

# Oxygen Isotopes in the Solar System



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**Having formed the isotopic composition of the primitive Solar nebula, what caused the observed oxygen isotope fractionation?**

<b><math>^{16}\text{O}</math></b> 15.9949 99.76%	<b><math>^{17}\text{O}</math></b> 16.9991 0.04%	<b><math>^{18}\text{O}</math></b> 17.9991 0.20%
Stable	Stable	Stable

- ❖ Most abundant element after H and He
- ❖ Forms 50% of all silicate and oxide minerals
- ❖ Occurs in solid (rocks), liquid ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ), organic materials and gases
- ❖ Three stable isotopes
- ❖  $^{16}\text{O}$  is a primary product of nucleosynthesis and therefore very abundant
- ❖  $^{17}\text{O}$  and  $^{18}\text{O}$  are secondary products, therefore these isotopes were formed in different stellar environments

**How did oxygen isotopes behave during stages of condensation and accretion of the solar nebula?**

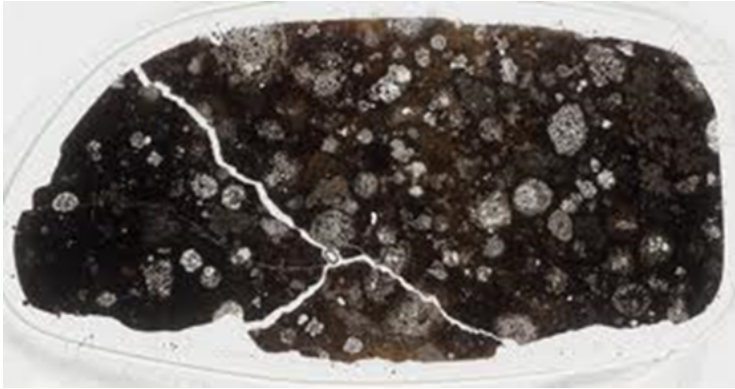


Primitive solar nebula condenses and accretes to form dust, then minerals, rocks and ice. We analyse the earliest rocks and minerals to see how oxygen isotopes behaved.



Chondritic meteorite

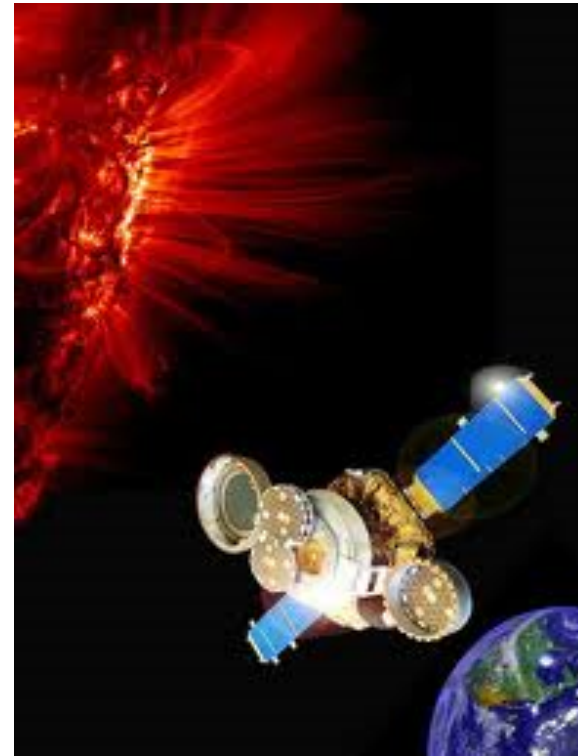
## What do we analyse for oxygen isotopes?



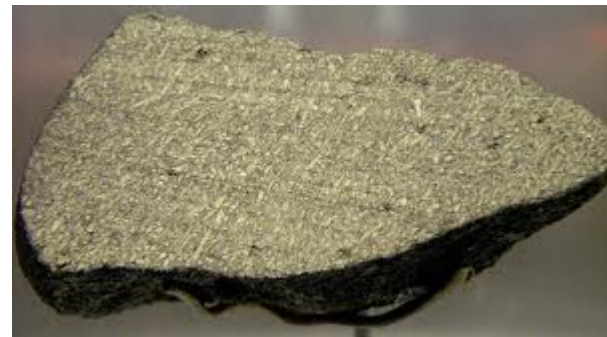
Primitive meteorites



Samples directly from comets (Stardust) and asteroids (Hayabusa)



Samples of Solar Wind (Genesis mission)



Fragments of planets (e.g. Mars)

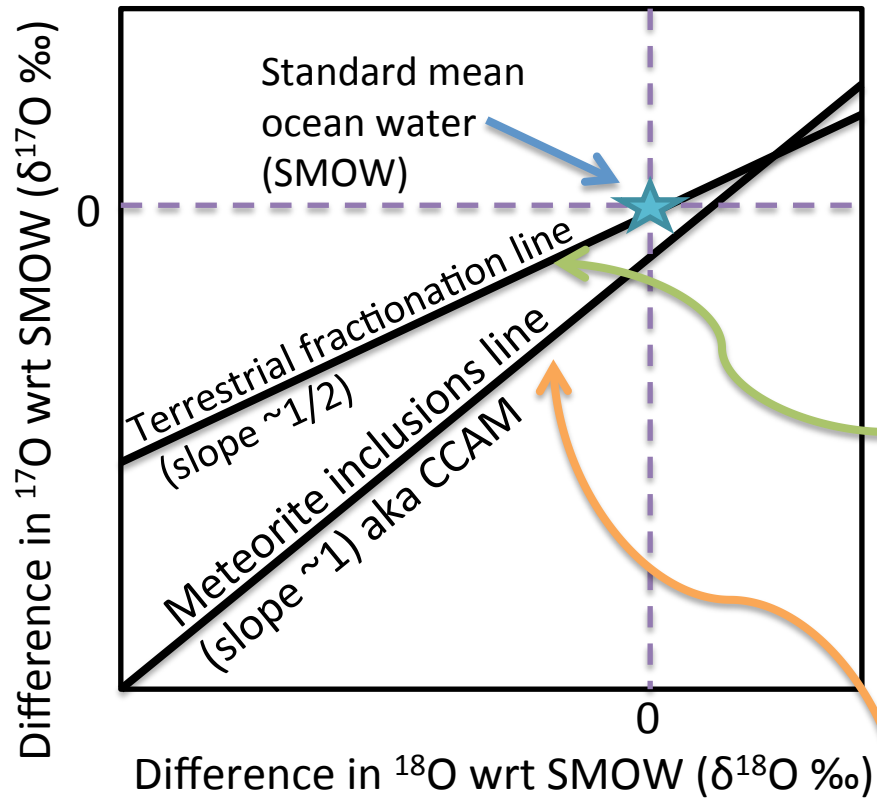
## Analytical methods

1. Analyse “bulk rock” by grinding the whole meteorite to a powder; react with  $\text{BrF}_5$  to liberate oxygen; send oxygen gas to mass spectrometer.
2. Separate minerals from the meteorite by hand; heat minerals with a laser; react with  $\text{BrF}_5$  to liberate oxygen; send oxygen gas to mass spectrometer.
3. Analyse minerals “in situ” by ion-beam techniques (SIMS and nano-SIMS) or laser. Prepare a polished surface of rock; carefully map minerals on surface; release oxygen atoms from surface by ion beam or laser; send oxygen gas to mass spectrometer.



## Reporting oxygen isotope data from Solar System material

The only diagram you need to know:



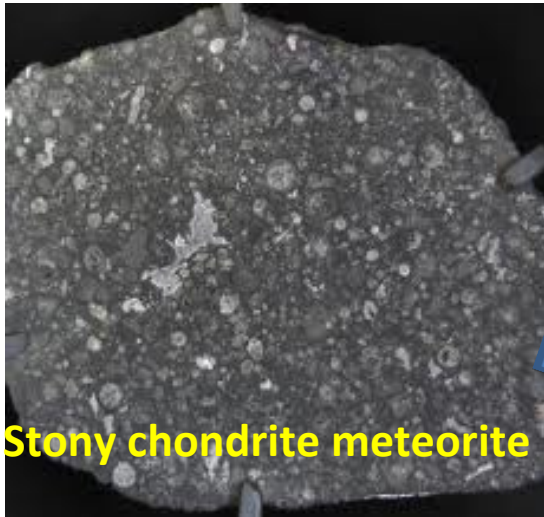
For historical reasons, we measure oxygen isotope compositions in per mil deviations from a terrestrial standard (Standard Mean Ocean Water “SMOW”, which has  $\delta^{17}\text{O} \text{ ‰}$  and  $\delta^{18}\text{O} \text{ ‰} = 0$  by definition)

We also usually report the Terrestrial Fractionation Line (TFL) which has a slope of  $\sim 1/2$ , on which all material from Earth plots. This is due to mass-dependent fractionation (due to melting, evaporation, etc).

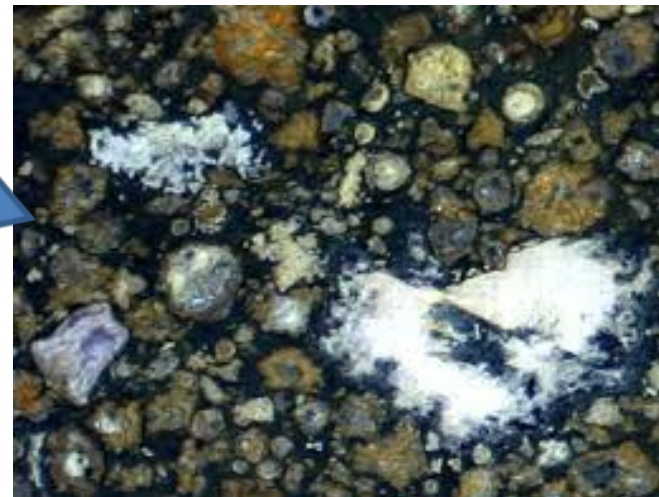
We usually report the line on which minerals from carbonaceous chondrite meteorites plot (CCAM line) which has a slope of  $\sim 1$  (mass-independent).

## What is available for analysis?

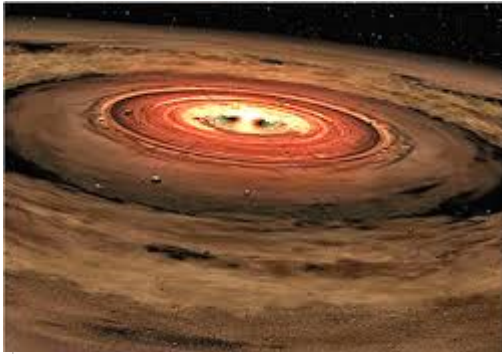
It seems obvious to start our journey through the oxygen isotopic variation of the Solar System with the Sun, but analysing the Sun's oxygen isotope composition is frustratingly difficult. So we started by analysing the oldest components of the Solar System found in meteorites.



Chondrules – early solar system unprocessed left-overs



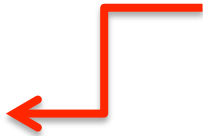
Calcium aluminium inclusions (CAIs) – refractory material formed by condensation of the primitive solar nebula



## Ages of material and events in the early Solar System



Formation of highly refractory CAIs taken to represent time of condensation of primitive solar nebula ("time zero")



CAIs

0.1 My

Chondrules

1 My

planets

Aqueous alteration

Note the log scale!!

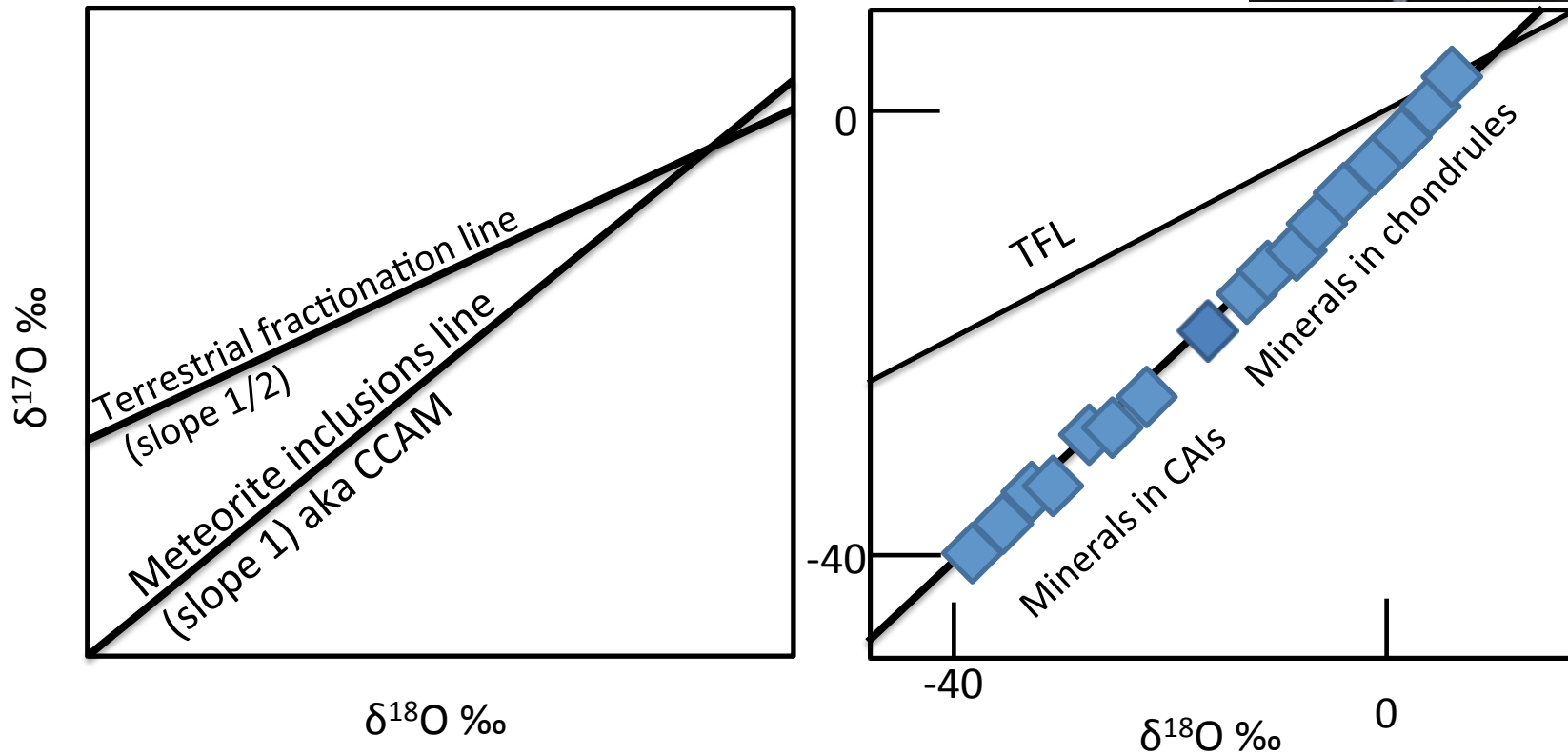
10 My

100 My

Time (in units of Millions of years after Solar System formation)

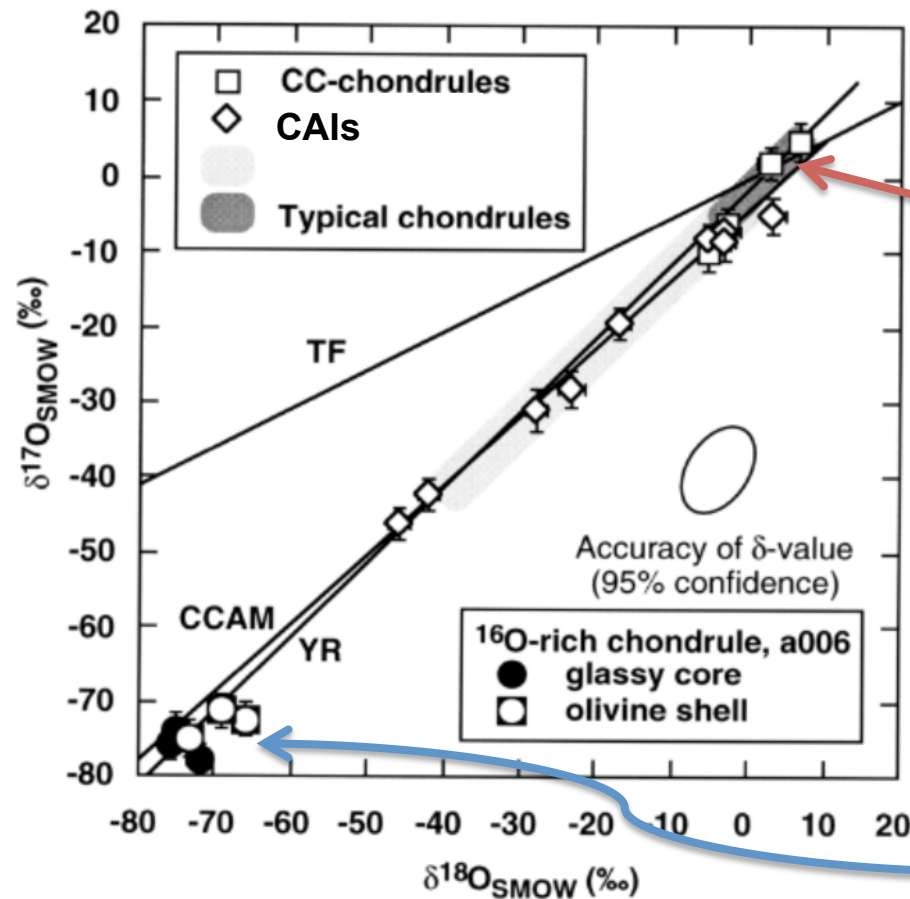
After Kleine and Rudge (2011) Elements vol. 7, issue 1

**Oxygen isotope data from early Solar System material (anhydrous minerals from Ca-Al inclusions and chondrules)**



Early work by Clayton and Mayeda gave us the “carbonaceous chondrite anhydrous mineral” (CCAM) line which represents early-formed solar system solid material.

## Solid material in the primitive Solar System



Carbonaceous chondrite chondrules plot near the intersection of the TFL and the CCAM lines

Kobayashi et al (2003) found the most extreme  $^{16}\text{O}$ -rich chondrule minerals with  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O} = -75 \text{‰}$

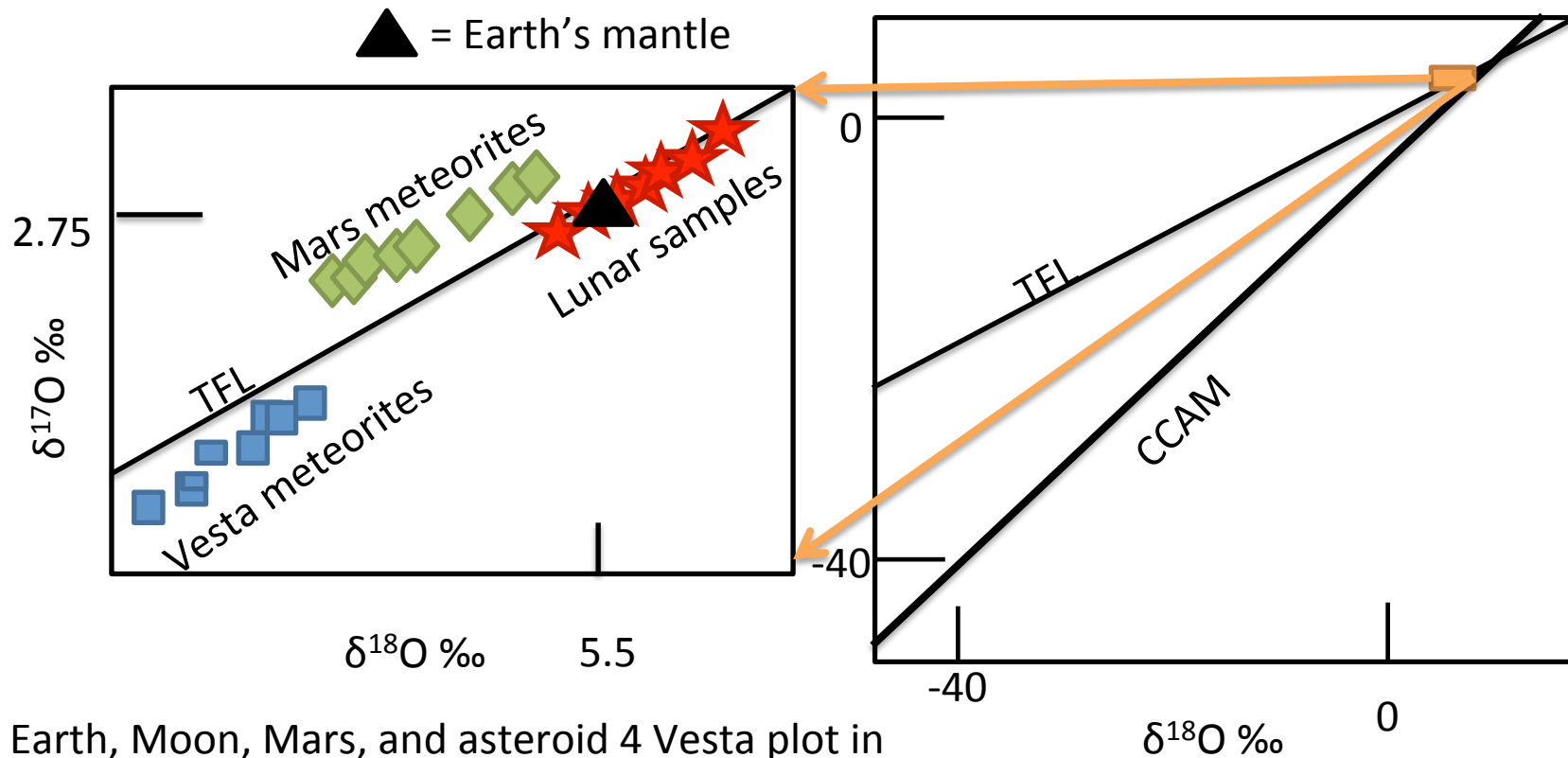
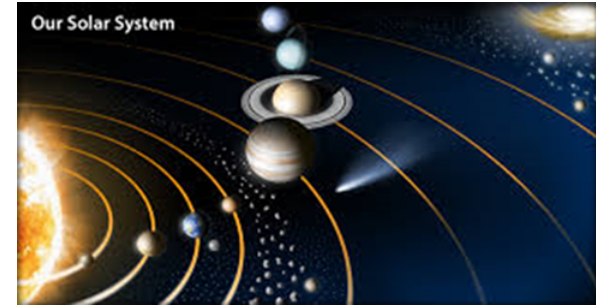
**What about the oxygen isotope compositions of planetary bodies?**



We have samples of four terrestrial planets or differentiated asteroids

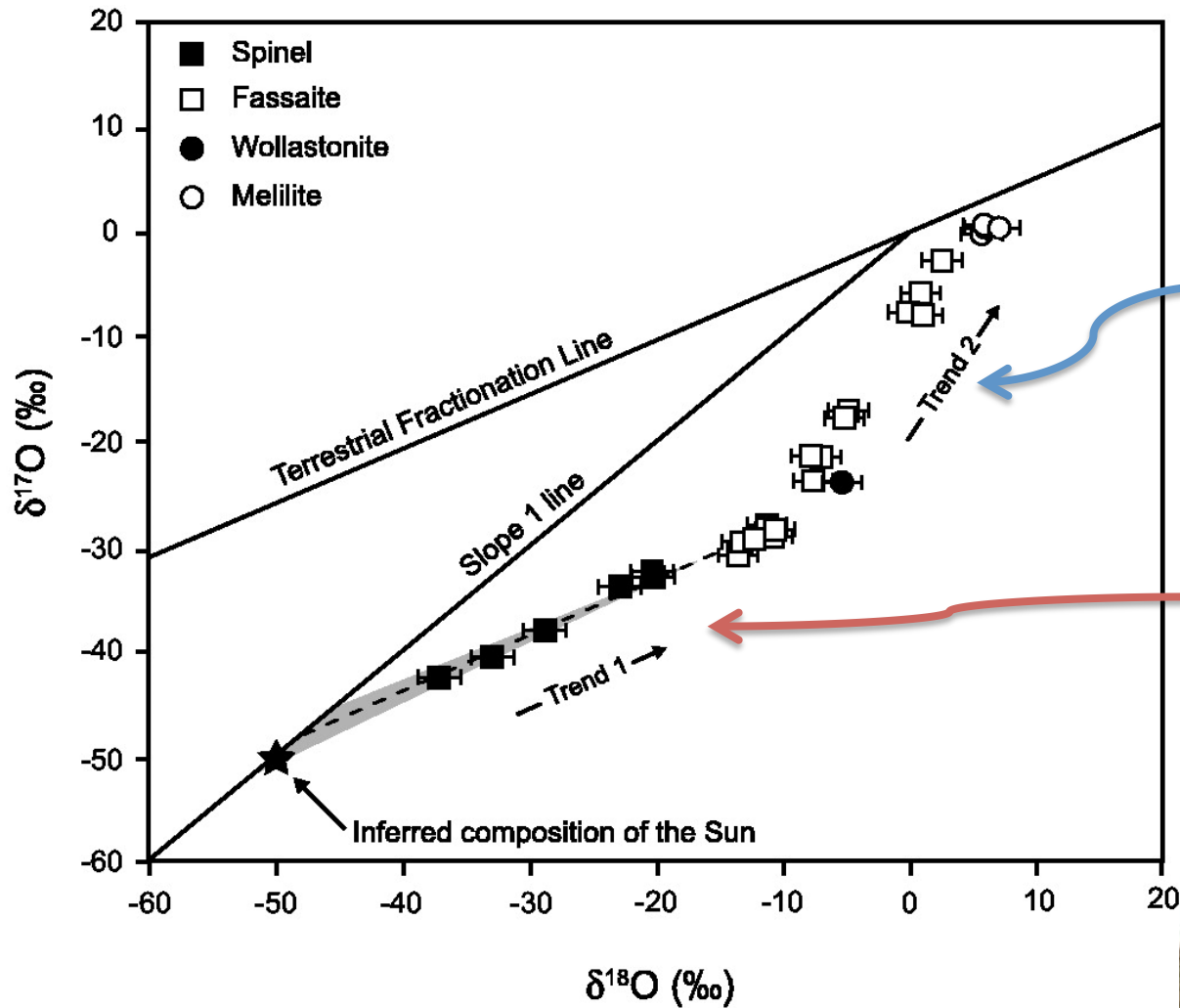


Oxygen isotope data from differentiated planetary bodies



Earth, Moon, Mars, and asteroid 4 Vesta plot in a very limited oxygen isotope range but show slightly different fractionation lines (parallel to TFL, or exactly on TFL in the case of the Moon)

The Sun's oxygen isotope composition may be inferred from the composition of some unusual CAIs that don't plot of the CCAM line



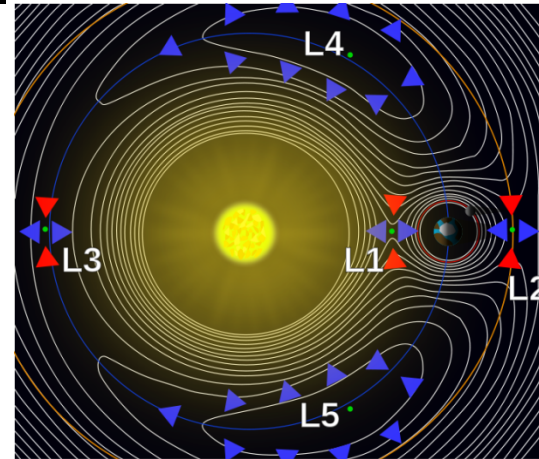
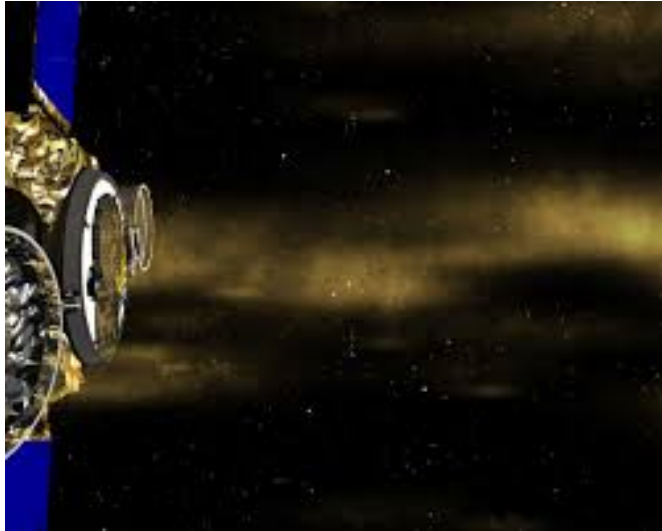
Trend 2 = isotope exchange between  $^{16}\text{O}$ -rich CAI melt and  $^{16}\text{O}$ -poor nebular gas

Trend 1 = mass dependent evaporation of CAI melt (i.e. slope  $\sim 1/2$ ) parallel to TFL

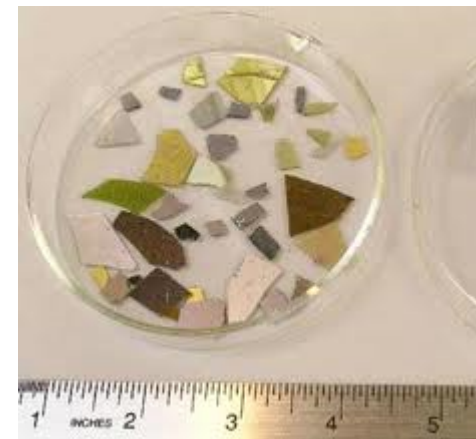


Thrane et al 2008 Astrophysical Journal

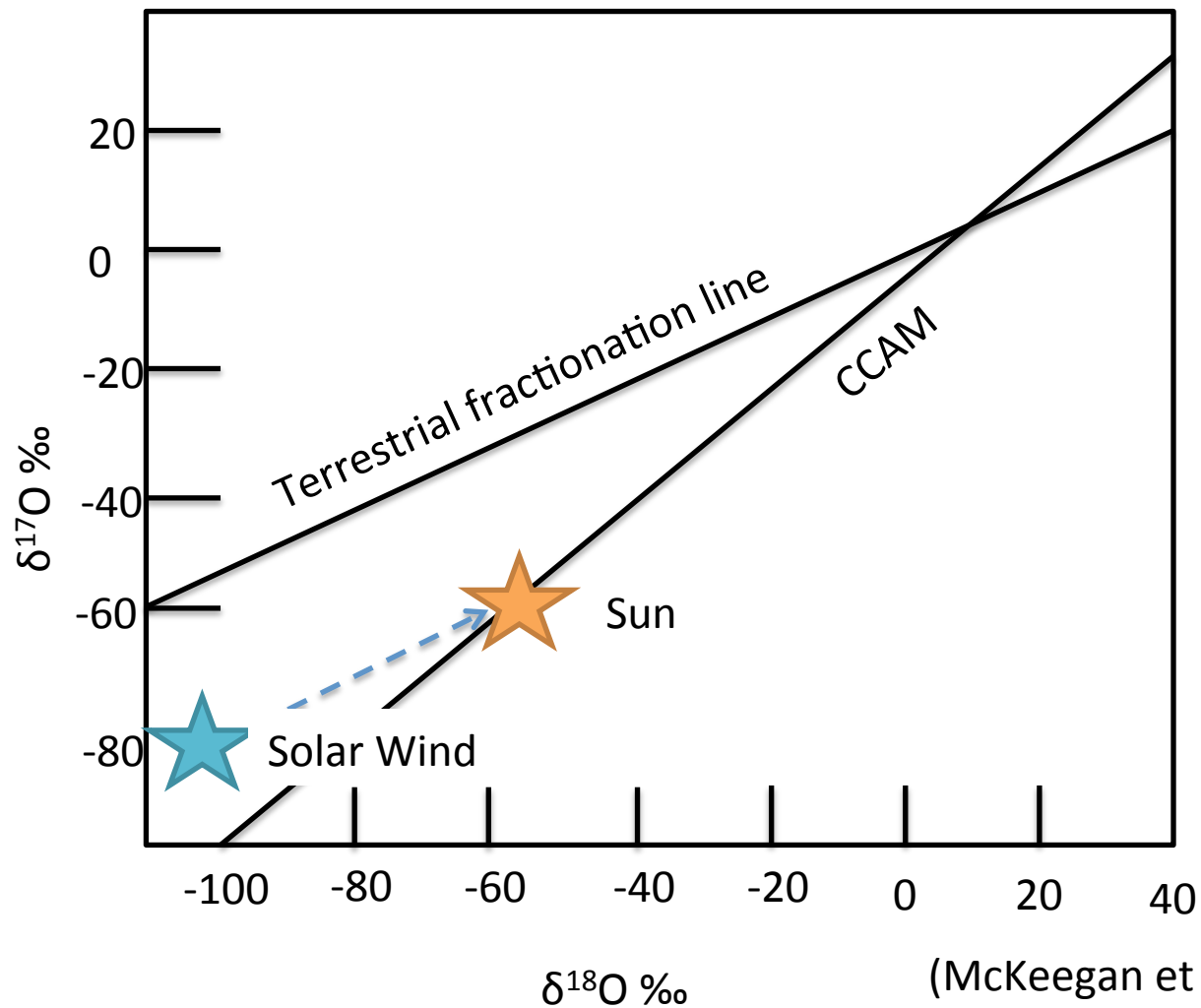
## What about the Solar Wind composition?



Genesis sat at Lagrange point 1, between Earth and Sun, collecting Solar Wind, then returned to Earth with a very nasty bump.

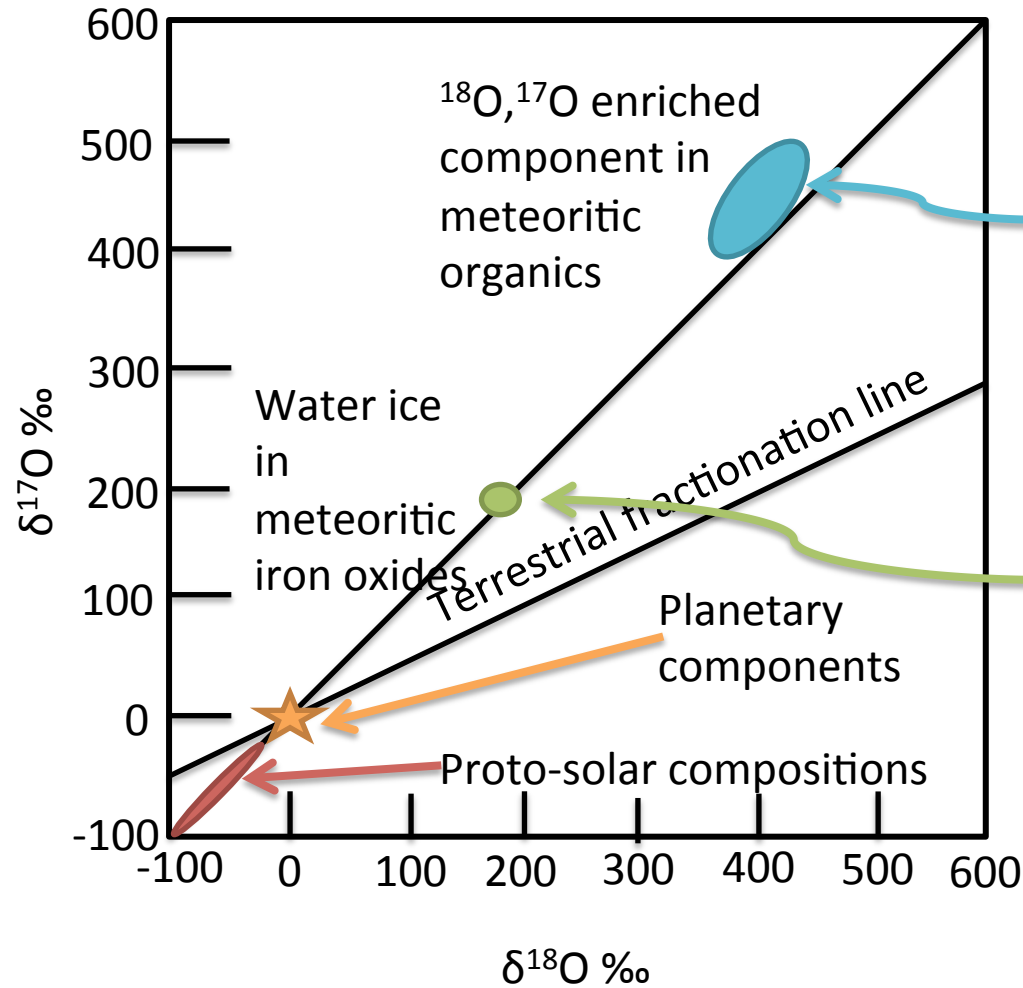


## Isotopic composition of Solar Wind analysed from Genesis mission



SW values corrected for mass fractionation yield oxygen isotope composition of Sun

**Two analyses show that low temperature volatile material (ice, organics) in the early Solar System had high  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$**

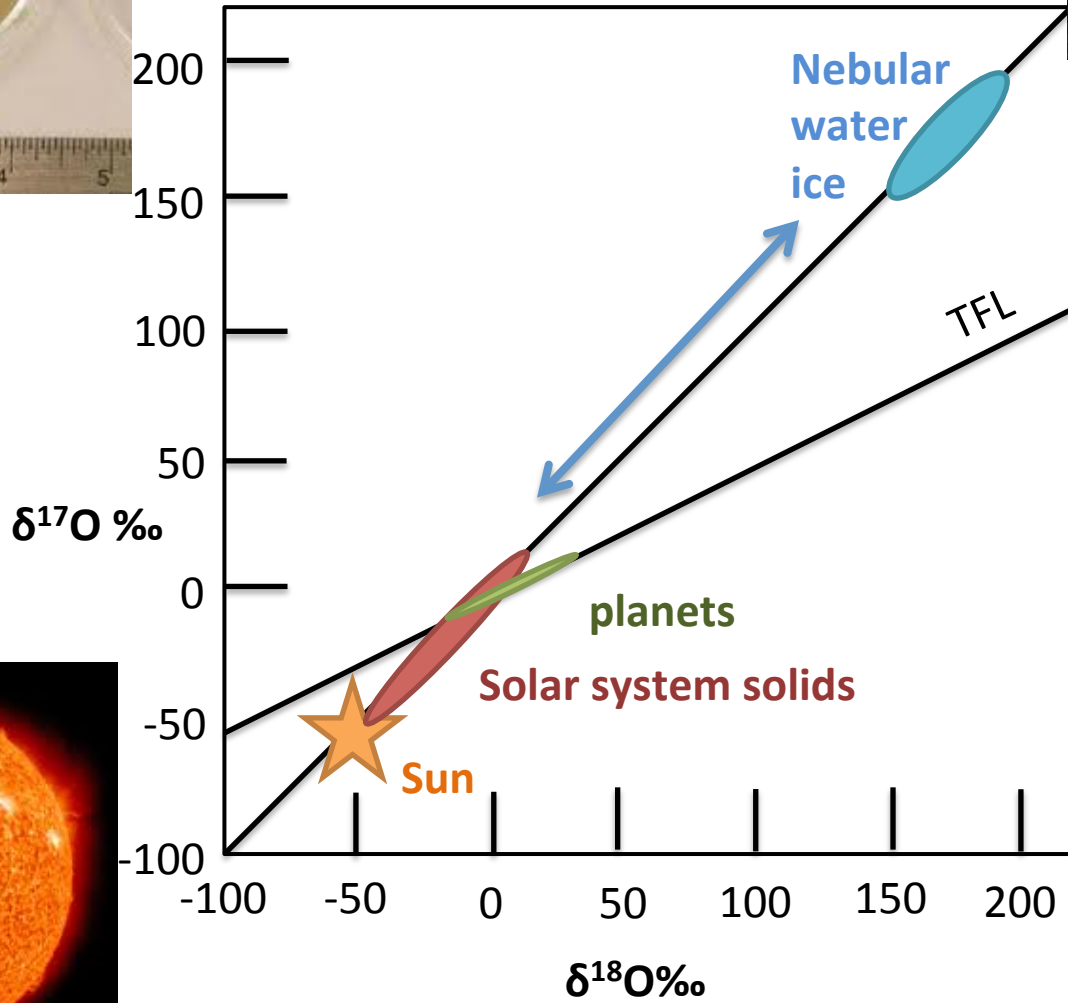
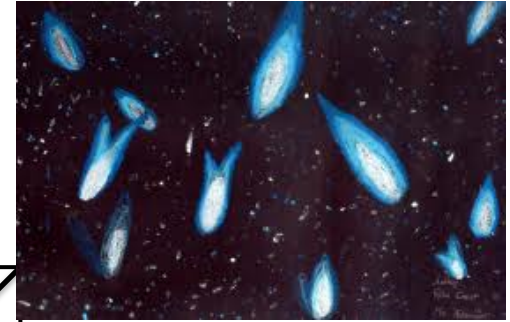
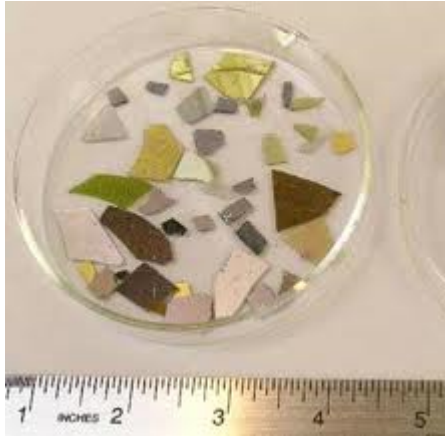


Extreme enrichment in  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$  found in organic molecules in a chondrite meteorite (Hashizume et al. 2011)

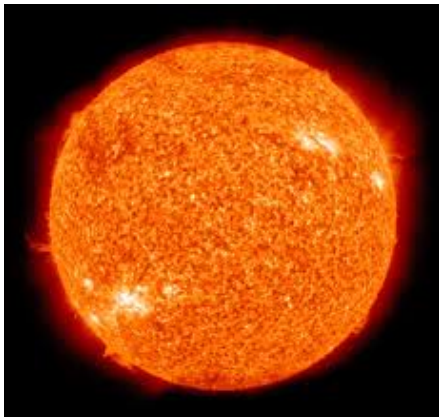
$\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$ -enriched products of the reaction of Fe with  $\text{H}_2\text{O}$  inside the snowline of the solar nebula (Sakamoto et al. 2007)



Putting it all together...



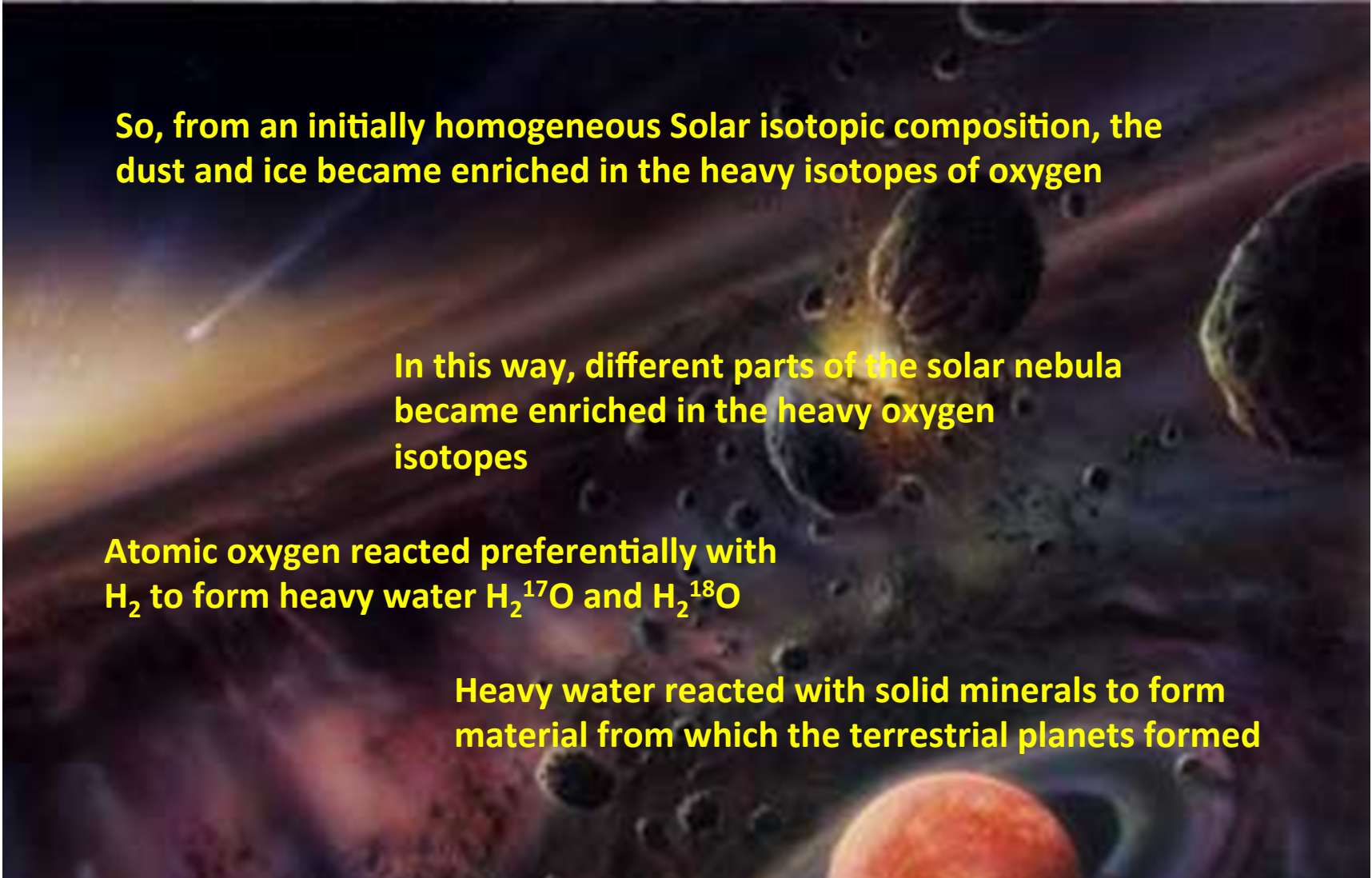
Reactions between water ice and solid minerals formed the material from which terrestrial planets were accreted



## What causes so much early Solar System material to plot on the slope ~1 line?

This has to be a process that is isotope specific, not mass specific.

- The most popular explanation was put forward by Clayton (2002) and Lyons and Young (2005) who suggested this is “self-shielding”, due to photo-dissociation of gaseous CO by far ultra-violet (FUV) light.
- Each isotopic species of CO ( $C^{16}O$ ;  $C^{17}O$ ;  $C^{18}O$ ) absorbs a different characteristic wavelength (line) of FUV while dissociating.
- Because  $^{16}O$  is much more abundant than  $^{17}O$  or  $^{18}O$ , the lines that cause dissociation of  $C^{16}O$  become saturated, whereas those leading to dissociation of  $C^{17}O$  and  $C^{18}O$  are not saturated within the solar nebula.
- This process only acts in one direction, increasing the abundances of atomic  $^{17}O$  and  $^{18}O$  in the solar nebula, compared with the Sun’s composition.



**So, from an initially homogeneous Solar isotopic composition, the dust and ice became enriched in the heavy isotopes of oxygen**

**In this way, different parts of the solar nebula became enriched in the heavy oxygen isotopes**

**Atomic oxygen reacted preferentially with  $H_2$  to form heavy water  $H_2^{17}O$  and  $H_2^{18}O$**

**Heavy water reacted with solid minerals to form material from which the terrestrial planets formed**

**Take home message:**

16 $\text{O}$ 15.9949 99.76%	17 $\text{O}$ 16.9991 0.04%	18 $\text{O}$ 17.9991 0.20%
Stable	Stable	Stable

**Oxygen isotopes of Solar System solid material are not the same as those of the Sun**

**Two processes have operated to cause this:**

**Mass-independent fractionation possibly due to “isotopic self-shielding”**

**Mass-dependent fractionation in planetary and asteroidal bodies due to processes such as condensation and evaporation**