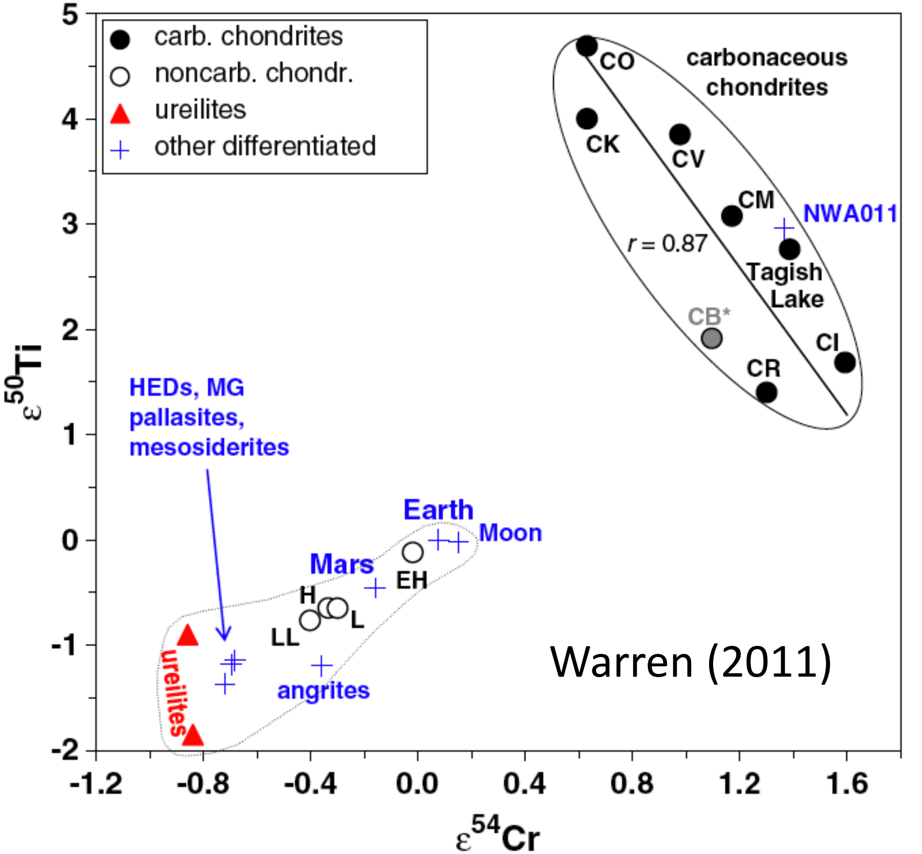


Marty et al. (2012, 2013)

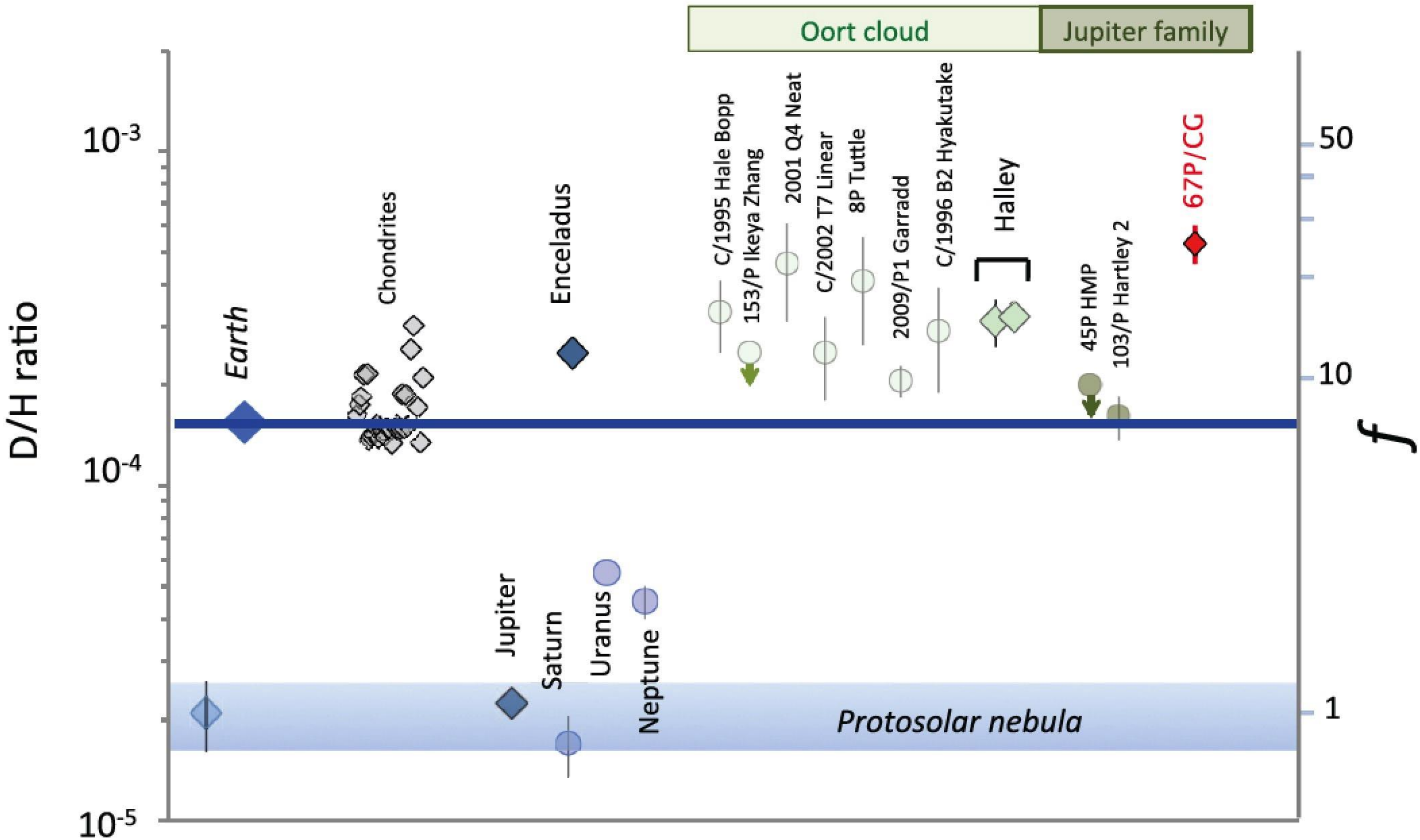
Asteroidal Sources





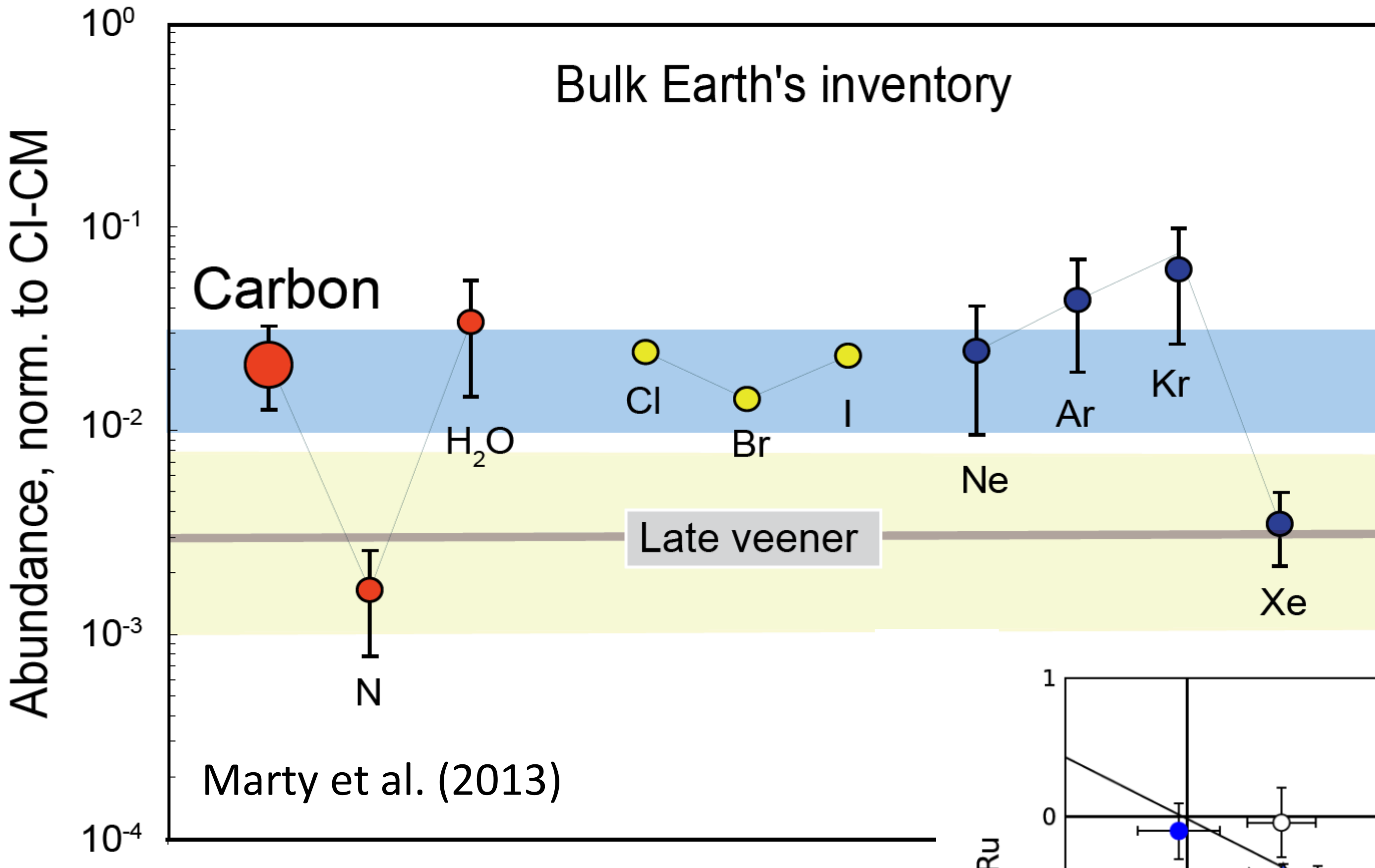


D/H in Solar System objects

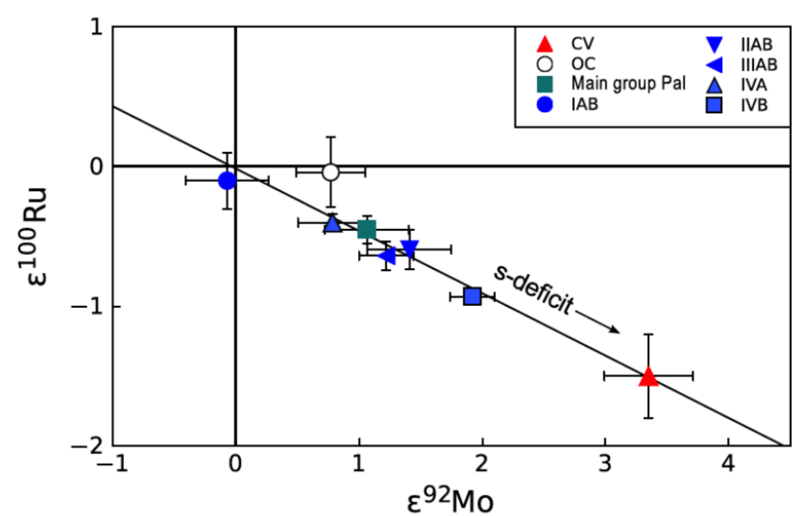


Altwegg et al. (2015)

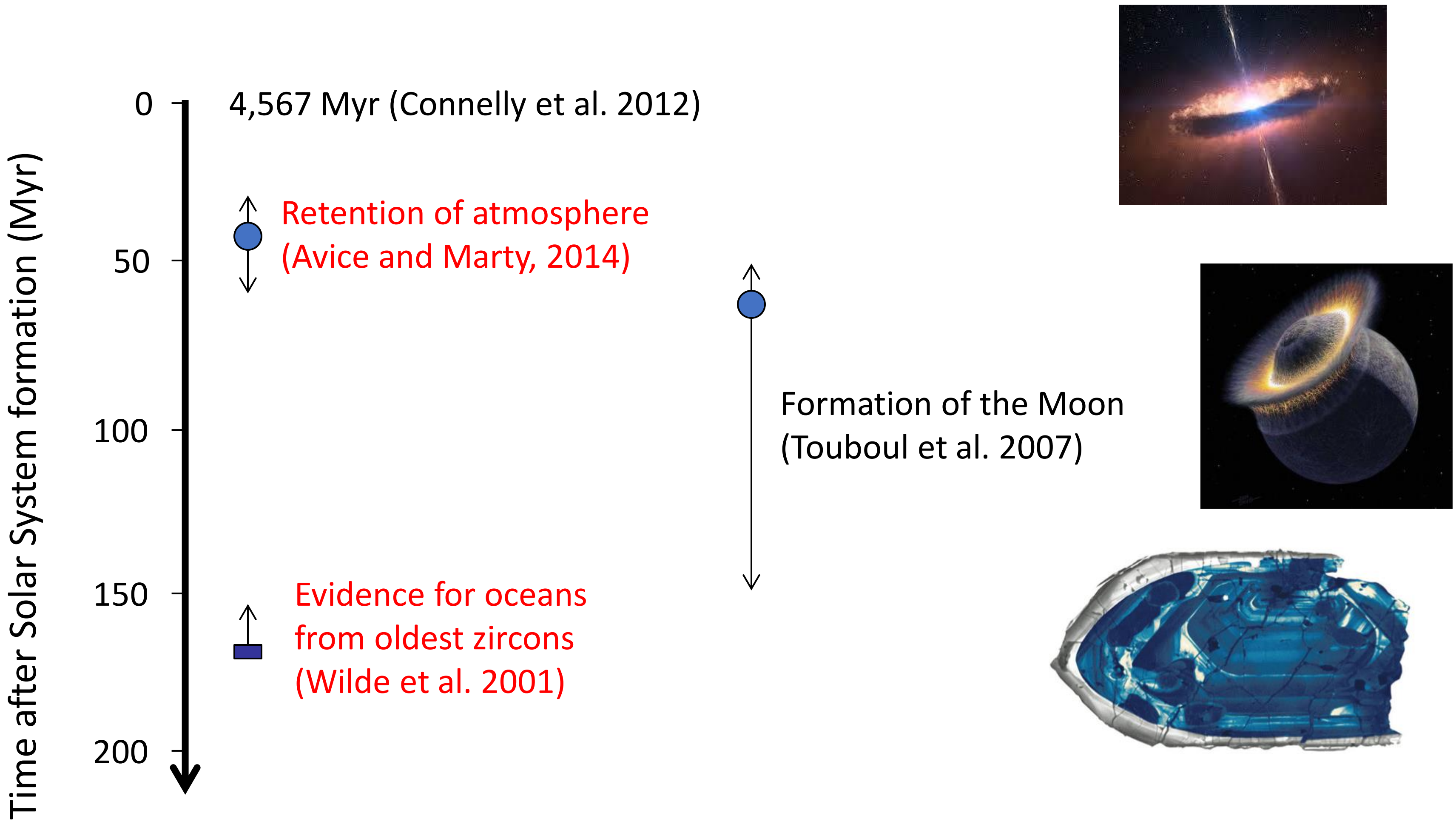
Volatiles from primitive meteorites

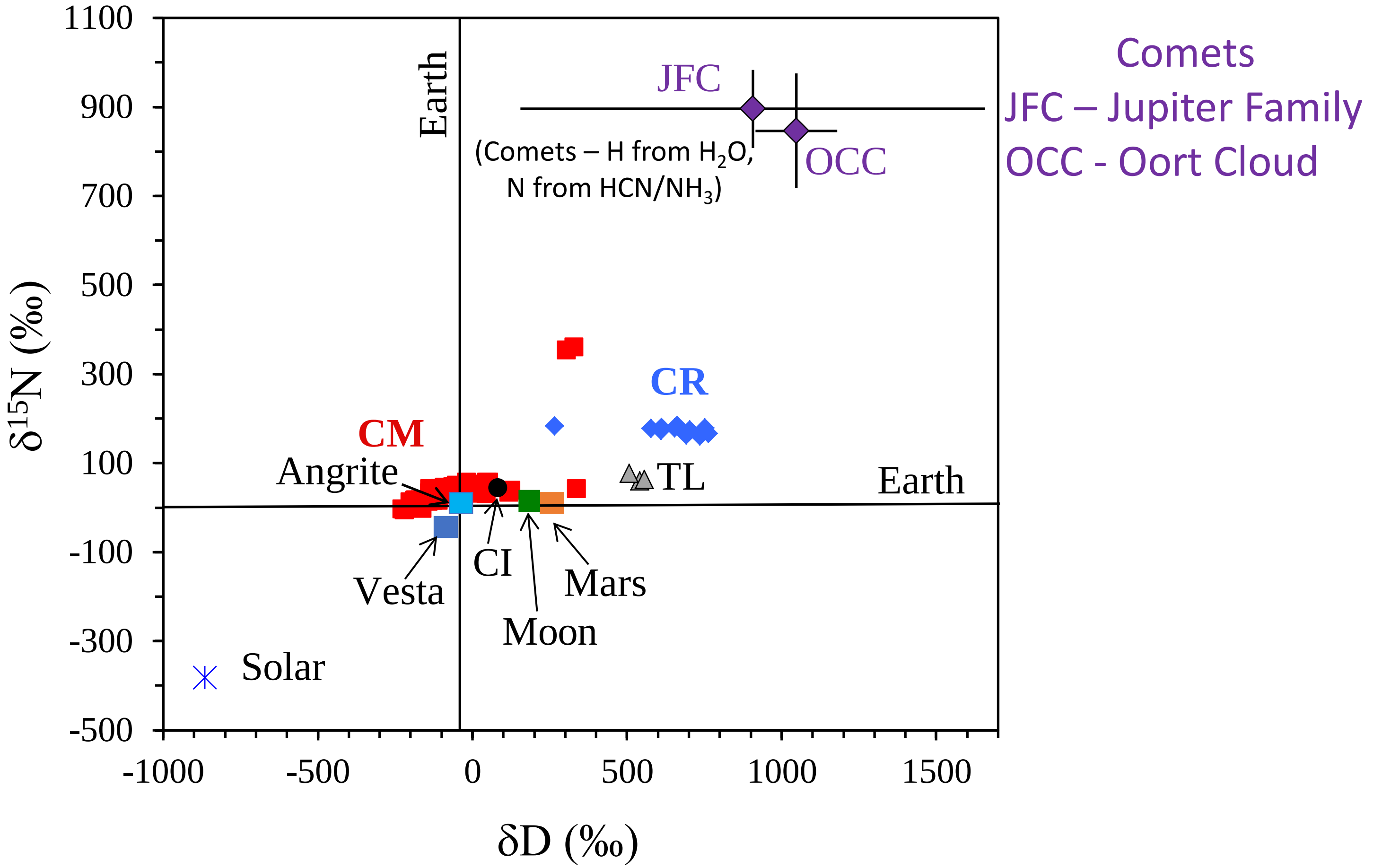


Marty et al. (2013)



Time constraints





Comets
JFC – Jupiter Family
OCC - Oort Cloud
JFC
OCC
Earth
(Comets – H from H_2O,
N from HCN/NH_3)
CR
CM
Angrite
TL
Earth
CI
Vesta
Mars
Moon
Solar
1100
900
700
500
300
100
-100
-300
-500
-1000
-500
0
500
1000
1500
$\delta^{15}N$ (‰)
δD (‰)

What's the issue?

- There was CI/CM-like material in the inner Solar System well before there could have been a Grand Tack (>4 Ma), but after Jupiter may have sealed off the inner Solar System (≤1 Ma).

- Minor irritant or big problem? Depends on how much and how much earlier.