Origin of the Earth´s atmosphere

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Origin of the Earth´s atmosphere

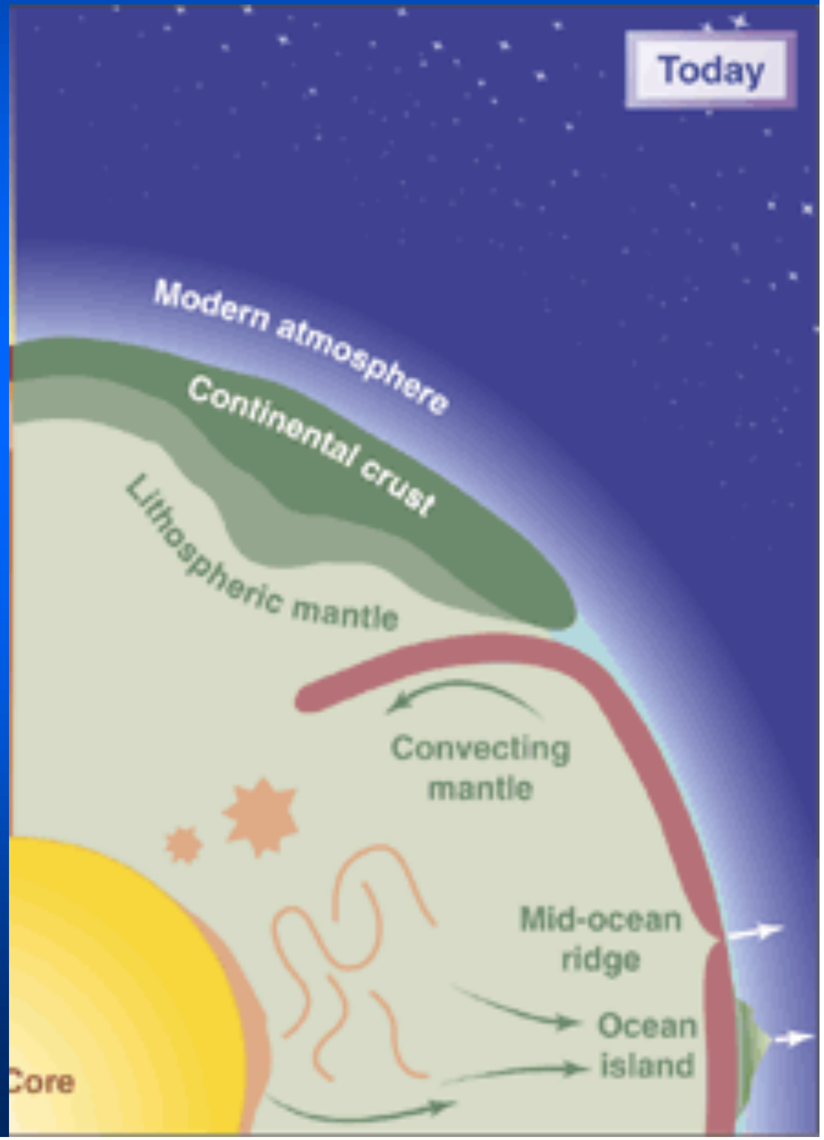
Layered structure of Earth

- Core
  (Fe, Ni, siderophile elements)

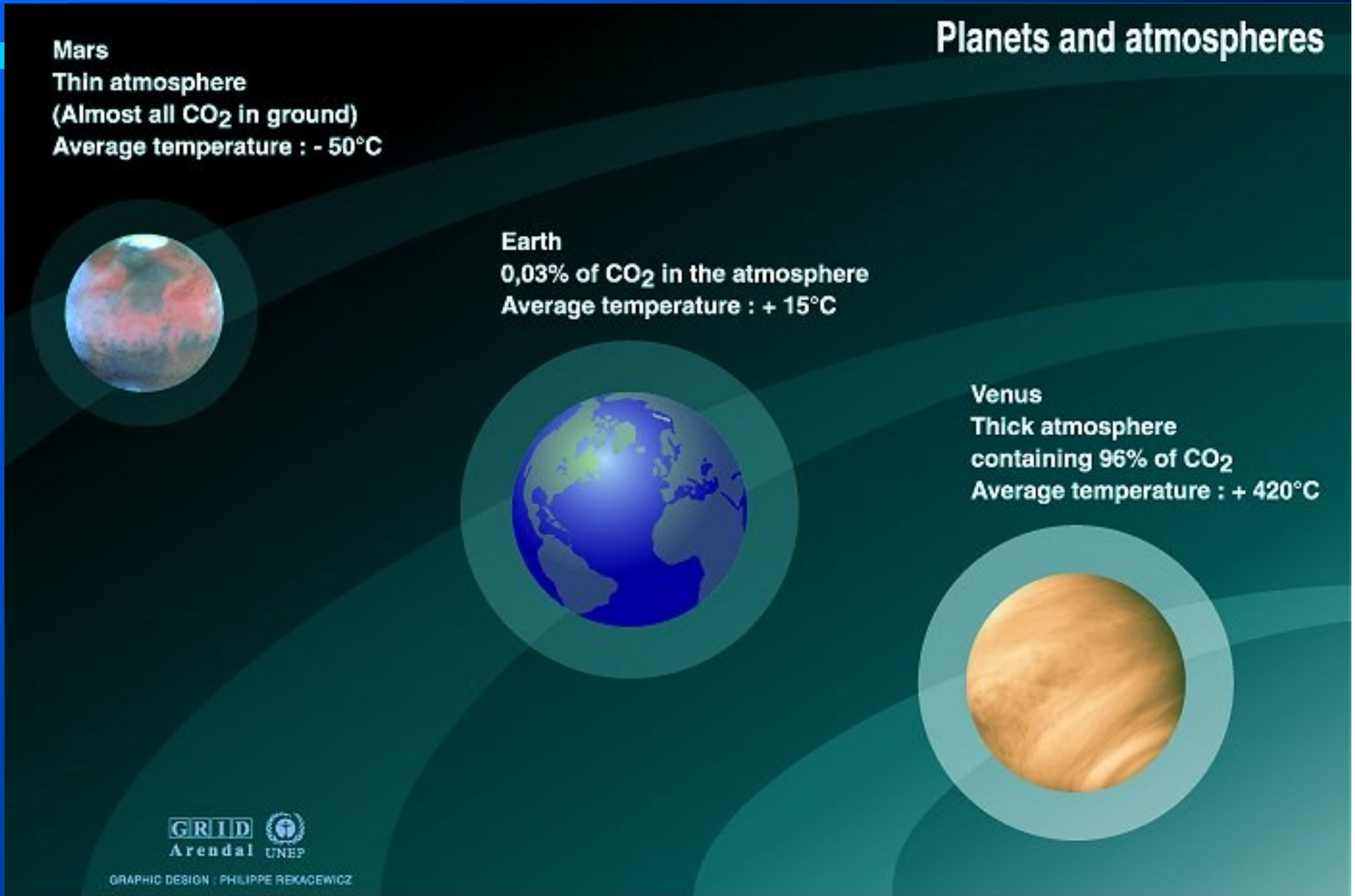
- Mantle
  (O, Mg, Si, Fe, Al, Ca, Na …)

- Crust
  (O, Si, Al, Fe, Mg, Ca, …)
  incompatible elements enriched

- Atmosphere
  (N_2, O_2, atmophile elements)



Atmospheres of Venus and Mars: dominated by CO_2



Sources: Calvin J. Hamilton, Views of the solar system, www.planetscapes.com; Bill Arnett , The nine planets, a multimedia tour of the solar system, www.seds.org/billa/tnp/nineplanets.html

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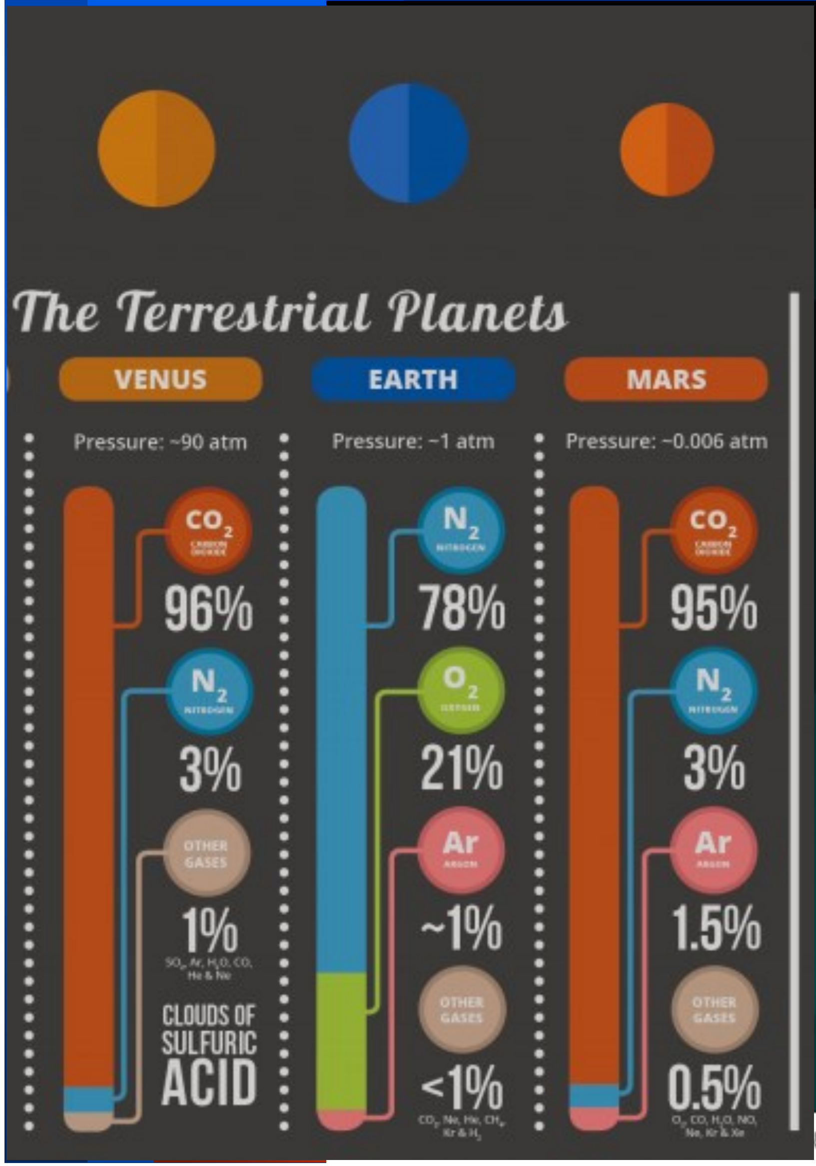

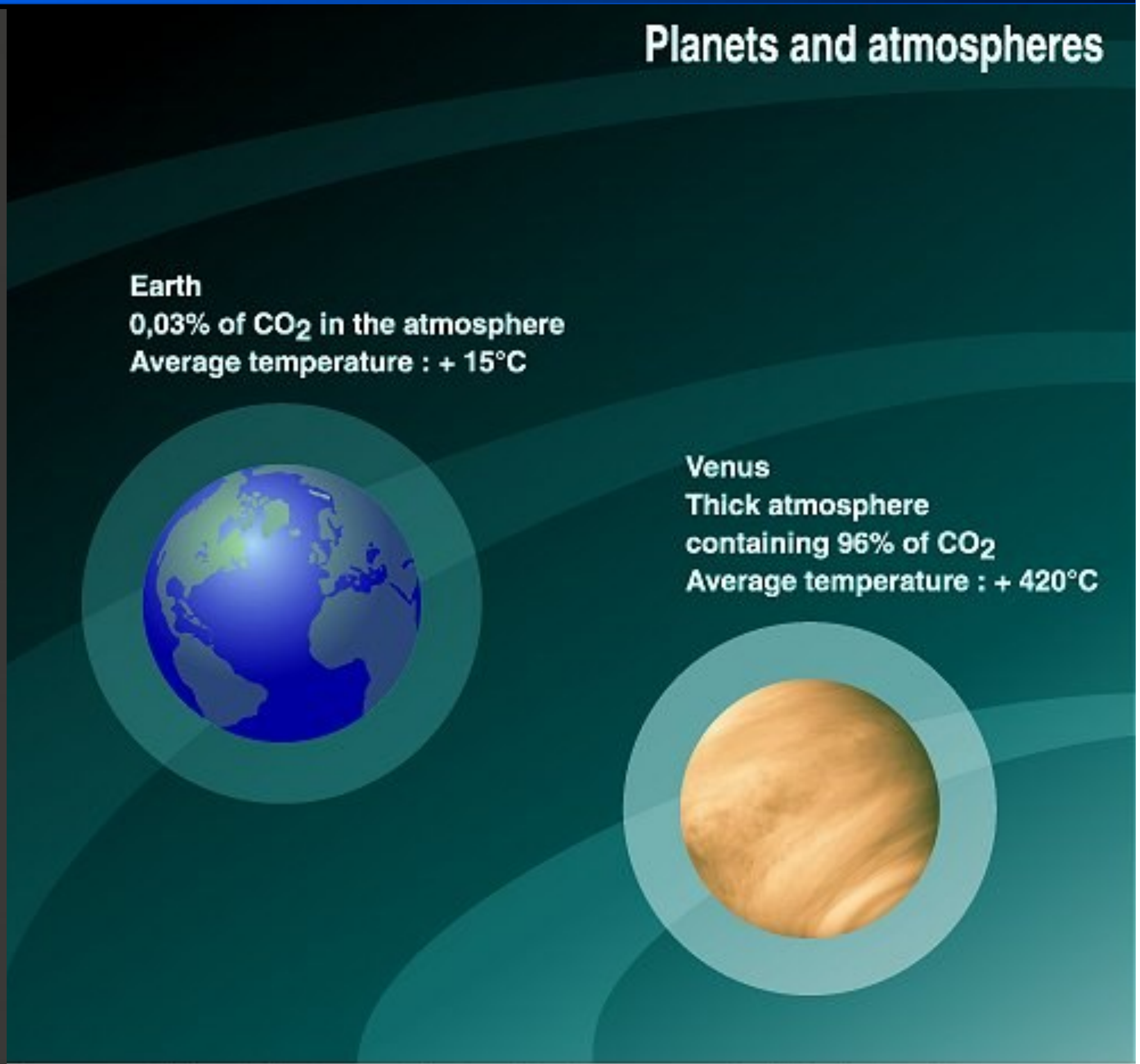

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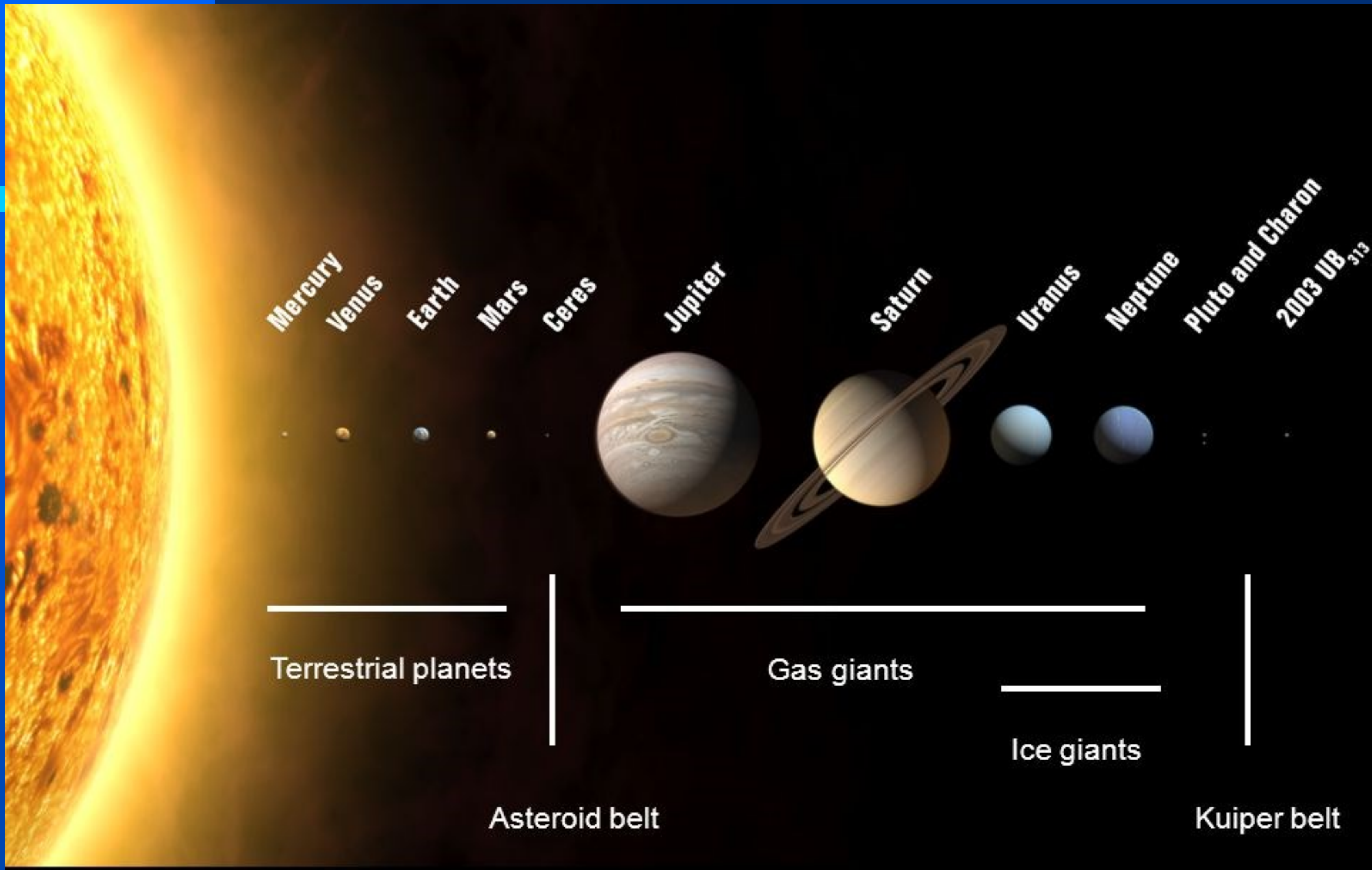
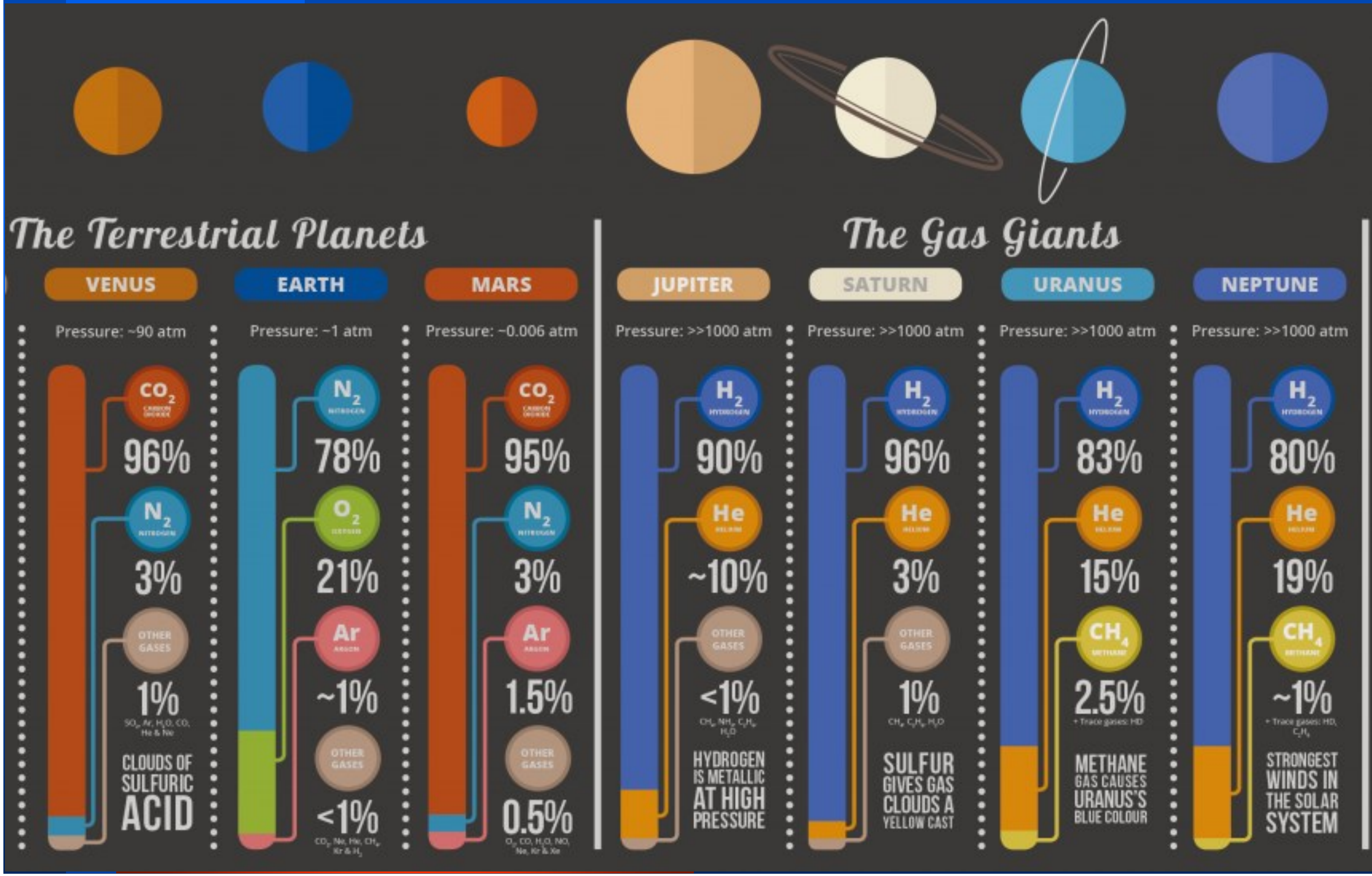
The solar system: Rocky terrestrial planets and gas/ice giants



Thin atmospheres dominated by less abundant C, O, N, Ar

Dense atmospheres dominated by H, He (most abundant elements in the universe)



Why are the most abundant cosmic elements (H, He) so depleted on terrestrial planets?

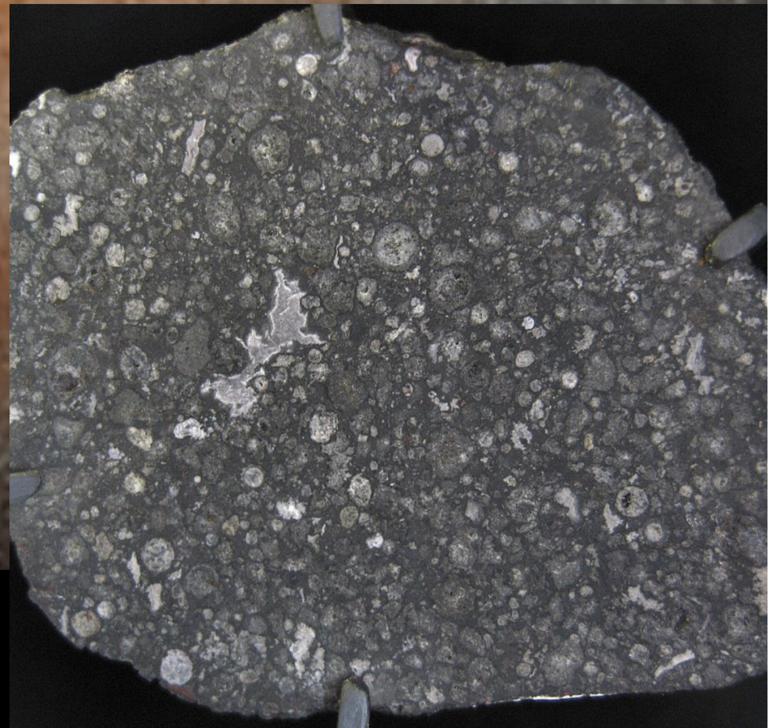
When and how did planetary atmospheres form, were formation processes different for gas giants and terrestrial planets?

Solar Nebula - 4 567 Ma ago

→ Collapse of interstellar cloud

→ 99% gas (mainly H, He) 1% dust (“condensable elements”)

→ Formation of protosun and protoplanetary disc



Solar Nebula - 4 567 Ma ago

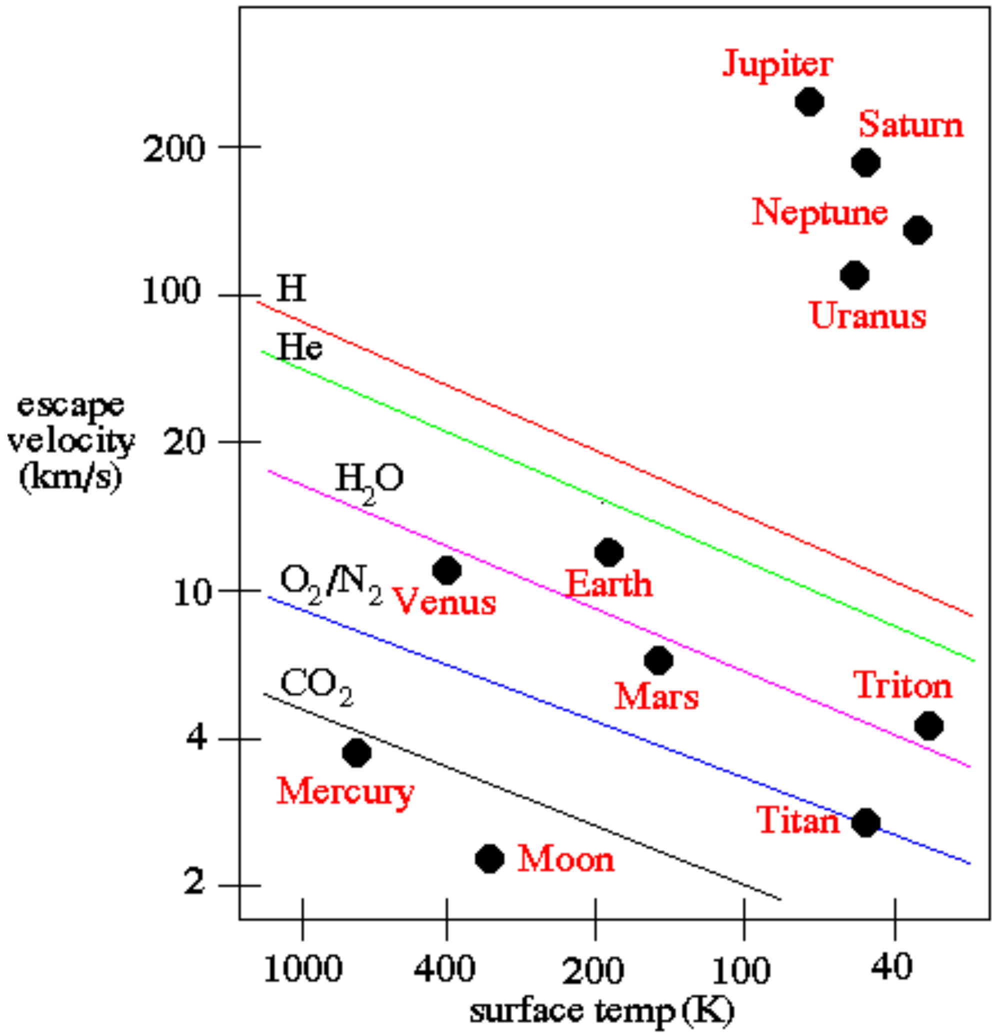
→ First solids (mm-sized chondrules and cm-sized CAIs)
→ Growth of planetesimals and protoplanets
(few 100 km size) within disk lifetime (5-6 Ma)
→ Outer solar system: Formation of gas and ice giants
→ Inner solar system: volatile poor planetesimals

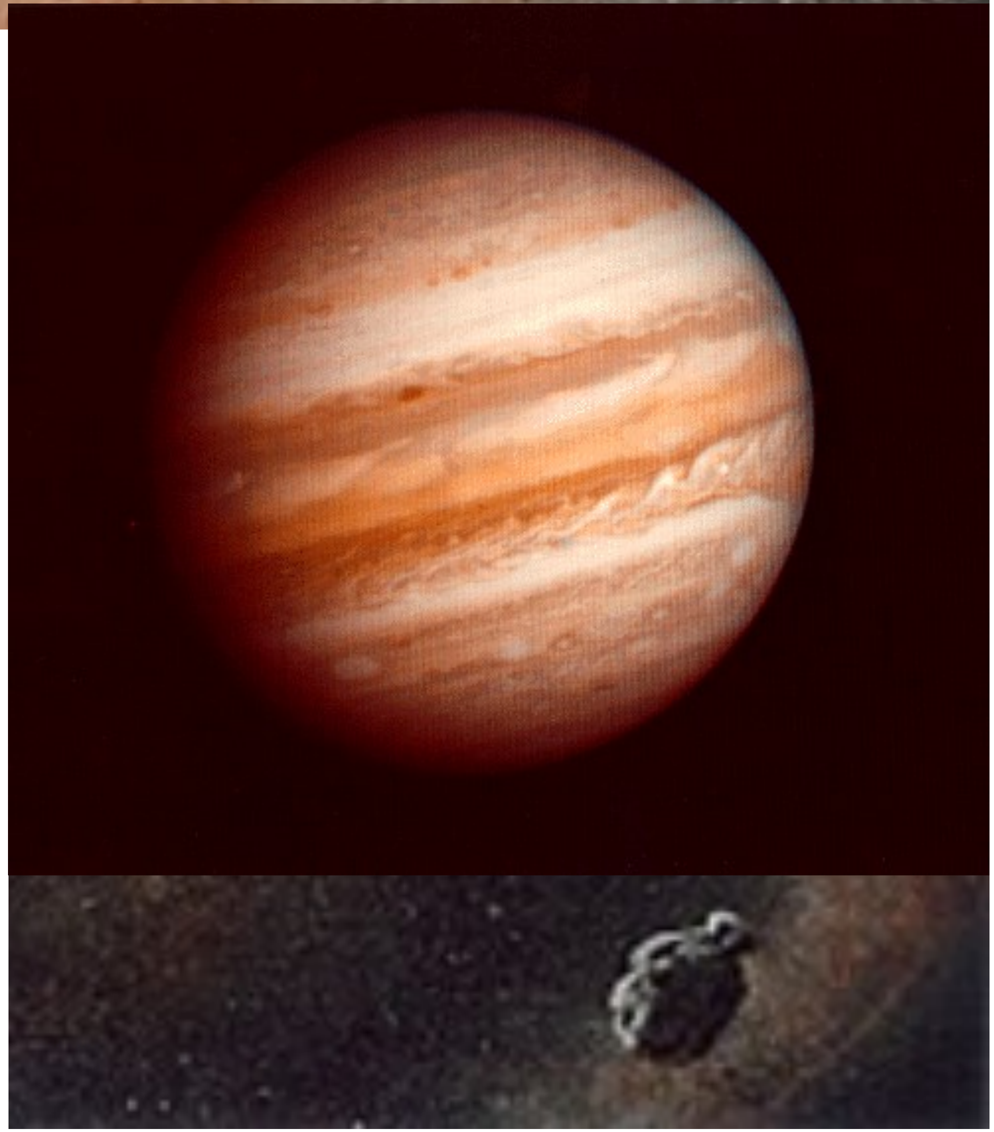
Standard model for Jupiter formation

1) Accretion of a core (10 x Earth mass) of icy rocky planetesimals

2) Subsequent acquisition of solar gas (within 5-6 Ma)

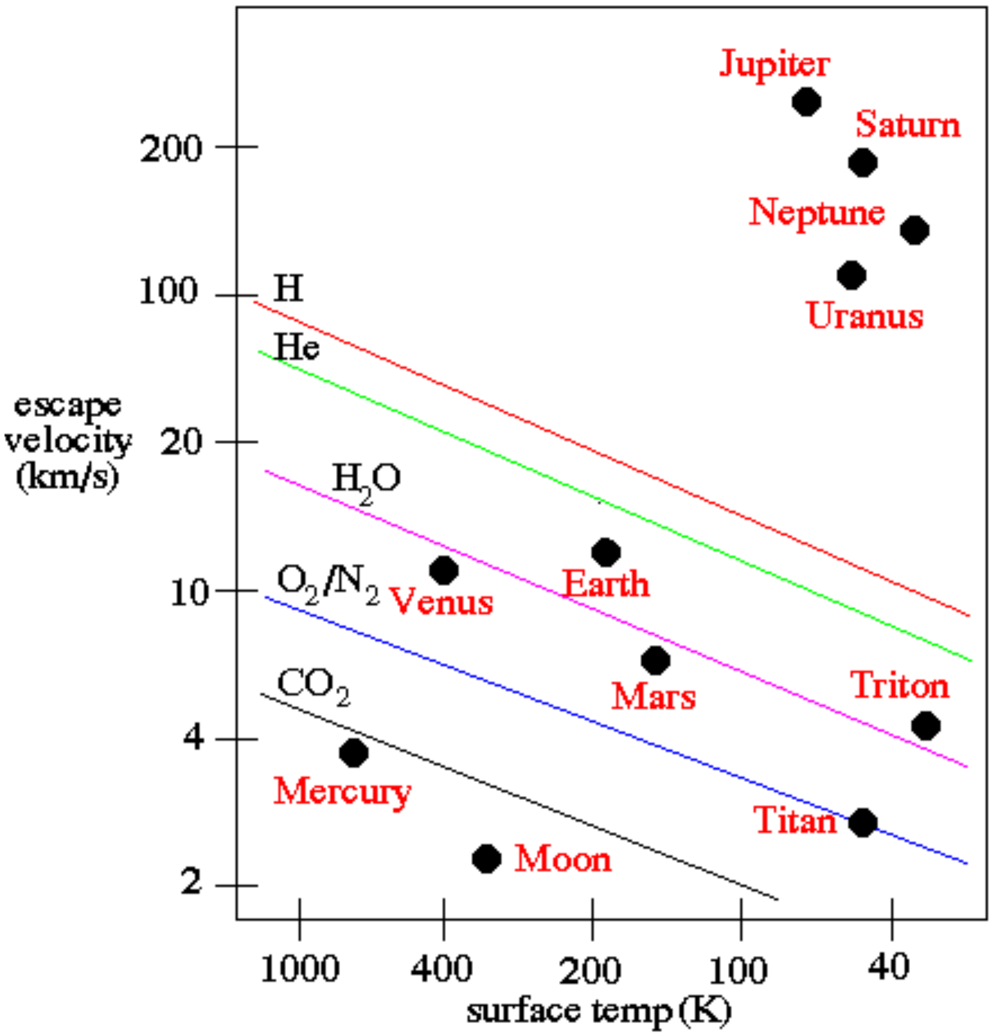
Gas giants: sufficient mass to attract and retain light gases

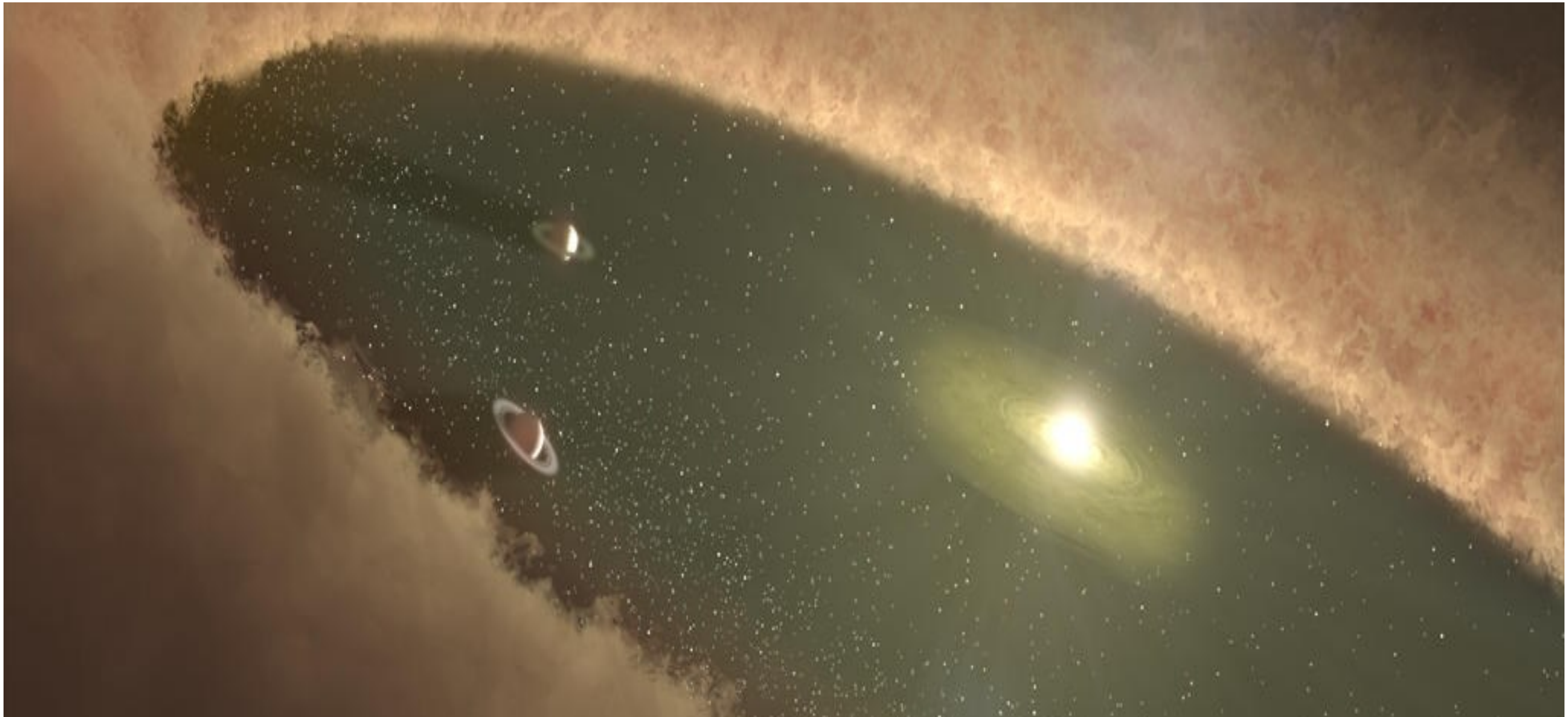




Problems for terrestrial planets:

- Mercury (and Moon) atmosphereless
- Mars, Venus, Earth may keep CO_2, N_2, H_2O… BUT: how were they acquired?
- If gases directly from solar nebula, terrestrial planet formation and capture of gases MUST have occurred before nebular dissipation (within 5-6 Ma)

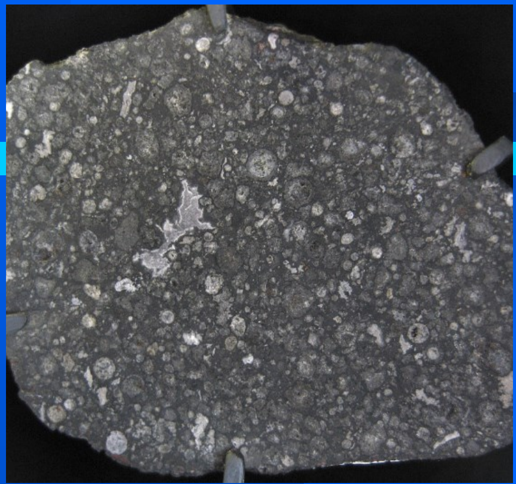


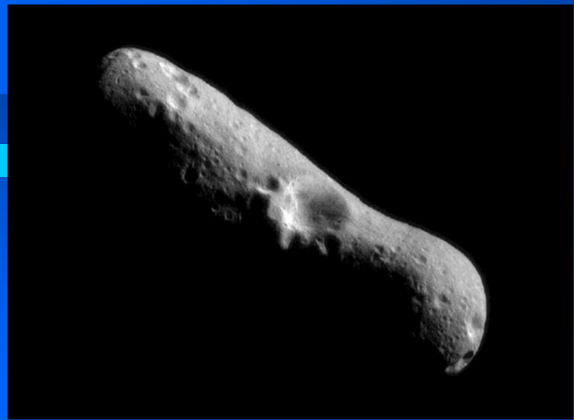


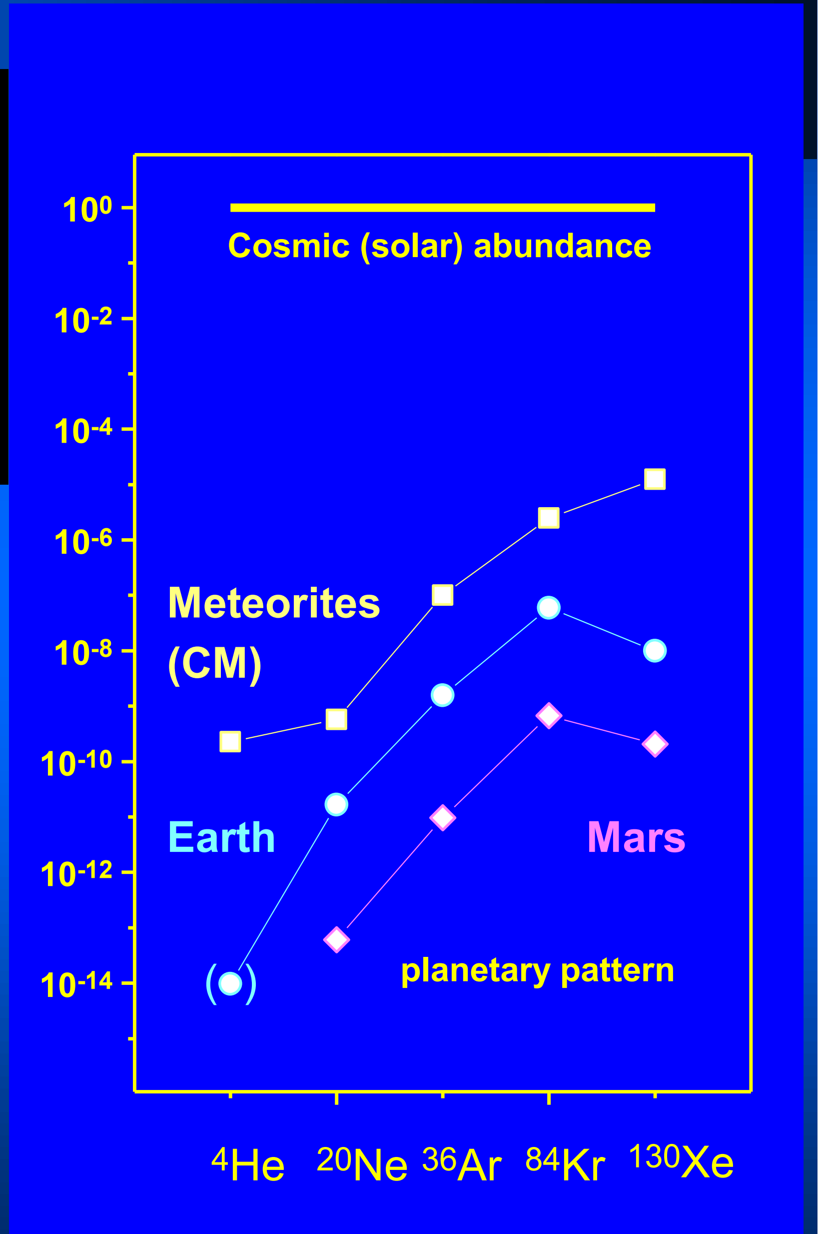
Solar Nebula – after 5-6 Ma

→ Planet formation regions cleared from gas and dust
→ Terrestrial planet growth by collisions of protoplanets
→ Mars full-sized, but Earth and Venus need 50-100 Ma for full growth (n-body simulations, isotopes)
→ Volatiles accreted within planetesimals

Noble gas abundance pattern in terrestrial planet atmospheres: non-solar, but similar to planetary precursors (meteorites from asteroids)







Acquisition of volatile elements in solid material
(ices beyond the snow line)

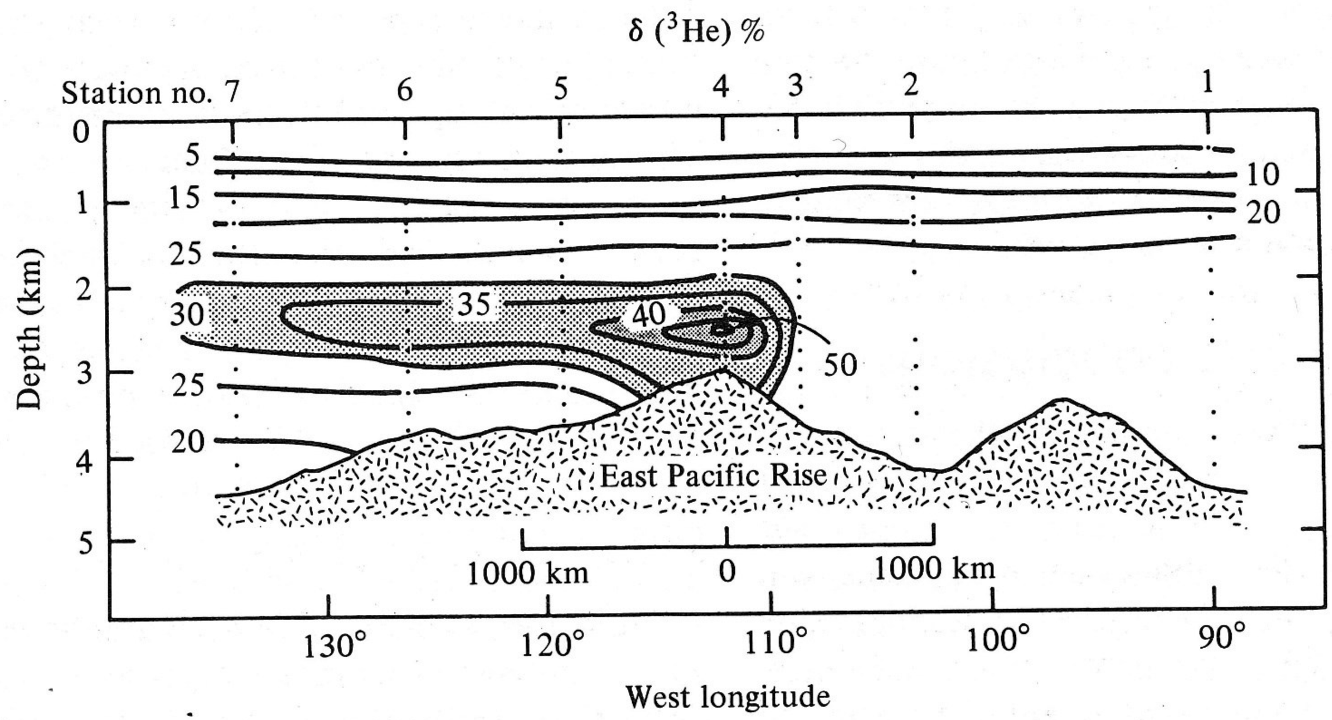
Requires planetary outgassing (and significant losses) → when?

Terrestrial atmosphere by planetary outgassing? Primordial helium is still degassing from the Earth

Parent	Radiogenic	Primordial
U, Th (α decay chains)	^4He	^3He

Ratio	Upper mantle	Atmosphere
^4He / ^3He	90 000±11000	714 800

^3He degassing from the east pacific rise
(Lupton and Craig, 1981)



→ primordial (non-recycled) ^3He in Earth´s mantle, because of He leakage from atmosphere into space

→ degassing of primordial isotopes from Earth´s mantle as ongoing process

When did the atmosphere form by degassing of the solid Earth?

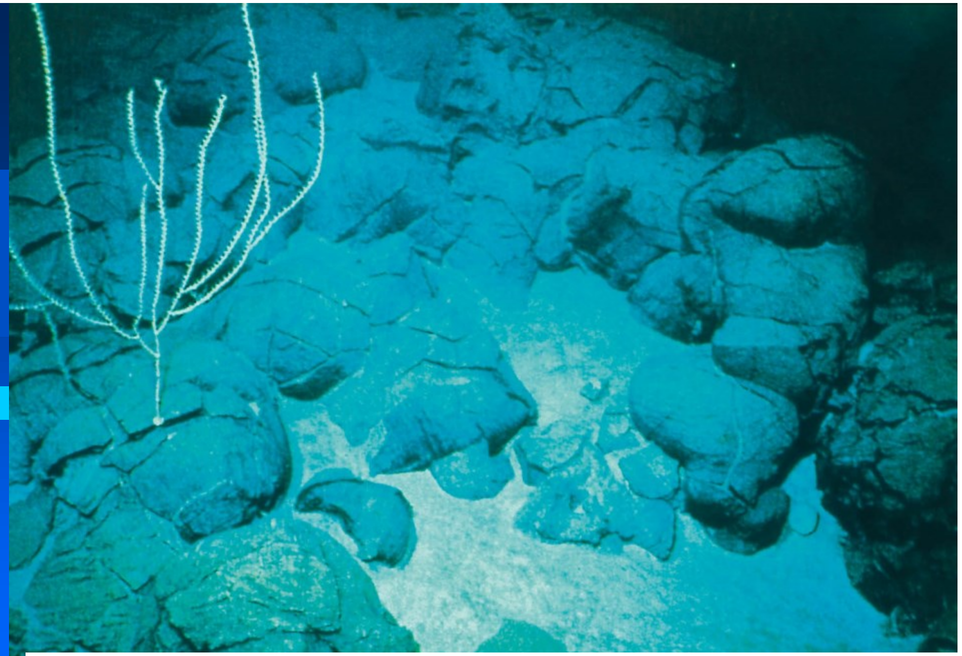
The Earth´s atmosphere contains 1% argon (mostly ^{40}Ar; ^{40}Ar / ^{36}Ar =296)

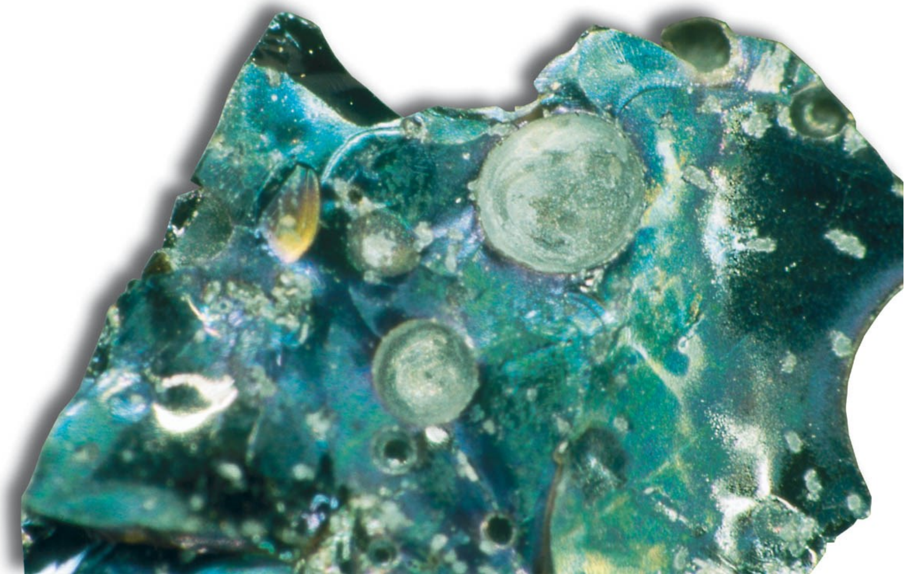
v. Weizsäcker (1937): Atmospheric ^{40}Ar due to ^{40}K decay (half-life 1.25 Ga) and degassing of the solid Earth

→ Terrestrial atmosphere is result of mantle degassing (volcanic activity)

Measured ^{40}Ar / ^{36}Ar ratios at mid ocean ridges (bubbles in glassy rinds of basalt pillows): ^{40}Ar/ ^{36}Ar up to 32 0000

→ Mantle degassing producing the atmosphere occurred mostly in the past (when ^{40}Ar was less abundant)





Noble gas state of the atmosphere and upper /lower mantle

(Moreira et al. 1998; Trieloff et al. 2000, 2003, 2005, 2018)

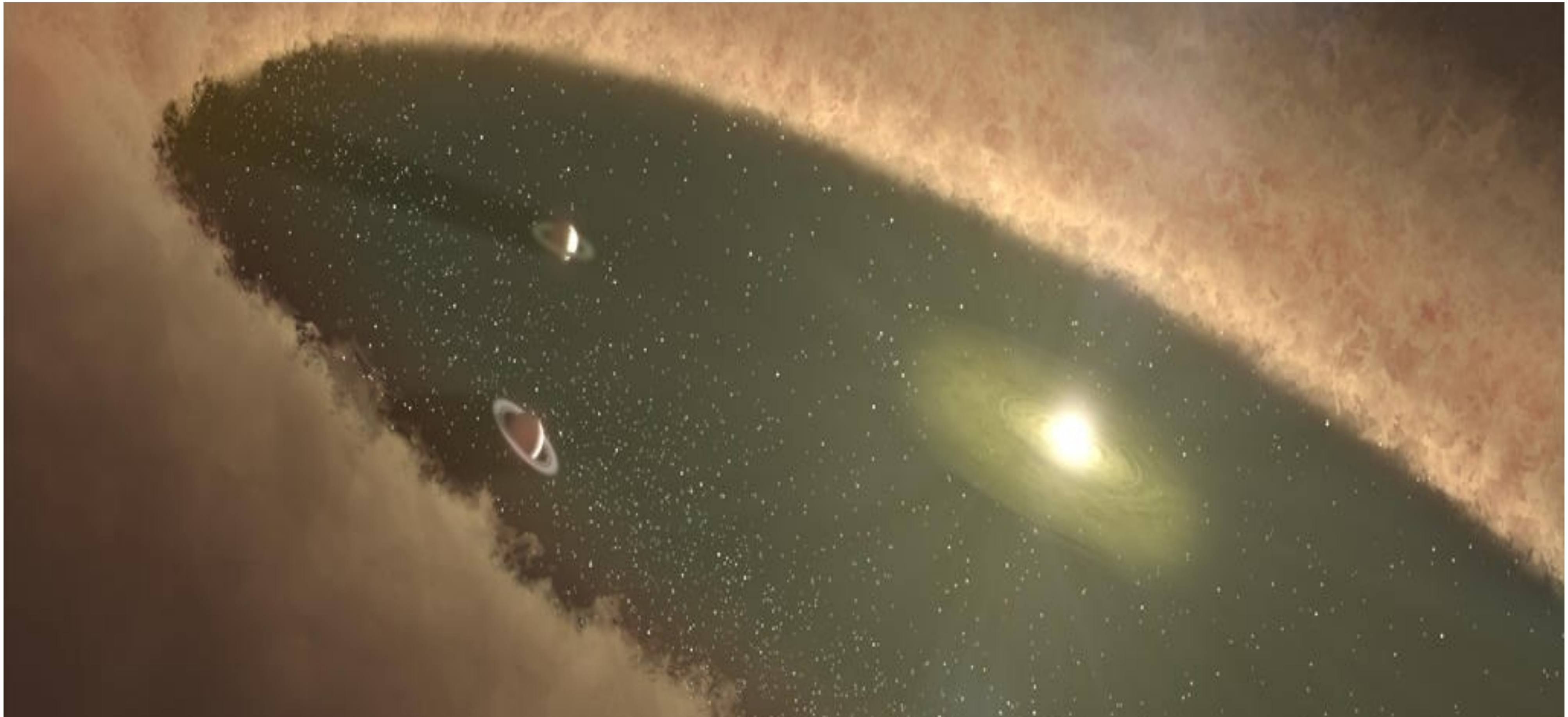
Parent	Radiogenic	Primordial
^{40}K (electron capture)	^{40}Ar	^{36}Ar
^{238}U ^{244}Pu ($\tau_{1/2}$=80 Ma)	^{136}Xe	^{130}Xe
^{129}I ($\tau_{1/2}$=16 Ma)	^{129}Xe	^{130}Xe

Ratio	Upper /lower mantle	Atmosphere
$^{40}Ar/^{36}Ar$	32400±4200 8000±1000	296
$^{136}Xe/^{130}Xe$	2.62±0.10 2.26±0.02	2.176
$^{129}Xe/^{130}Xe$	7.79±0.25 6.75±0.06	6.496

Excess of radiogenic ^{40}Ar and ^{129}Xe in Earth´s mantle:

Evidence for early mantle degassing, within ~100 Ma after accretion!

(primordial nuclides early degassing, subsequent accumulation of radiogenic nuclides)



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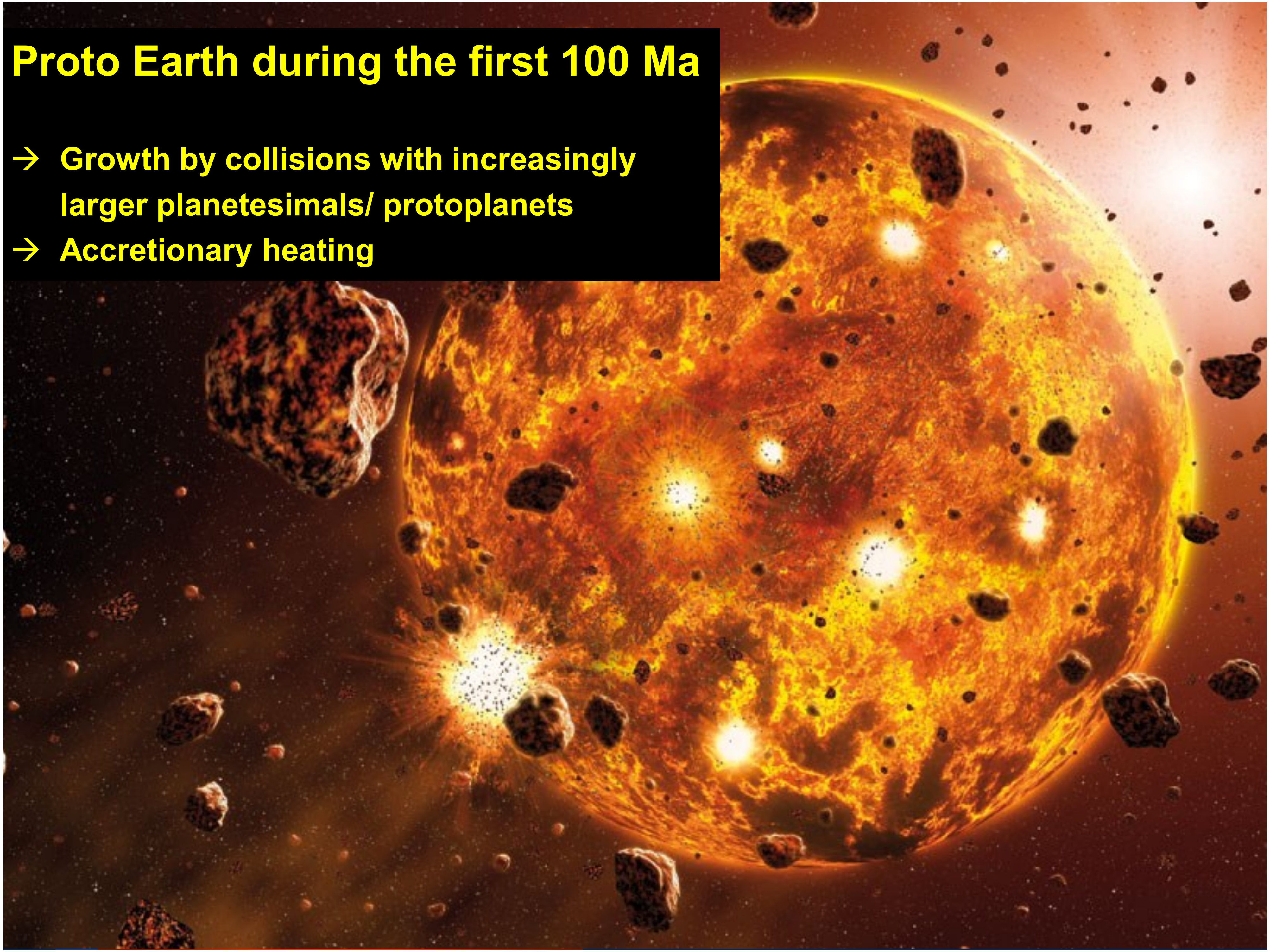
Proto Earth during the first 100 Ma

→ Growth by collisions with increasingly larger planetesimals/ protoplanets
→ Accretionary heating



Proto Earth during the first 100 Ma

- → Growth by collisions with increasingly larger planetesimals/ protoplanets
- → Accretionary heating
- → Planetary type volatiles: Larger bodies from beyond the snow line (few %) deliver water, carbon, nitrogen, noble gases (carbonaceous chondrites)

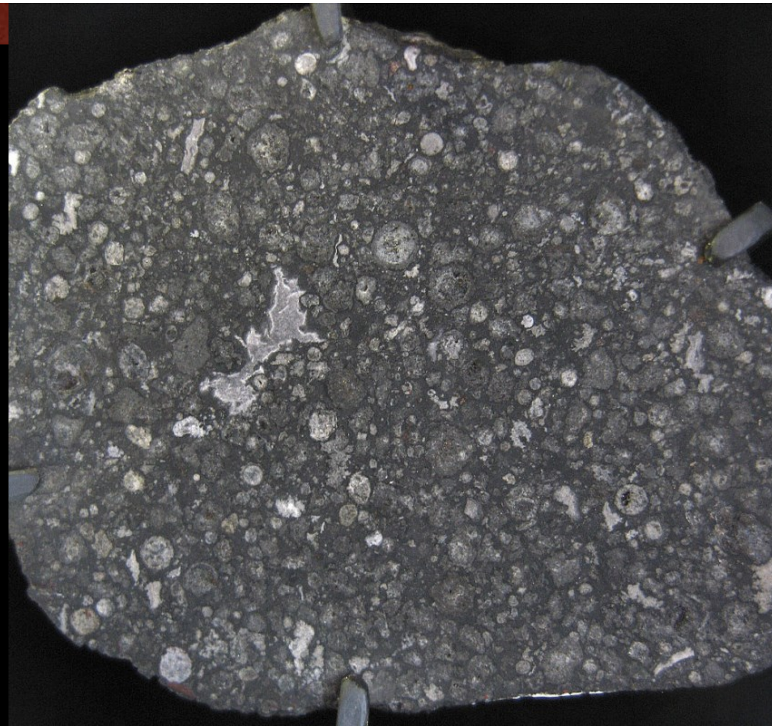


Table 3. Average chemical composition of
not otherwise indicated (light grey backgrou

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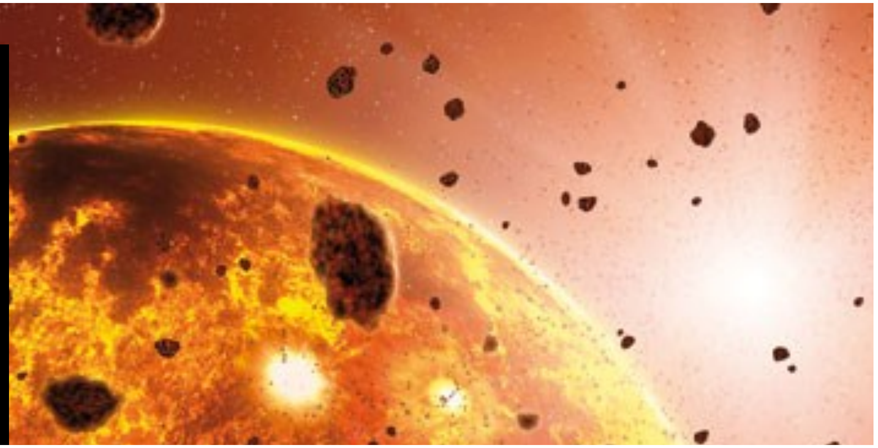
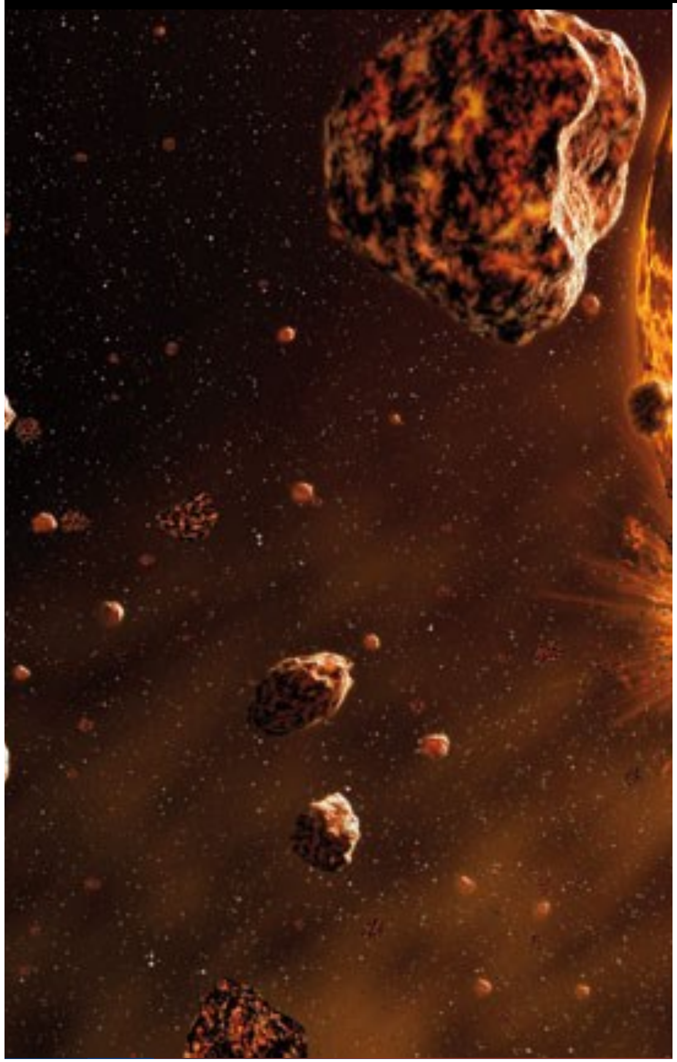
Be	0.025	0.040	0.050	
B	0.87	0.48	0.30	
C [wt%]	3.45	2.20	0.53	0.44
N	3180	1520	80	90
O [wt%]	46.4	43.2	37.0	37.0
F	60	38	24	30
Na	5000	3900	3400	4200
Mg [wt%]	9.70	11.50	14.30	14.50
Al [wt%]	0.865	1.13	1.68	1.40
Si [wt%]	10.64	12.7	15.7	15.8
P	950	1030	1120	1210
S [wt%]	5.41	2.7	2.2	2.2

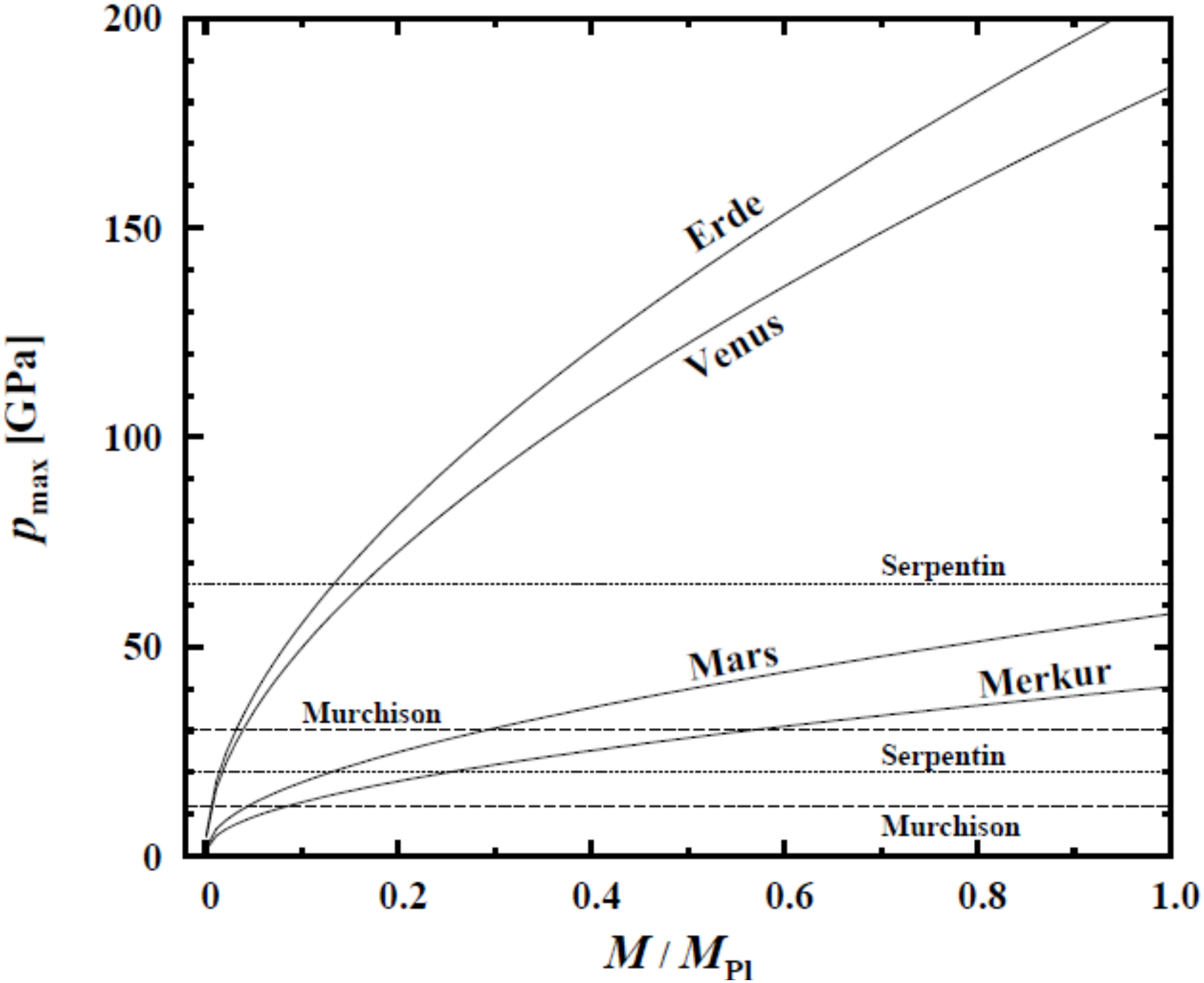
Proto Earth during the first 100 Ma

→ Impact degassing leads to steam atmosphere and greenhouse

→ Formation of magma ocean







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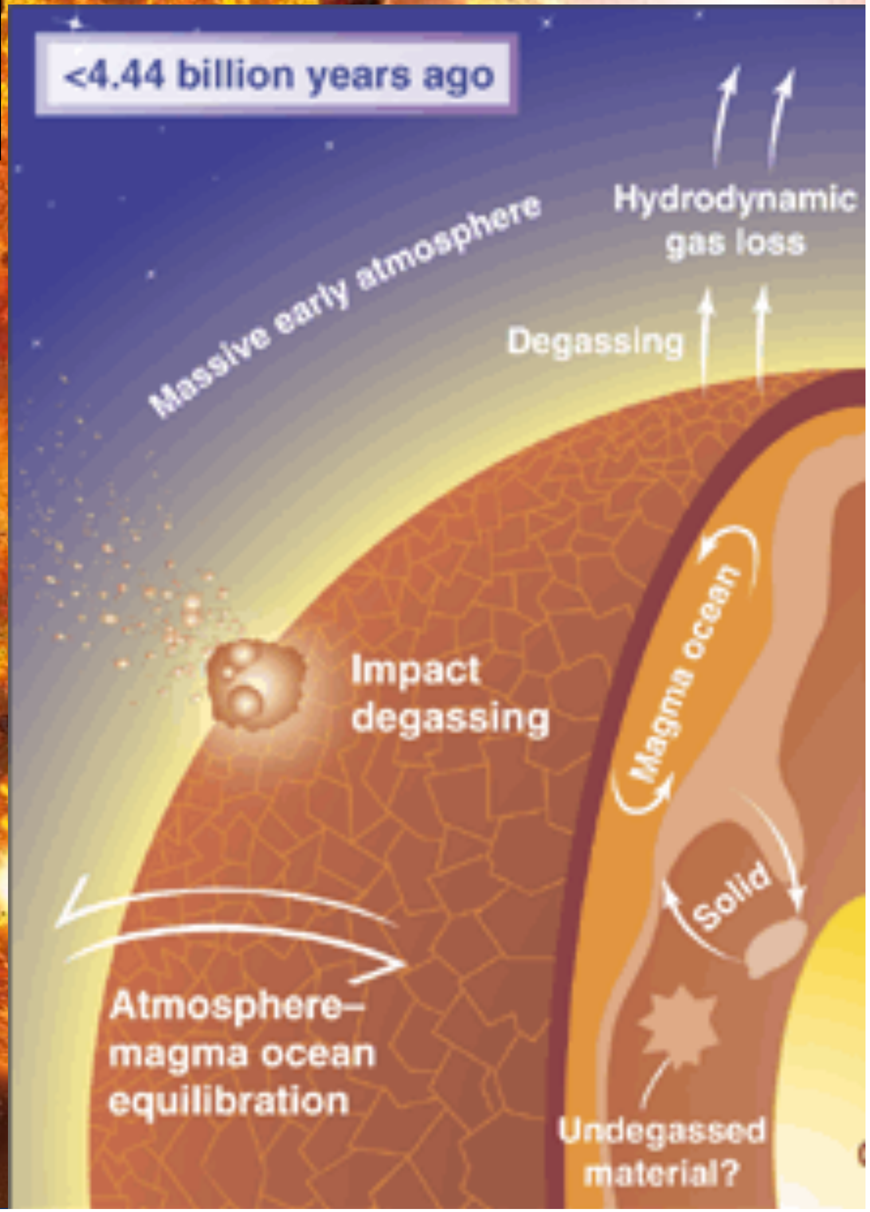

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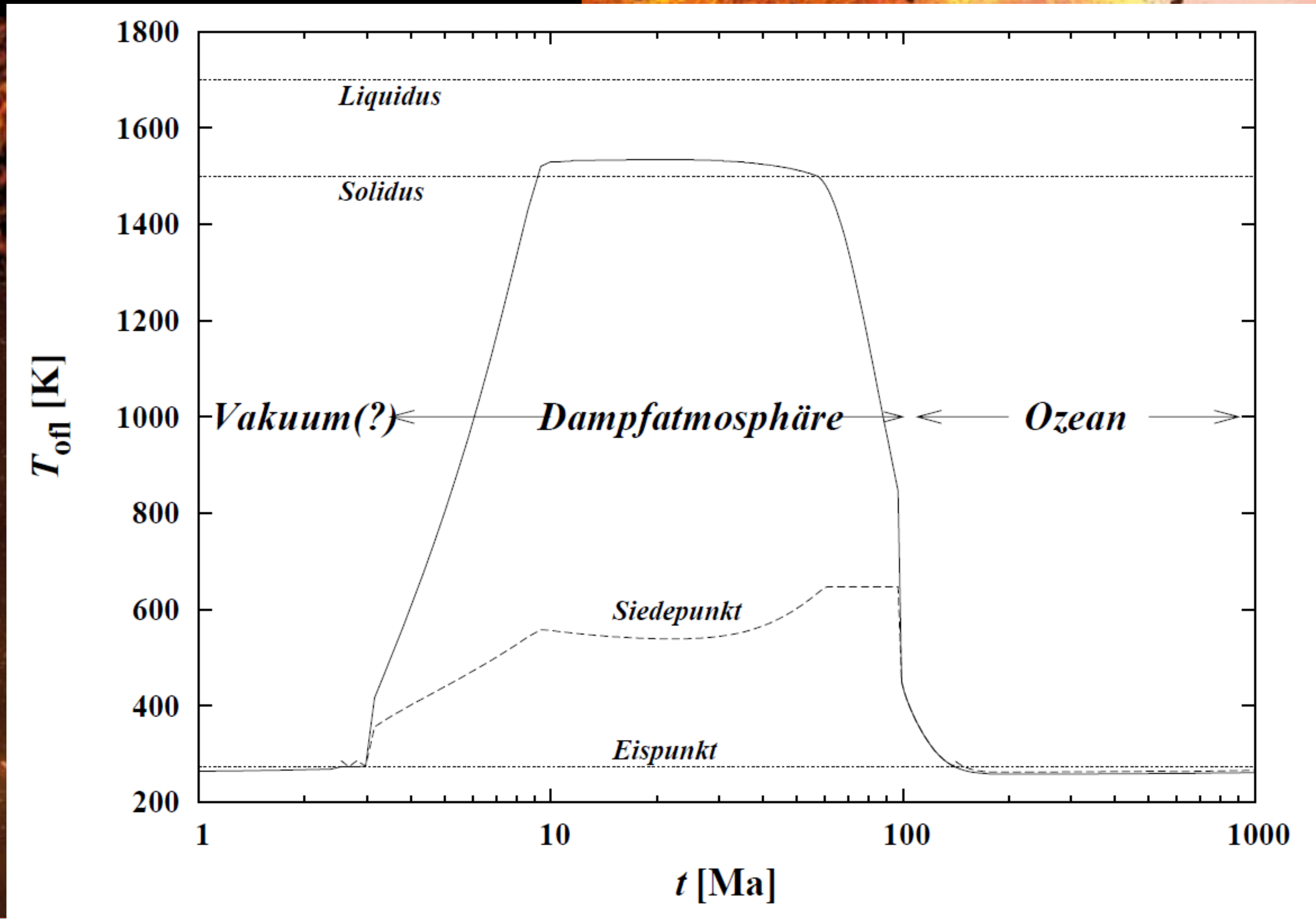


Terminal growth of the proto Earth – Collision with Theia (Benz et al. 1989)

Quelle: BBC

Earth after formation of the moon (100 Ma after CAIs)

→ Significant fraction of primary protoatmosphere lost by Theia Impact
→ Proto Earth cools and solidifies
→ Volatiles previously dissolved in magma ocean (C,H,O,N, noble gases) degas and form a secondary atmosphere
→ Formation of water oceans, CO_2, N_2 dominated atmosphere

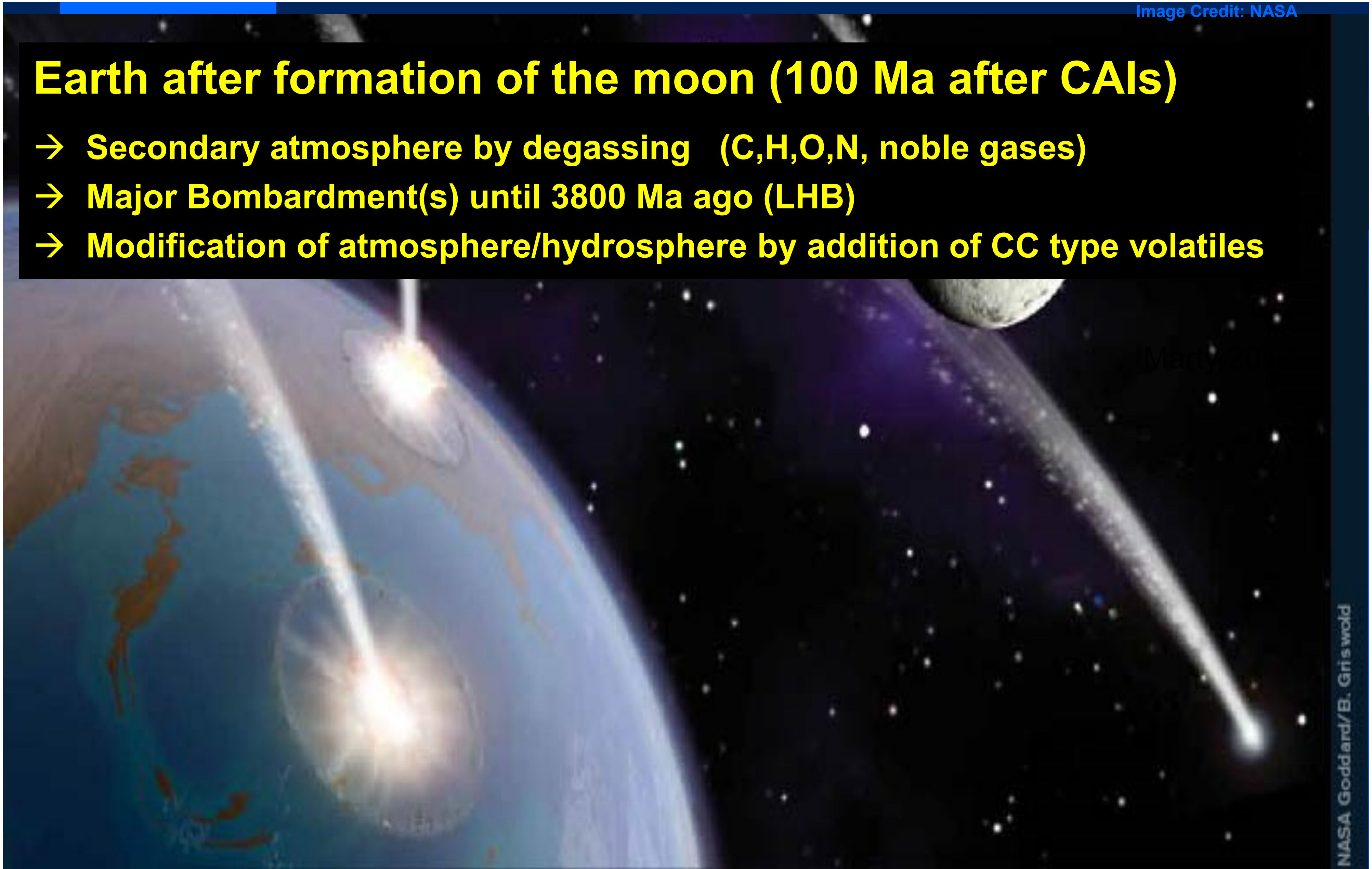
Image Credit: NASA

Earth after formation of the moon (100 Ma after CAIs)

→ Secondary atmosphere by degassing   (C,H,O,N, noble gases)

→ Major Bombardment(s) until 3800 Ma ago (LHB)

→ Modification of atmosphere/hydrosphere by addition of CC type volatiles



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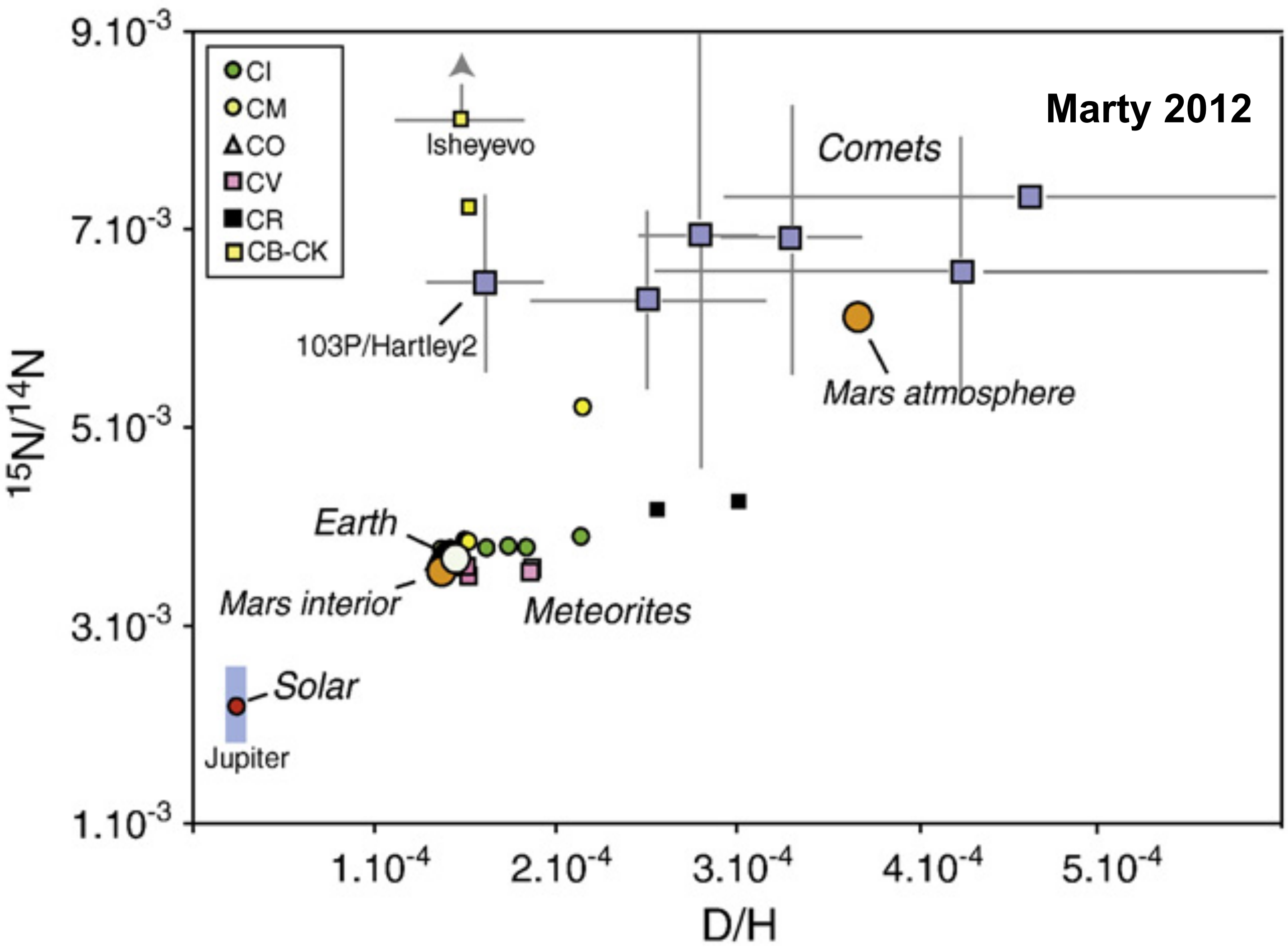


Earth after formation of the moon

→ Episodic evaporation of oceans

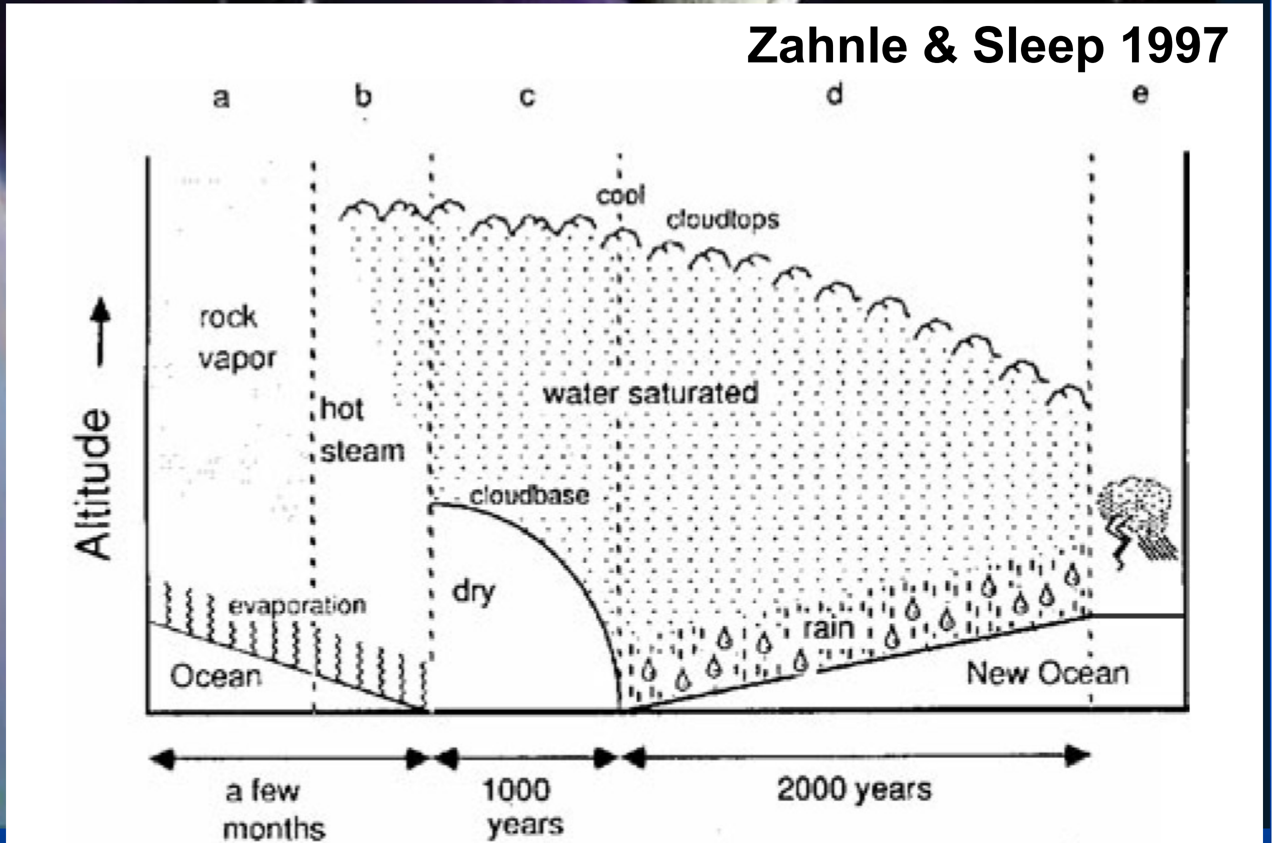
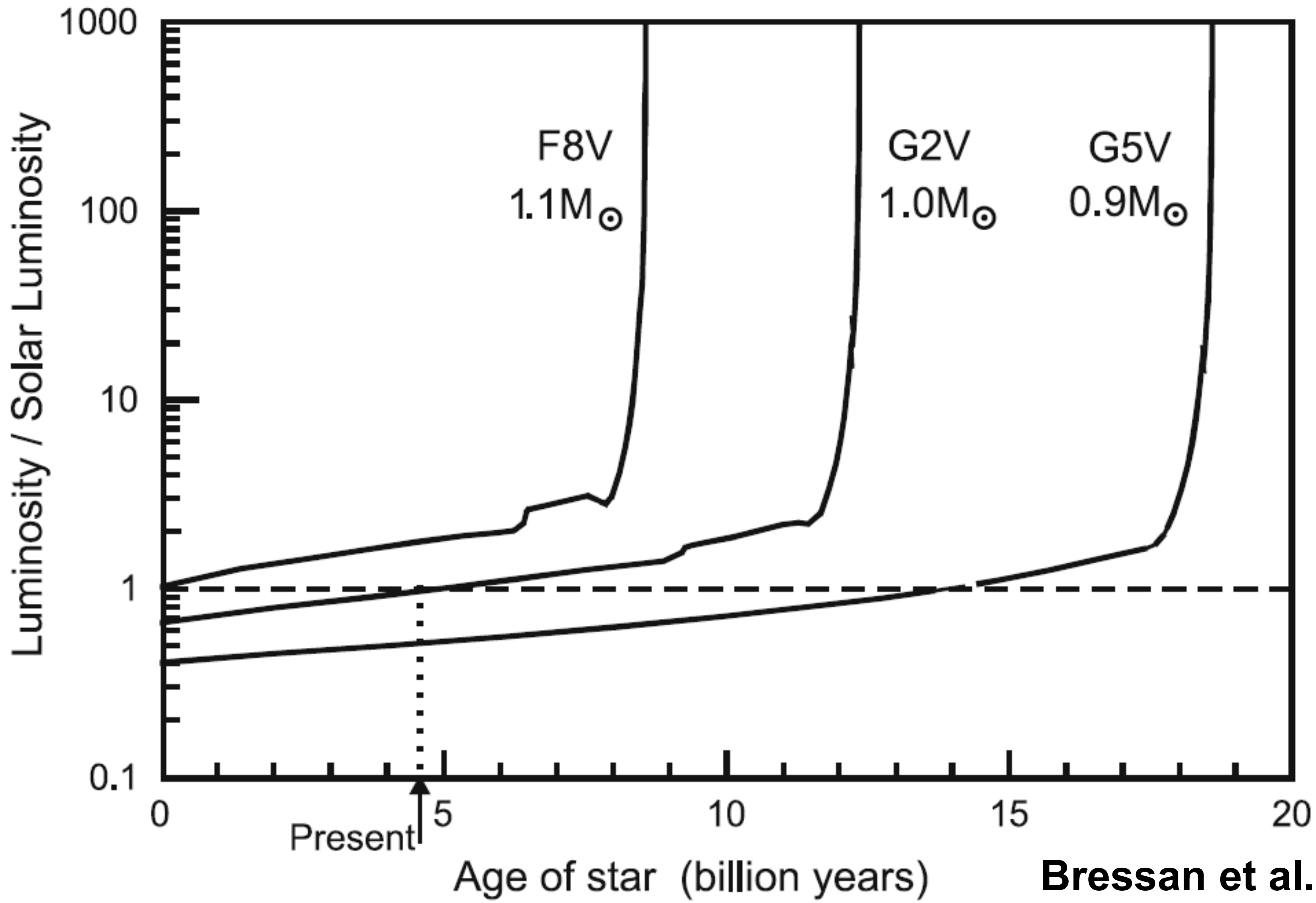


Image Credit: NASA

Earth after formation of the moon

→ Large CO_2 content, but no runaway greenhouse, Earth retained water

→ Compensation of faint (-30%) young sun

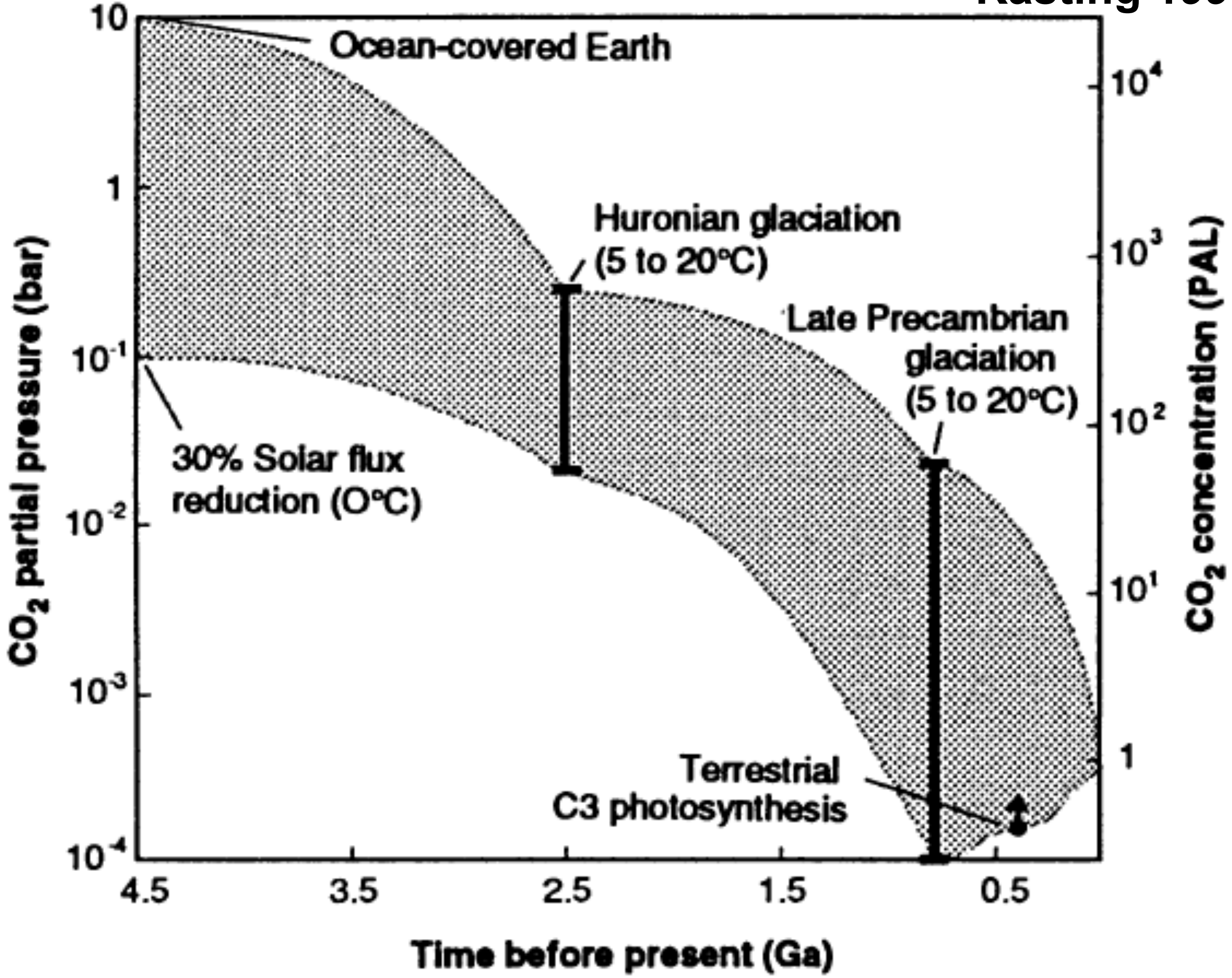


Bressan et al. 1993

Earth after formation of the moon

- → Large CO_2 content, but no runaway greenhouse
- → Compensation of faint (-30%) young sun
- → How was CO_2 removed from the atmosphere?

Kasting 1993

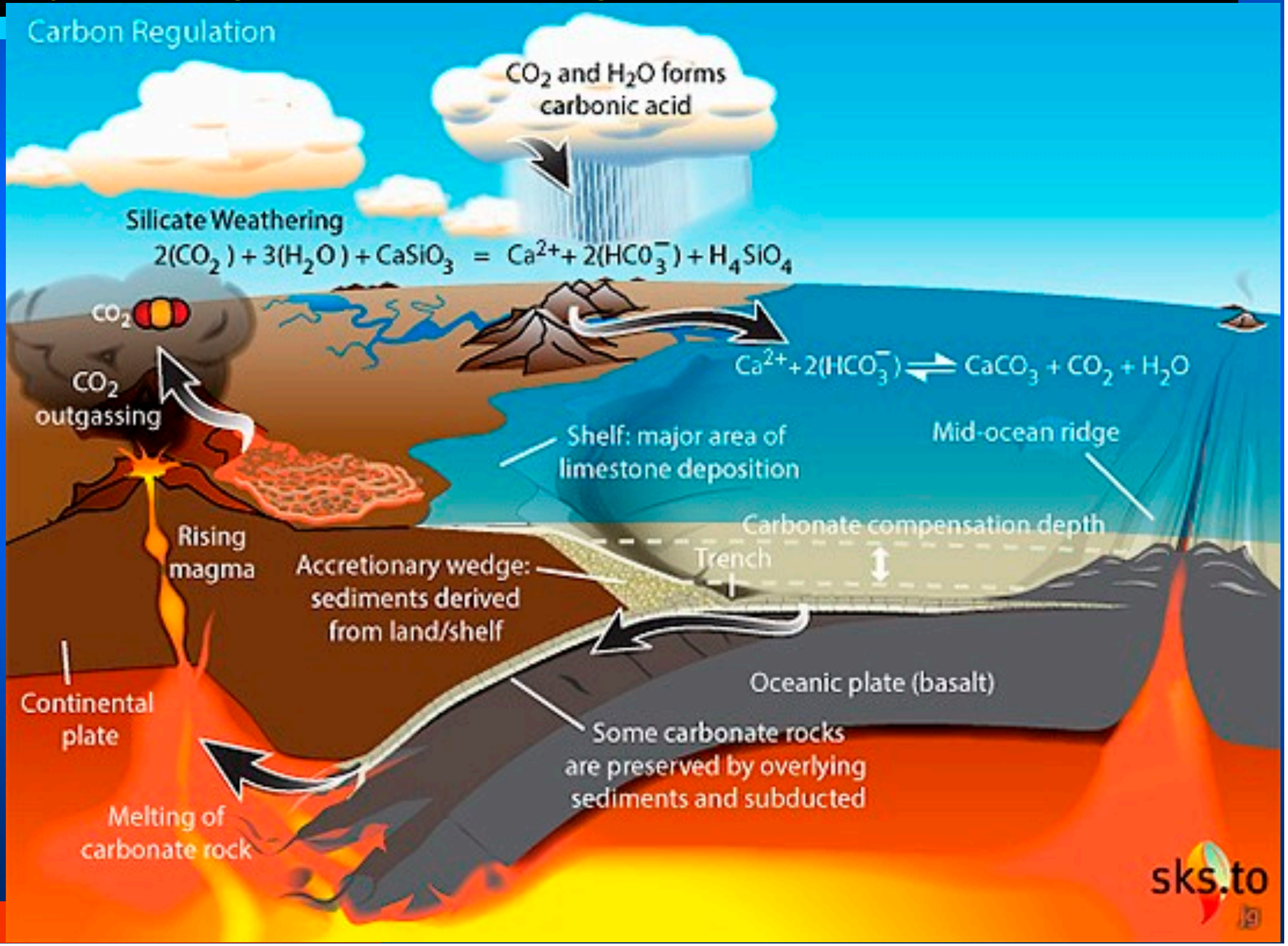


Earth after formation of the moon

→ Large CO_2 content, but no runaway greenhouse

→ Compensation of faint (-30%) young sun

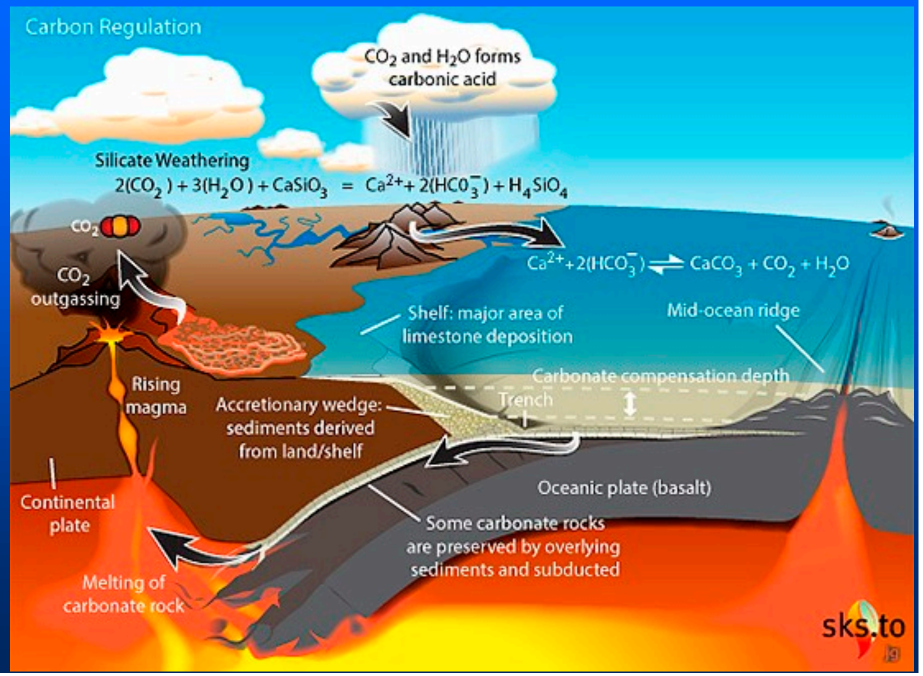
→ CO_2 content “adjusted” by carbon-silicate cycle → climate stabilisation



Earth after formation of the moon

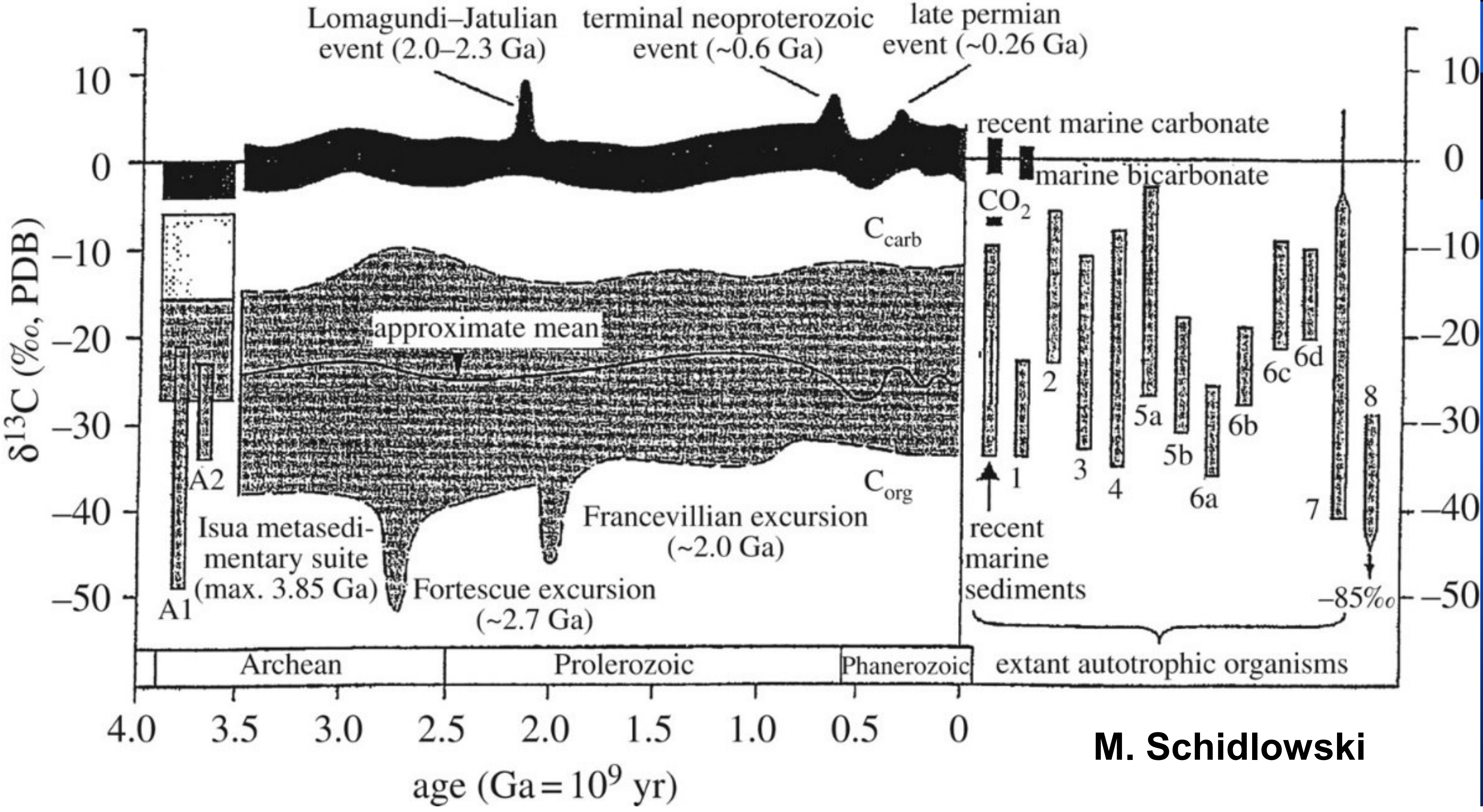
→ Large CO_2 content, but no runaway greenhouse
→ Compensation of faint (-30%) young sun
→ CO_2 content "adjusted" by carbon-silicate cycle → climate stabilisation

→ Requires BOTH oceans AND exposed crustal surface
(Confirmed by Hadean up to 4.4 Ga old zircons, O and Hf isotopes, presence of small continents by mantle plumes likely)
→ Even highest 10 bar CO_2 content estimate requires 90 % bound in carbonates



Earth after Hadean and "Late Heavy Bombardment"

→ Persistent oceans, stable continental crust (oldest rocks c. 3.8-4.1 Ga)
→ Biogenic fixation of carbon (Isua 3.8 Ga)



M. Schidlowski

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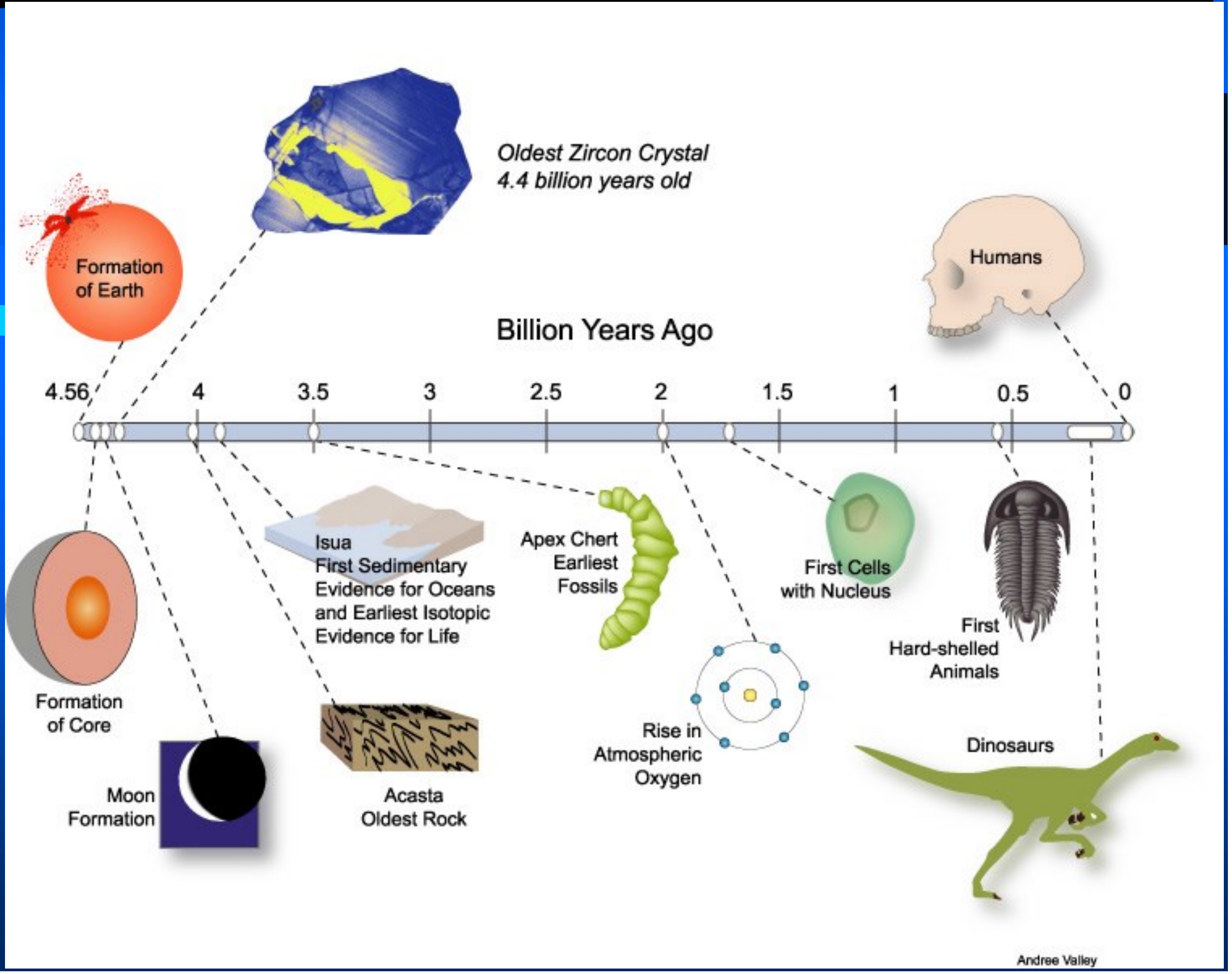
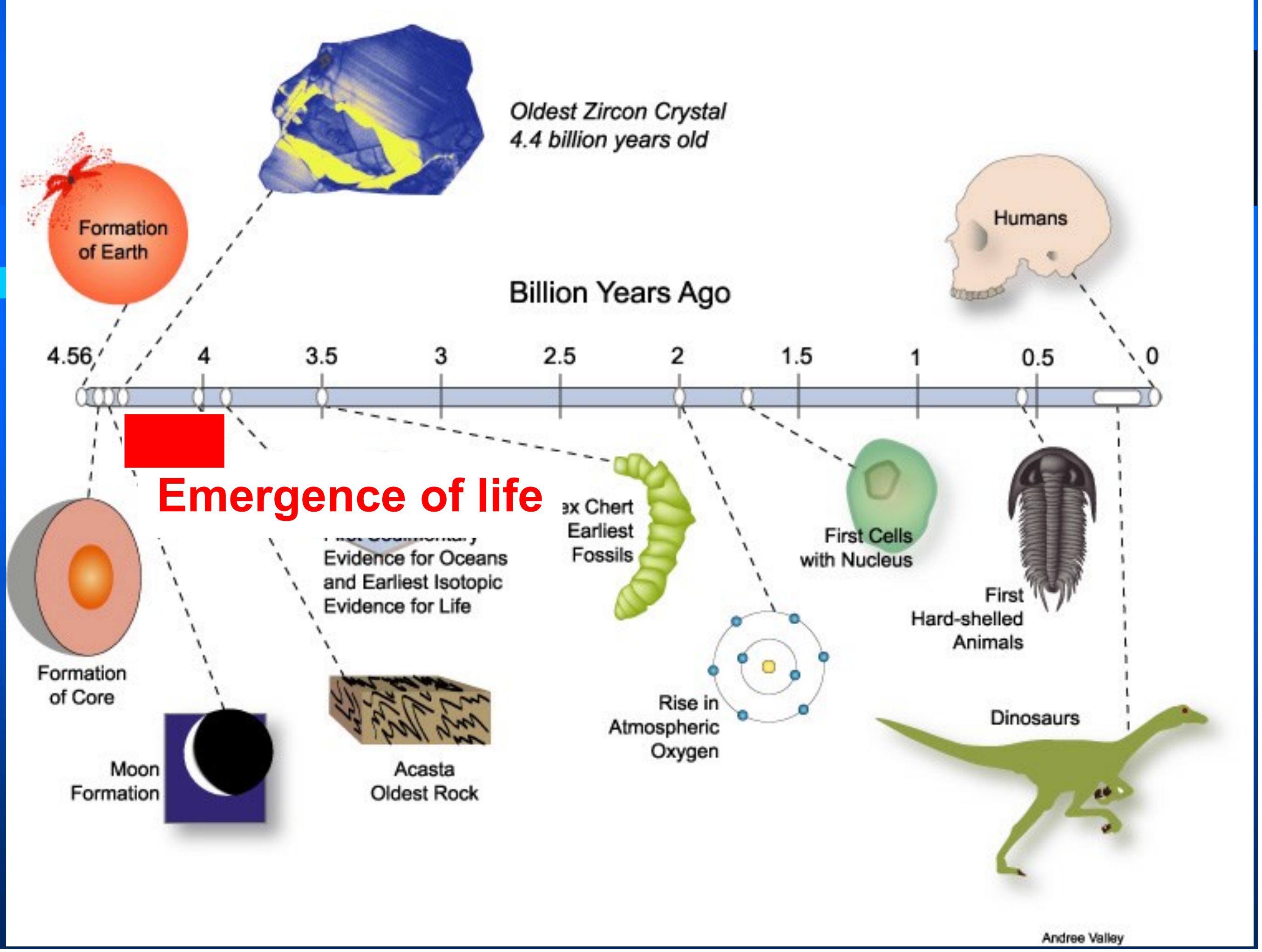


Earth between 4.4 - 3.8 Ga ago → Hadean zircons

- → Oceans, continental crust, subduction (partially or temporarily) present
- → Abiotic carbonate silicate cycle likely present
- → Biogenic fixation of carbon possibly present
- → Emergence and “impact frustration” of life?



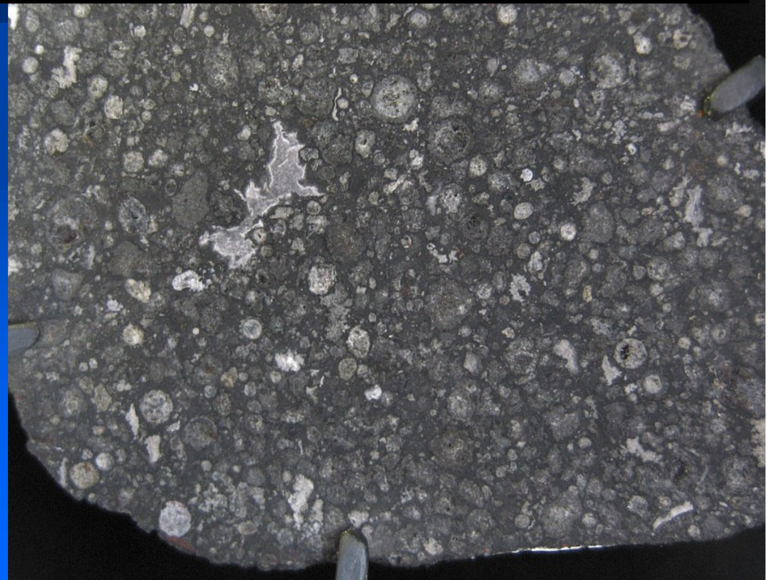
Earth between 4.4 - 3.8 Ga ago

Carbonaceous chondrites

- → Likely brought carbon (and other volatiles) to Earth (within first 100 – 800 million years)
- → During episodic bombardments: 5 x 10^9 kg/year

- → Porous and water rich, and their parent bodies had extended (100 km sized) low temperature hydrothermal systems during the first tens of million years
- → Hydrothermal systems produced phyllosilicates and clay minerals (e.g., serpentine, but also montmorillonite, observed to speed up vesicle formation by micelles, RNA formation from nucleotides in aqueous solution)
- → contain FeS (troilite) („Iron-sulfur world"), paramagnetic FeS_2, Fe_3S_4 (greigite), nonstoichiometric $FeS_{1-x}S$ pyrrhotite polytypes, mixed Fe-Ni sulfides, e.g. pentlandite $(Fe,Ni)_9S_8$
- → contain 0.1% P

Prerequisites for prebiotic chemistry



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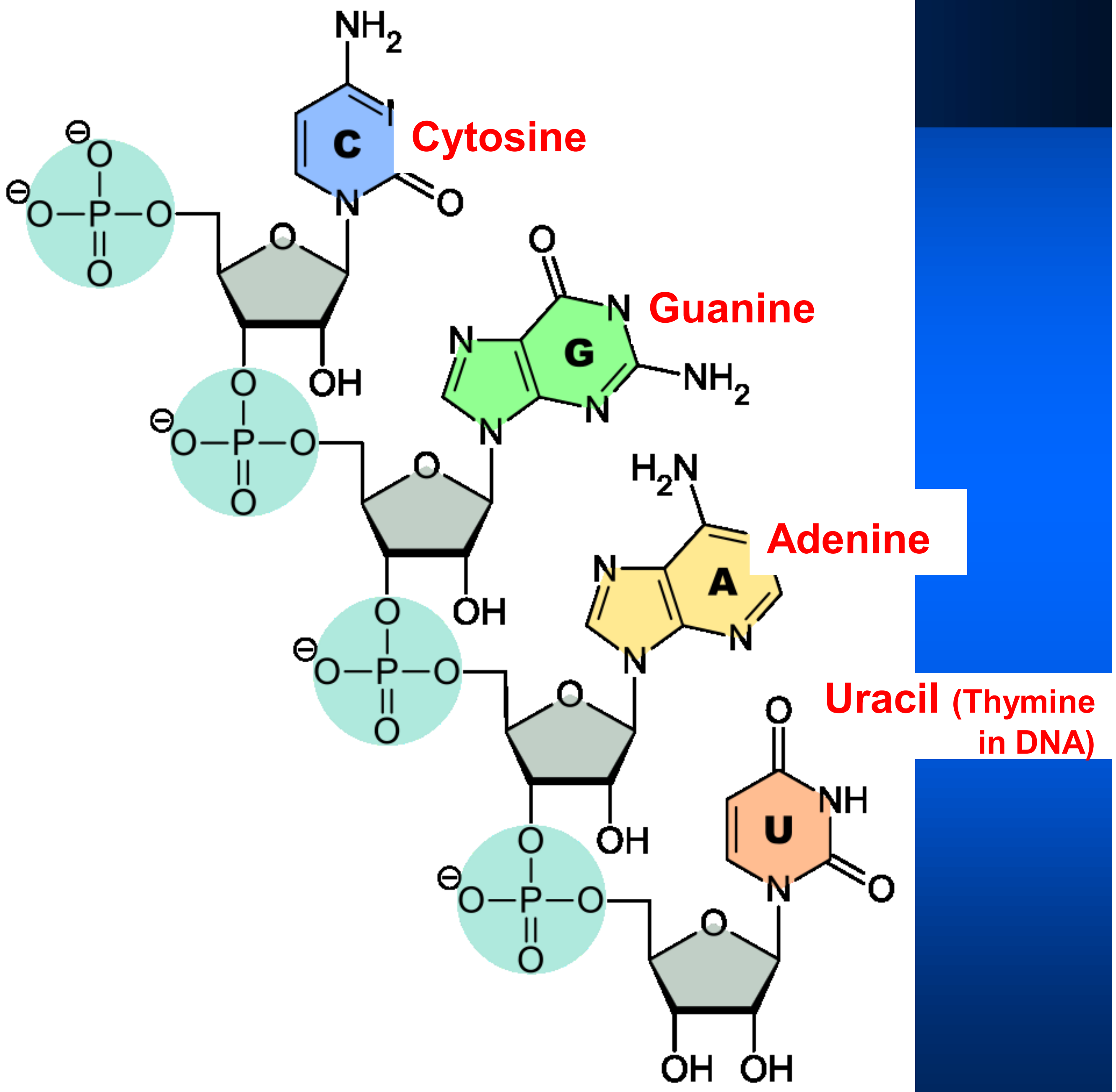
Earth between 4.4 - 3.8 Ga ago

The RNA world

The genetic code:
4 nucleobases
20 amino acids



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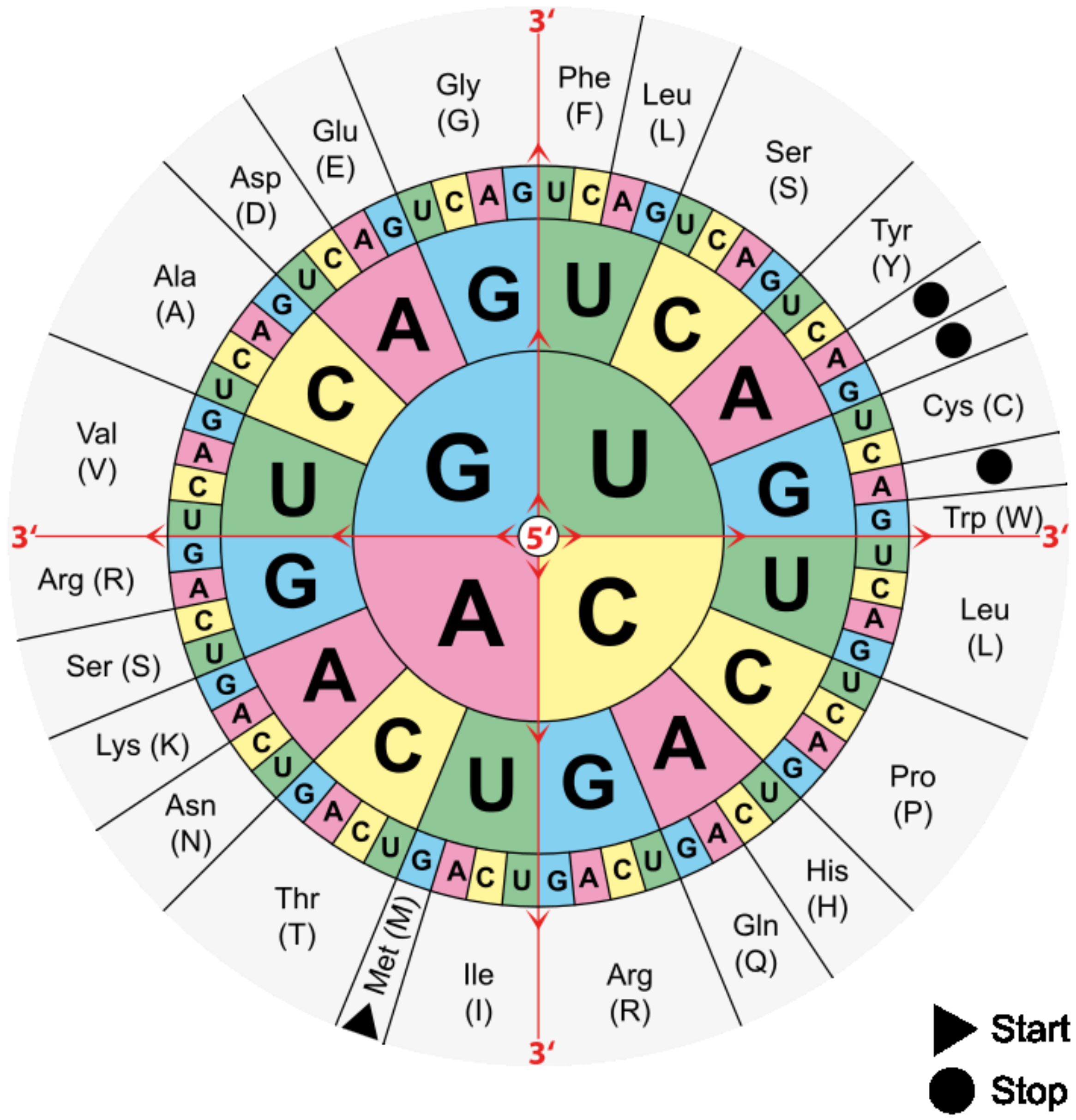
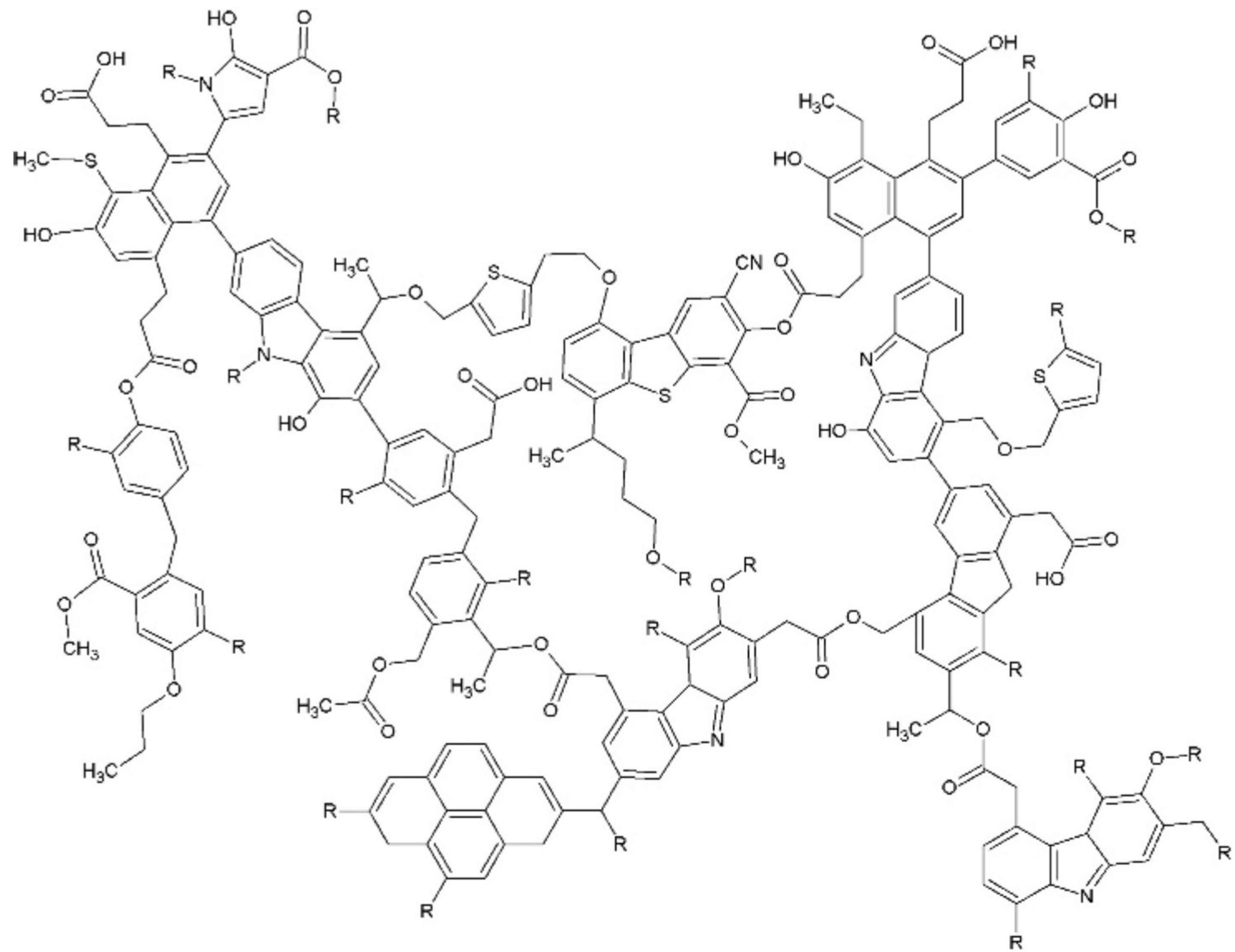


Carbon in carbonaceous chondrites

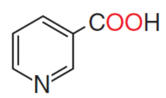
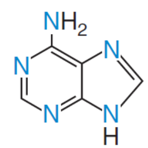
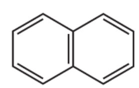
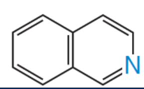
mostly insoluble, highly molecular organic matter (H/C < 1, <15% O, <3% N)



Carbon in carbonaceous chondrites

Significant fraction (30%) of soluble organic species
→ rich in H, O, N

Table 1. Classes of organic compounds in the Murchison meteorite.

Compound Class	Structure	Example Molecule
Carboxylic acids	$H_3C{-}COOH$	Acetic acid
Amino acids	$H_3C{-}CH(NH_2){-}COOH$	Alanine
Hydroxy acids	$H_3C{-}CH(OH){-}COOH$	Lactic acid
Ketoacids	$H_3C{-}C(=O){-}H$	Pyruvic acid
Dicarboxylic acids	$HOOC{-}CH_2{-}COOH$	Succinic acid
Sugar alcohols & acids	$H_2C(OH){-}CH(OH){-}CHO$	Glyceric acid
Aldehydes & Ketones	$H_3C{-}C(=O){-}H$	Acetaldehyde
Amines & Amides	$H_3C{\cdot}CH_2NH_2$	Ethyl amine
Pyridine carb. acids		Nicotinic acid
Purines & Pyrimidines		Adenine
Hydrocarbons: Alyphatic	$H_3C{-}CH_2{-}CH_3$	Propane
Aromatic		Naphthalene
Polar		Isoquinoline

Carbon in carbonaceous chondrites

- → 86 amino acids in Murchison meteorite
- → extraterrestrial isotopic composition
- → up to 2200 ppm amino acids in CR2 chondrites

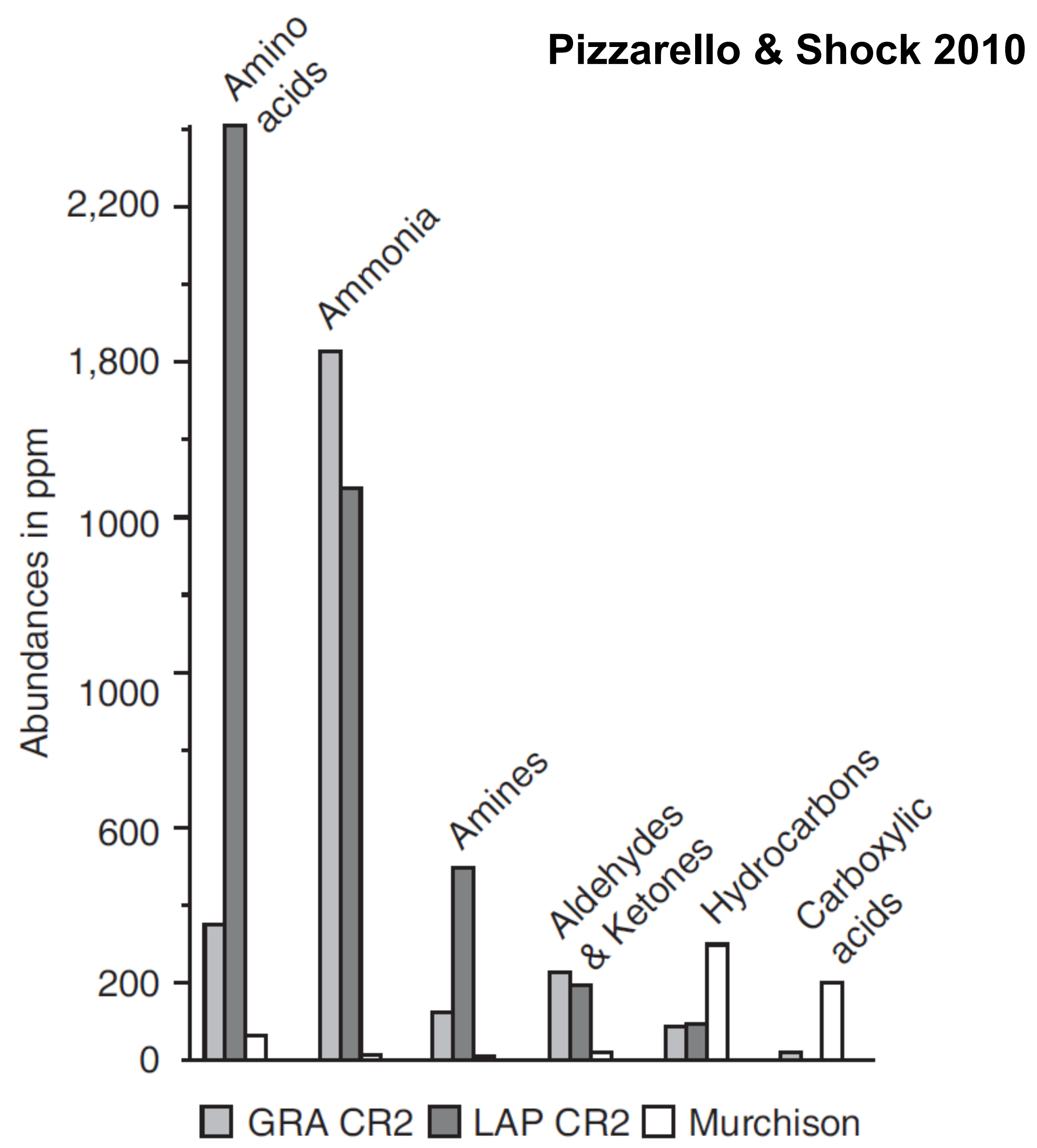
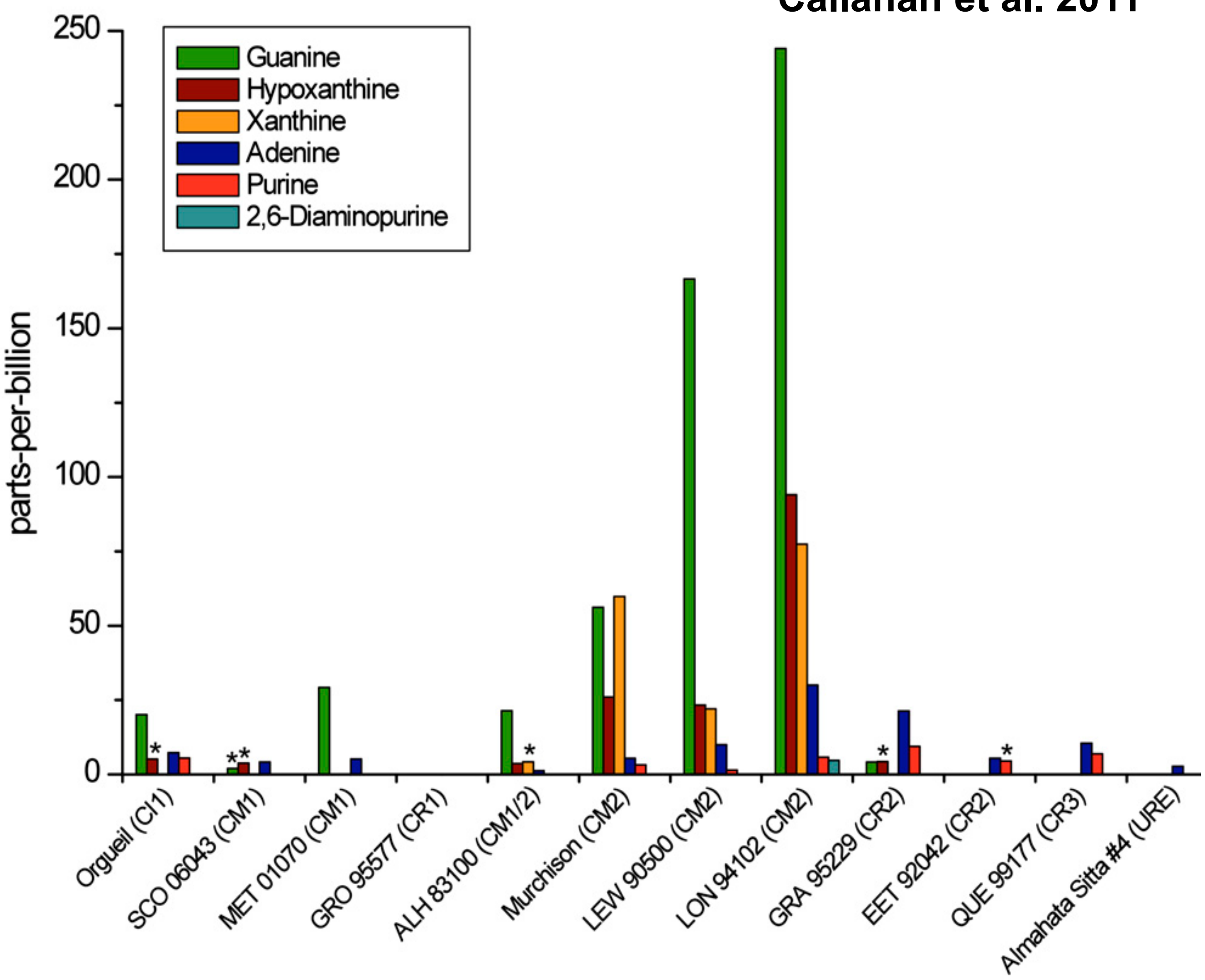


Figure 4. Comparative plot of major soluble organic compound abundances in the Murchison and CR2 meteorites (GRA 95229 and LAP 02342 shown).

Carbon in carbonaceous chondrites

Various nucleobases in various proportions
→ adenine, guanine, uracil present
→ no thymine, cytosine
→ unusual on Earth: purine, 2,6-diaminopurine

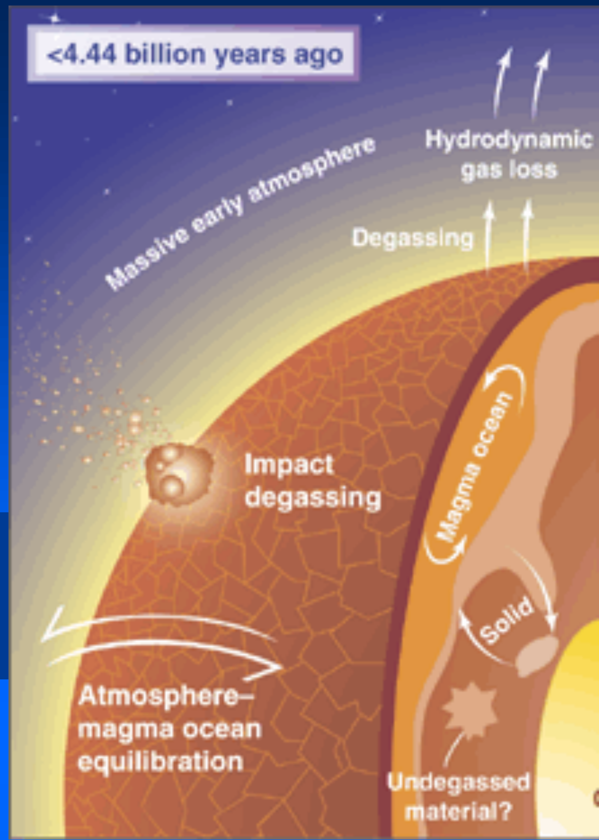
Extraterrestrial isotopic composition (Martins et al. 2008)



Callahan et al. 2011

Summary

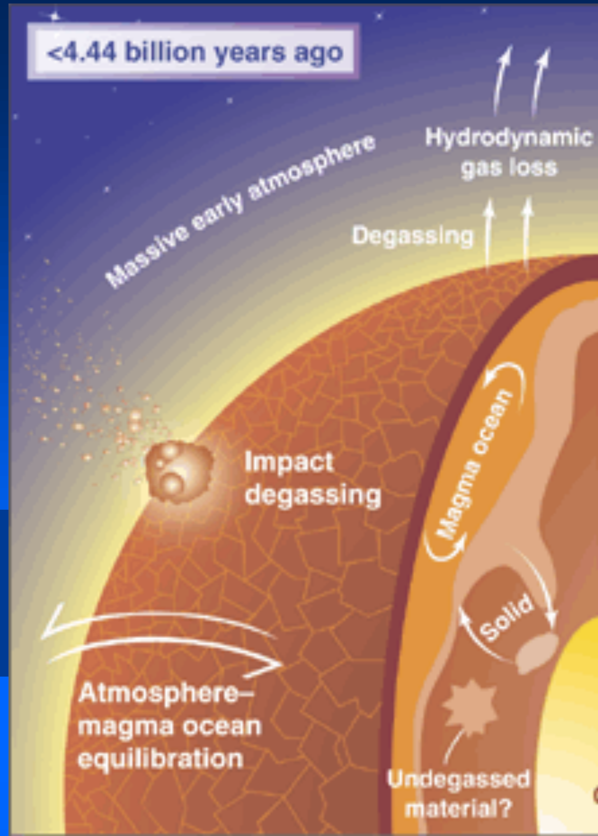
- → First 100 Ma: Accretion and impact heating, core formation, Equilibrium between magma ocean and massive protoatmosphere
- → Ca. 100 (±30) Ma after CAIs: Moon-forming Theia impact, dissipation of protoatmosphere



Summary

- → First 100 Ma: Accretion and impact heating, core formation, Equilibrium between magma ocean and massive protoatmosphere
- → Ca. 100 (±30) Ma after CAIs: Moon-forming Theia impact, dissipation of protoatmosphere
- → Cooling, solidification of crust and mantle, mantle degassing, formations of water oceans and CO_2 rich atmosphere

Concentration of atmophile/life promoting elements close to early Earth's surface

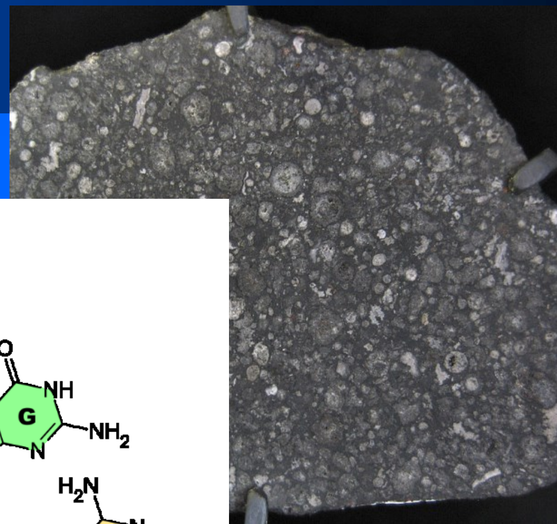


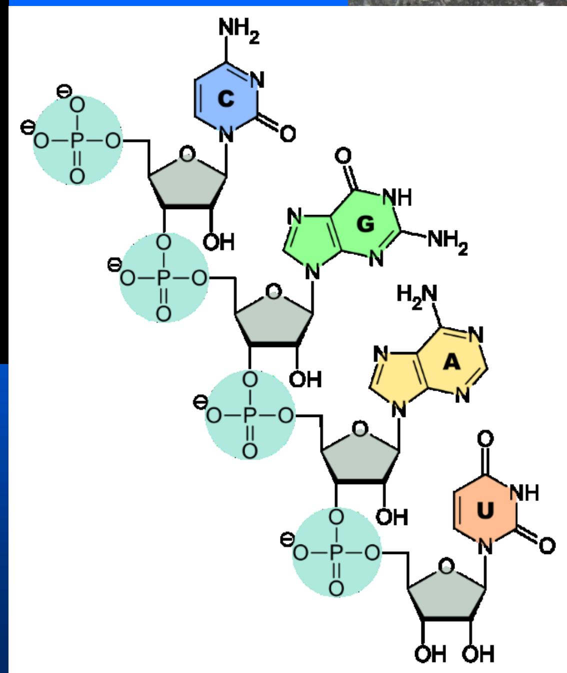
Summary

→ “Impact frustration” of life?

→ Substantial continuous addition of variety of complex prebiotic volatile compounds (incl. amino acids, nucleobases) by various types of CC meteorites

→ Pathways to RNA world?





Thank you for your attention!