# Geochemical constraints on volatile delivery to the inner solar system

*Comets and LHB, Gdynia June 2014*
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**Did water on Earth and Mars condense from the protosolar nebula together with the rest of the material that made the planets,**

**or did it come with the late veneer objects**

**or was Late Heavy Bombardment (LHB) the source ????**

No single source seems to be able to explain all the main observables,
so a combination of objects is most likely necessary;
The question is therefore ”which sources and in which proportion?”
How can a combined study of Earth, Moon, and Mars help?

**Isua tells us that the Earth’s crust was not marked by a chondritic bombardment 3.8 Gyr ago (the time of the Isua sedimentation).**

## Earth's water is not from the original nebula condensation.......

Core accretion models and observations of protostellar disks
do not support condensation of water at 1 AU around solar type stars.

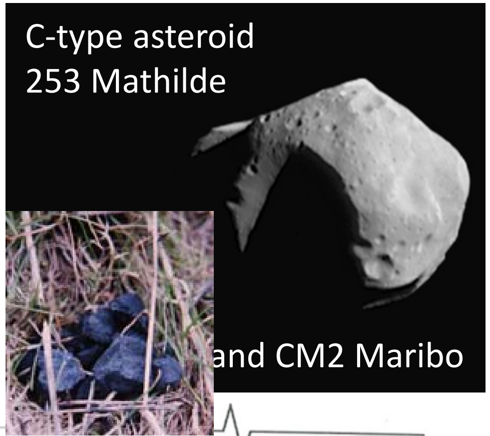
Asteroids inside 2.7 AU are dehydrated (e.g. S-type, E-type, ordinary chondrites), outside they may be hydrated (e.g. carbonaceous chondrites with 1% - 10% water, representing C-type asteroids).

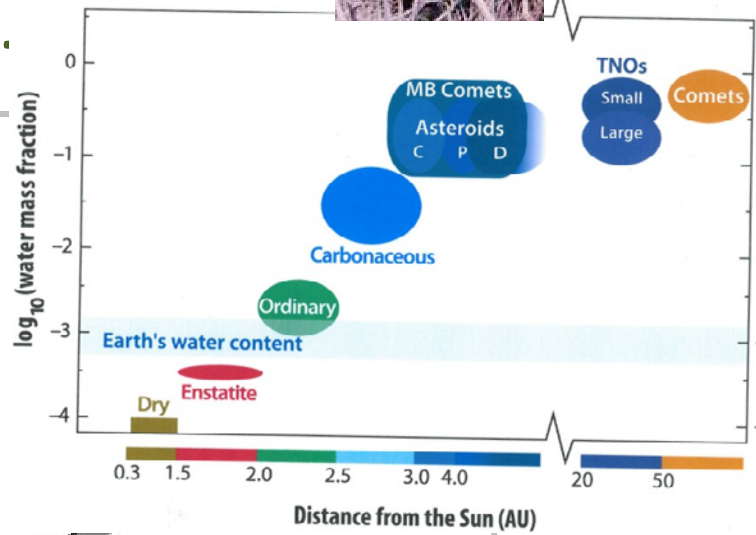
In the inner solar system, material forming the planets accreted locally
(as seen e.g. by the distinct oxygen isotopes)

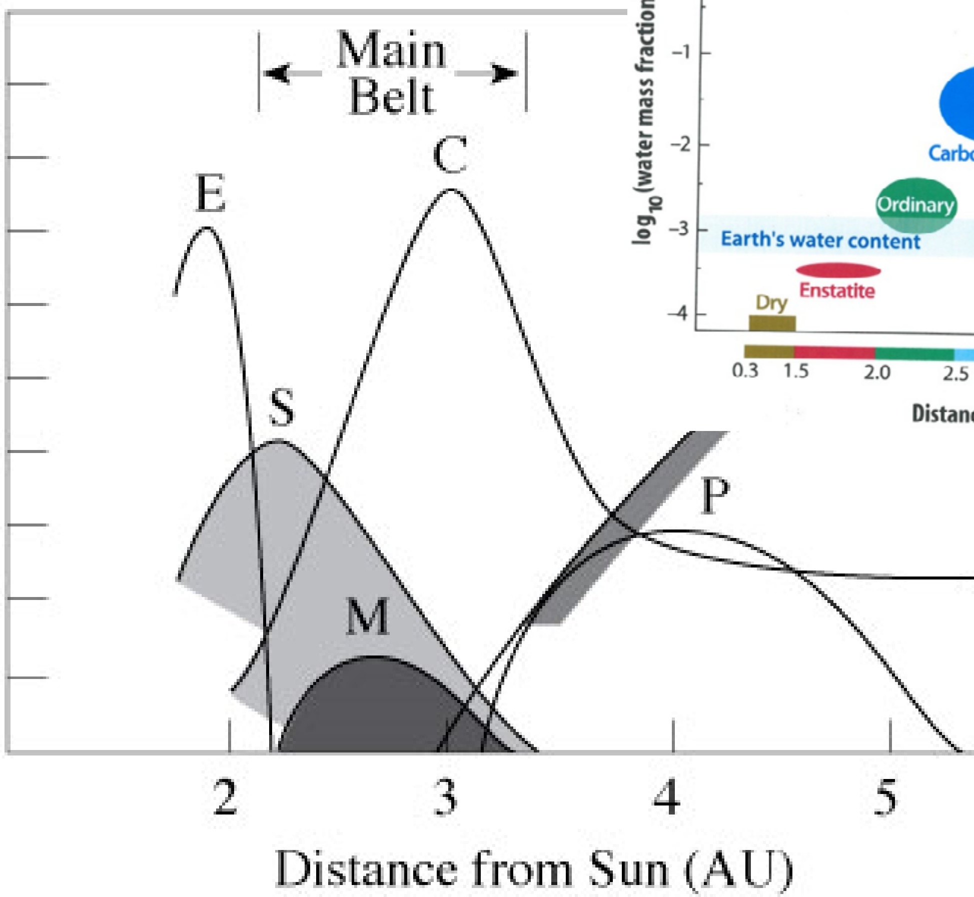
**Therefore the Earth most likely formed dry,
and water must have been delivered later,
during the late veneer (4.5-3.9 Gyr ago?)
or during the LHB (3.9-3.8 Gyr ago?)**

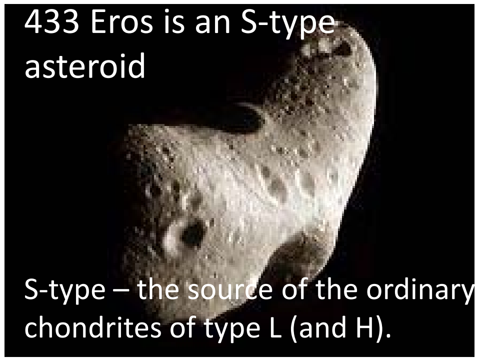
# Asteroids and water

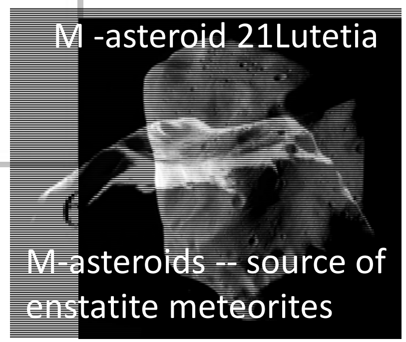
**Asteroids from the inner belt are dehydrated (e.g. S- and M-type, E-belt); Asteroids outside ~2.7 AU contain water (e.g. C-type asteroids, represented by carbonaceous chondrites with 1 – 10% water).**



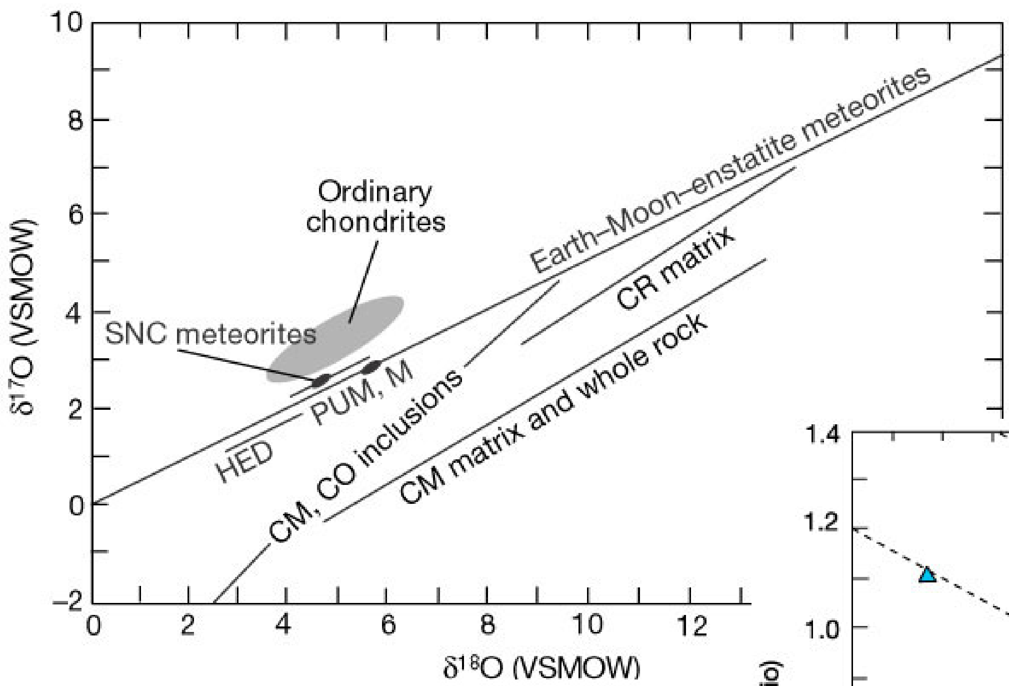



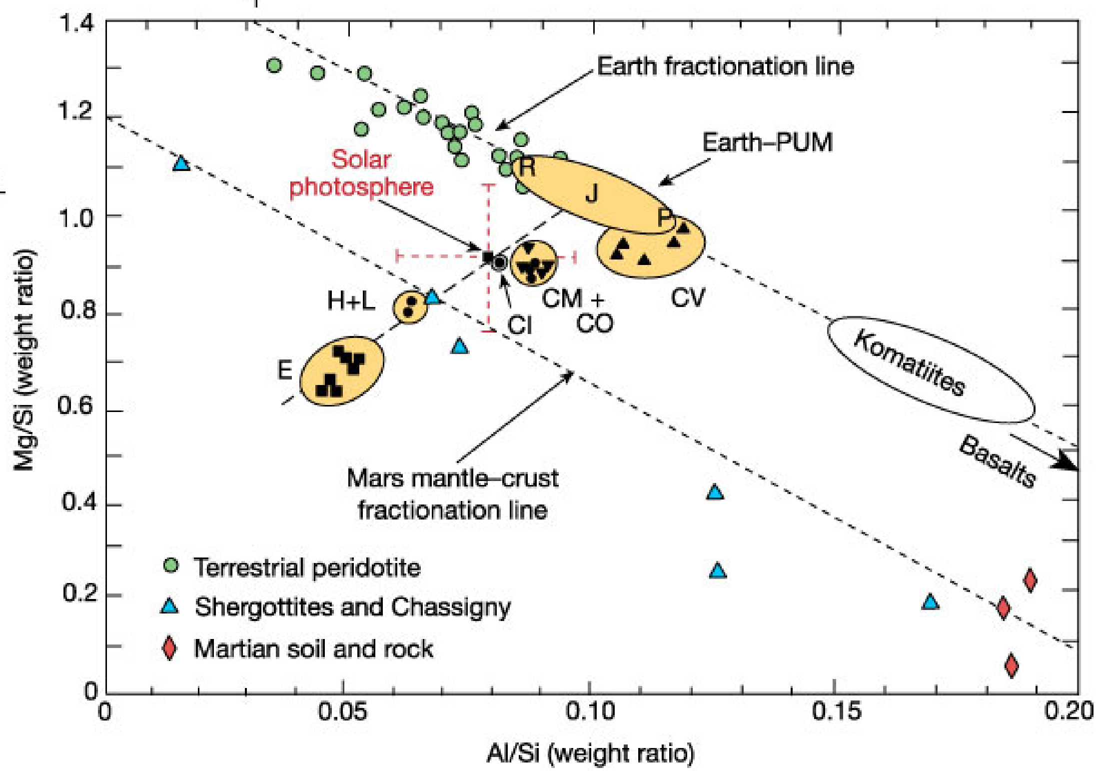



# Bulk Earth is *not* a mixture of material condensed at many places in the protosolar nebula, but asembled locally




**Ordinary** L+H meteorites ~
**S-type** (inner belt) asteroids
**Enstatite** E-type meteorites ~
**M-type** (mid-belt+Mercury?) asteroids
**Carbonaceous** (CI, CM, ...) meteorites ~
**C-type** asteroids

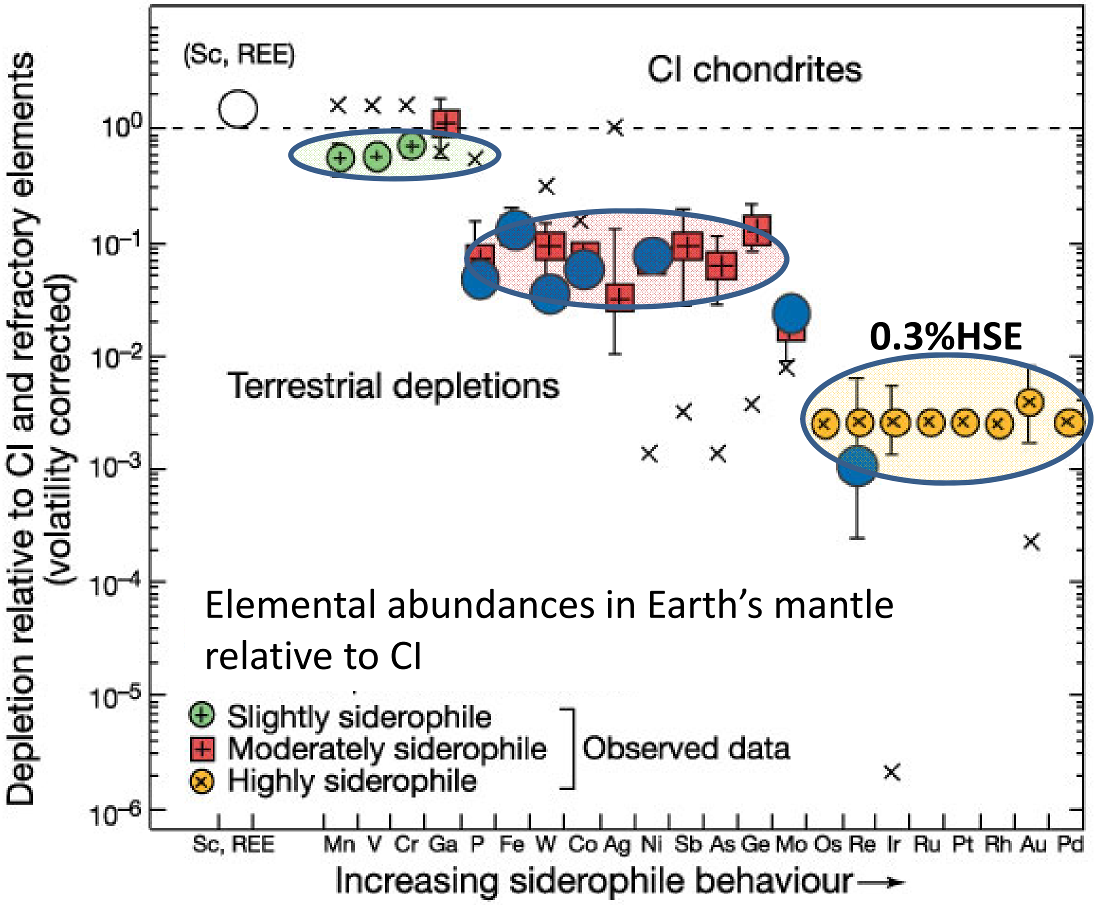
No simple mixture of meteorites can explain the bulk Earth




Chemical equilibrium explain gross elemental abundance as function of solar distance

Oxygen isotopic ratios reflect formation place;
Theia formed in Earth orbit

# The late veneer: Most likely Earth accreted 0.01 M_mantle chondritic material after the core separated from the mantle



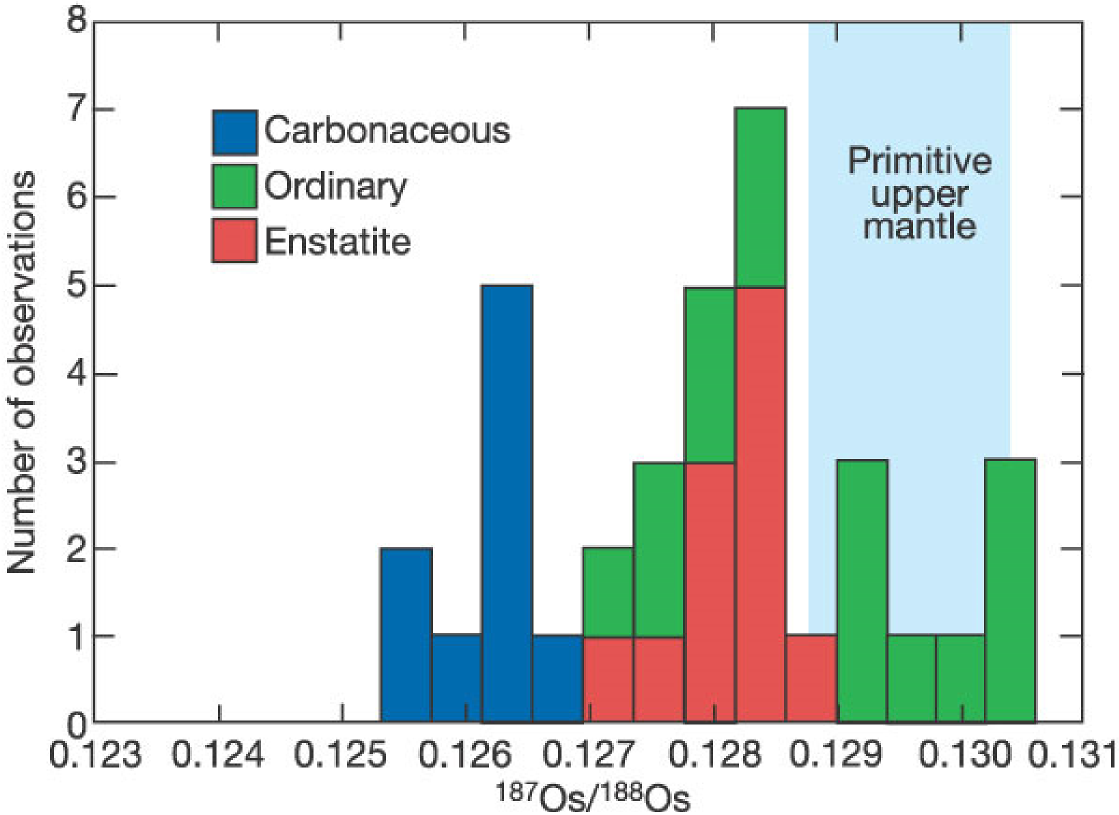

0.3% of PUM = 3.e21 kg CI
1 % of total mantle = 4.e22 kg
=> 5-10% water in CI ~ from 1.5e20 kg to 4.e21 kg water, or from 0.1 to 3 M_ocean masses
**(uncertainty of a factor 30)**

**Conclusion:**
the ocean could come from wet chondritic material, accreted early, after the core formation

Drake & Righter 2002 (Nature 416, 39), see also U.Mann et al 2012

The mass of the upper mantle is 1.e24 kg, of the full silicate mantle 4.e24 kg, the crust 2.4e22 kg, the ocean 1.4e21 kg, the full hysrosphere 1.6e21 kg, the total Earth 6.0e24 kg, the core 1.9e24 kg
Primitive Upper Mantle = PUM = upper mantle plus crust ~ 1.e24 kg

**$^{187}Os/^{188}Os$ ratios in carbonaceous, ordinary and enstatite chondrites, and in the Earth's primitive upper mantle** (from Drake & Righter 2002).




Core formation brought Os- and Ir down to ~ 5 pg/g

If today's mantle Os + Ir of 3 ng/g are due to a late veneer, they came from ordinary (H-L type) chondrites to fit Os-isotopes

**Carbonatious chondrites could have brought an ocean mass of water, but dry H-L type could not.**
**Cc cannot, however, explain the Os isotopes, while H-L can.**
**This may indicate that the late veneer bombardment was dry, and then ocean water came later than 0.5 Gyr into Earth's evolution.**

## If water

didn't accrete during the original assembling
(too hot nebula, local assembly with no water, ...)

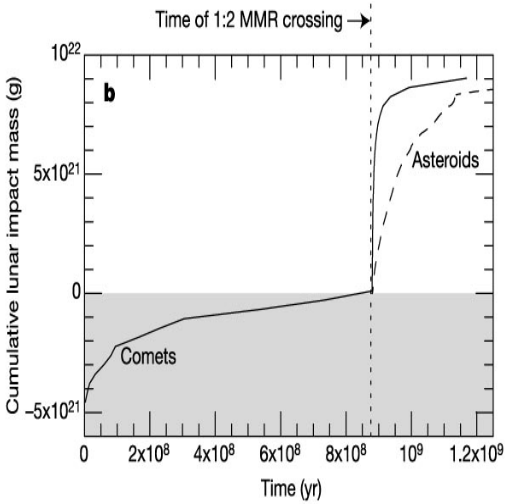
...and it
didn't come from the late veneer (wrong Os-isotopes,...),

couold it then have come during LHB ?
-- geological evidence show existence of oceans on Earth 3.8 Gyr ago, and zircons may indicate some water present before that

Various runs of the Nice model code suggest different resonances and disturbances as the cause of the transportation of smaller bodies inward to the inner solar system
-- some scenarios predict wet impactors, some dry impactors.

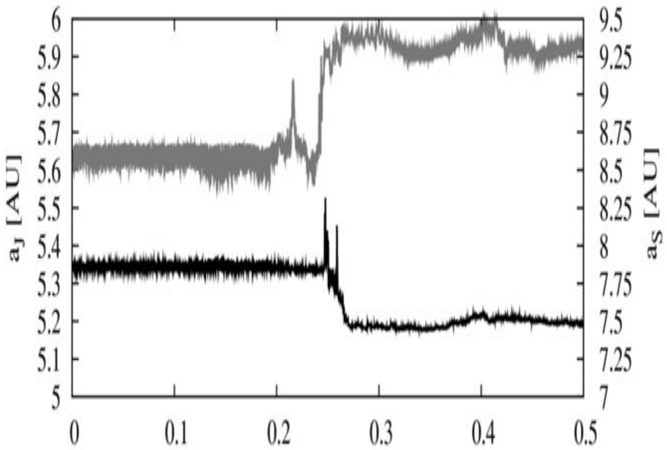
# Some of the Nice-model LHB scenaria:

Goomes et al 2005, **The 1:2 resonance scenario:** Jupiter and Saturn crossing1:2 resonance during LHB, delivering 6% ocean-mass of comets and a higher mass of asteroid impacts

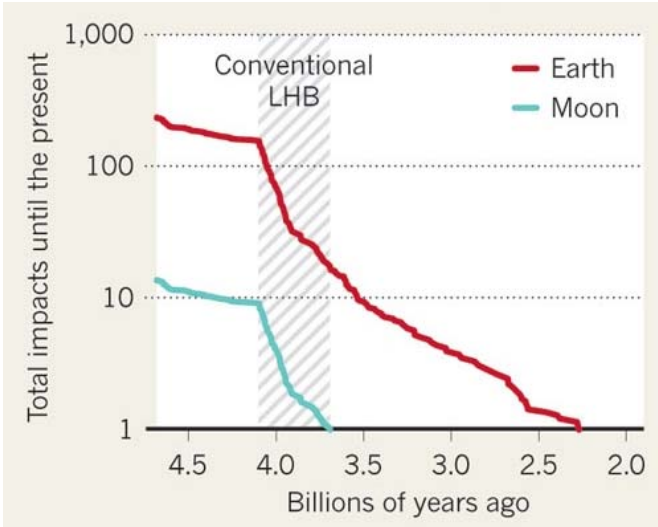



Morbidelli 2014, this meeting: Where are all the comets that the Nice model predicts?

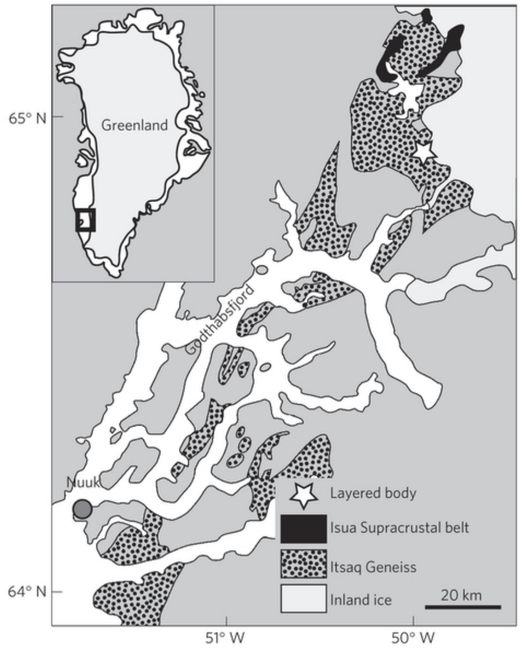
Morbidelli et al 2010,**The jumping-Jupiter scenario:** a large cometary LHB flux (~90% of the projectiles) and few asteroid impactors, giving a wet LHB and less excentric terrestrial planet orbits than the 1:2 scenario




Bottke et al 2012, **The long tail bombardment :** a very dry LHB bombardment by E-belt asteroids starting already 4.1 Gyr ago



## Hadean crust Os indicate a substantial mantle-depletion event 4.1 Gyr ago, in agreement with the Bottke et al 2012 dynamic model of an early LHB:




Samples from the Greenland Ujaragssuit Nunat intrusion indicate a global peak in mantle depletion at ~4.1 Gyr ago, which the authors interpret as the LHB, in agreement with an E-belt disturbance resulting in an early (and dry) LHB.

From: Coggon et al 2013, NatureGeosci 6, 871

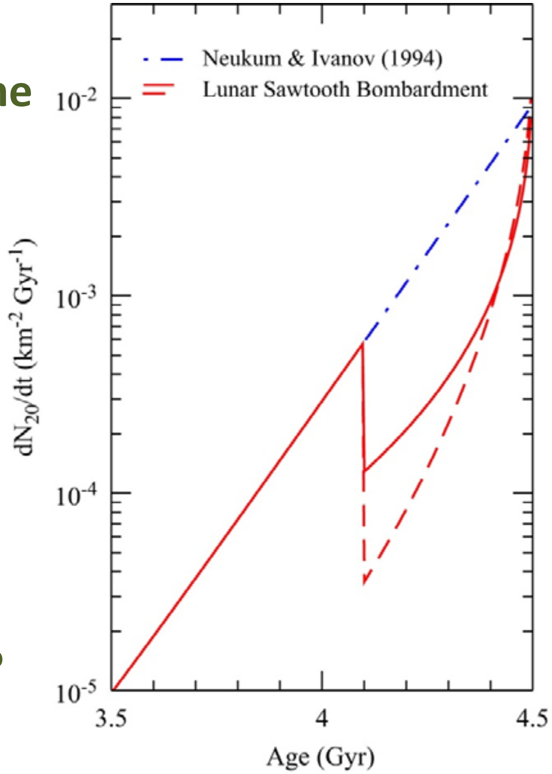
**If water didn't come during:**

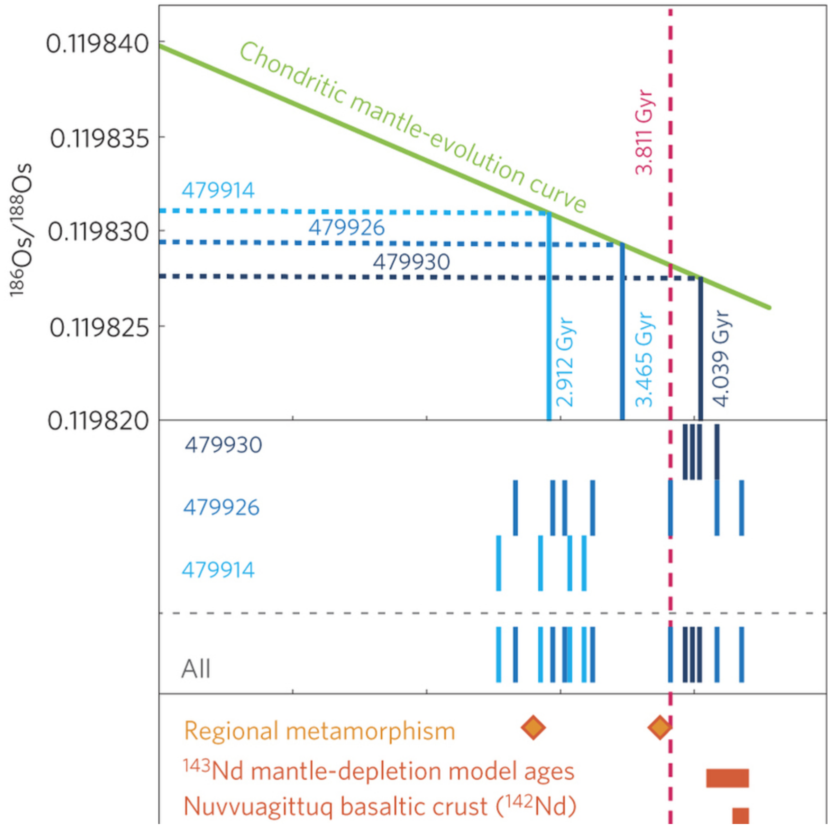
**Earth formation** (too hot)

**late veneer** (Os isotopes)

**LHB** (E-type asteroides)

**When did it come?**



# Searches for traces of the LHB at 3.8 Gyr old Isua

In Jørgensen et al (2009) we measured 40 samples of 4 different kind of sediments with an accuracy of 2 ppt, and concluded that the cosmic contribution of Ir is small but clear (150 ppt at Isua versus 20 ppt in present-day ocean crust and upper continental crust), contradicting a chondrite-like bombardment but consistent with a cometary dominated LHB.

Koeberl et al (2000) qualitatively found the same based on fewer and more random samples and poorer resolution near the abundance level. Assuming the LHB was condrites, they concluded that they could identify no cosmic contamination at Isua.

Akilia: Anbar et al 2001 found depleted Ir (~10 ppt?) in old Akilia (150 km SW of Isua) rocks, but both age and type of the rocks were later disputed (3.85->3.65 Gyr, no sediments but rather basaltic; Moorbath 2005).

Hf-W at Isua: 182Hf(litrofile)->182W(sidrofile)=>crustal 182W/183W on Earth is up. Schoenberg et al 2002 find 3 sigma lower 182W/183W at Isua than present crust, which they interpret as cosmic mixing at Isua, but is should be 1000 lunar impact.

Cr at Isua: 53Mn->53Cr affects the 53Cr/52Cr ratio, but again the meteoritic value is only slightly different from the Earth's crustal value. Frey & Rossing (2005) found the Isua 53Cr/52Cr value almost present day terrestrial, as opposed to K/T which is almost as in Allende because of the large meteoritic to terrestrial abundance ratio in K/T layers.

## Moon and Earth iridium (HSE) abundance is sensitive in a different manner to cometary and asteroid bombardment

Scaling of lunar crater counts =>2000 tons per m^2 on Isua

**Comets:**

2000 tons comets with 50% mixing efficiency, 10% CI of 465,000 ppt Ir, mixed into 50 km crust => expected **130 ppt** in **Isua** sediments,

Moon: very low mixing => **low iridium abundance on the Moon**

**Asteroids:**

2000 tons CI with 90% mixing efficiency and 465,000 ppt Ir

⇒expected **3000 ppt** at 3.8 Gyr old **Isua**, Greenland,

and 50% mixing on Moon => **5000 ppt on the Moon**

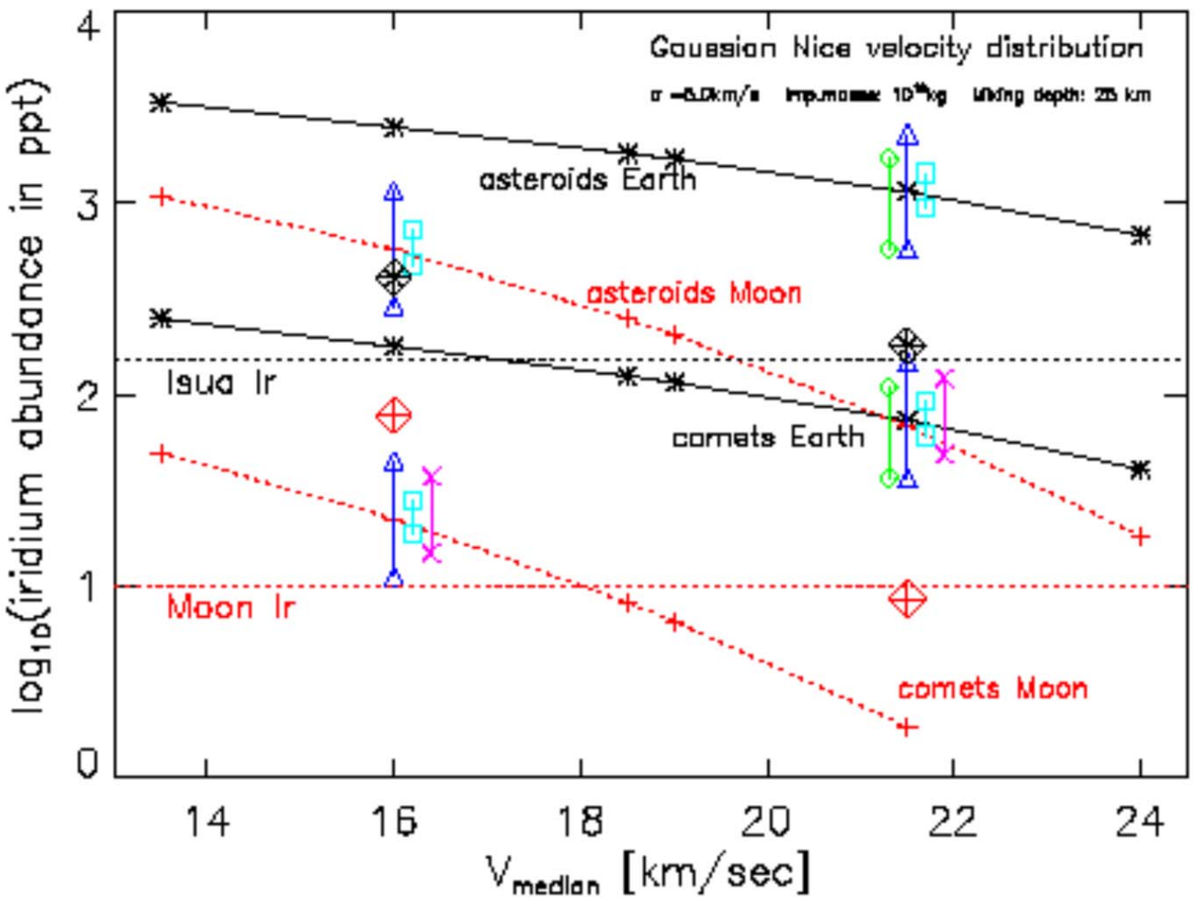
**Measurements:**

**150 ppt iridium at Isua**

**maybe low Ir in lunar rocks**

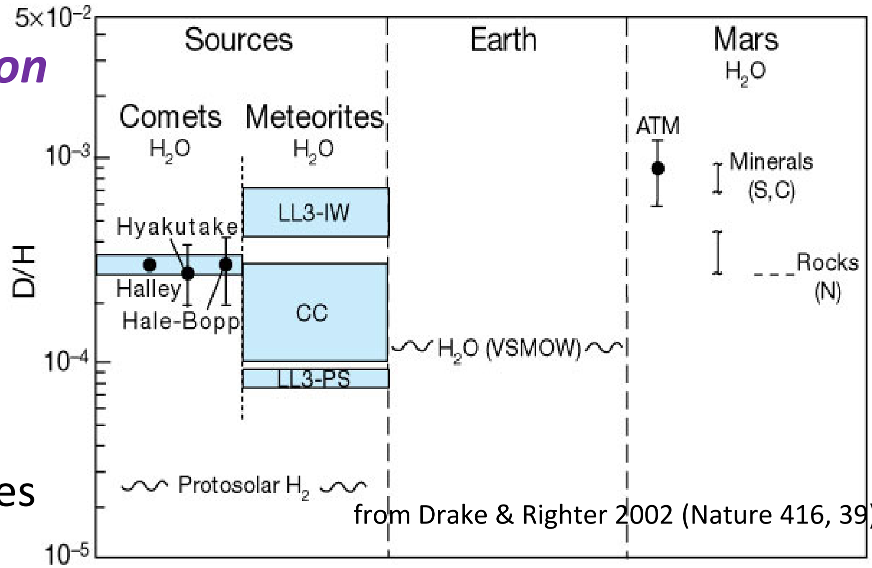
**~expected from comets**

**Uncertainties in inputdata are large (e.g. length of LHB, velocity of impactors, mixing depth in crust, iridum abundance in bulk lunar crust, angle dependence of plume mass), but the HSE abundance in comets, asteroids (and various meteorite types), and planetary mantles  differ with such a huge factor that HSE (e.g. iridium and osmium) is one of the most sensitive indicators of imact parameters.**



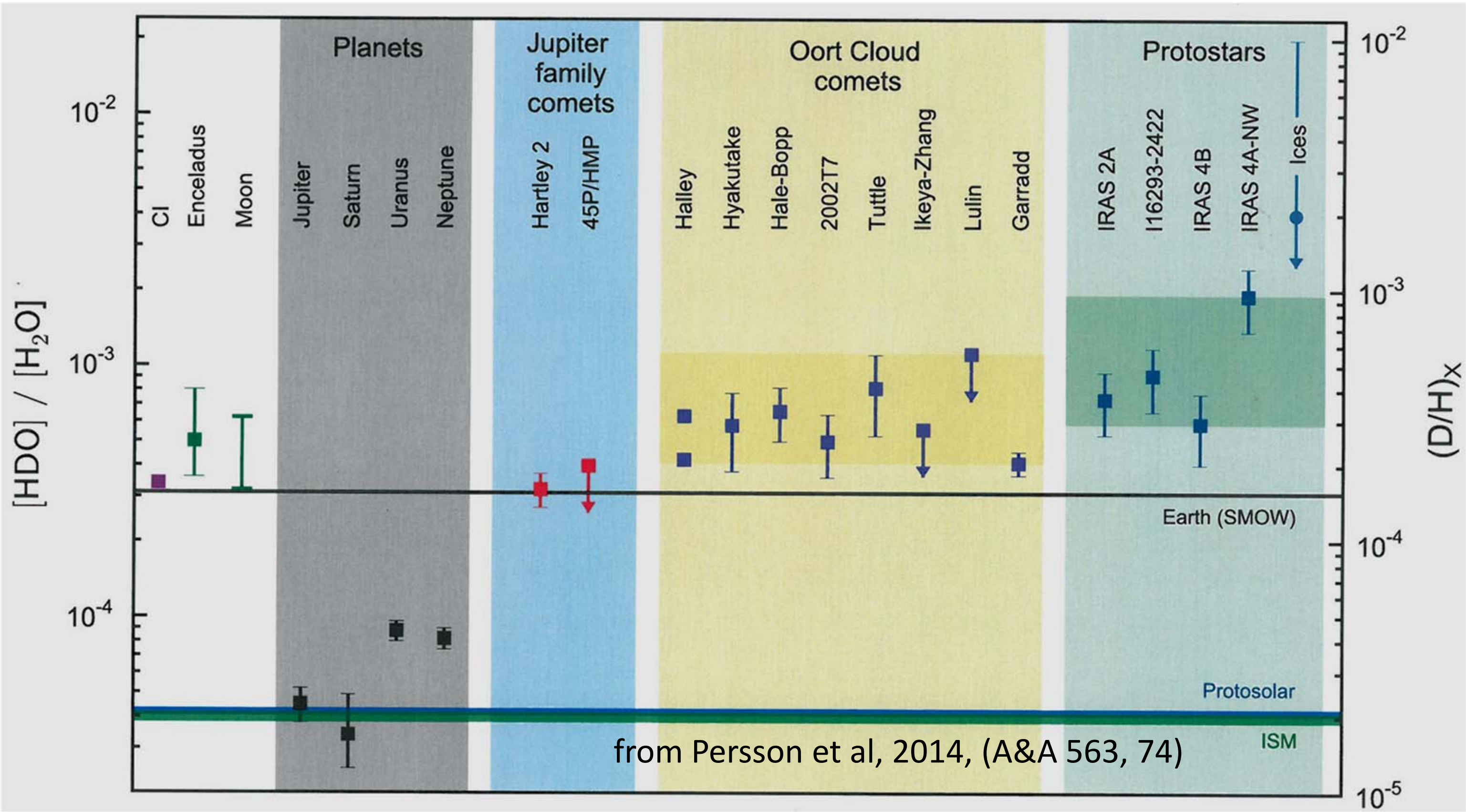

**Formulas and assumptions given in Jørgensen et al 2009, Icarus 204, 368.**

**The D/H ratio in water contain *no information* about the origin of Earth's water – it could be explained by carbonaceous chondrite impactors as well as by comets.**




from Drake & Righter 2002 (Nature 416, 39)

Water in rocks from Mars has D/H as Oort cloud comets, while Earth's oceans have D/H as Jupiter family comets and carbonaceous chondrites




from Persson et al, 2014, (A&A 563, 74)

Sub-mm observations indicate cometary infall through young stellar debris disks, such as the beta-pictoris system. With full capability of ALMA such observations can be spatially extended, and already show D/H comparable to comets in our solar system.