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TERRESTRIAL PLANET ACCRETION CONSTRAINED BY ISOTOPES: IMPLICATIONS FOR EARTH-LIKE HABITATS

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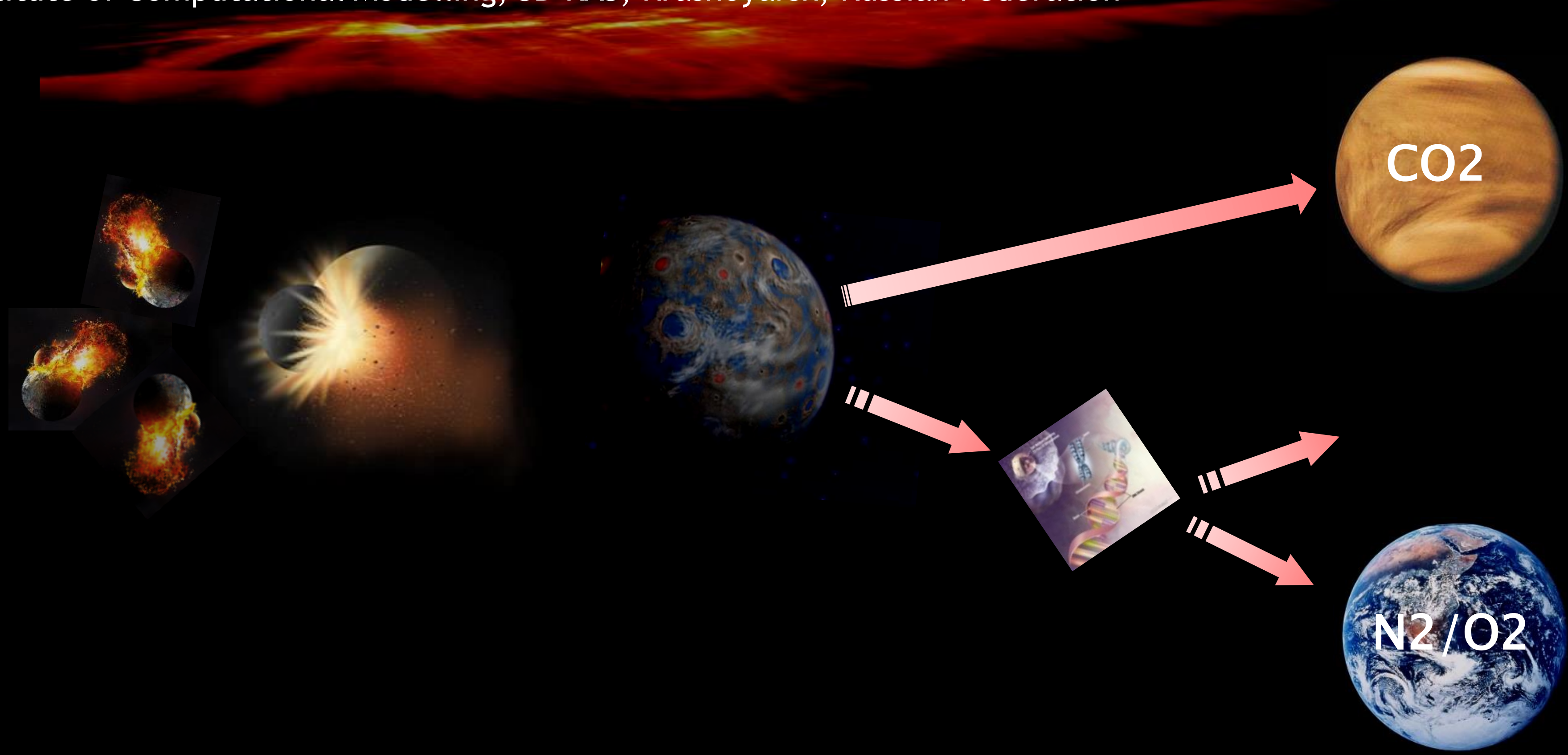

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MAIN REQUIREMENTS FOR EARTH-LIKE HABITATS

- Cosmo-chemical aspects for the building blocks of life
  - H_2O (solvent), C, N_2, O_2, etc. → CHNOPS

- H_2O molecules:
  - A large dipole moment;
  - The capability of forming hydrogen bonds;
  - To stabilize macromolecules;
  - etc.

[Catling et al., Astrobiology, 2005]

- Oxygen molecules:
  - Atmospheric O_2 is an essential molecule for the high energy-demands of large aerobic complex life forms with cm and m-sizes

The 10 most abundant elements: H_2, He, O_2, C, Ne, N_2, Mg, Si, Fe, S
[Smith, The Cambridge Encyclopedia of Earth Sciences. New York, 1981]

- Accretion phase in the planetary system
  - Not too much primordial gas
  - Right amount of H_2O and radioactive heat producing elements (i.e., U, Th, K) isotopes
  - Large Moons?
- Stellar X-ray & EUV activity, luminosity and plasma environments
  - Sun-like G stars vs. F, K, and M-stars
- Functioning C-silicate & N-cycles
  - Right tectonics during billion of years
  - Magnetic dynamo? Weathering & nutrient cycles, climate, etc.

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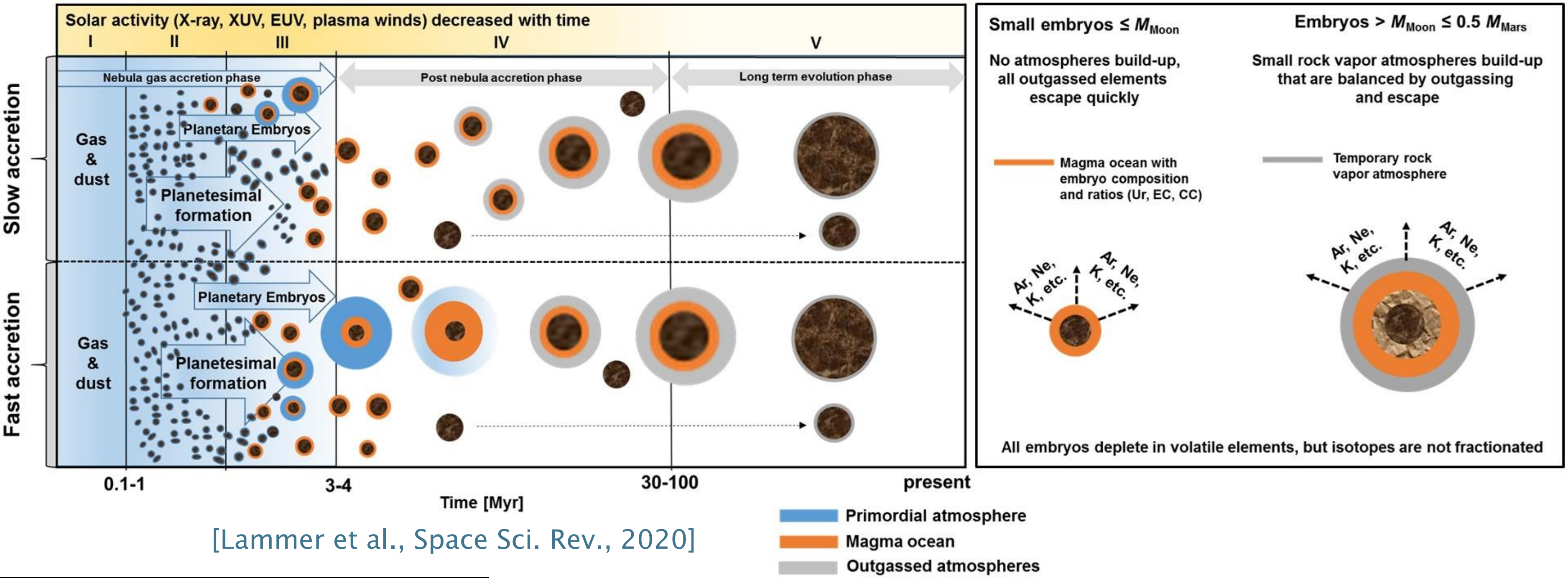
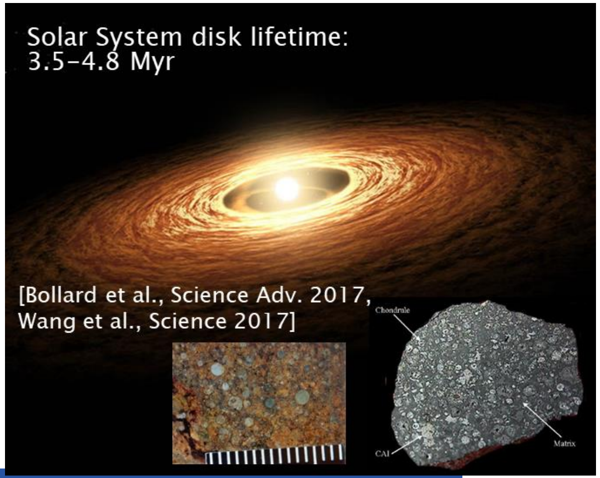
ACCRETION PHASE



[Lammer et al., Space Sci. Rev., 2020]



- 1st stage: Accretion within the gas disk phase Δt < 10 Myr (~ 4 Myr in the Solar System)
- 2nd stage: "Continuous" accretion after the nebular evaporates Δt ≤ 10 – 100 Myr
- 3rd stage: Catastrophic outgassing of a steam atmosphere from final "deep" magma ocean
- 4th stage: Evolution of secondary atmospheres "N_2" related to tectonics

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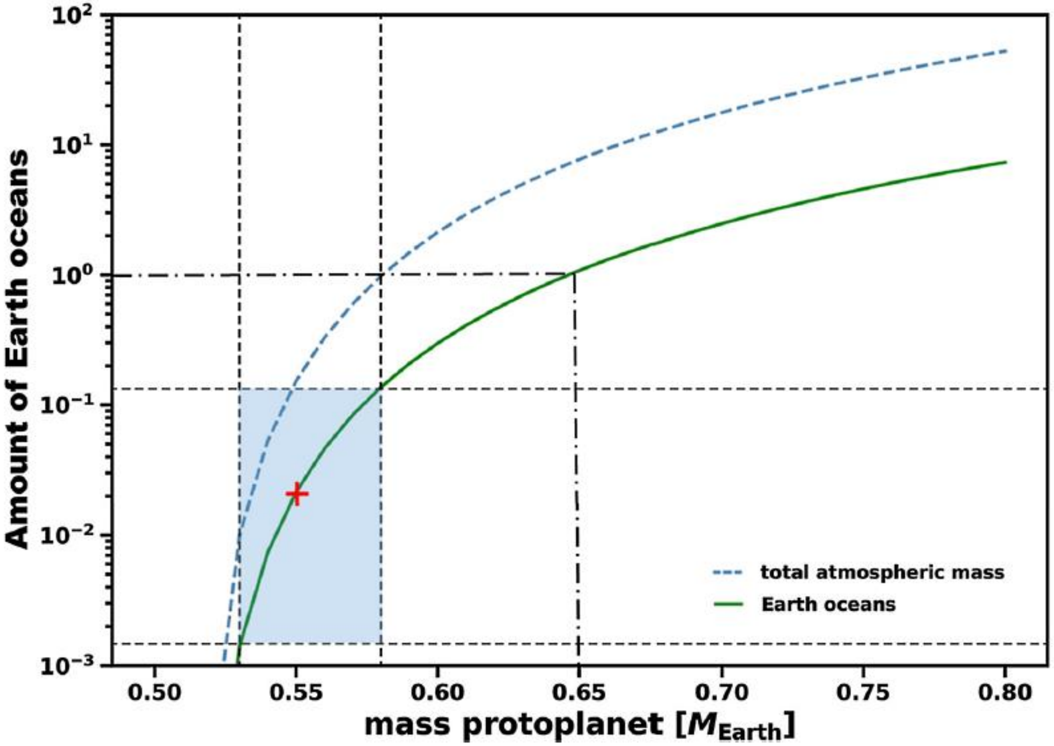
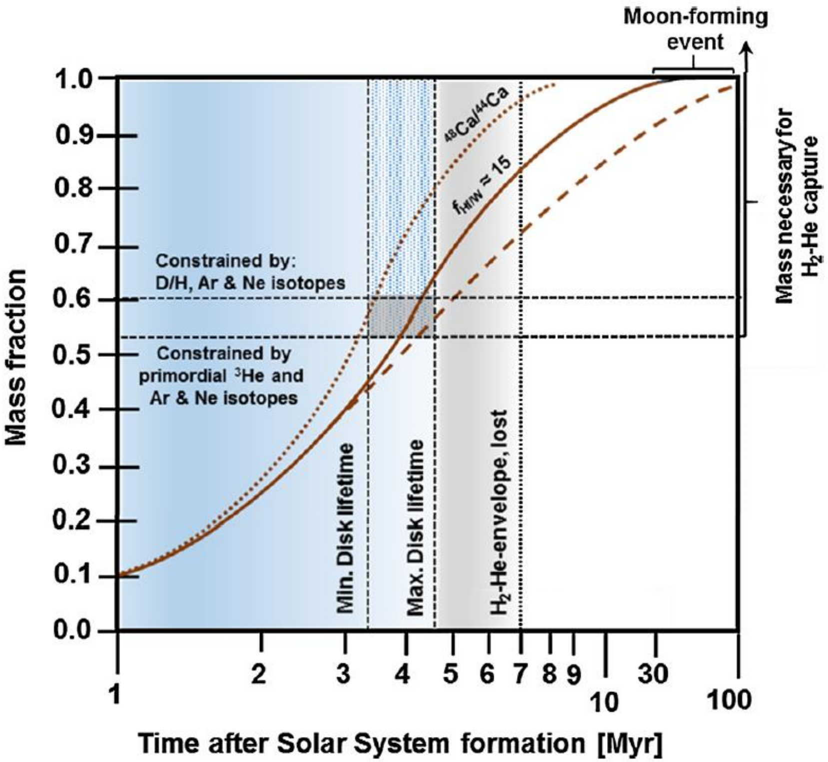
PROTO-EARTH EVOLUTION





- Nebula produced H2O: [Lammer et al., SSR, 2021] [Lammer et al. Icarus, 2020]
  - depends on the mass of the surrounding primordial atmosphere and on the available ion oxides and fayalite (Fe2SiO4) in the magma ocean

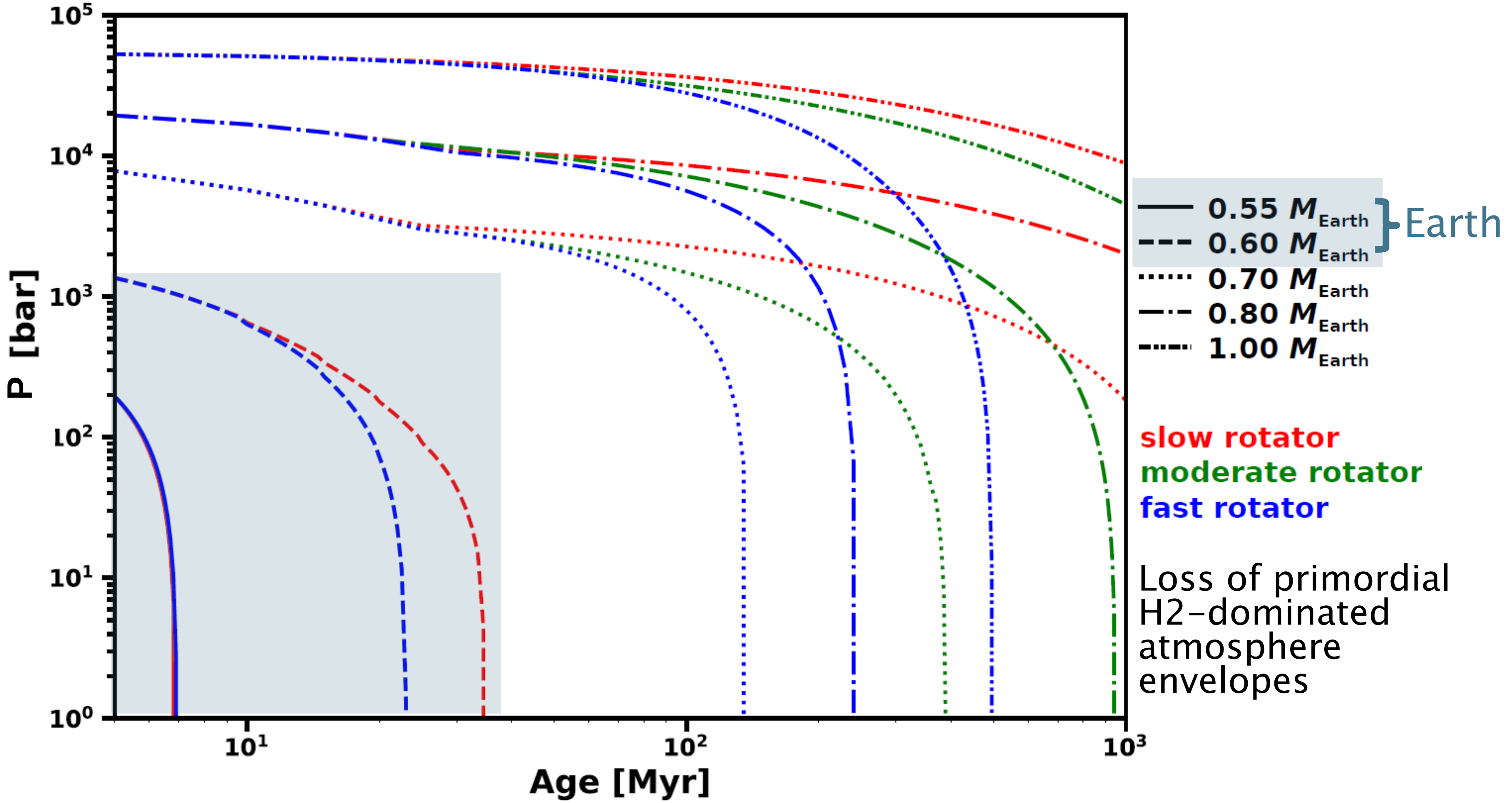
[first studies Ikoma and Genda, 2006; Kimura and Ikoma, 2020]

D/H nebula gas: $(530 \pm 10) \times 10^{-6}$ [Altweg et al., Science, 2015]

D/H Earth ocean & carbonaceous chondrites: $(150 \pm 10) \times 10^{-6}$ [e.g., Robert et al., SSR, 2012]

PRIMORDIAL ATMOSPHERE CAPTURE & ESCAPE

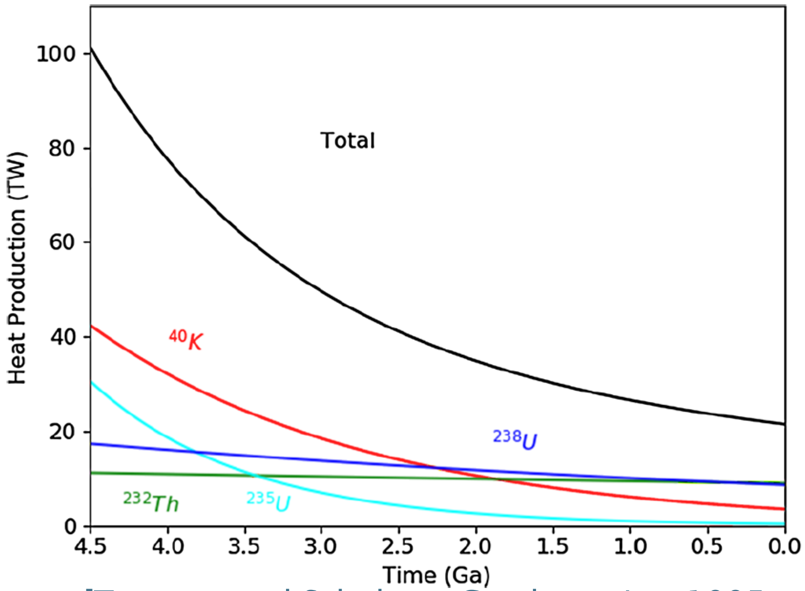
- Multispecies hydrodynamic upper atmosphere evolution model
  - No scaling of energy-limited formula, includes dragging of minor and trace species (He, outgassed volatile elements and noble gases)



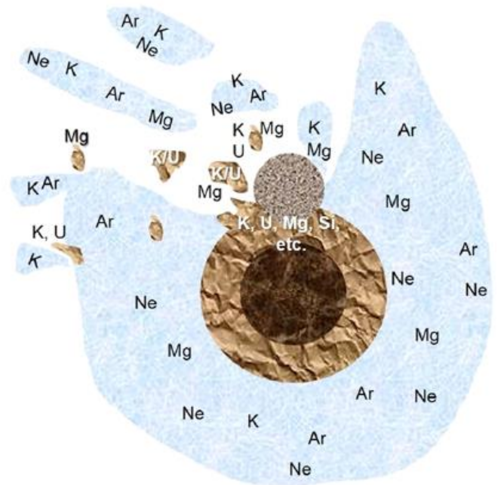
Loss of primordial H2-dominated atmosphere envelopes

[Erkaev et al., to be submitted to MNRAS, 2021]

MODIFICATION OF HEAT BUDGETS VIA IMPACT EROSION & 40K ESCAPE



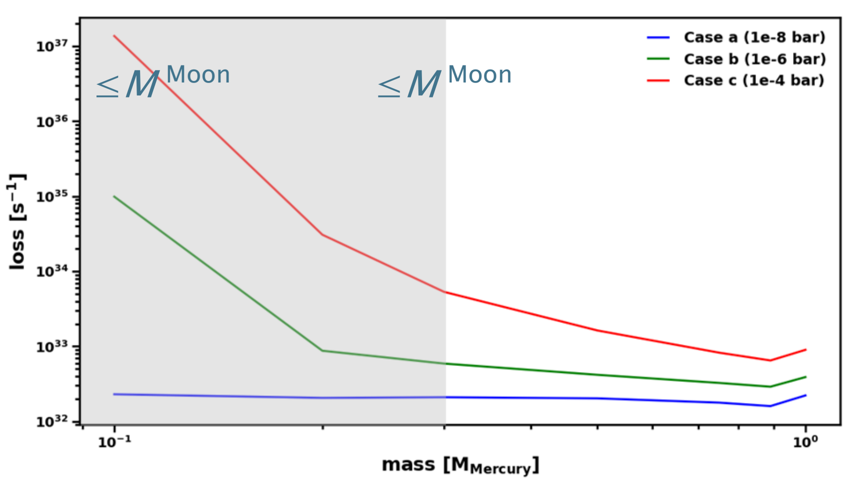
[Turcotte and Schubert, Geodynamics, 1995; O'Neill et al., SSR, 2021]



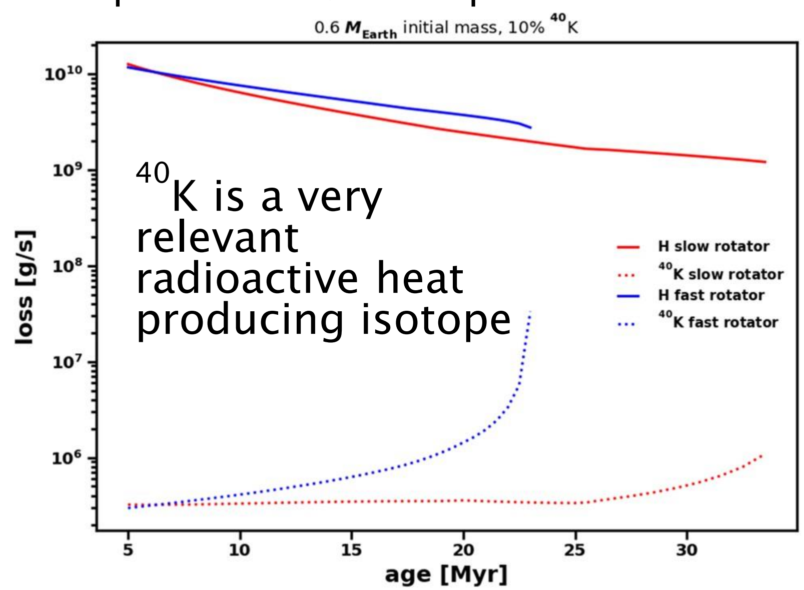
Depletion of moderate volatile rock-forming elements such as:

(K, Na, Si, Mg, Fe, Ca, Al, S, P. Cl…)

Loss via impact erosion of U,Th, K isotopes



Loss via H-dragging from escaping primordial atmospheres of 40K isotopes



^{40}K is a very relevant radioactive heat producing isotope

[Erkaev et al., to be submitted to MNRAS, 2021]

CONCLUSION

- From 182Hf-182W, U-Pb, lithophile-siderophile elements, 48Ca/44Ca isotope samples from planetary building blocks, recent reproduction attempts from 36Ar/38Ar, 20Ne/22Ne, 36Ar/22Ne isotope ratios in Earth's atmospheres, the expected solar 3He abundance in Earth's deep mantle and Earth's D/H sea water ratios that shed light on the accretion time of the early protoplanets one can expect an initial core mass when the disk evaporated (~4 Myr) for proto-Earth: between >50 - 60 % Earth-masses
- Earth can best be reproduced if the post-H_2-envelope impactors contained ≈ 5% CCs (Dauphas, Nature, 2017) – in agreement with Marty EPSL (2012) - or 70 – 100% CCs but a faster growth rate (Schiller et al., Nature, 2018]
- A slow to moderate rotating young Sun reproduces the observed isotope (Ne, Ar) and K/U fractionation on Earth (K/U)
- Venus !!! Mission!
- Accretion time, disk life time, stellar X-ray/EUV activity, impact history, and delivery of volatiles by carbonaceous chondrites set the initial stage for the evolution of Earth-like habitats:
  - bulk composition,
  - geodynamics and radioactive heat producing elements → ^{40}K, U Th
  - habitability, especially the evolution of long time geological active habitats (i.e., tectonics, outgassing, secondary atmosphere evolution, water, etc.)
  - build up of a N2-dominated atmosphere that represents an Earth-like biosphere
  - because of many different formation possibilities, one may expect that many terrestrial planets may have problems for developing long-time plate tectonics important for habitability and life as we know it