EARTH: The dangerous Life of a Habitable Planet

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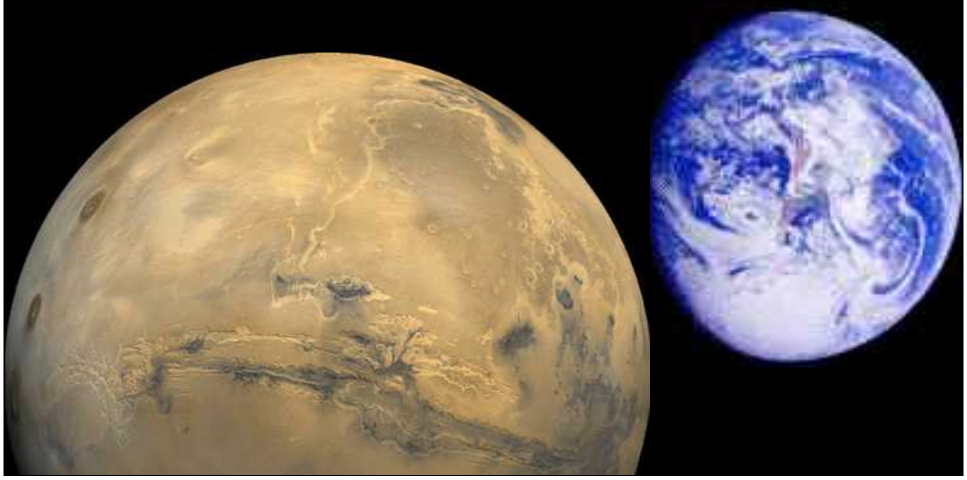


•Earth formation (general aspects)

- •Classic models of terrestrial planet formation -> the Mars mass problem
- •Necessity to links terrestrial planet formation to giant planet evolution
- •A new model that explains the small mass of Mars
- •The Earth could have easily formed as a small, inhabitable planet

•Earth formation (more in-depth look)

- •Timescales, giant impacts vs. planetesimal accretion
- •Accretion of oxidized material, volatiles, water…
- •The nature of the Late Veneer

•Earth evolution

- •The heavy bombardment period (timescales, mass)
- •Late orbital excitation
- •The Earth could have easily become an eccentric (non-habitable?) planet

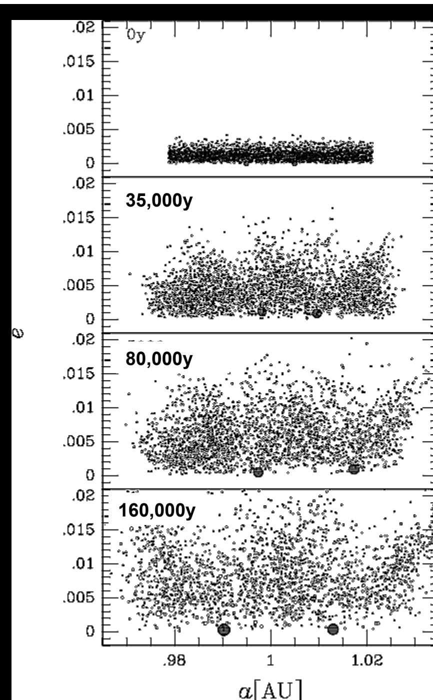
Dynamics of planet formation I: Runaway/ Oligarchic growth

Lunar to Martian-mass Planetary Embryos are formed in ~10^5-10^6 y, separated by a few mutual Hill radii

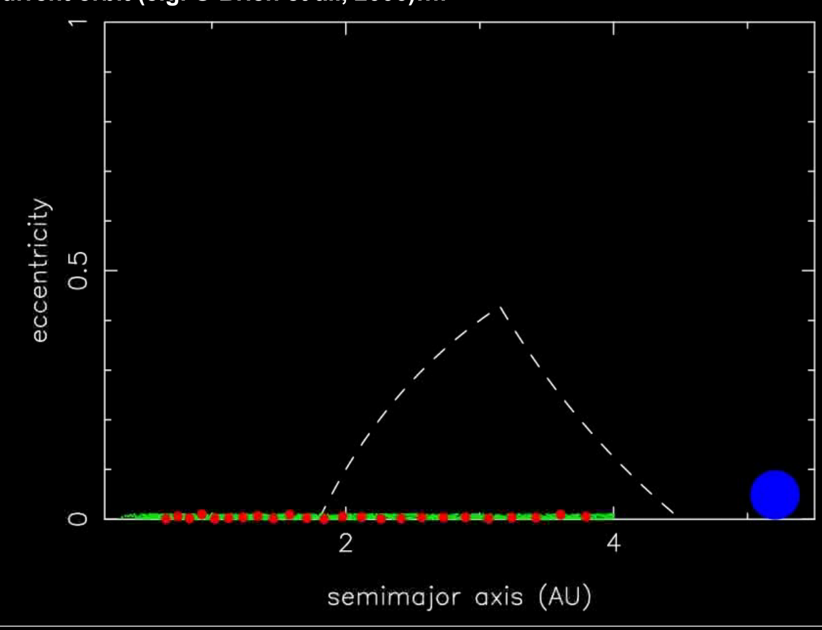
Planetary embryos are NOT terrestrial planets!

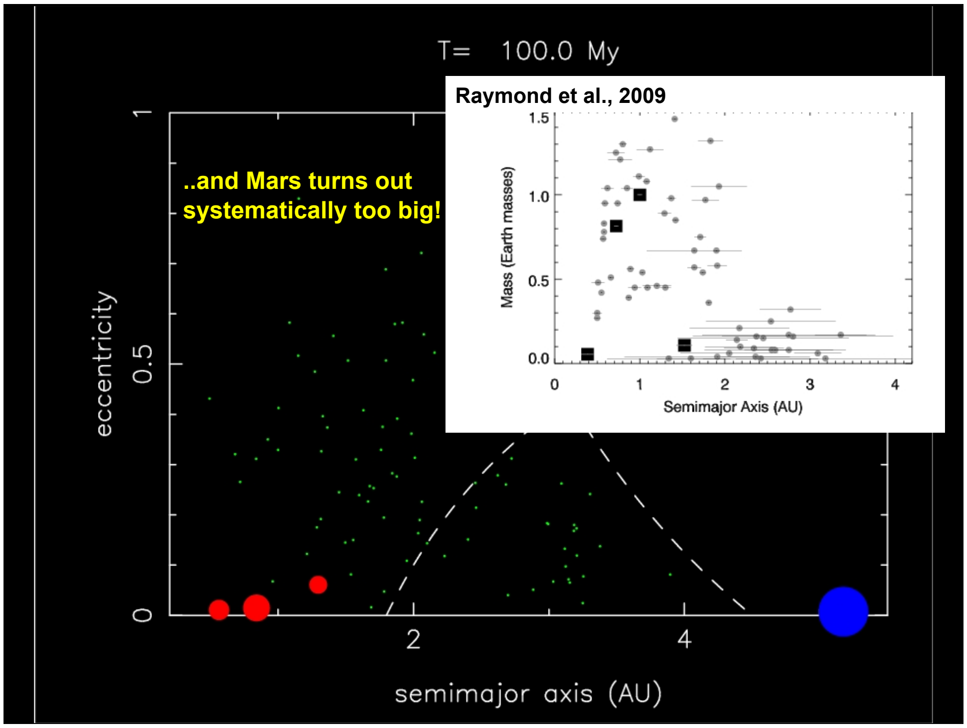
Accretion of embryos is a local process

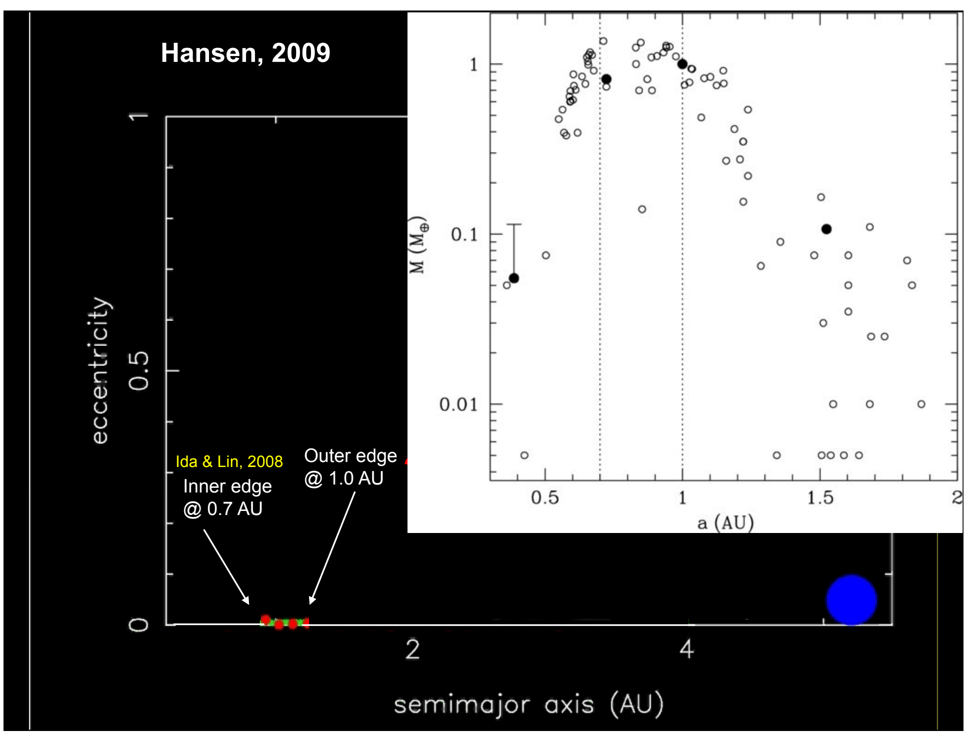
Ida and Makino (1993), Kokubo and Ida (1995, 1996, 1998), Thommes et al. (2003), Chambers (2006) …..



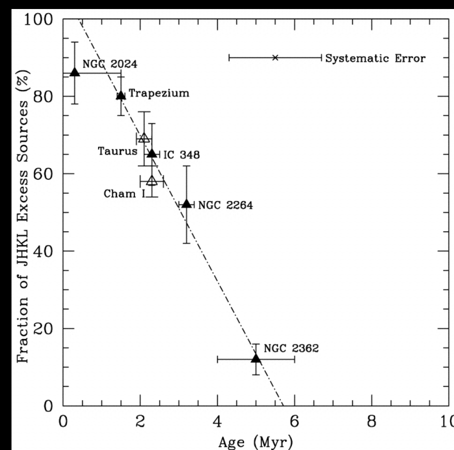
Simulations of Terrestrial Planets formation, usually start from a disk of planetesimals and planetary embryos, ranging from the Sun to Jupiter's current orbit (e.g. O'Brien et al., 2006)….




T= 100.0 My
Raymond et al., 2009
..and Mars turns out systematically too big!
eccentricity
semimajor axis (AU)
Mass (Earth masses)
Semimajor Axis (AU)


Hansen, 2009
Ida & Lin, 2008
Inner edge @ 0.7 AU
Outer edge @ 1.0 AU
eccentricity
semimajor axis (AU)
M ($M_\oplus$)
a (AU)

- Giant planets accreted a lot of H and He, thus they formed before the disappearence of the circum-stellar disk of gas
- Observations of disks around stars in young clusters of various ages show that the circum-stellar disks last only a few My (Haisch et al., 2001).

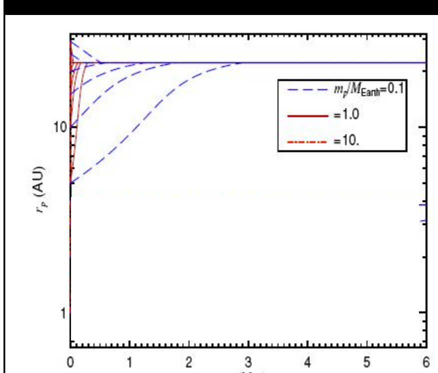


- The Earth formed several 10My to form, from radioactive chronometers (Kleine et al., 2009)
- Thus, giant planets formed well before the terrestrial planets
- The formation and early dynamical evolution of the giant planets may have sculpted the distribution of solid material in the inner solar system affecting terrestrial planet formation

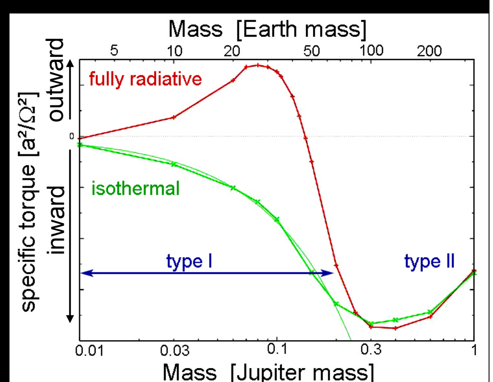
WHAT WE KNOW ABOUT MIGRATION

i) Classical inward type-I migration does not apply to realistic disks

ii) Planetary embryos move to the intermediate region of the disk, where migration is cancelled out. That is where we expect the cores of the giant planets to form, on non-migrating orbits.



Lyra et al., 2010



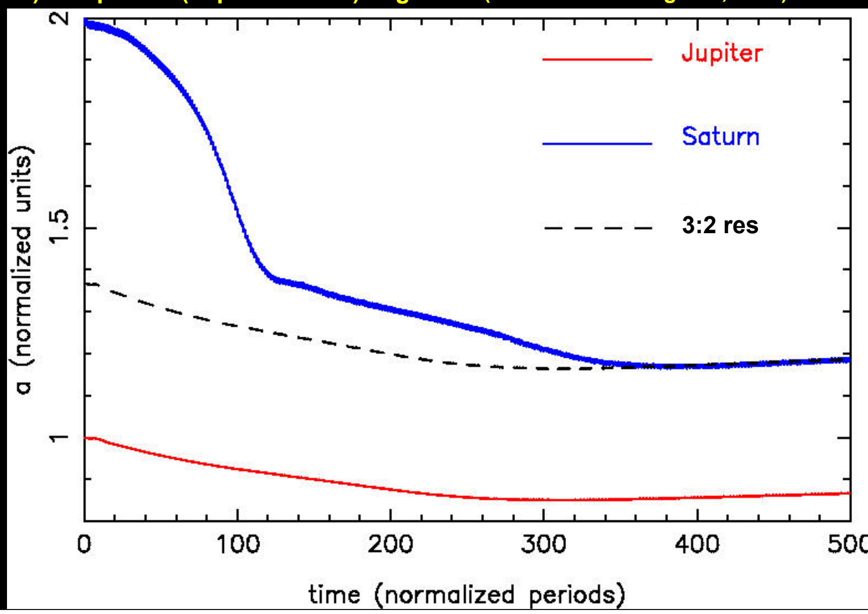
Kley and Crida, 2008

iii) Inward migration is resumed when planets exceed 30-50 Earth masses. Thus, Uranus/Neptune don't migrate, Saturn/Jupiter eventually do

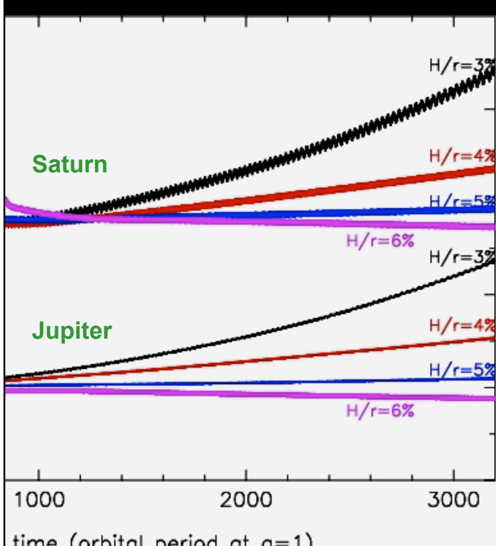
iv) Saturn's mass maximizes migration speed. Possibility of runaway migration (Masset and Papaloizou, 2003)

WHAT WE KNOW ABOUT MIGRATION

V) two-planet (Jupiter-Saturn) migration (Masset and Snellgrove, 2001)



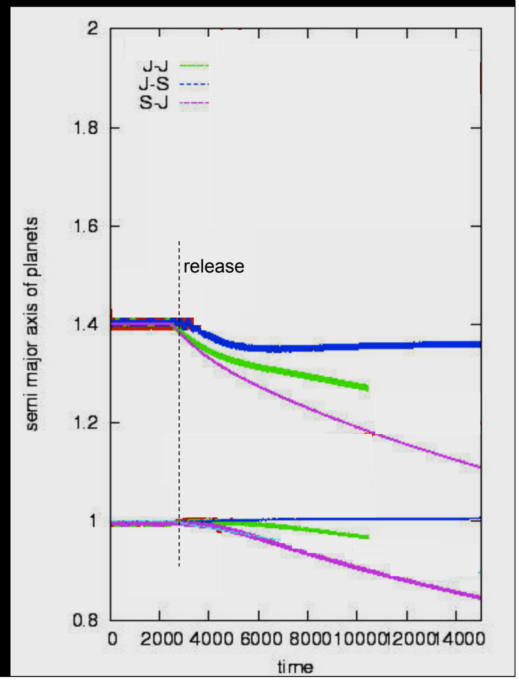
WHAT WE KNOW ABOUT MIGRATION

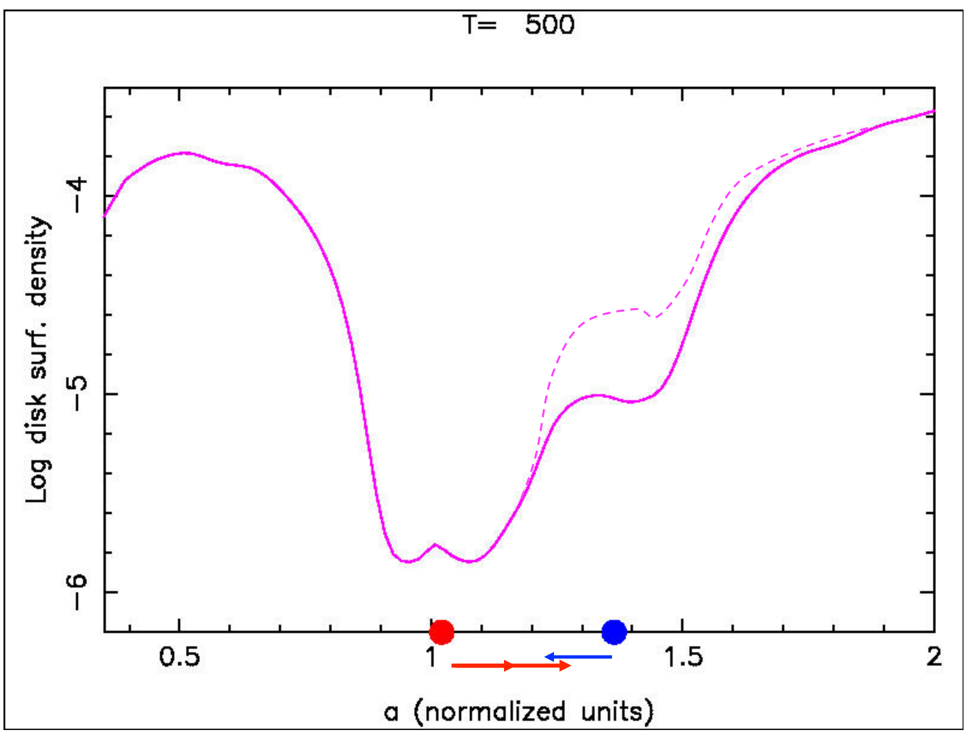


vi) Once locked in resonance, the evolution of Jupiter and Saturn depends on disk parameters
(Morbidelli and Crida, 2007)

WHAT WE KNOW ABOUT MIGRATION

vii) Evolutions with no migration or outward migration are possible ONLY if the outer planet is less massive than the inner one

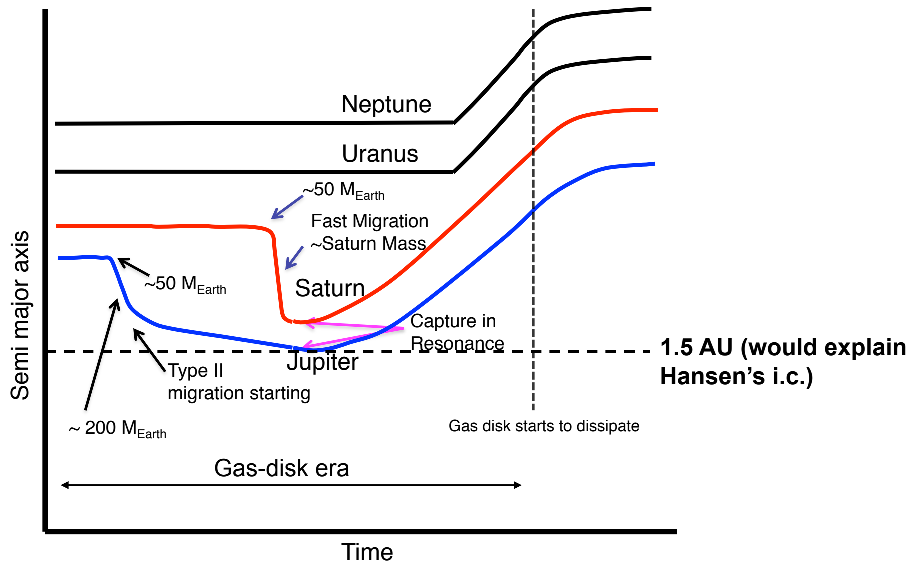




Plausible evolution of the giant planets in the solar system

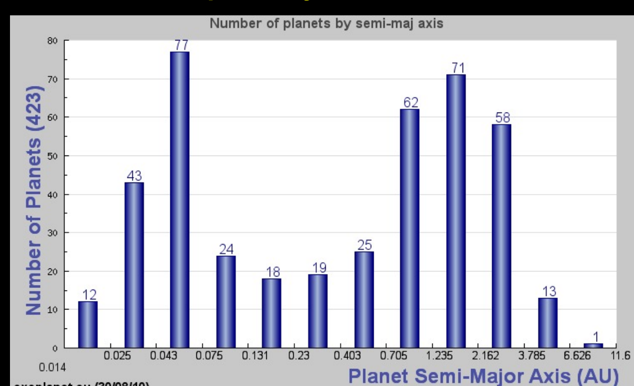
(as emerging from hydro-dynamical simulations):

The « Grand Tack » hypothesis



A tack of Jupiter at 1.5 AU would explain the outer edge of the rocky planetesimal disk at 1 AU, as required by Hansen's model

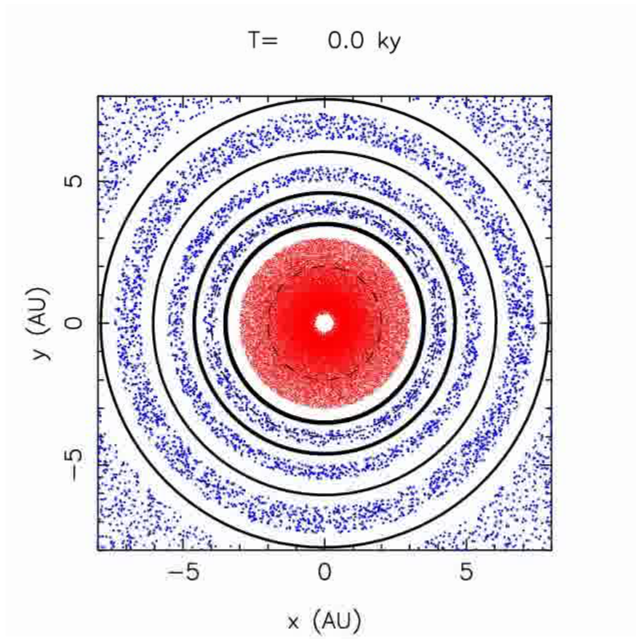
Is it crazy?



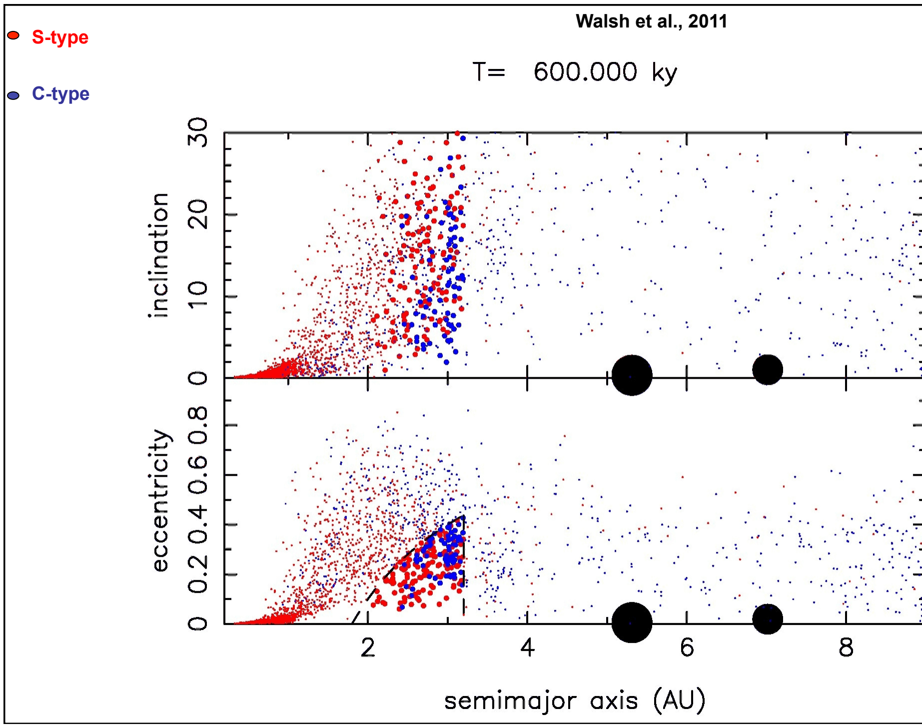
Not really, given that 1.5 AU is a peak of the semi major axis distribution of giant extra-solar planets

BUT… what about the asteroid belt? Would any asteroid survive if Jupiter migrates in and out of the main belt region?

Walsh, Morbidelli, Raymond, O'Brien, Mandell, NATURE, 2011

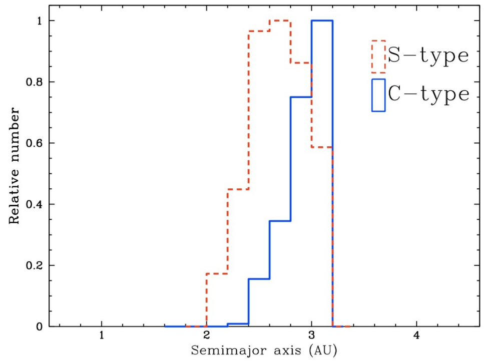


Walsh et al., 2011



Walsh et al., Nature 2011

Relative semi major axis distribution of an-hydrous and primitive planetesimals (S and C types) captured in the asteroid belt



This model explains better than any other the striking dichotomy of physical properties of the asteroid population (i.e. why an-hydrous and primitive asteroids are so different from each other, with the latter being very similar to comets)

This model explains:

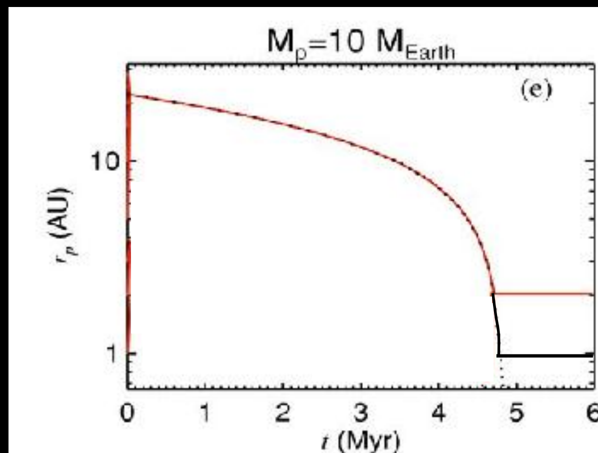
- **The physical structure of the asteroid belt (S/C dichotomy)**
- **The small mass of Mars and its short formation timescale**
- **The mass, orbit, accretion timescale of the Earth**
- **Earth's composition**

What would have happened if…….

- **Jupiter had reversed migration closer to the Sun than 1.5 AU?**
  - **The Earth would have been as small as Mars, probably non-habitable**
- **Jupiter and Saturn had not migrated outwards after resonance locking?**
  - **The Earth would not have received water via the primitive planetesimals that have been scattered into the inner solar system during giant planets outward migration – the Earth would be much more dry**

What would have happened in a system without gas-giant planets?

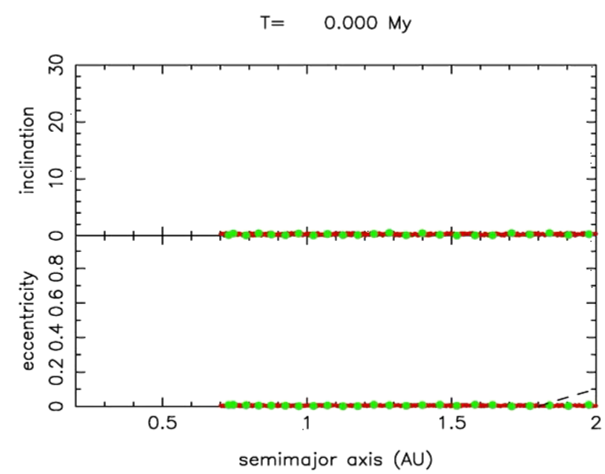
The non-migration radius where the ice-giants are locked at, moves towards the star as the disk is dissipating (Lyra et al., 2010)



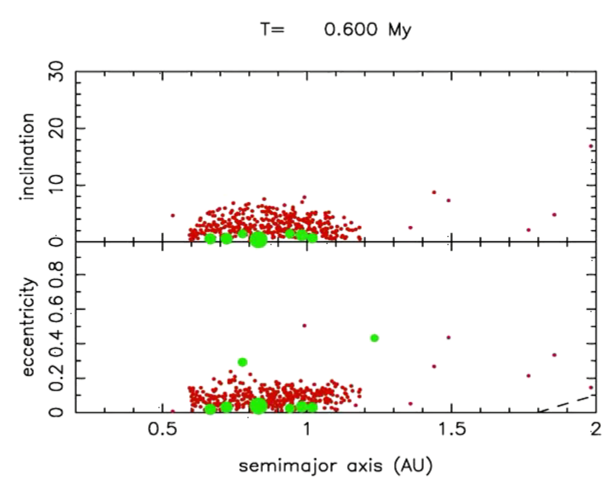
Super Earths and Neptune-like planets would have invaded the inner solar system (e.g. the Kepler systems of low density planets –K11). – Which consequences for the local Earth?

A more in-depth analysis of terrestrial planet formation

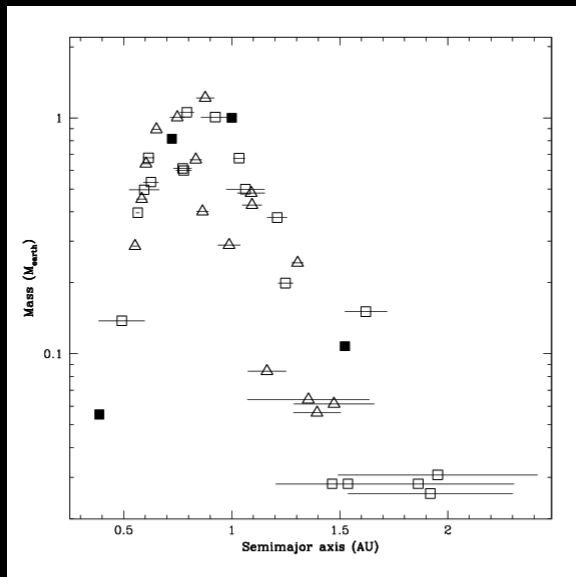
Walsh et al., 2011



Walsh et al., 2011

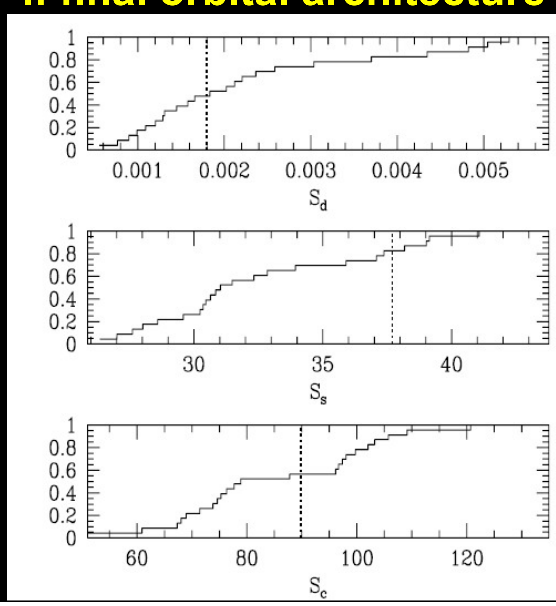


As in Hansen (2009), the statistical mass distribution of the synthetic planets produced in our simulations reproduces the observed distribution very well.



IMPLICATIONS

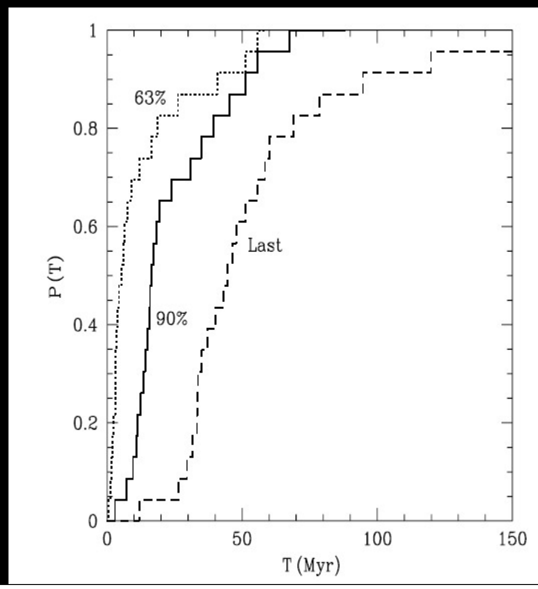
I: final orbital architecture



Hansen, 2009

IMPLICATIONS

II: Earth accretion timescale



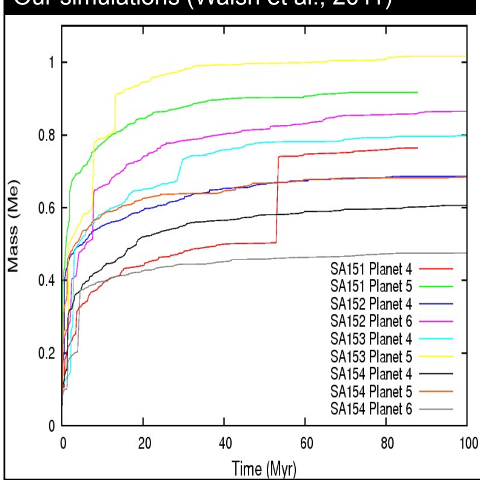
Hansen, 2009

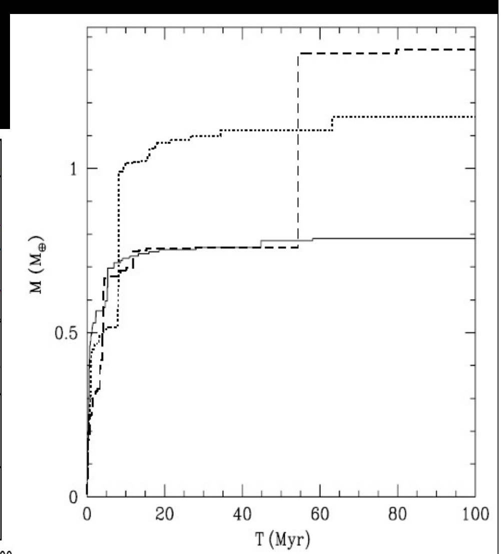
IMPLICATIONS

III: Earth accretion mode

Is the 2-stage scenario OK?

Our simulations (Walsh et al., 2011)

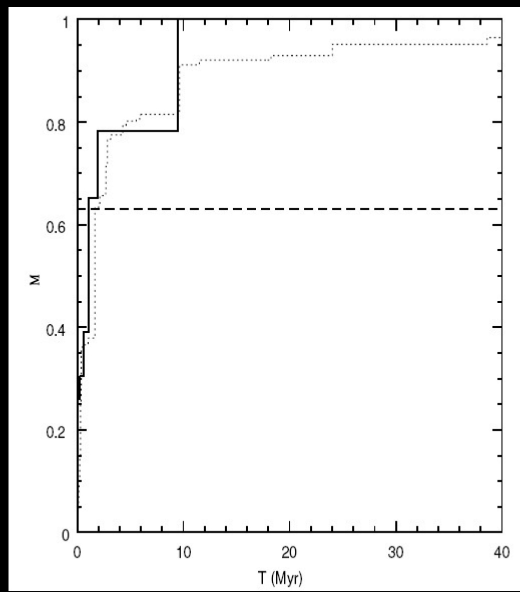




Hansen, 2009

IMPLICATIONS

IV: Mars accretion timescale

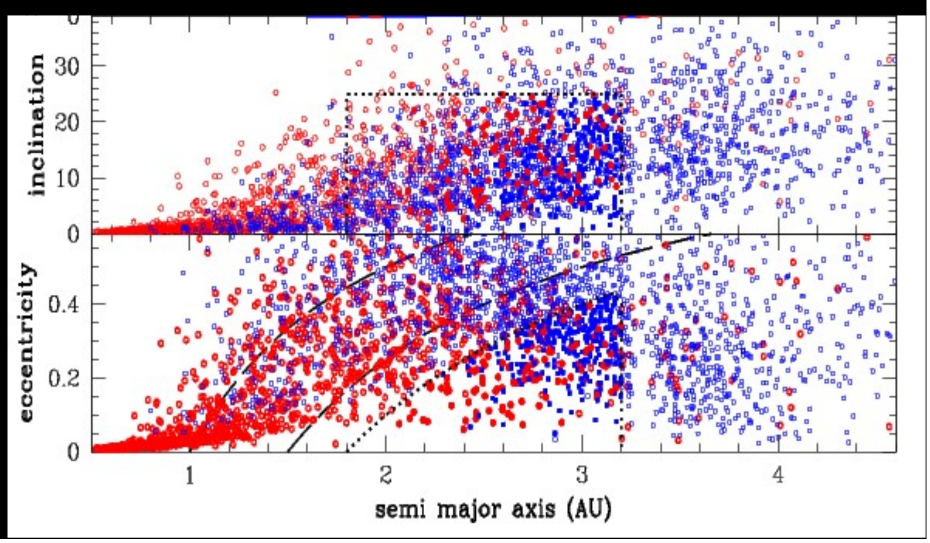


Hansen, 2009

IMPLICATIONS

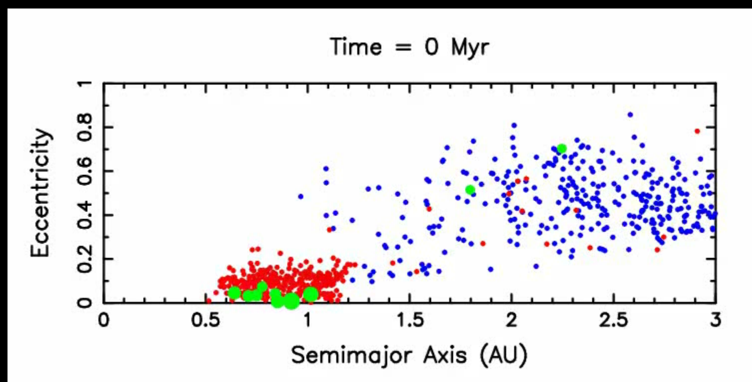
V: water delivery

O'Brien et al., 2010



IMPLICATIONS

V: water delivery



O'Brien et al., 2010

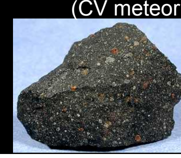
Water delivery

- Planets > 0.5 Earth mass accrete median value of ~2% Earth mass of C-type material. ~3% not rare.

- Assuming 10% water by mass (consistent with carbonaceous chondrites), this gives ~1x10^{-3} Earth masses of water
  - Earth has ~5x10^{-4} Earth masses of water

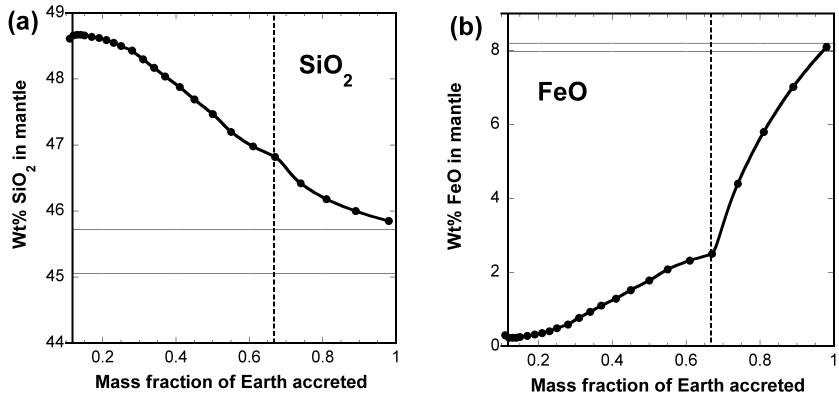
- Additional water may be delivered through more massive embryos that were not included in the simulations

Murchison
(CV meteorite)



A bit of geochemistry…

Rubie et al. (2011) showed that the chemistry of the Earth can be reconstructed if the first 70% of the Earth formed from reduced material (99% of Fe as metal) and the rest from oxydized material (60% of Fe as metal) – see also Wood et al. 2008



$$2Fe + SiO_2 \rightarrow Si + 2FeO$$

Metal Silicate Metal Silicate

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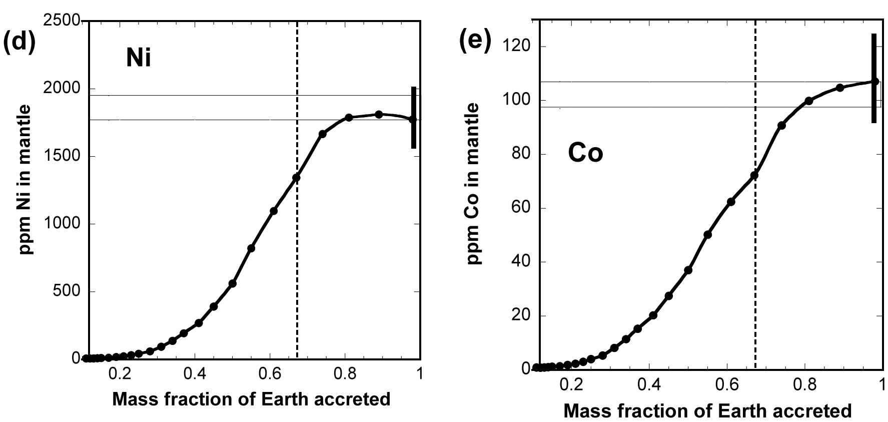
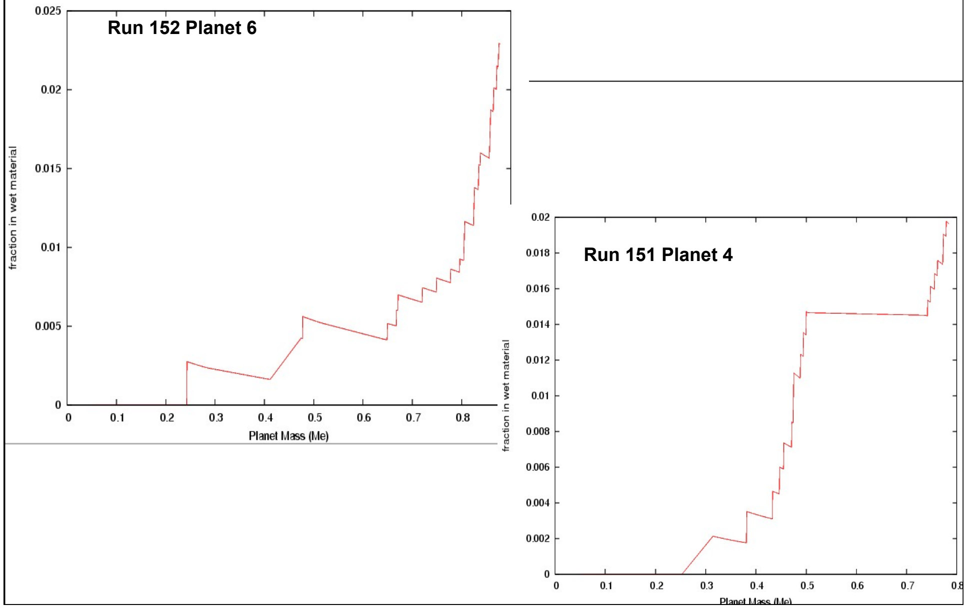


Delivery of primitive material in the Grand Tack scenario



GOAL: Match Earth-mantle concentrations of Al, Ca, Mg and the non-volatile siderophile elements:

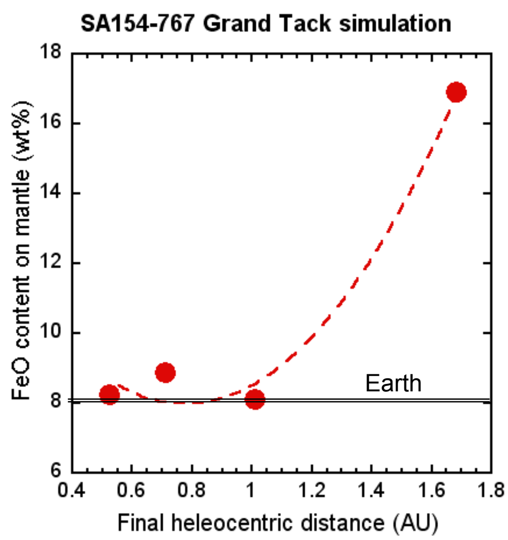
Fe, Si, Ni, Co, W, Nb, V, Ta and Cr

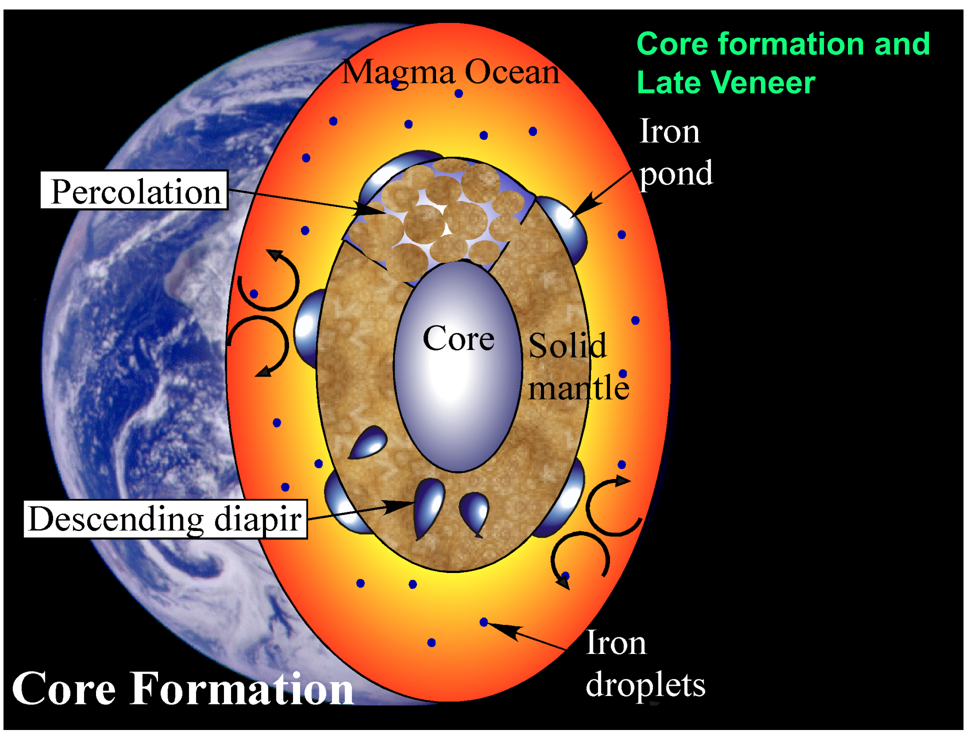
(FeO contents of mantles of Mars & Mercury)

4 least-squares fitting parameters:

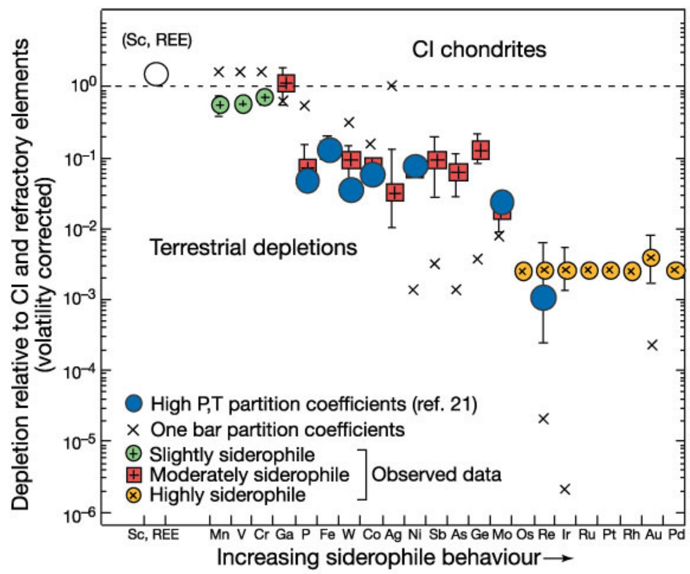
- Oxygen contents of reduced and oxidised compositions
- Original distribution of reduced and oxidized compositions in the early solar system
- Metal-silicate equilibration pressure – as a fraction of a proto-planets's CMB pressure

Mantle FeO concentrations of four planets from Grand Tack simulation SA154-767 (Rubie et al.. in prep.)



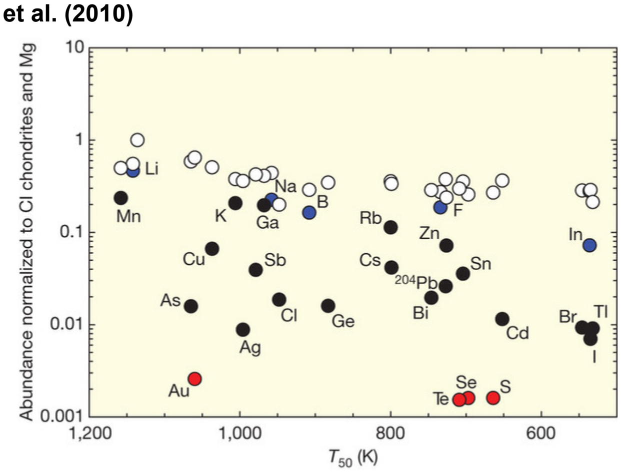


HSE in the mantle: Late Veneer



Were volatiles accreted during the LV?

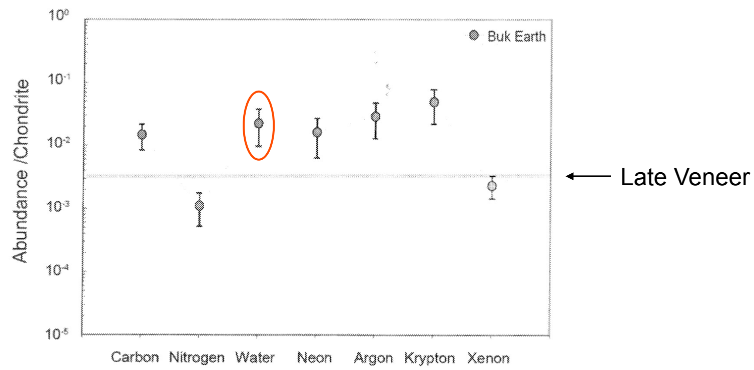
No: Wood et al. (2010)



The abundance of elements with same condensation temperature is clearly dependent on affinity with iron (red=HSE, black=MSE, white=lithophile)

Was water accreted during the LV?

NO: Drake and Righter, 2001; Marty (2011)



A Late Veneer of 3×10^{-3} M_E would give 1.5-3 x 10^{-4} M_E of water… a bit short

From HSEs abundances:
The LV on Earth is 3×10^{-3} M_E, i.e. 1.8×10^{25}g
The LV on the Moon is 2×10^{22}g

Ratio LV_{earth}/LV_{moon} ~ 1,000; Ratio of accreted material Earth/Moon < 20 !

Two possibilities:
a) Most of the HSEs on Earth predate the Moon-forming event and somehow escaped core-mantle equilibration during the GI (Walker and Touboul, 2012)
b) Most of terrestrial HSEs have been acquired in <20 impacts with large projectiles (Bottke et al., 2011)

If (a) is right, then the mass accreted by the Earth after the GI is only ~ 10^{-4} M_E
Even harder for the simulations!

If (b) is right, then the mass accreted by the Earth after the GI could have been larger than 3×10^{-3} M_E if part of the cores of the impactors merged with the Earth core without equilibrating with the mantle.
Could a LV of $2 \times 10^{-2} M_E$ have brought the water to Earth?

NO!

The Earth and the Moon have indistinguishable oxygen isotope composition.

All carbonaceous meteorites (with the exception of CI) have clearly different Oxygen isotope composition

The delivery of water AFTER the Moon forming event would have made the Earth and the Moon distinguishable!