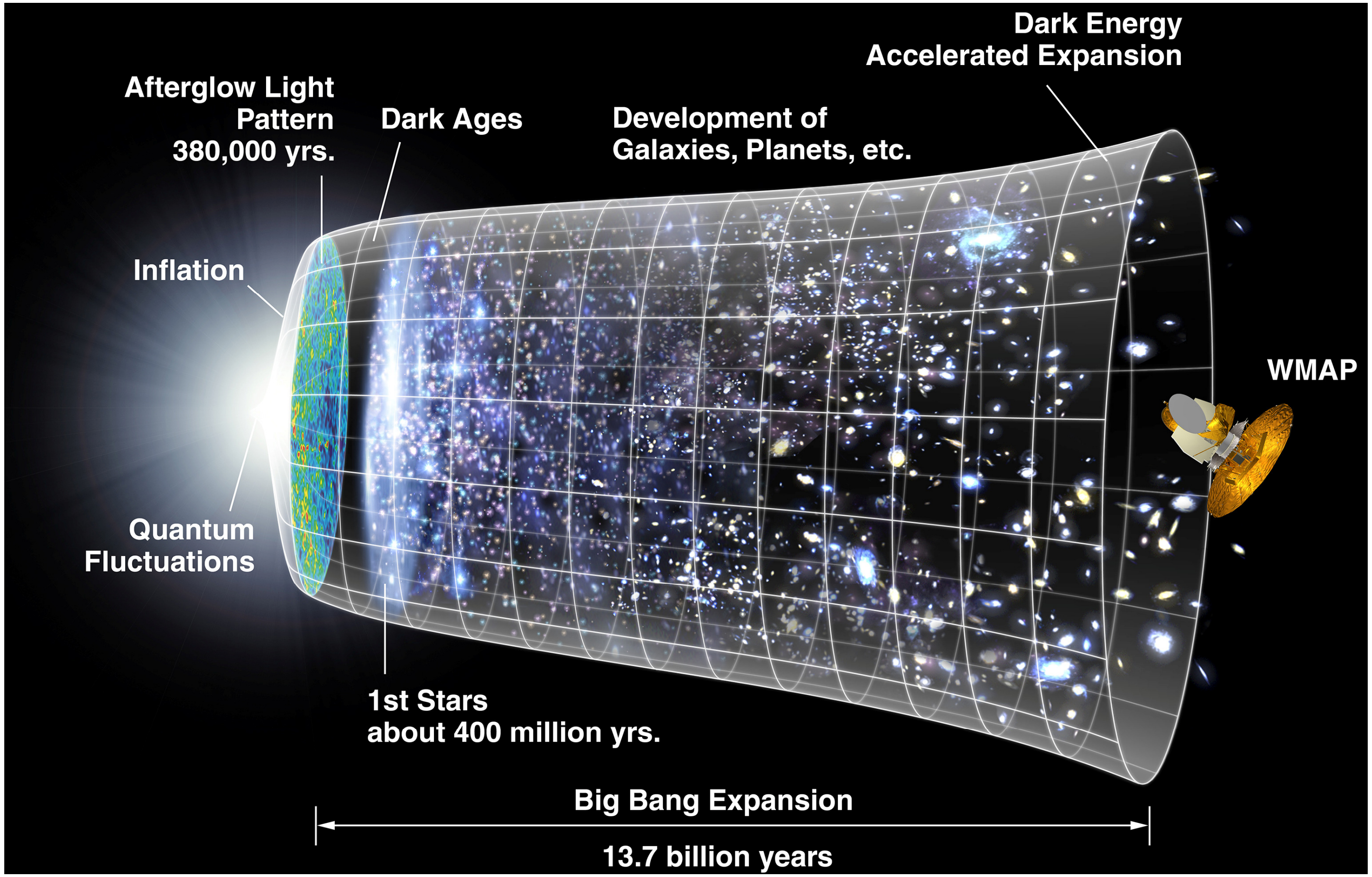
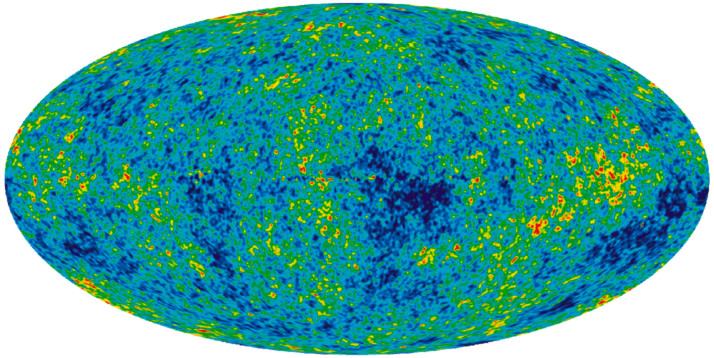
Echoes of the earliest Universe

Red shift of spectral lines in far galaxies (Hubble, 1929)
Theory of the Big Bang – Gamow (1948)

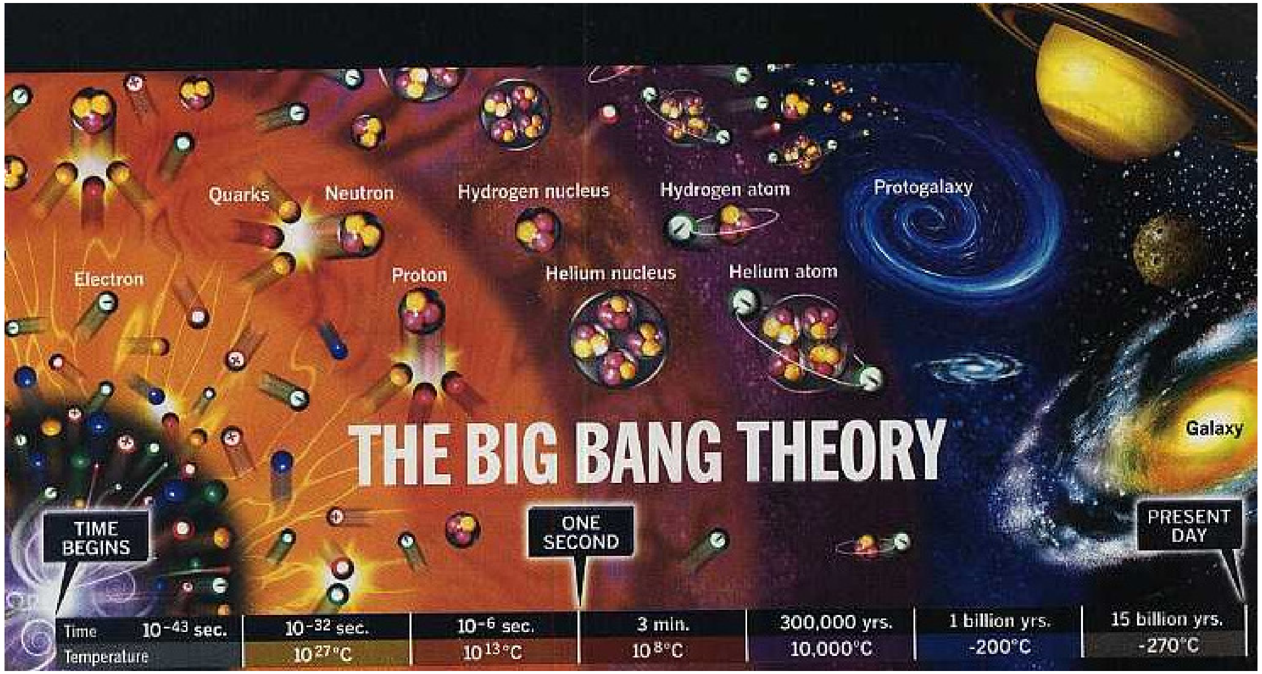


Cosmic microwave background
(Penzias, Wilson,1965 Bell AT&T)



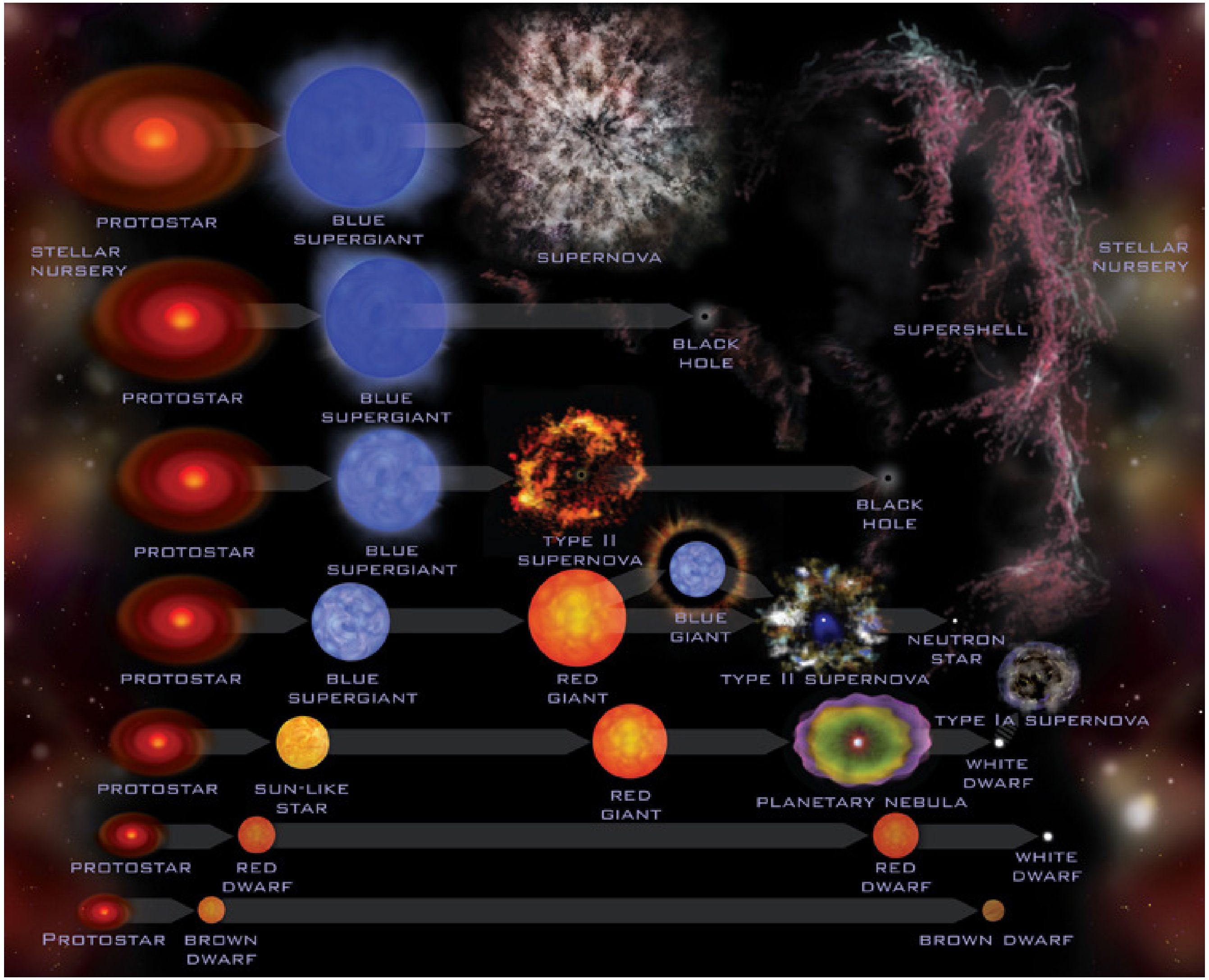
Heat of the Big Bang dissipated in the Universe as the 4 K residual radiation

Origin of the Universe



- Unsymmetric matter/antimatter anihilation
- only H and He elements formed during the Big Bang
- The Universe transparent aftr 377.000 yrs. → background µwave radiation
- Fluctuations registered there → autocatalytic formation of protogalaxies

Stellar evolution

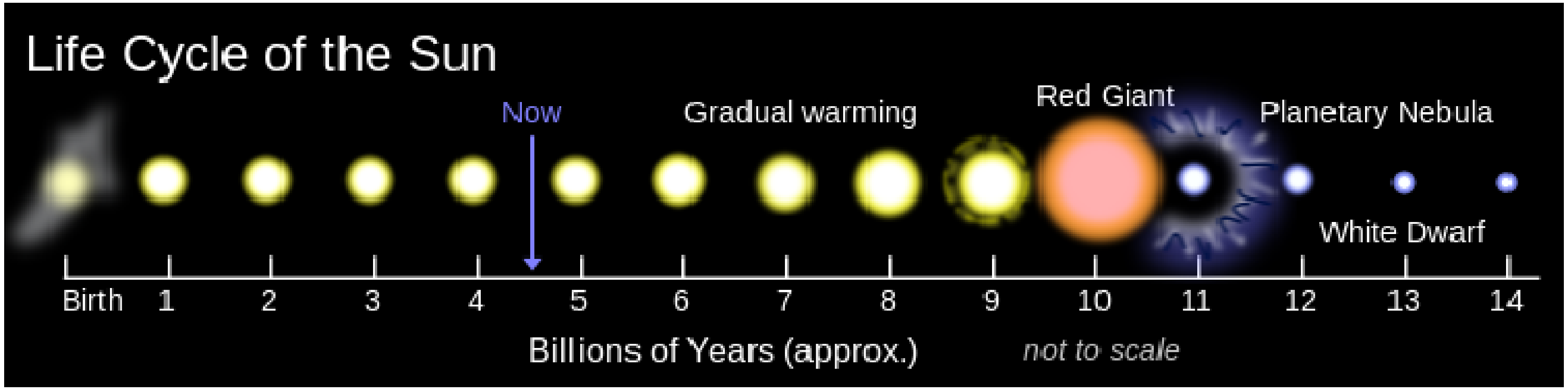


Star that burned all its ^{1}H (red giants), beginns to synthesize ^{12}C and ^{16}O from ^{4}He

Big stars (>8 sun masses) ignite ^{12}C and ^{16}O to form ^{24}Mg, ^{23}Mg (-^{0}n), ^{23}Na (-^{1}H^{+}), and ^{28}Si
Last step: 2x^{28}Si → ^{56}Fe

Supernova:
heavier elements synthesized by neutron irradiation of iron

Evolution of the Sun

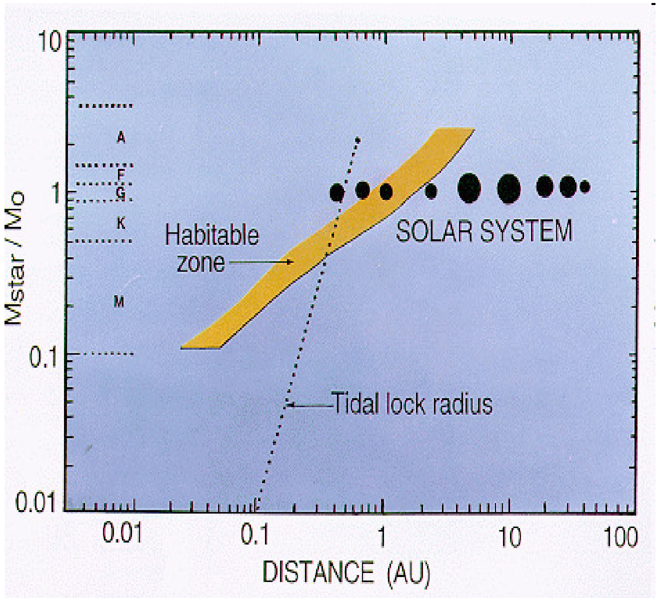


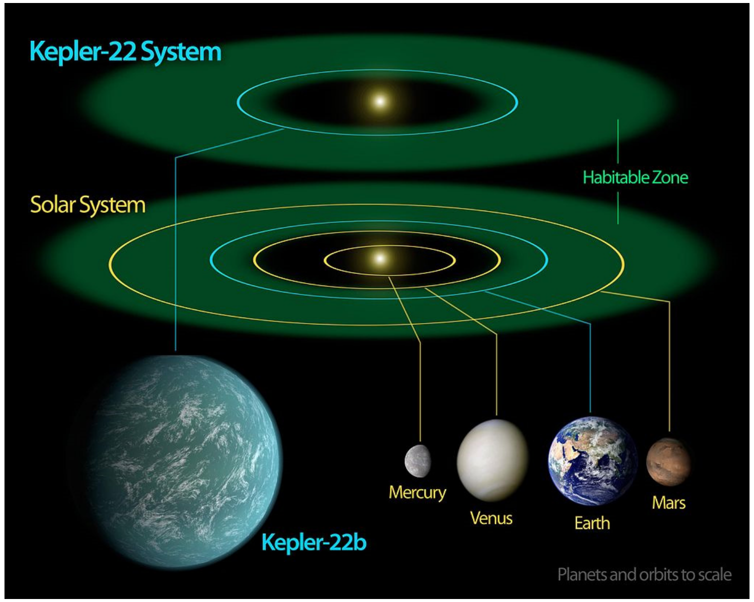
- The sun is solitary, 85% stars are multiple
- The sun is relatively massive (within top 10%)

Habitable zone

Habitable zone – the region where liquid water can occur

Tidal lock - tidal energy converts planet rotation into heat and „locks” its position so that it faces the star with one side only (high constant gradients of heat distribution)





tidal lock – detrimental for life in star systems below 40% of the Sun mass

Too large star – fast burnout and explosion

Only 5% of all known stars are large enough to avoid tidal lock and small enough to be stable

Galactic requirements for evolution of life

Sun orbit – 26000 Light years from the center
(225 Mio yrs. to make the full circle)

Closer to the center –sterilization by notorious supernova explosions, X-rays from black holes

Far beyond the Sun’s orbit – lack of elements heavier than carbon and oxygen
→ planet formation inhibited

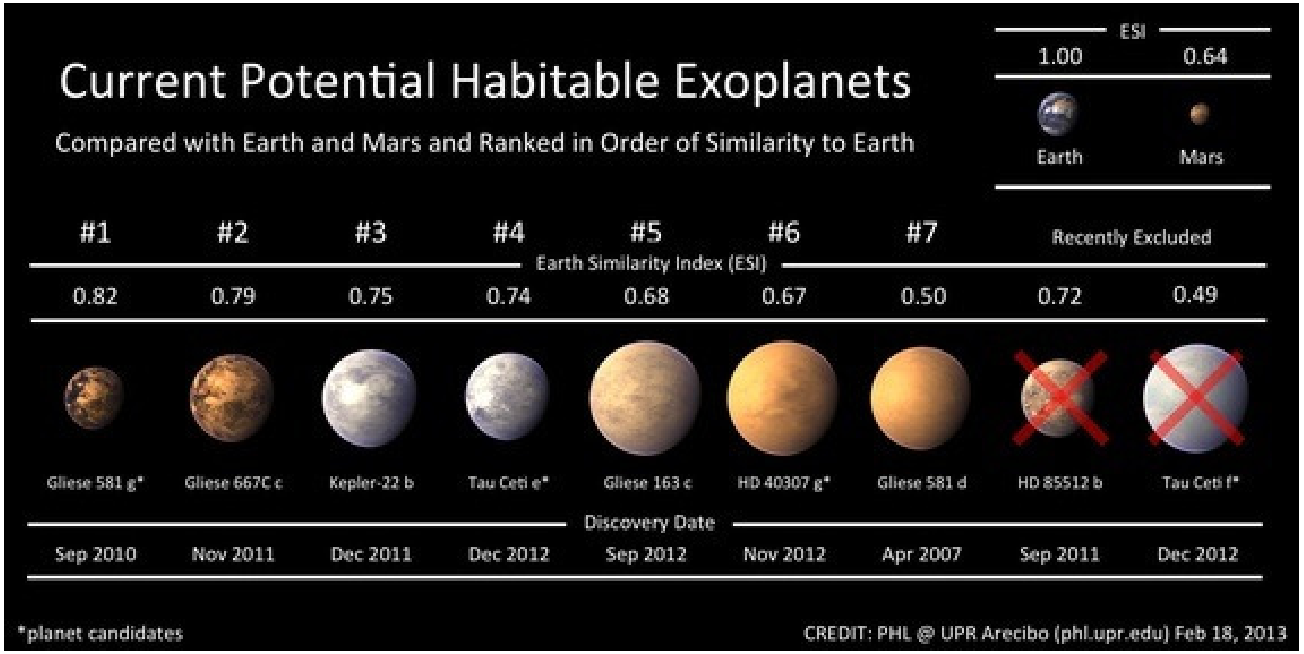
GHZ – Galactic Habitable Zone – weekly populated (c.a. 10% stars from the Milky Way)

Moreover, a star must REMAIN in the GHZ all the time to host life development
Less than 5% of all stars do.

Quantification of habitable planets

$$P_{\text{habitable}} = P_{\text{solitary}} * P_{\text{size}} * P_{\text{GHZ}} = 0.00075$$

1 star in 1300 seems to be habitable



Current Potential Habitable Exoplanets

Compared with Earth and Mars and Ranked in Order of Similarity to Earth

ESI	1.00	0.64
	Earth	Mars

	#1	#2	#3	#4	#5	#6	#7	Recently Excluded	
Earth Similarity Index (ESI)	0.82	0.79	0.75	0.74	0.68	0.67	0.50	0.72	0.49
	Gliese 581 g*	Gliese 667C c	Kepler-22 b	Tau Ceti e*	Gliese 163 c	HD 40307 g*	Gliese 581 d	HD 85512 b	Tau Ceti f*
Discovery Date	Sep 2010	Nov 2011	Dec 2011	Dec 2012	Sep 2012	Nov 2012	Apr 2007	Sep 2011	Dec 2012

*planet candidates

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Feb 18, 2013

Still 100.000.000.000 stars in our Galaxy, and 100.000.000.000 galaxies in the Universe

Origins of a habitable universe - Summary

Good understanding of the origins of the Universe
– the Big Bang model highly quantitative and confirmed

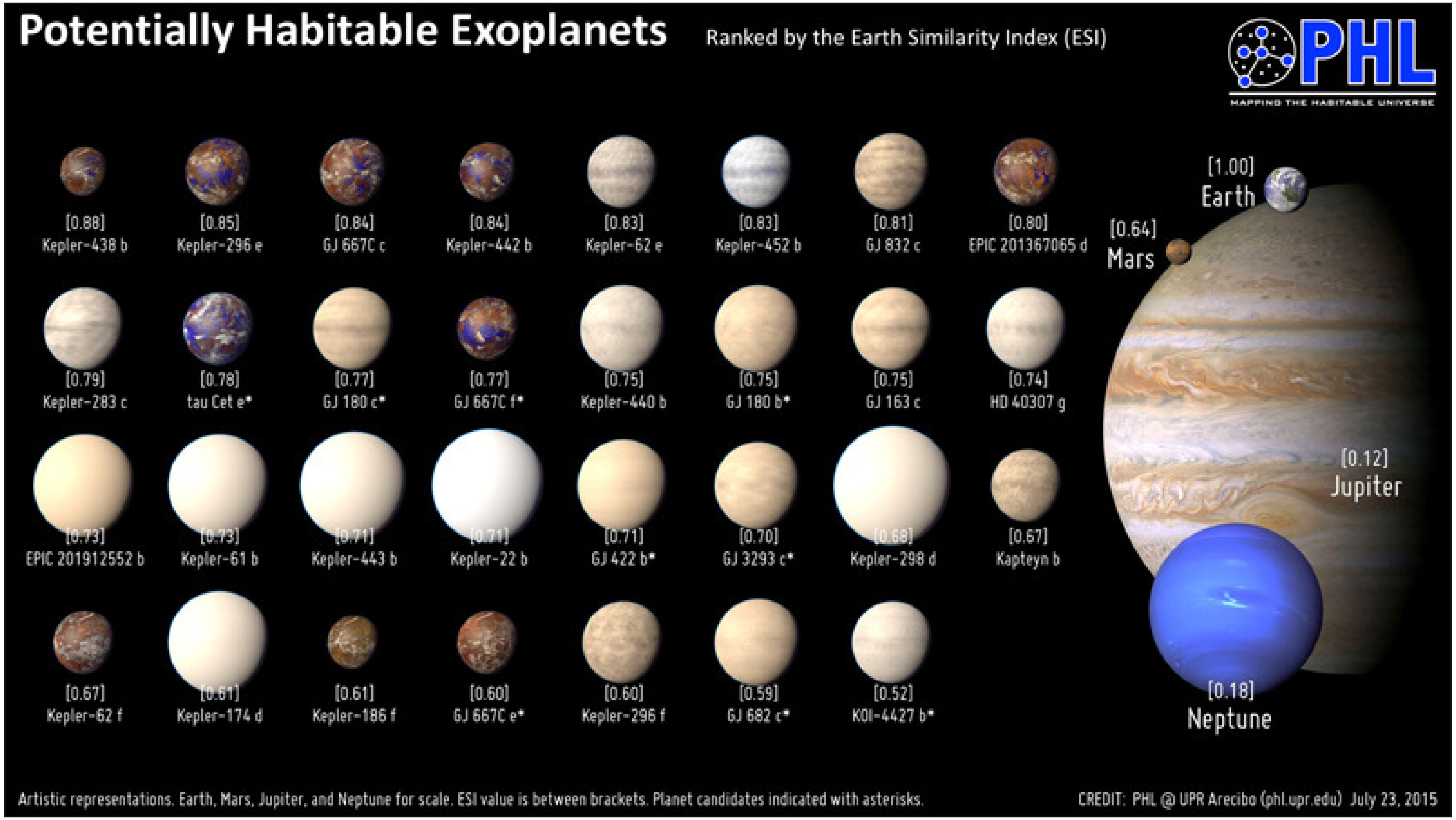
Too dense universe → wouldn’t survive long enough to host life
Too sparse universe → Galaxies, stars and heavy elements would not have formed

The size of the Sun, its location in our galaxy, and its regular orbit (low eccentricity) optimal to support life development.

We have defined size range and optimal location (HZ, GHZ) for other life-friendly worlds.

1 star in 1300 may to be habitable

Origins of a habitable planet

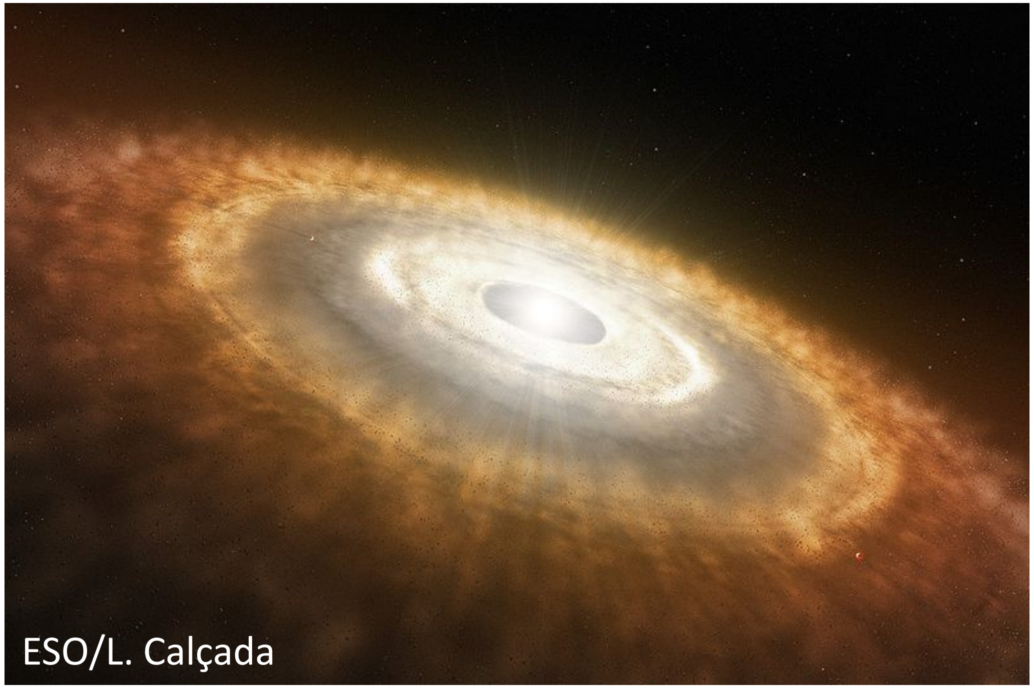


Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI value is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) July 23, 2015

Evolution of the solar system

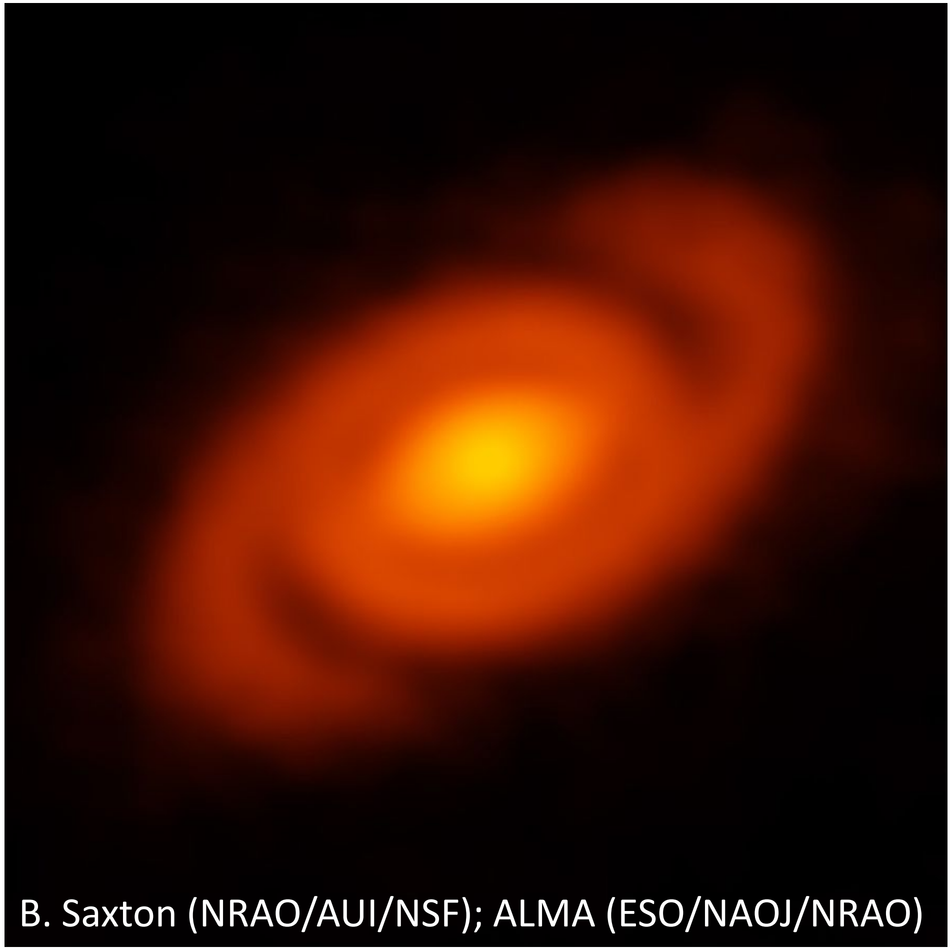
Pre-solar nebula – artistic vision



ESO/L. Calçada

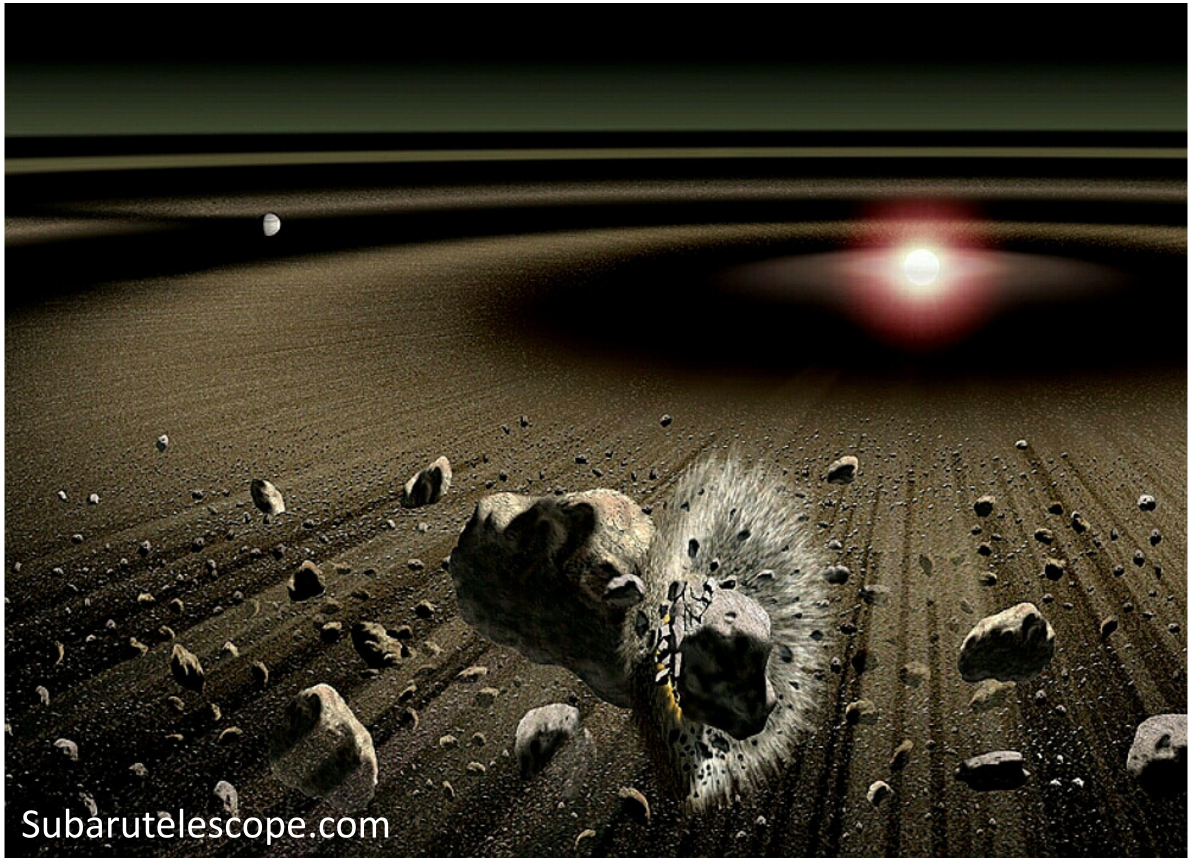
most matter into the proto-sun,
0.1%-2% remained in the acretion disc
Liquids unstable, only sublimation
10 Mio. K → ignition of the star (^1H→ ^4He)

Protoplanetary disc surrounding a star
Elias 2-27, 450 light years away



B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

Evolution of the solar system

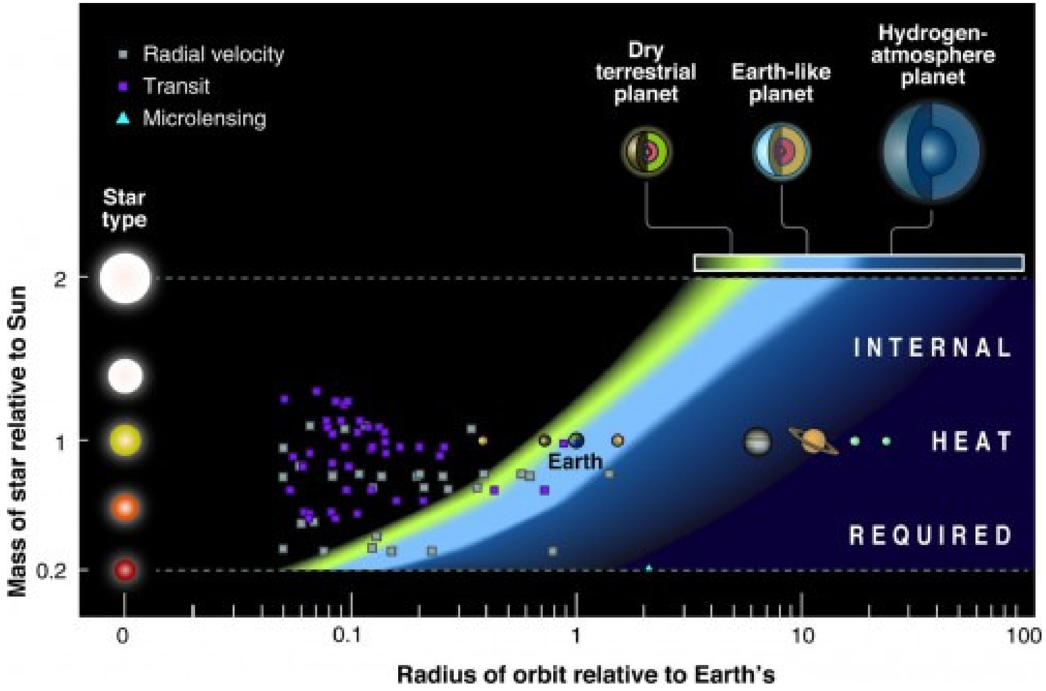


Subarutelescope.com

Conglomerations of particles → km-sized planetesimals,
frequent collisions → accretion
the km-sized bodies gravitationally attractive for gases around → growth of proto-planets

Evolution of the solar system

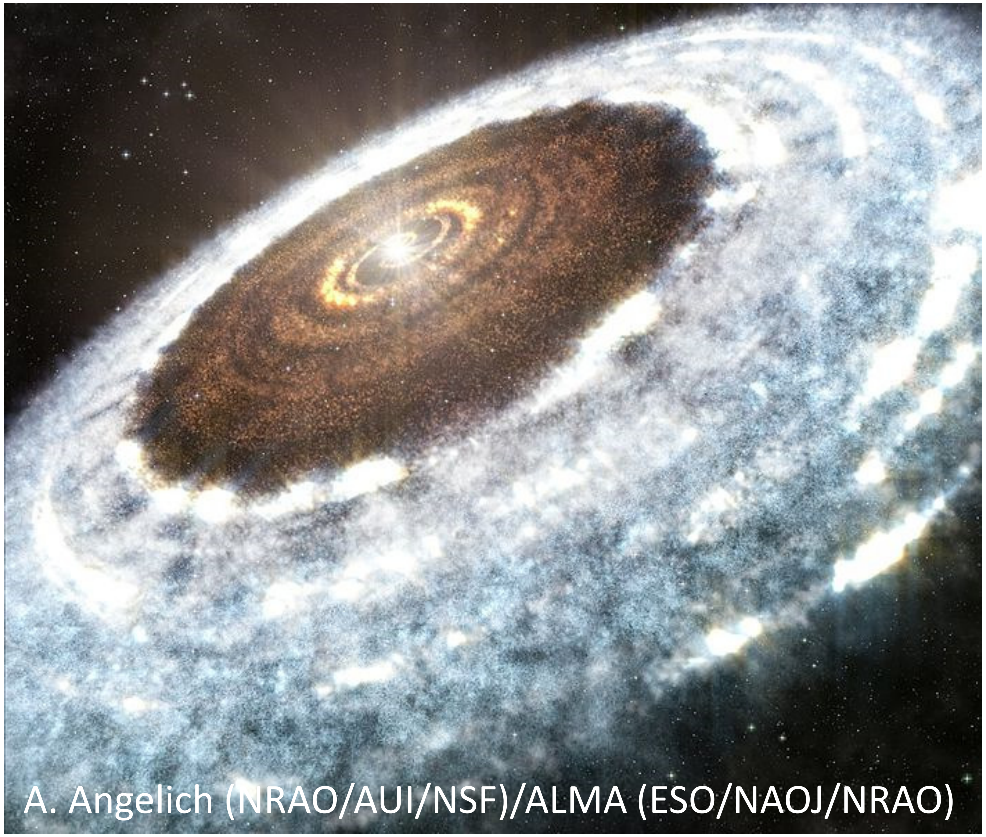
Composition of planetesimals depends on their distance from the star:
Metal-rich – center
Silicate-rich – middle
Volatile-rich – outer part



The equilibrium condensation model
temperature determines equilibrium chemistry which defines the composition
The prediction is rough (scattering)
Exceptions: volatiles on Earth and Venus, composition of the Moon

Composition of the planets in the solar system

Water – a major component of the solar nebula, but under the very low pressure does not condense above 150 K („snow line” in the nebula, 2.7 AU in the Solar system).



A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

Asteroids that form above 2.7 AU contain significant amount of water

Composition of the planets in the solar system

dense highly refractory metals (8 g/cm^3), silicates (3 g/cm^3)

Mercury

5.4 g/cm^3 avg. density, rock-to-metal ratio 1:1, has magnetic field (conducting metallic core)

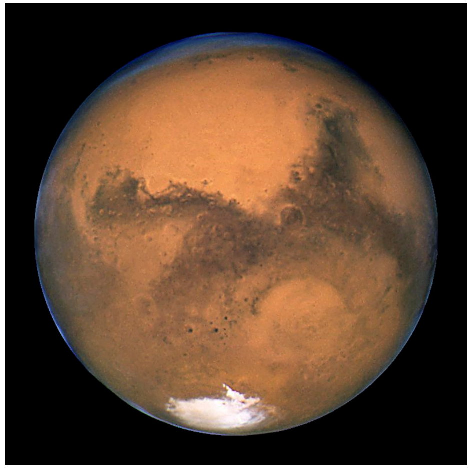
Venus

5.3 g/cm^3; 14x more massive than Mercury – corrected with mass compression rock-to-metal ratio 3:1 (uncompr. 4.2 g/cm^3)

Earth

5.5 g/cm^3; 17x Mercury mass, rock-to-metal ratio 3:1 (uncompr. 4.2 g/cm^3)

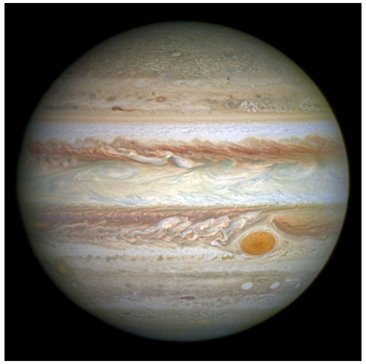
Mars



4.0 g/cm^3; rock-to-metal ratio >5:1 (uncompr. 3.3 g/cm^3)

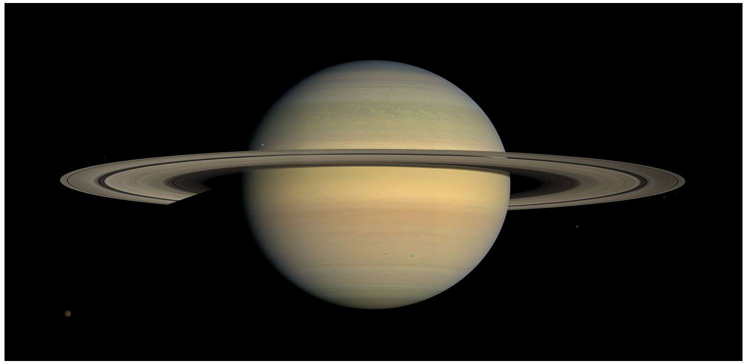
Composition of the planets in the solar system

Jupiter



1.3 g/cm^3
300 masses of Earth

Saturn



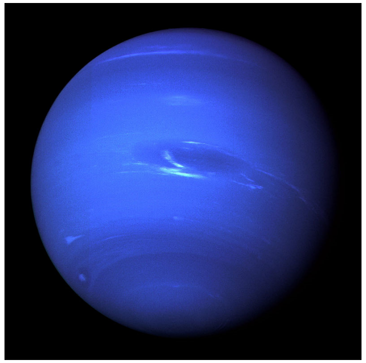
0.7 g/cm^3
90 masses of Earth

Uranus

1.3 g/cm^3
15 masses of Earth

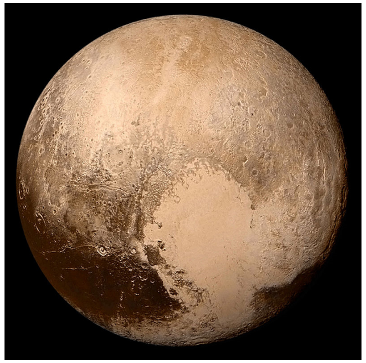
the outer Solar System
dominated by Jupiter

Neptune



1.6 g/cm^3
17 masses of Earth

Pluto(*)

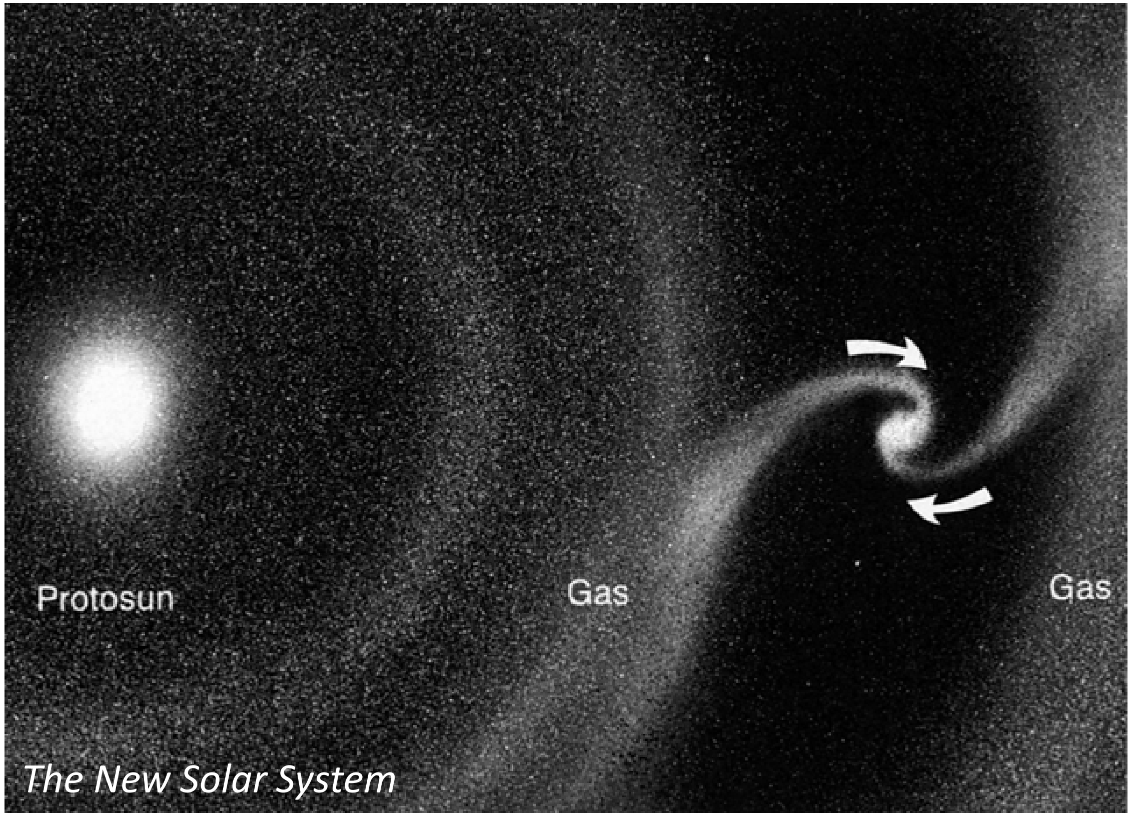


2.0 g/cm^3
0.003 masses of Earth

Composition of the planets - Jupiter

Jupiter – 5.21 AU – first planet beyond the snow line – silicates and water condensed in largest amounts of the whole Solar System around a small metal core, and formed a proto-Jupiter
(10-15 Earth masses, fast).

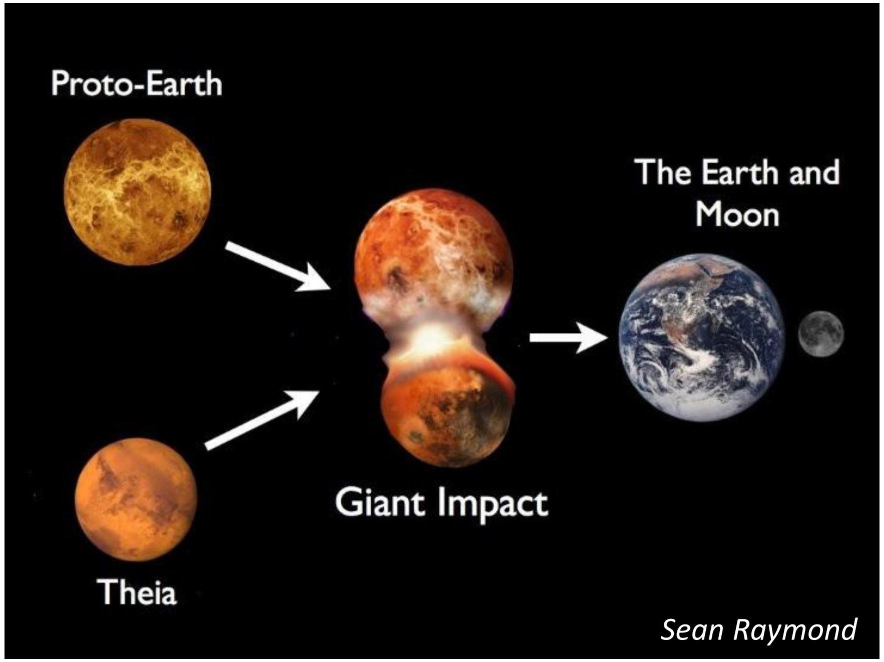
Then gravity strong enough to pull in all available gases around, until it mainly consisted of H_2 and He (strongly pressurized)



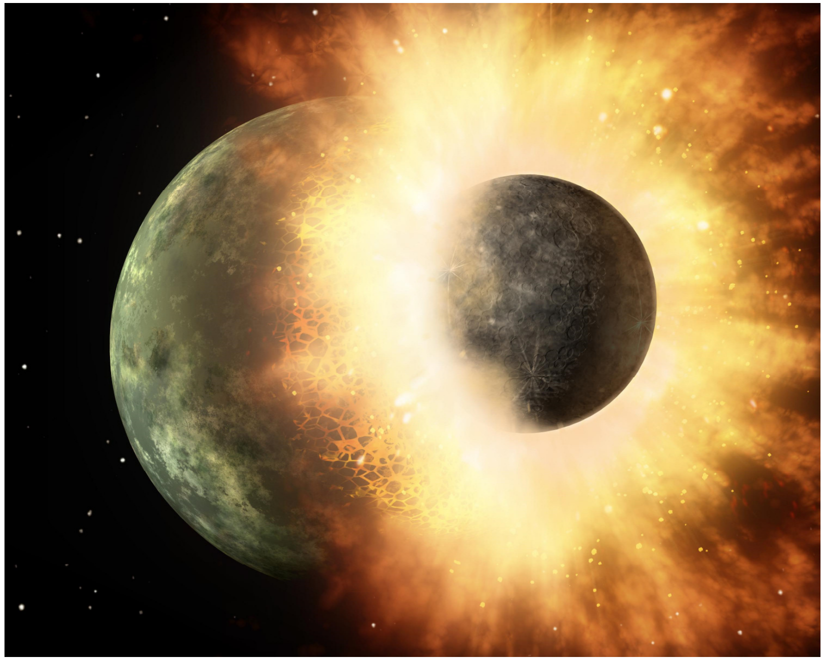
The New Solar System

Origin of the Moon

Lunar rock samples (*Apollo* mission): Isotopic distribution like on Earth
Surface of the Moon is different from the Earth surface – lack of „volatile” metals like sodium, the Moon’s density only 3.4 g/cm^3→ contains almost entirely silicates



Sean Raymond

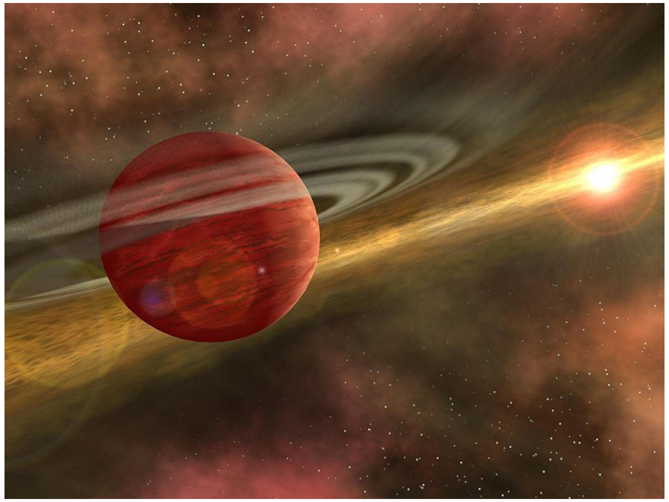


„Daughter-like” Moon’s origin – impact of a Mars-size object into Earth splashed a big chunk of liquid rock from its mantle (mostly silicates) into space
Isotope dating (^{182}Hf/^{182}W): Moon formed 30 Mio. Yrs after accretion

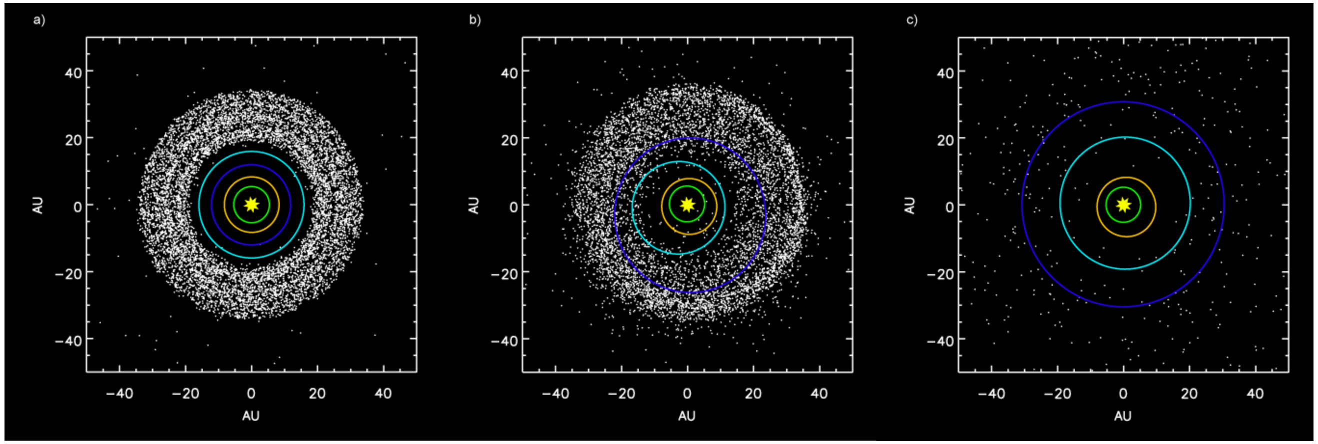
Origin of volatiles on terrestrial planets

Proto-Earth was too hot to condense water
but 0.035% Earth mass is water!!

Water came from beyond the snow line:
Jupiter ejected the remaining planetasimales outwards and inwards: „big cleanup”



The Nice model



Explains the formation of the
Kuiper’s Belt, Oort’s Cloud
and Planetoid Belt

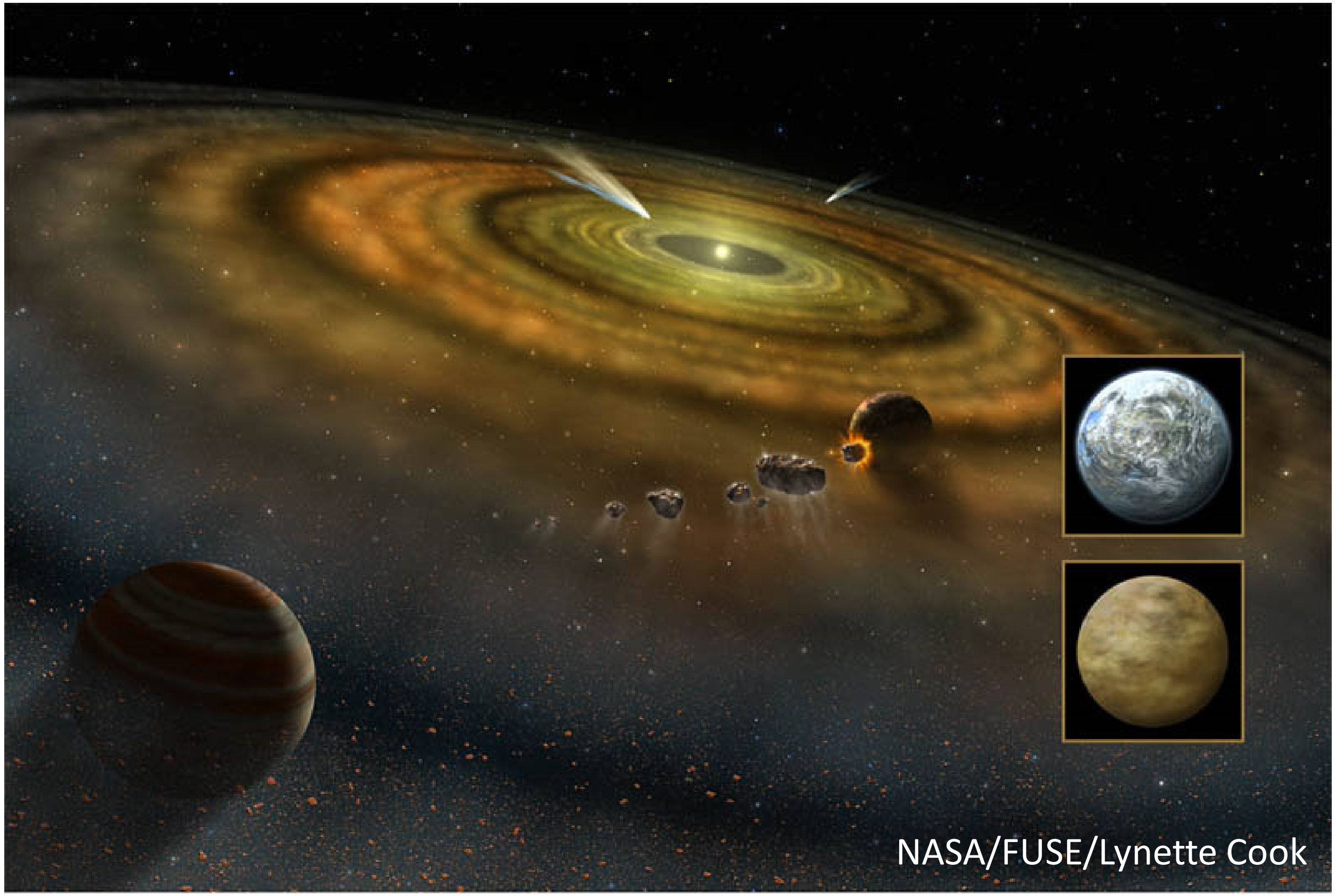
The ejected planetasimales delivered volatiles to Earth and other terrestrial planets

Late Heavy Bombardment

Late Heavy Bombardment 3.8 Bio. Yrs. ago was the last intensive impact period. Then no more planetasimales.

100-km-wide object can sterilize the surface of the whole planet, but nothing like that happened since.

Migration of exocomets and planetasimals

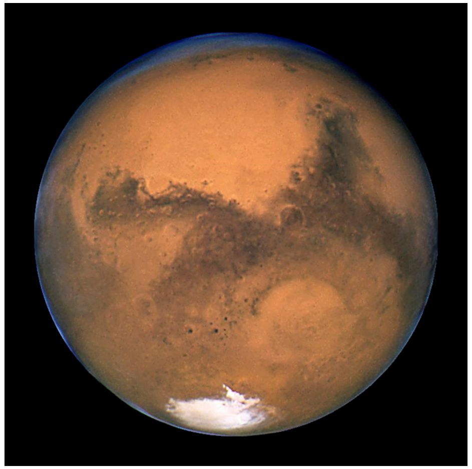


NASA/FUSE/Lynette Cook

Fate of volatiles on terrestrial planets

Mercury – volatiles escaped into space.
Exeptions: craters at the poles
No seasons at Mercury (rotation axis does not move), so bottoms of these craters always in shade (chilled to few Kelvins) → cold traps, filled with ice;

Same situation on the Moon, but gravity much weaker, so smaller amounts of water ice left



Mars – weak atmosphere, significant amount of water ice detected in polar caps (mix of water ice and frozen CO_2), and underground in the polar regions,
In the past - much of surface water (canyons, sedimentary rocks).
Liquid water still possible around warm volcanoes under the crust

Fate of volatiles on terrestrial planets

Venus – the closest Earth's sibling, but extremelly DRY
Atmosphere: 30 ppm water vapor (Earth: 1.000-40.000 ppm + 120.000 more in oceans). Atmospheric pressure on Venus' surface: 90 atm (96.5% CO_2, 3.5% N_2)
Due to CO_2 strong greenhouse effect: 460^0C on the surface.

On Earth, a lot of liquid water, CO_2 bound in limestone
Warm water + CO_2, Ca^{2+}, Mg^{2+} → $CaCO_3$, $MgCO_3$
volcanic activity liberates it again.
Too cold Earth („snowball Earth") → water freezes, no contact with CO_2
Plate tectonics → limestone is transported inside, decomposed → CO_2 is liberated again to the atmosphere → warming up

Liquid water + plate tectonics → temperature stabilization

Fate of volatiles on terrestrial planets

Venus had a lot of water, but lost it. How?
D_2O evaporates slower than H_2O.

Jupiter’s H:D ratio is 44.000:1 (the primordial ratio of the solar system)
Venus: 60:1 (700x less!) → lost several OCEANS of water
Earth: 6000:1 (7x less) → it also lost some water

Blackbody temperature on the Earth’s orbit is 255 K (-18^{0}C)
→ outer shell of Earth’s atmosphere is well below freezing of water
→ any water vapor condenses and falls backas rain or snow

Venus’ atmosphere is warmer than 0^{0}C → water difuses to its top
UV light from Sun → photolysis (H_2 + O_2) part of H_2 irreversibly escapes with the solar wind.
Over last 4 Bio. Yrs. almost all water lost that way

Origins of a habitable planet - conclusions

Earth formed in the inner region of the solar nebula
Predominantly composed of refractory metals and silicates – non-biogenic materials
Jupiter provided proto-Earth with icy, volatile-rich material, and allowed cleanup of the Solar System from planetasimales, so no more big, planet-sterilizing impact possible anymore.
Earth is optimally positioned (0.95-1.15 AU) to maintain the acquired water as liquid, and stable surface temperature over billions years.