Water delivery to planets in habitable zones by pebble accretion

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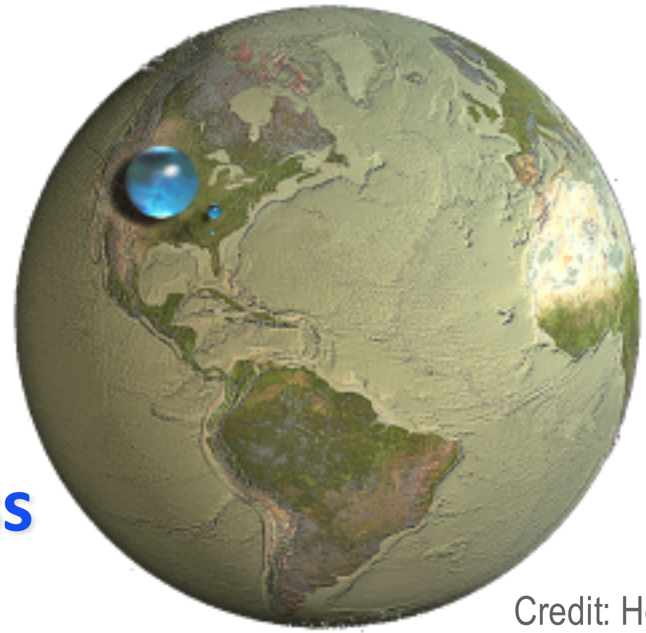


Credit: Howard Perlman

Earth ocean mass
~ 2 x 10^{-4} M_E
reproduced?
Special or common?

EARTH - LIFE SCIENCE INSTITUTE

Abstract

- H_2O delivery by pebble accretion after snowline passage
  - ✓ 1D sim. of dust growth & migration in evolving disk
  - ✓ Water weight fraction f_{water} is approximately given by

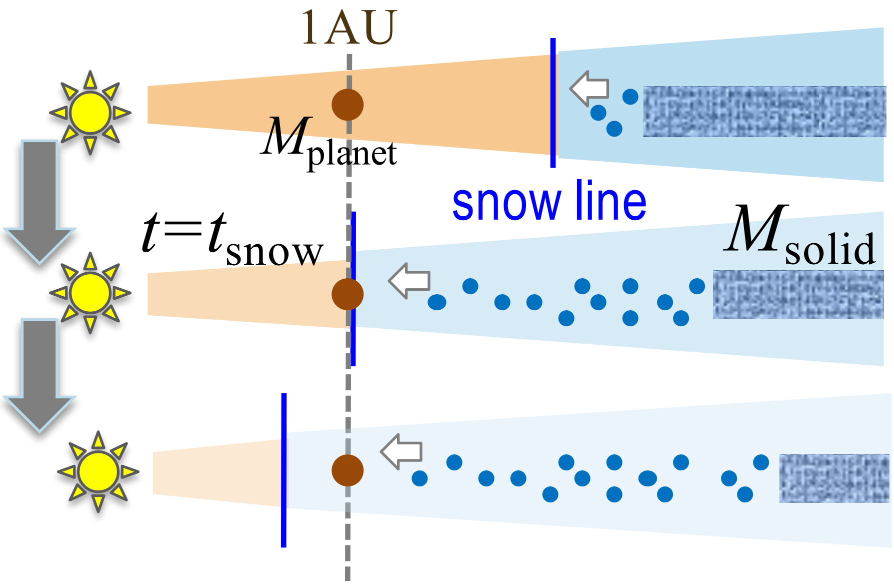
$$f_{water} \sim 0.5\, M_{solid}(t=t_{snow})\, P_{pebble}/M_{planet}$$

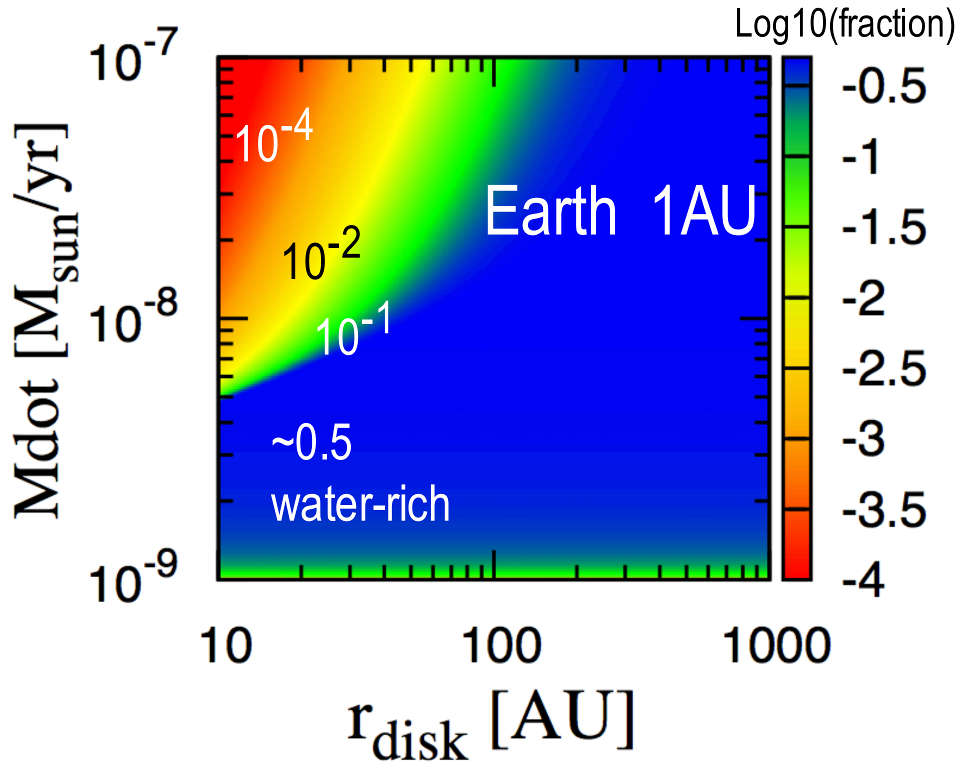
M_{solid} ← disk model

P_{pebble} ← disk model & M_{planet}

- f_{water} ← disk parameters
  - generally more water-rich than the current Earth
  - ~2 x 10^{-4} : ocean (10^{-3} ? : mantle)

- Massive & small disk ?
- Ancient Mars is more water-rich ?





Snow line migration

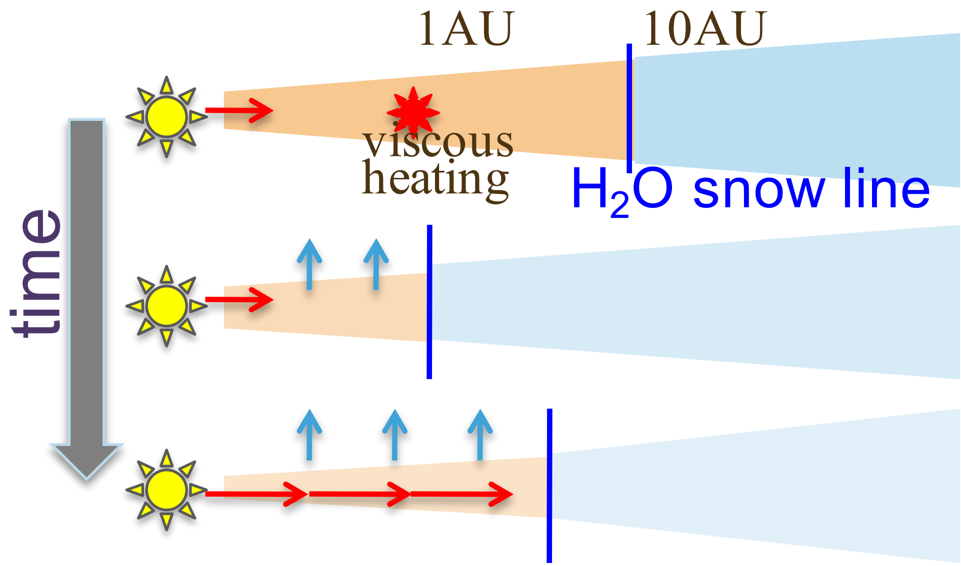
Disk thermal evolution

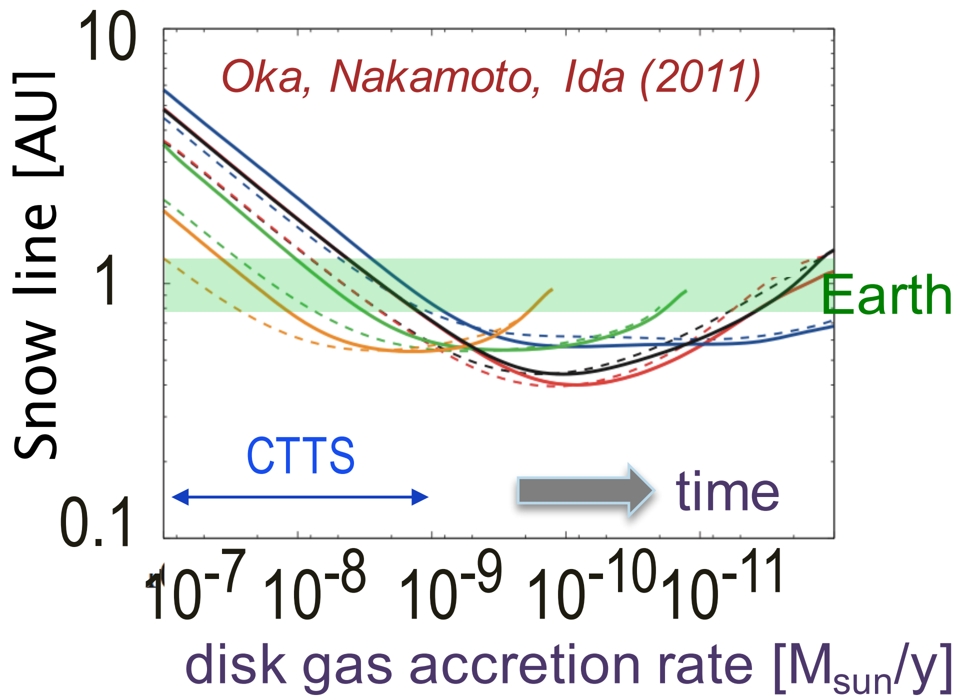
■ early stage: **HOT**
r, *z*: opaque, viscous heating

■ middle stage: **COLD**
r: opaque *z*: transparent

■ late stage: **MEDIUM**
r, *z*: transparent

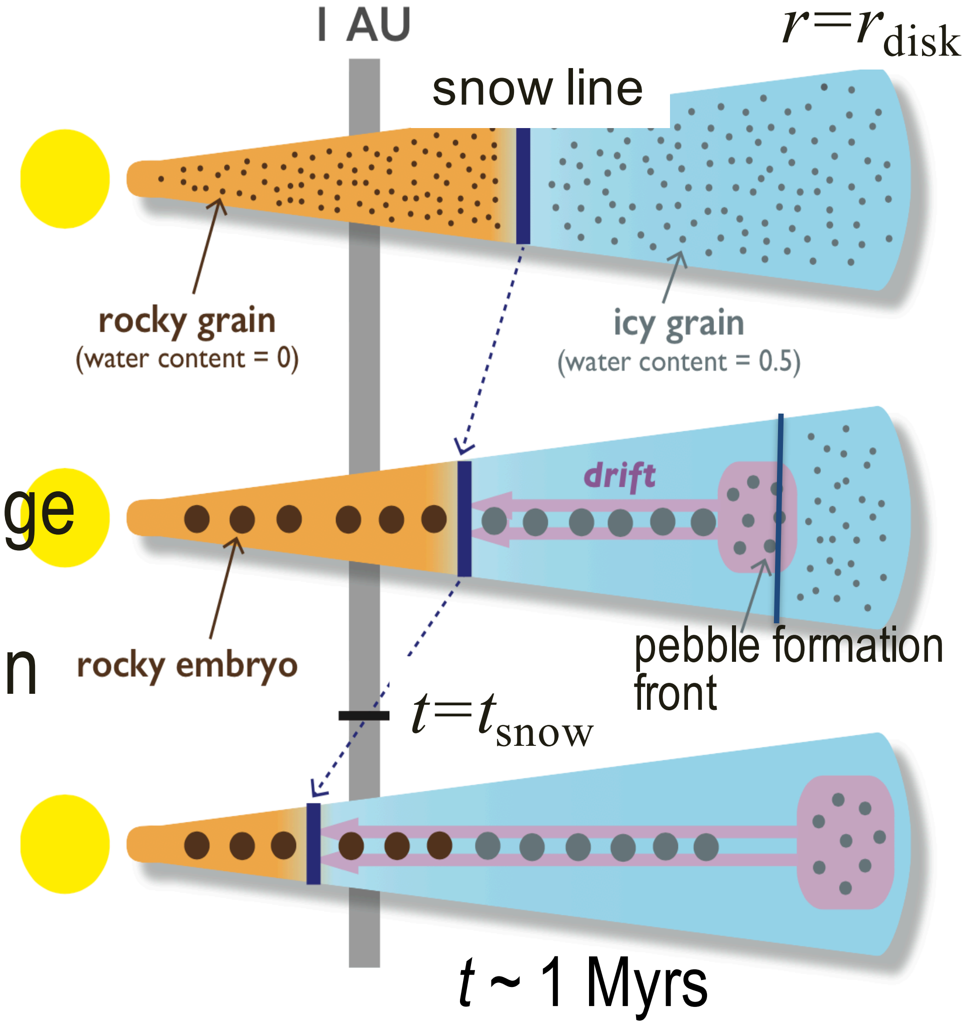
→Snow line can be inside Earth orbit at *t* >~ 1Myrs



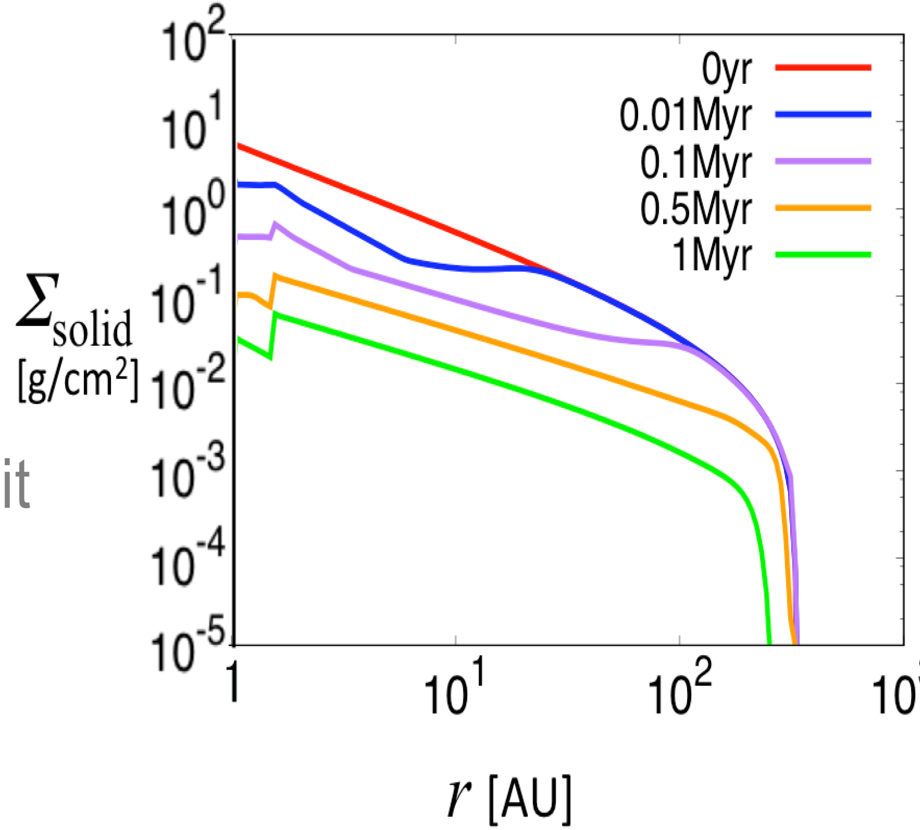


H_2O delivery to Earth by pebbles

- icy pebbles
  - ➢ formed in disk outer region
  - ➢ quickly migrate
  - ➢ sublimate inside snow line
- H_2O accretion onto Earth
  - ➢ Start at the snow line passage
    $t = t_{snow}$
  - ➢ Decay after pebble formation front reaches r_{disk}
    $t = t_{pebf}$



Σ_{solid} - evolution



Important parameter: t_{snow}/t_{pebf}

t_{snow} : snow line passage at planet's orbit ~ O(10^6) yrs

t_{pebf} : pebble formation front arrival to disk outer edge ~ O(10^5) yrs

- Σ_{solid} decays as $\Sigma_{solid} \propto (t/t_{pebf})^{-1.5}$

→ $M_{solid} \propto (t_{snow}/t_{pebf})^{-1.5}$

$$M_{solid}(t) = \int 2\pi r \Sigma_{solid}(t) dr$$

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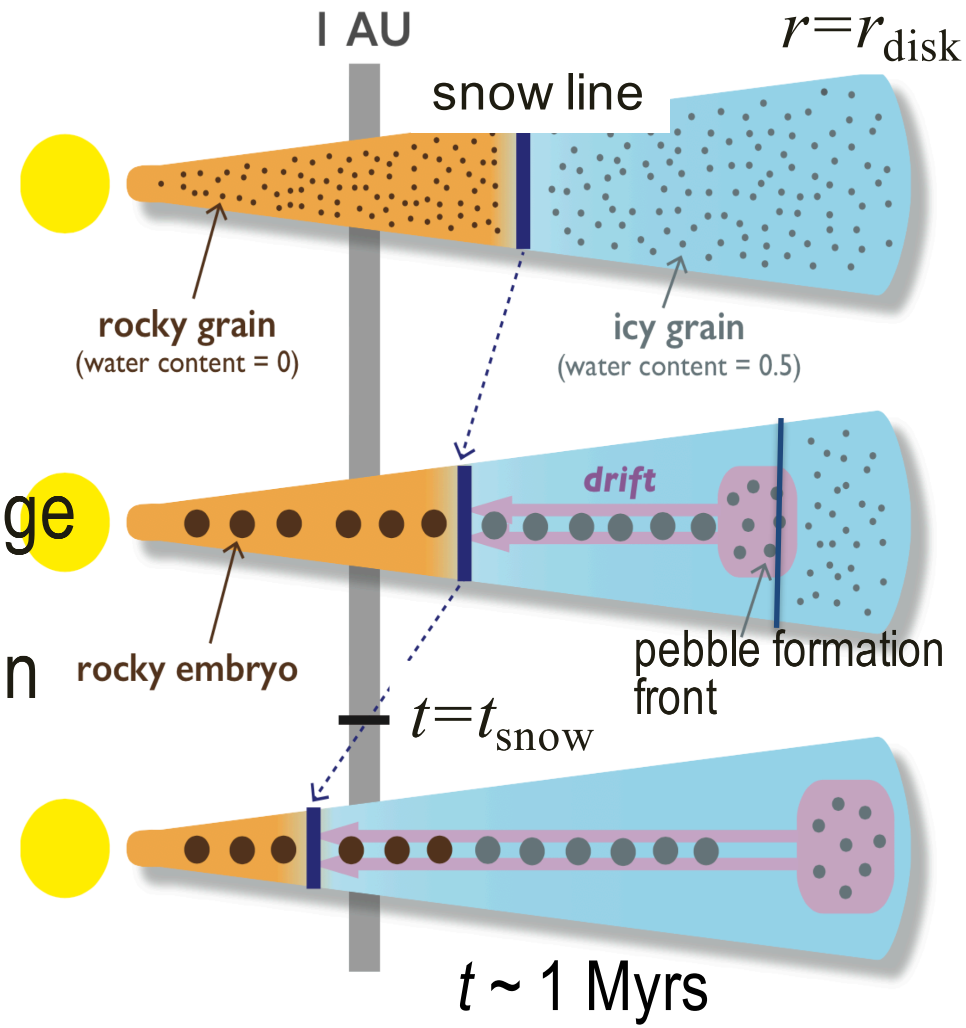
→ disk evolution is a key

t_{snow} vs. t_{pebf}

Sato, Okuzumi, Ida (2016)



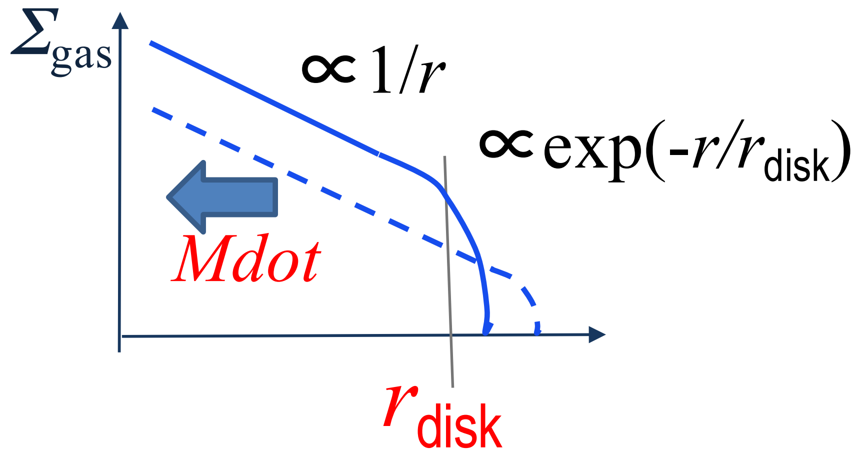
Pebble growth/migration 1D calculation in a viscously evolving disk

Yamamura, Ida, Okuzumi (in prep)

- pebble growth & migration: method of Sato et al. (2016)
  [considered a static disk]

+

- An evolving gas disk: self-similar solution
  (w/ modification to viscous/irradiation, photoevaporation)
  t_{dep} = 3 x 10^6 y: fixed
  parameters: $Mdot$, r_{disk}



→ Predict H_2O fraction of planets as a function of the disk parameters

Result : f_{water} as a function of $Mdot$ & r_{disk}

- Fitted results

$$f_{water} \sim 0.5 P_{pebble} M_{solid} / M_{planet}$$

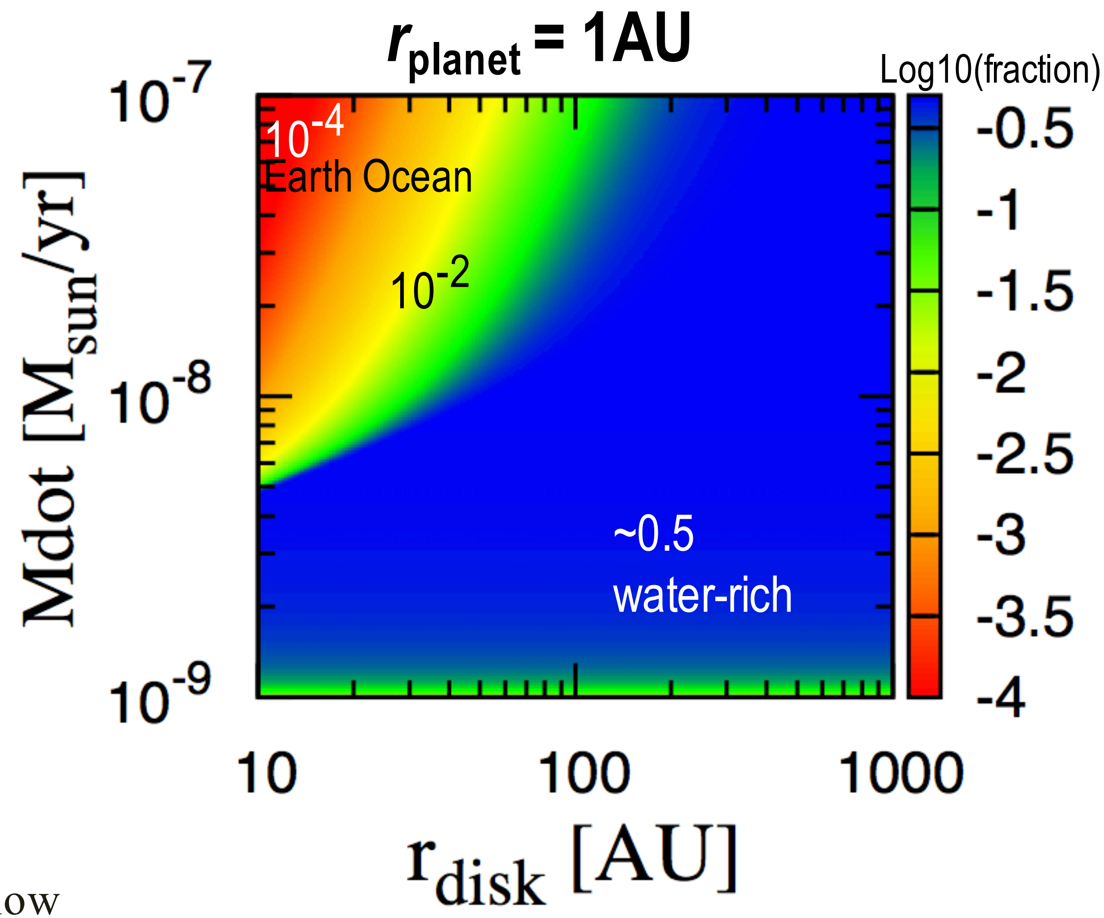
accreted ice

$$\sim 0.2 M_{solid} / M_{planet}$$

for Earth-mass planet

M_{solid} ← disk model: t_{pebf} / t_{snow}

- For $f_{water} \sim 10^{-4}$-10^{-2} (Earth), pebble accretion for $t > t_{snow}$ must be small enough
  - ← significant dust depletion by t_{snow}
  - ←→ massive & compact disk:
    - $Mdot > 10^{-8}\ M_{sun}/y$
    - r_{disk} < 30-50AU



$Mdot$: initial disk accretion rate

r_{disk}: disk outer radius

Result : Earth vs. Mars

- **Earth (1AU) vs. Mars (1.5AU)**

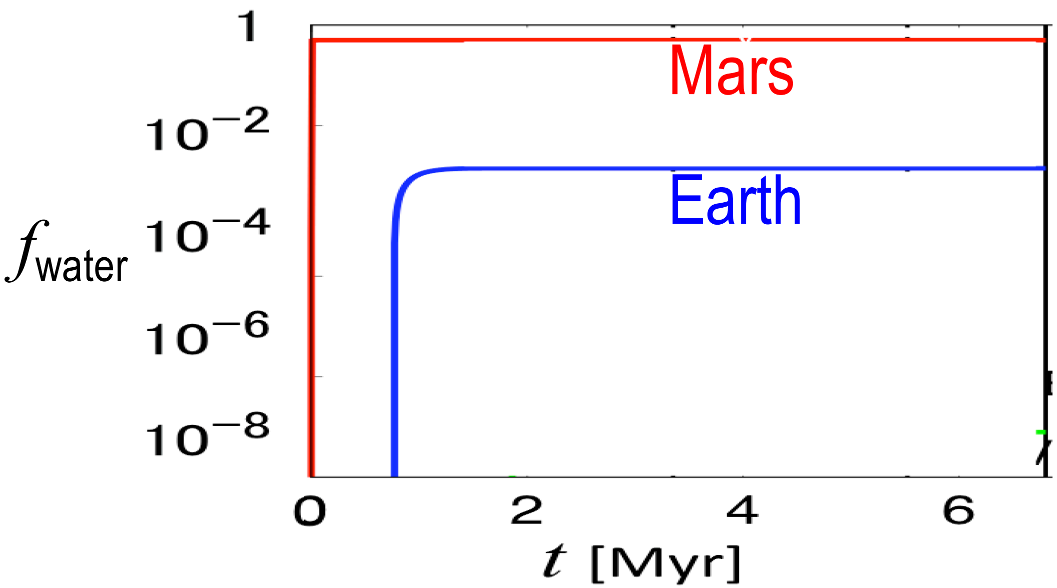
  Snow line passes earlier for Mars

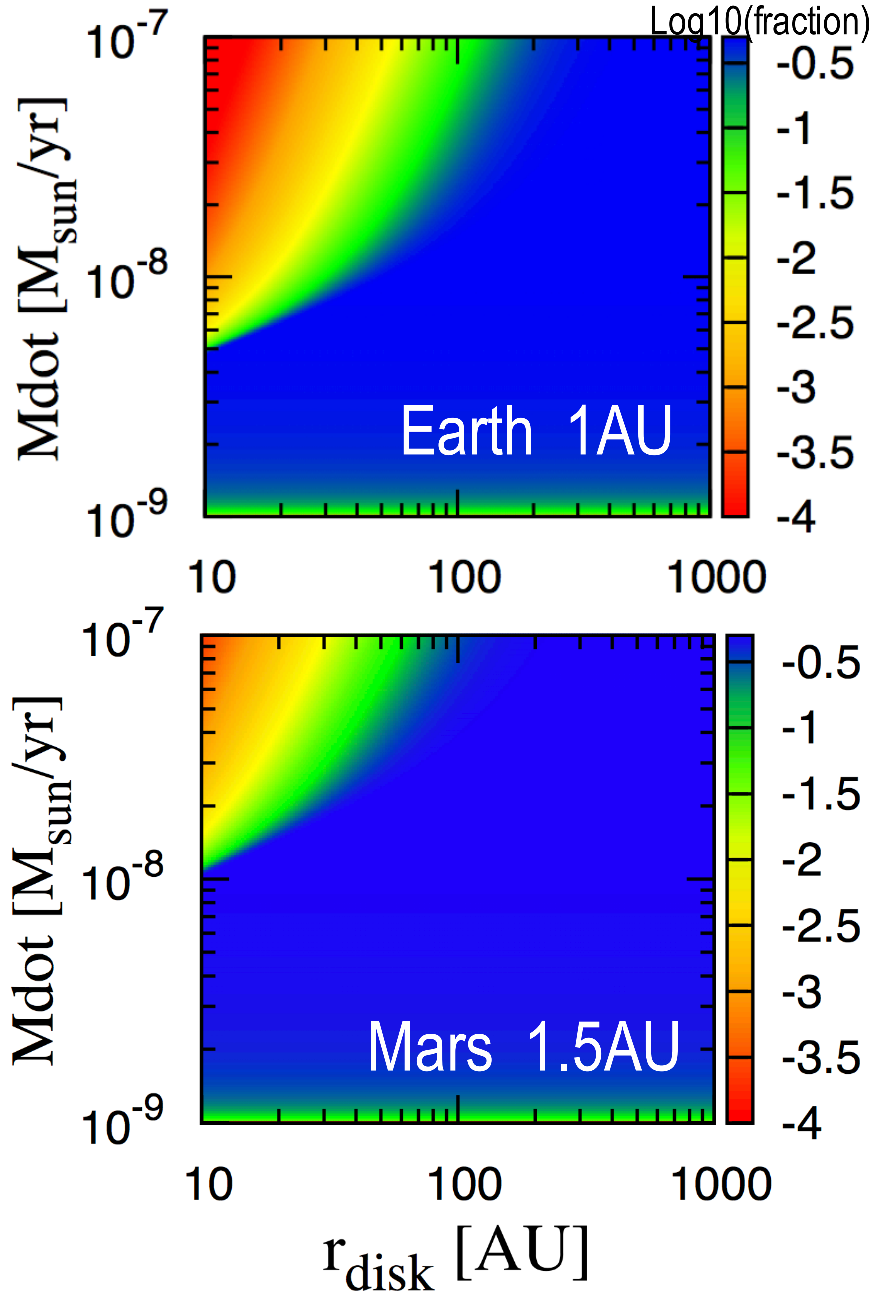
  → Mars starts ice accretion earlier

  → More $M_{\rm solid}$ for Mars

  → ancient Mars:

  more ice-rich than Earth?

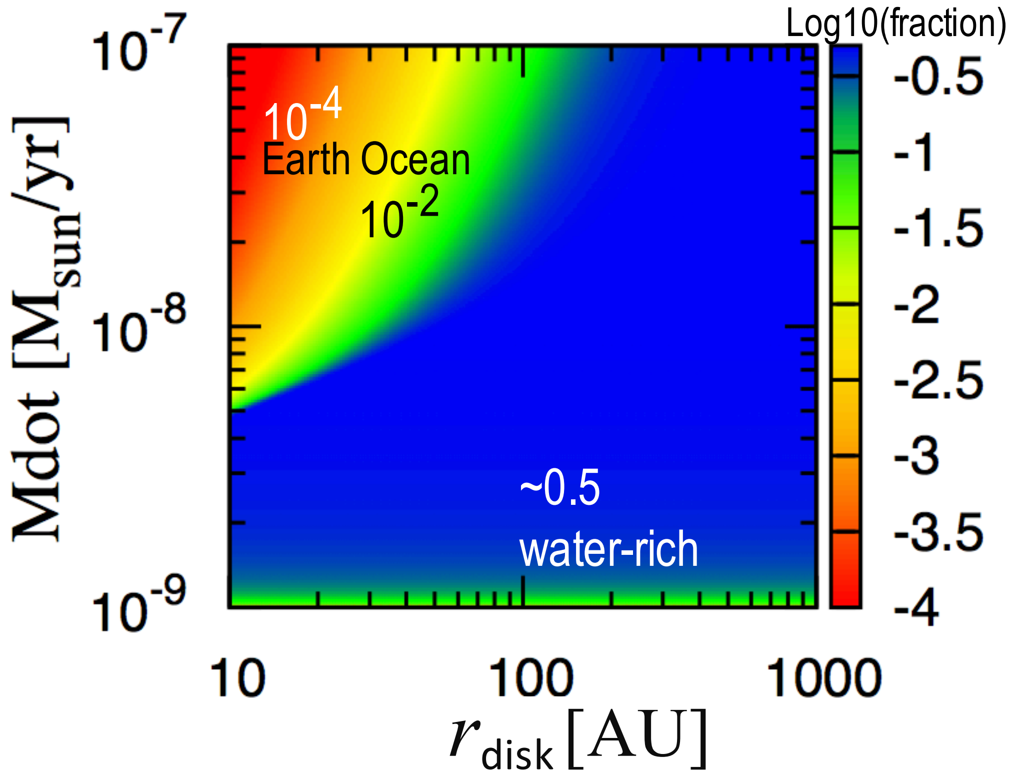




fast icy peb. acc. → truncation by Jupiter formation: difficult → $f_{\rm water} = 0$ or final value

Summary & Discussion

- Water fraction f_{water}
  ~ [M_{solid} in outer disk
  at the snow line passage]
  x [pebble filtering rate]/M_p
- Earth $f_{water} << 1$
  → large $Mdot$ & small r_{disk}
  → **How to survive**
  fast type I migration?
- Mars was more water-rich
  than Earth? → **observation?**



Alternative:

1. self-regulated decay of pebble accretion
   "pebble isolation mass": too big
   "atmosphere recycling"? : now working on
2. store some icy dust longer?