Origin of water on Earth: the clues from pre-planetary phase of the Solar nebula

Dmitry Semenov, Tobias Albertsson, Thomas Henning

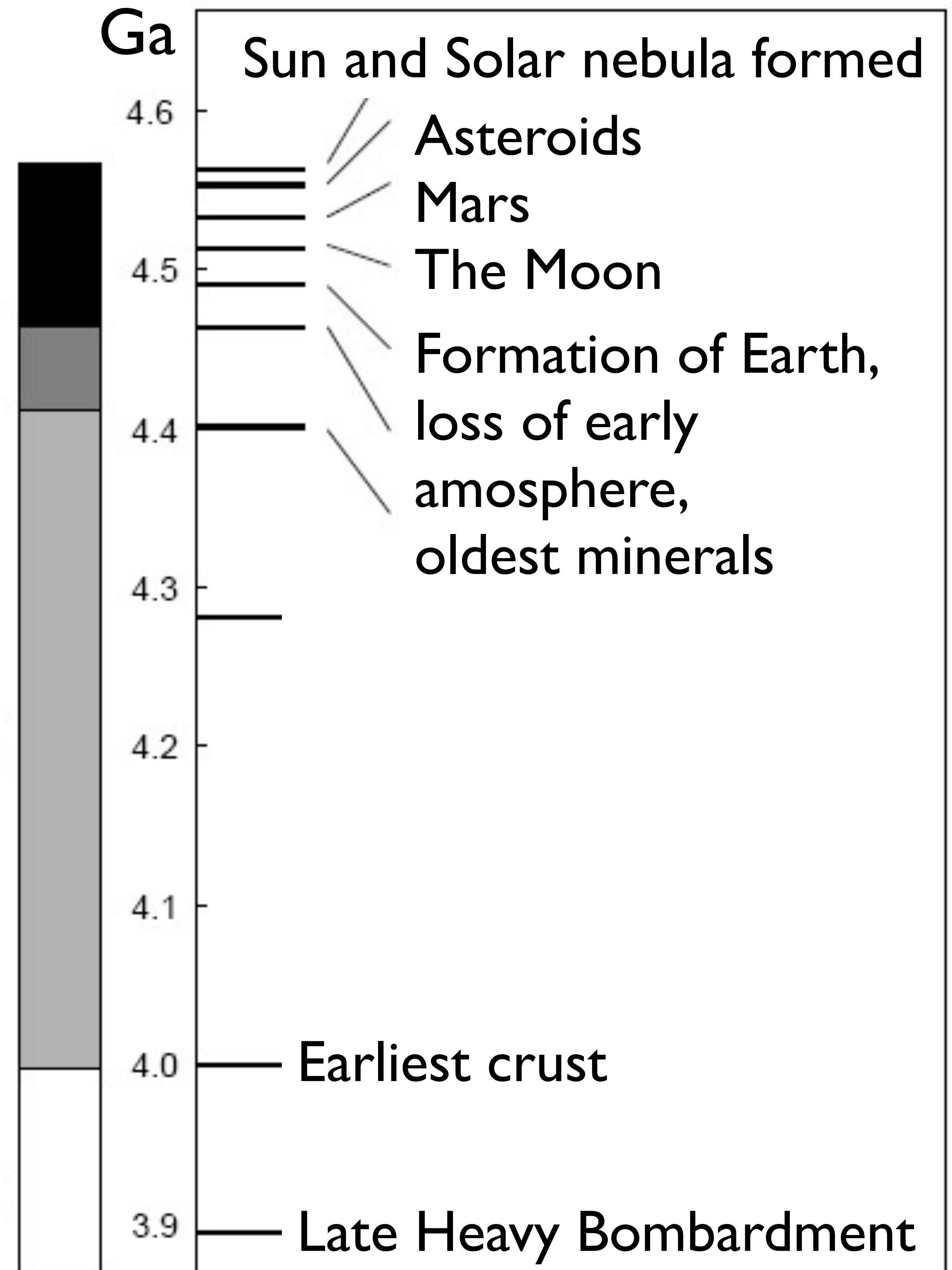
Max Planck Institute for Astronomy
Heidelberg, Germany

Outline

- Motivation
- New model of deuterium chemistry
- D/H ratio of water during pre-planetary phase
- Conclusions

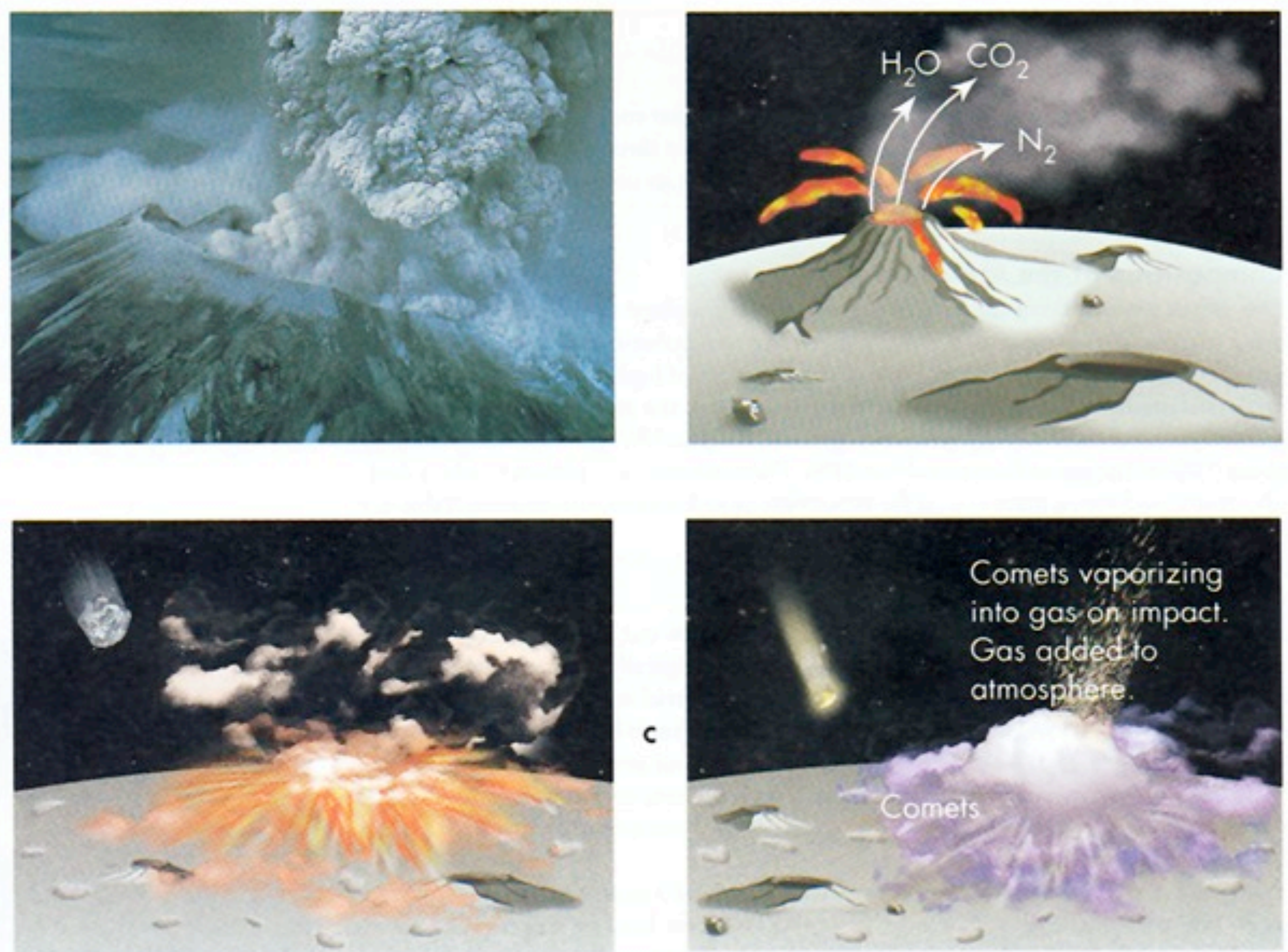
History of early Earth

- 4.568 Ga: Sun & Solar nebula
- -100 Myr: Earth accretion, core formation and degassing
- -112 Myr: Formation of Moon
- -150 Myr: first rocks
- -250-350 Myr: liquid water?
- -600 Myr: Late Heavy Bombardment
- -700 Myr: first life



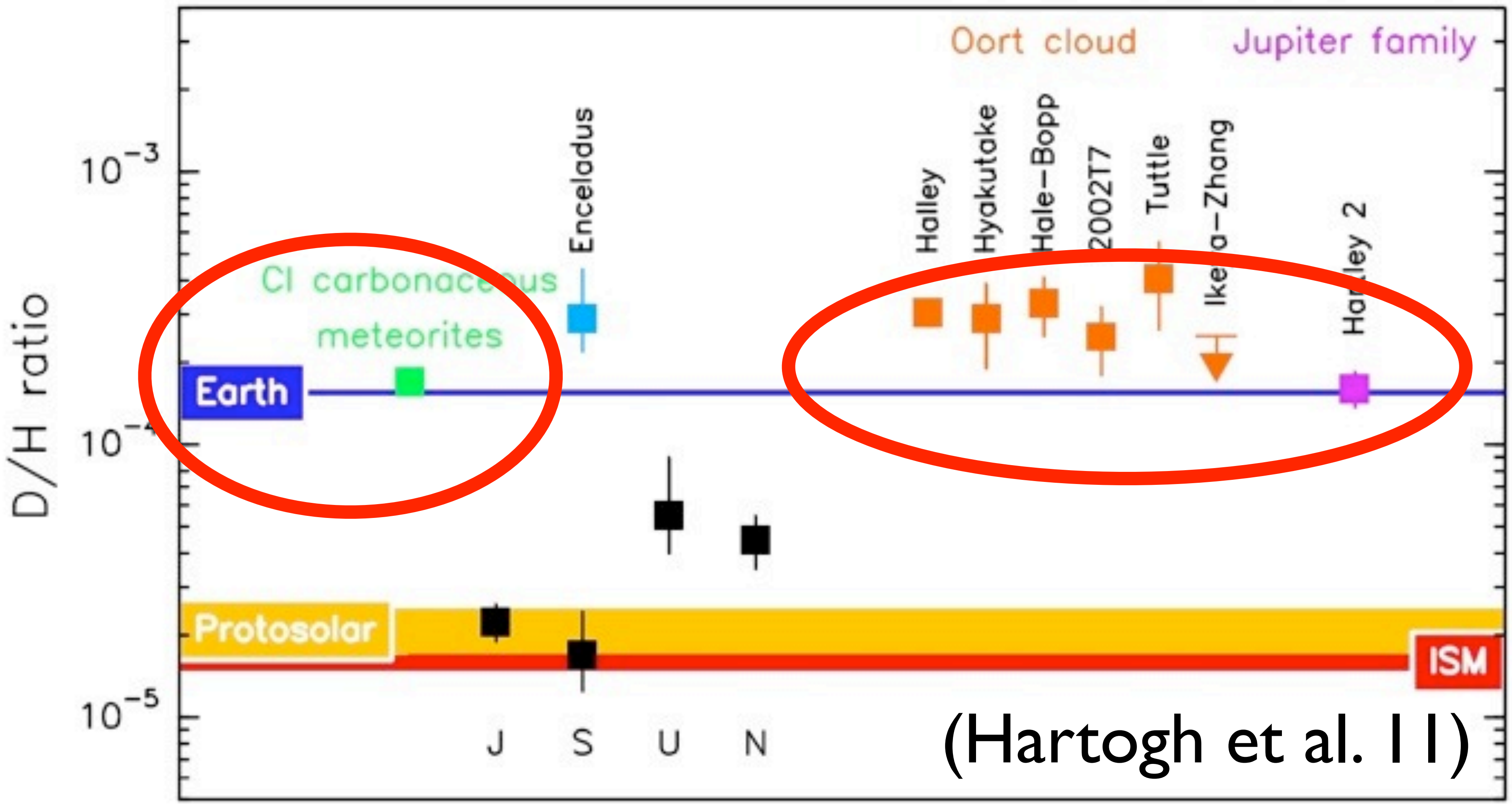
Halliday (2003)

What is the source of water on Earth?



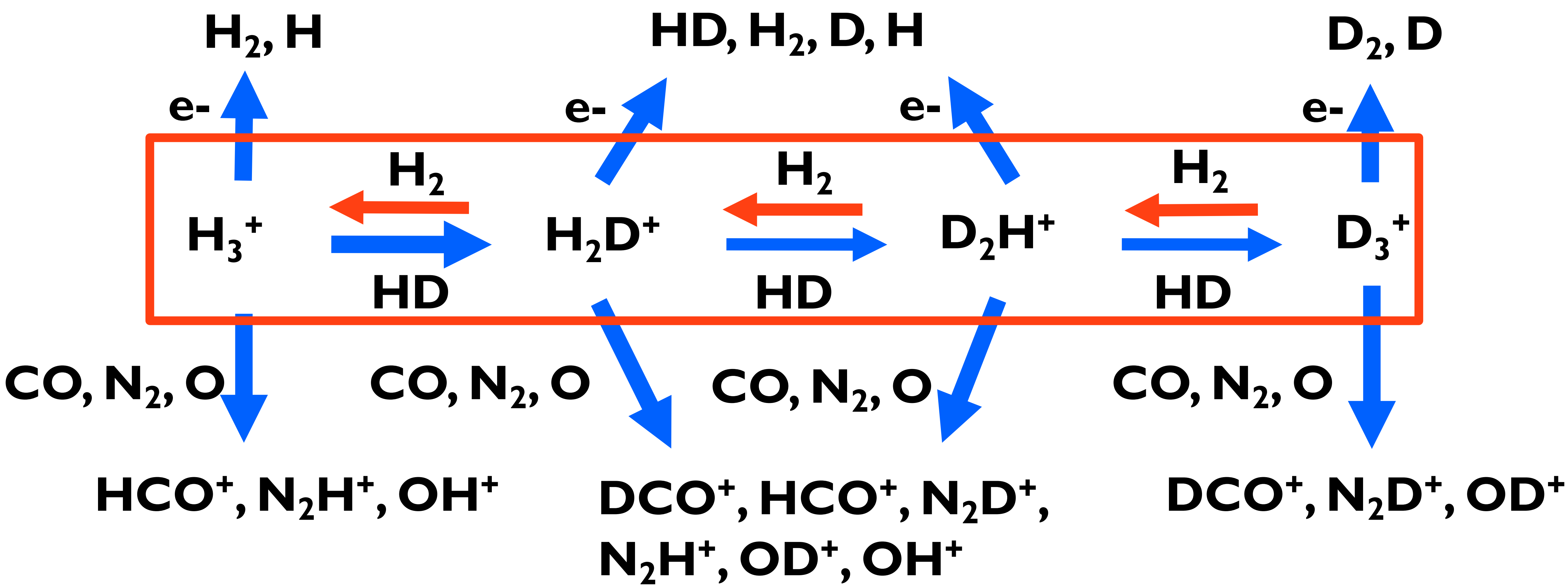
- Outgassing of volatiles by volcanoes
  - But inner Solar nebula was too warm for "wet" planetesimals
- Brought by comets & asteroids from outer region

Origin of water on Earth



- Earth' oceans: H_2O D/H = 1.56 x 10^{-4}
- Carbonaceous asteroids (~ 1–3 AU): ~ Earth's value
- Oort-family comets (~5–20 AU): ~ 3–6 x 10^{-4}
- Jupiter-family comet Hartley-2 (~5–20 AU): Earth's value

Deuterium fractionation



- "Cold" fractionation via H_2D^+, D_2H^+, D_3^+: T ~ 10 – 40 K
- "Warm" fractionation via CH_2D^+ & C_2HD^+: up to T ~ 80 K
- Surface processes

Courtesy of H. Roberts

Deuterium chemistry model

Albertsson et al. (2011), astro-ph/1110.2644

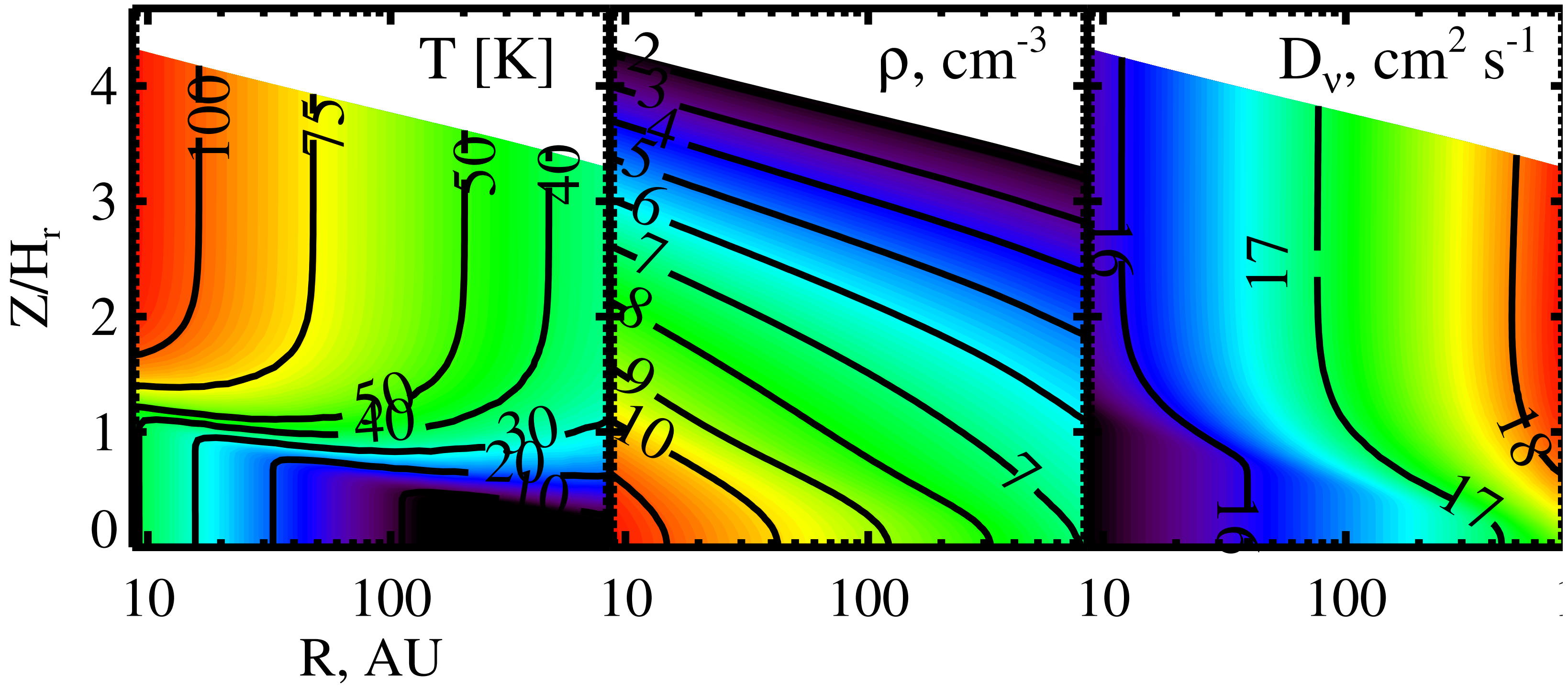
- Chemical code "ALCHEMIC" (Semenov et al. 2010)
- Gas-phase reactions: KIDA (Sep 2012)
- Surface reactions (Garrod & Herbst 2006)
- High-temperature gas-phase reactions (Harada et al. 2010)

- Cloning of H-bearing reactions (except of –OH)
- Isotope exchange rates from literature
- 57,000+ reactions & 1,900+ species

- Reproduces observations

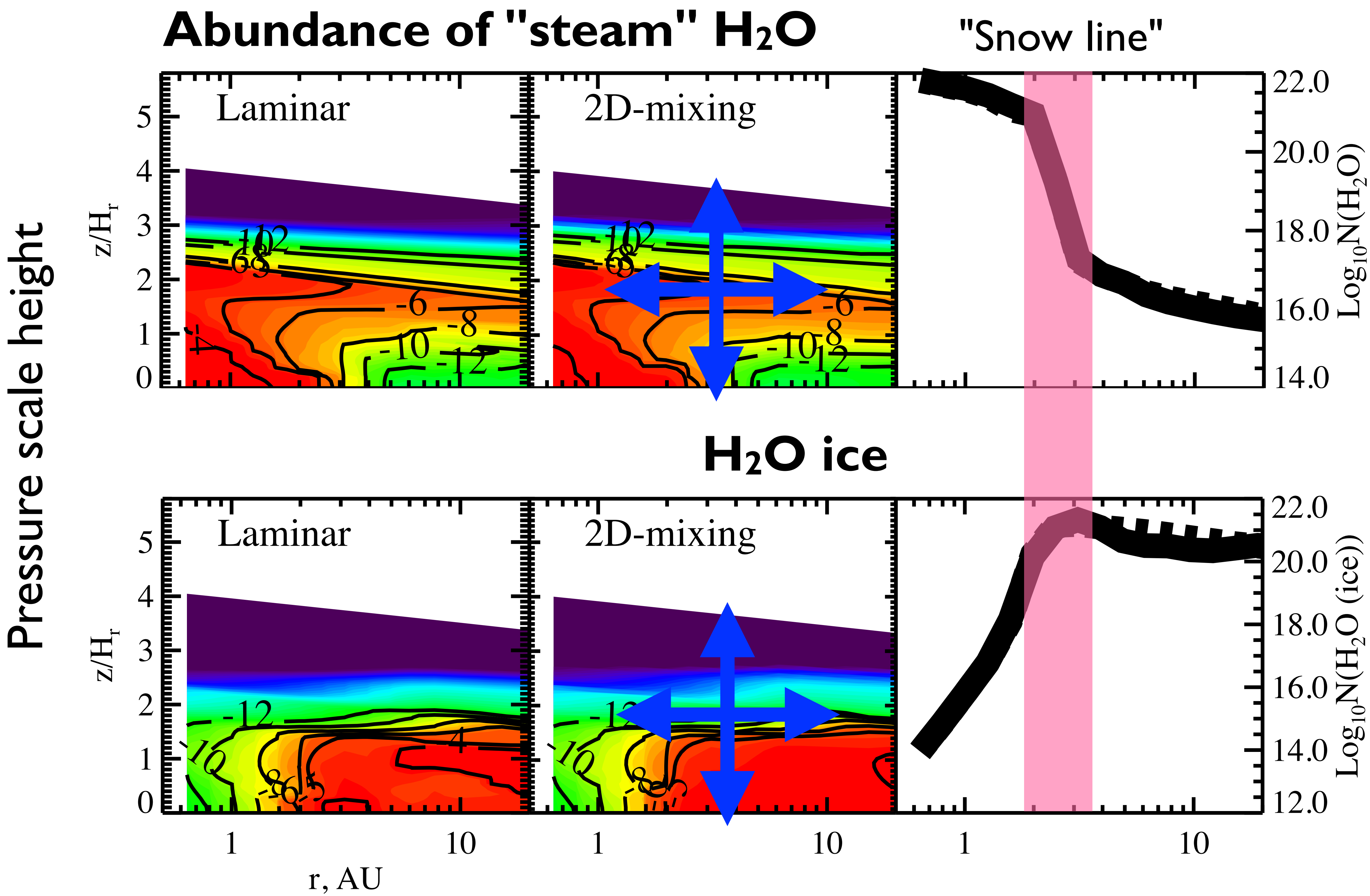
Chemo-dynamical model of Solar nebula

- 1+1D physics
- $1 M_{sun}$, $1 R_{sun}$, $M_{dot} = 10^{-8} M_{sun}/yr$
- alpha-viscosity: $\alpha=0.01$, diffusion coefficient @ 800 AU: $\sim 10^{18}$ cm^2/g



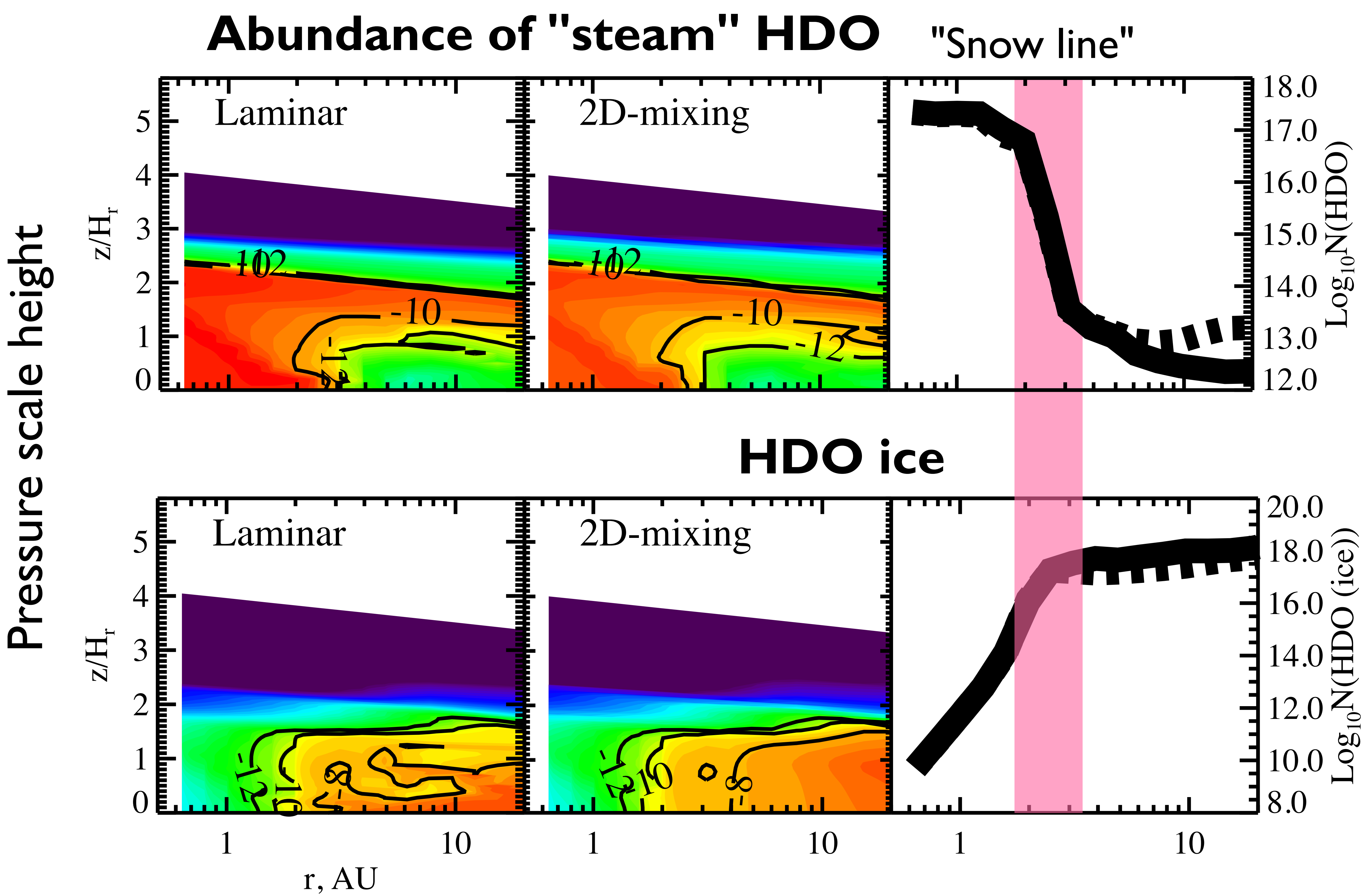
- 2D chemistry with turbulent mixing transport: 1 Myr
- New deuterium network

Water in early Solar nebula



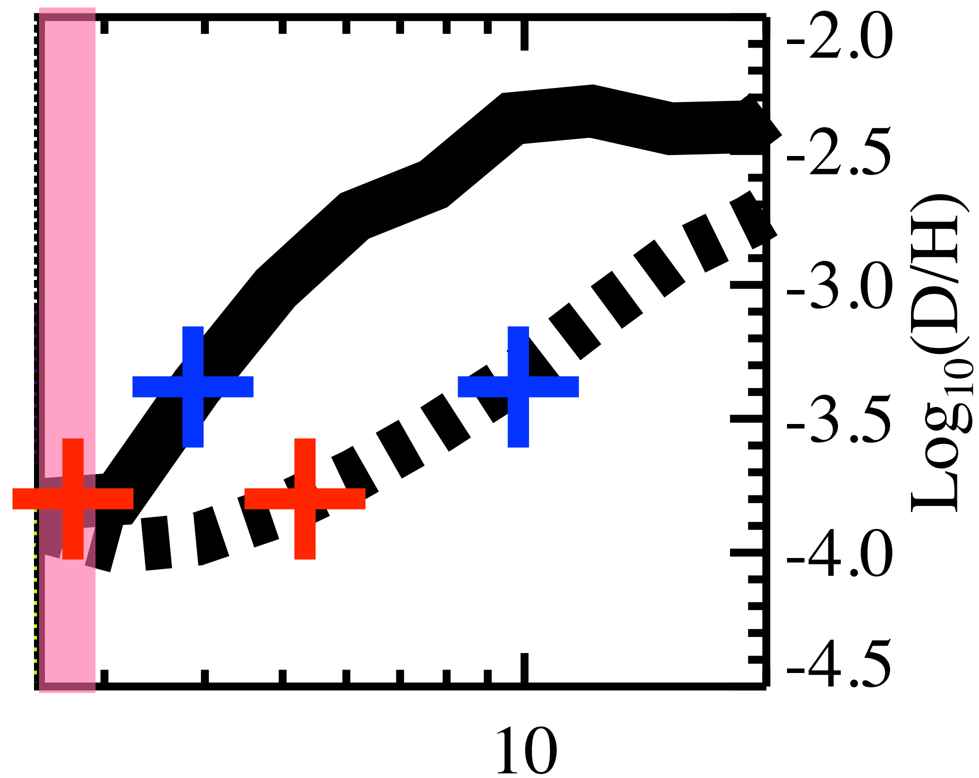
- Turbulent mixing does not bring H_2O ice to 1 AU: fast evaporation & freeze-out << mixing timescale

Heavy water in early Solar nebula



- Mixing brings HDO in warm regions ⇒ partial de-fractionation in gas & recondensation

All together: D/H of water ice



- Cometary D/H of H_2O at 5 – 20 AU:
  - Laminar model: ~ 5 10^{-3}
  - ✓ Dynamical model: ~ 10^{-4} – 2 10^{-3}
    - D/H of H_2O of Oort-family comets: ~ 10 AU
    - D/H of Earth H_2O: ~ 2.5 – 6 AU
- Both models show D/H of Earth's water: ~2–3 AU

Conclusions

- New deuterium network
- 2D chemo-dynamical model of Solar nebula
- No icy grains at 1 AU
- Dynamical processes are important for D/H of cometary water
- Not so for asteroids

- Source of Earth water: comets vs asteroids?

Thank you!

and

DFG Priority Program 1385: "The first 10 million years of the Solar System" (SE 1962/1-1 & 2-1)

Deuterated species in space

- Elemental D/H ratio is ~1.5 10^{-5}
- ISM, protoplanetary disks, comets: D/H ~0.1–50%
- Sensitive to T and freeze-out
- A link between D/H of water on Earth and in comets or asteroids?

Species	D/H
HD	<0.05%
H_2D^+	< 0.3%
N_2D^+	0.5–44%
DCO^+	0.1–18%
ND_3	0.1–3%
HDO	0.2–7%
HDCO	0.6–170%
D_2CO	1–29%
CD_3OH	<1–5%
$DCOOCH_3$	<2–15%
DCN	0.8–11%
DNC	0.8–12%