Evolution of planetary water: The perspective on planet formation and material transport in the Solar System

H. Kurokawa[1], H. Sakuraba[2], T. Shibuya[3], Y. Sekine[1], B. L. Ehlmann[4], and F. Usui[5]
1: ELSI. Tokyo Tech, 2: Tokyo Tech, 3: JAMSTEC, 4: Caltech/JPL, 5: Kobe Univ.

Asteroids in the outer Solar System are volatile rich and record the origins of planetary water. Their distribution in the main belt shows gradient in the spectral types (DeMeo et al. 2015) which are thought to be related to meteorites' classification: e.g., S-type – Itokawa, ordinary chondrites (Nakamura et al. 2011), C-type – carbonaceous chondrites (CCs)?, and D-type – Tagish Lake? (Fujiya et al. 2019), from the inner to outer population. However, several large outer main-belt asteroids show characteristic absorption features in infrared wavelengths at 3.1 μm (NH_4-saponite) and at 3.4 μm and 3.9 μm (carbonates) (Takir & Emery 2012; De Sanctis et al. 2015; Usui et al. 2019), which are no commonly found in CCs. The origins of those features and of the difference to CCs have not been elucidated.

By combining the data taken by AKARI space telescope (Usui et al. 2019) and the models for water-rock reactions and synthetic spectra, here we show that the C- and D-type asteroids having the diagnostic absorption features experienced reactions in the presence of NH_3 and CO_2, under the water-rock ratio (W/R) >1, and with the low temperature. Those results suggest that the asteroids formed beyond the NH_3 and CO_2 snow lines, experienced water-rock differentiation, and retained its water during the period of heating. CCs likely originate from the rocky cores of the differentiated bodies.

Earth's seawater is only a tiny fraction of the bulk Earth mass (0.023 wt.%). However, Earth's mantle and possibly core contain 1-10 M_{EO} and ~100 M_{EO} (as H) of water (Bodnar et al. 2013; Umemoto & Hirose 2020), where M_{EO} is the total mass of seawater. Consequently, Earth's hydrogen to carbon and hydrogen to nitrogen ratios (H/C and H/C) are higher than CCs. We propose that the discrepancy may be explained by the supply of volatile elements from the water ice-rich progenitors of the asteroids during the early stage of planet formation before the sublimation of water to space.

Evolution of planetary water:

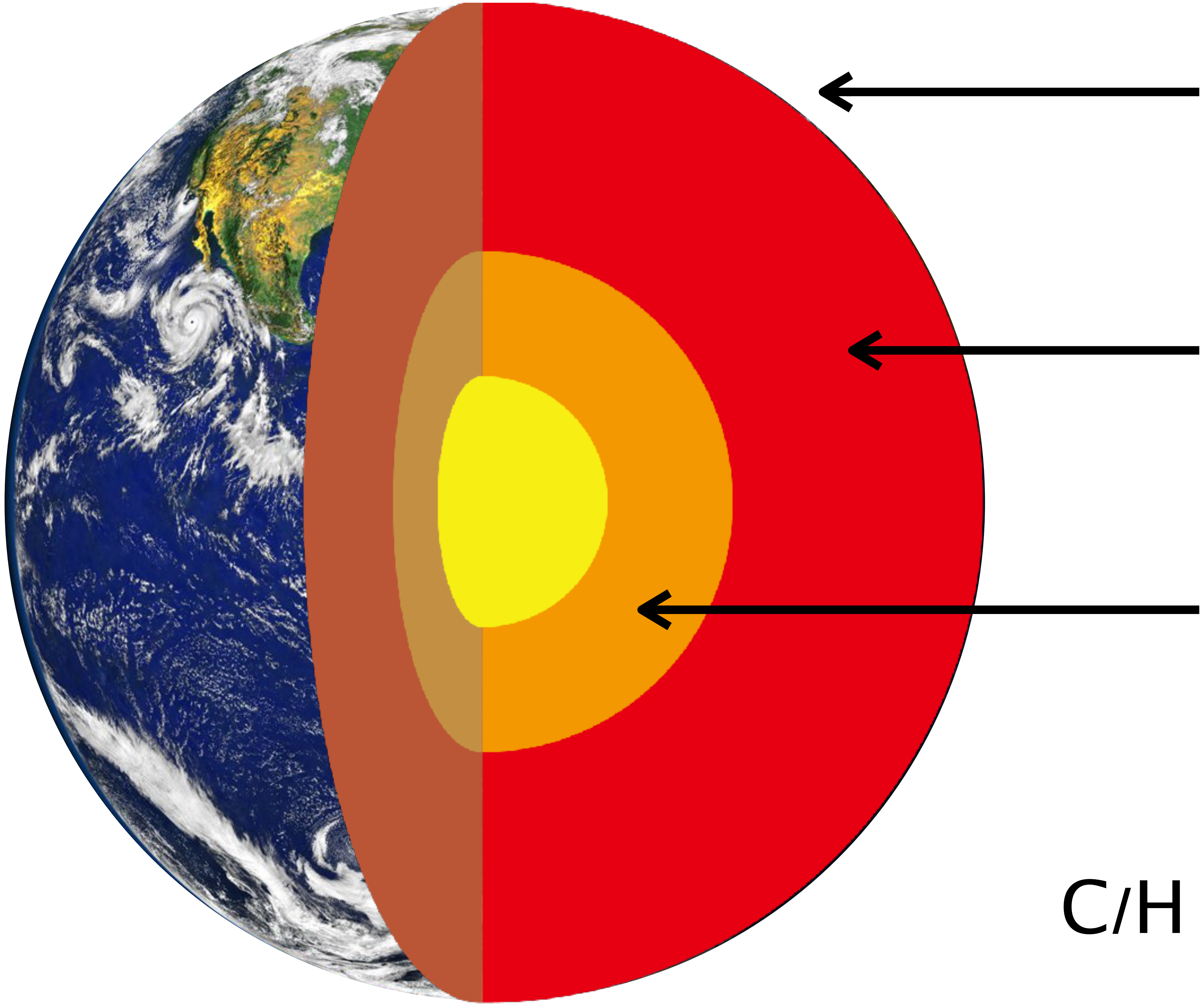
The perspective on planet formation and material transport in the Solar System

Hiroyuki Kurokawa (ELSI)

in collaboration with

Haruka Sakuraba (Tokyo Tech), **Takazo Shibuya** (JAMSTEC),
Yasuhito Sekine (ELSI), **Bethany L. Ehlmann** (Caltech),
Fumihiko Usui (Kobe Univ.)

Water budget of Earth



Oceanic water (H_2O):

1.4×10^{21} kg ($\equiv$ 1 M_{EO})

Mantle water (OH):

1–10 M_{EO}

(e.g., Bodnar et al. 2013)

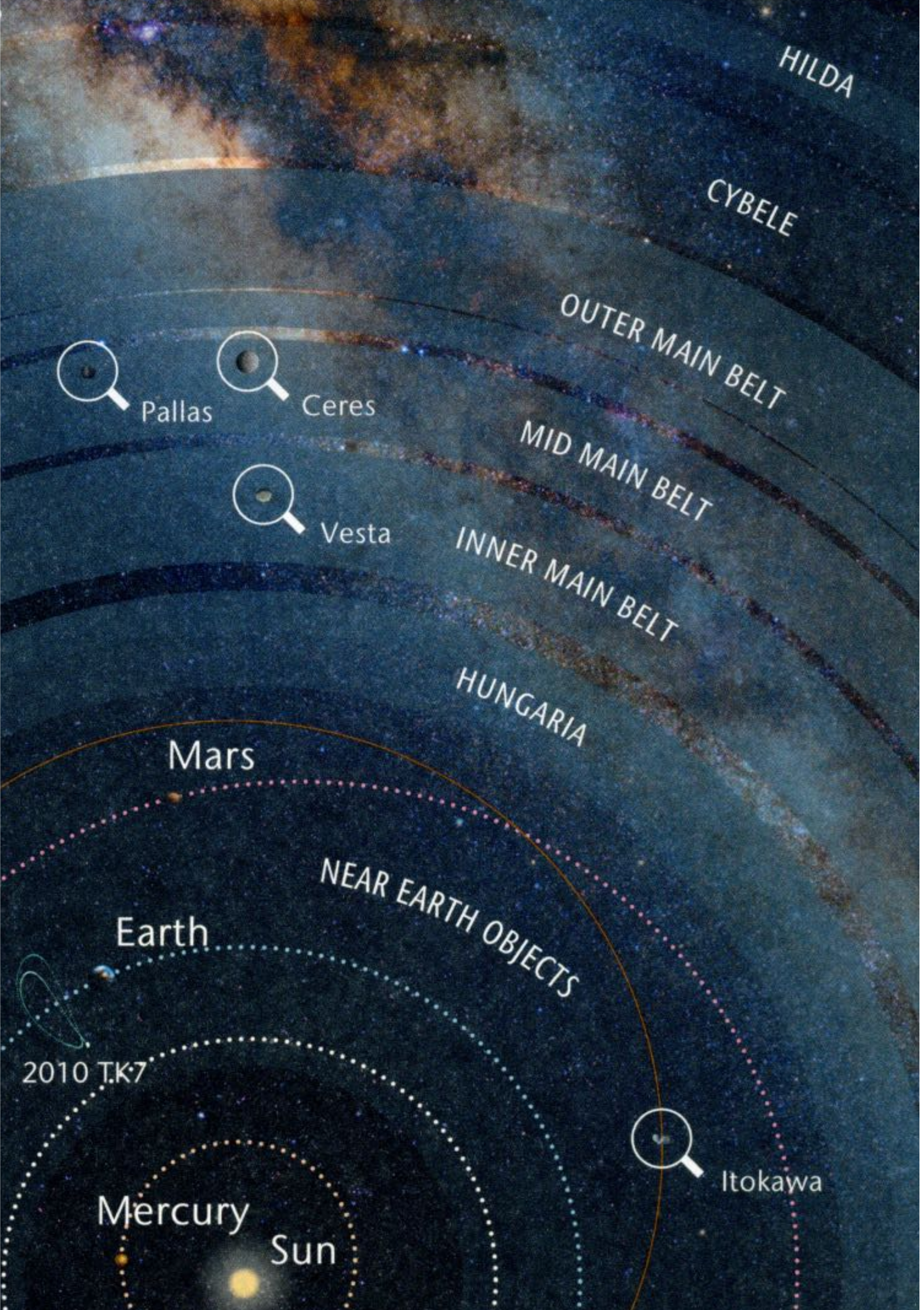
Core water (H):

~100 M_{EO}? (in maximum)

(Umemoto & Hirose 2015; 2020)

C/H & N/H lower than chondrites

(Hirschmann 2016)



Gradient in asteroids' spectral types and the link to meteorites

e.g., DeMeo et al. (2015)

D-type
= Tagish Lake (CC), micro meteorites?
(Fujiya et al. 2019)

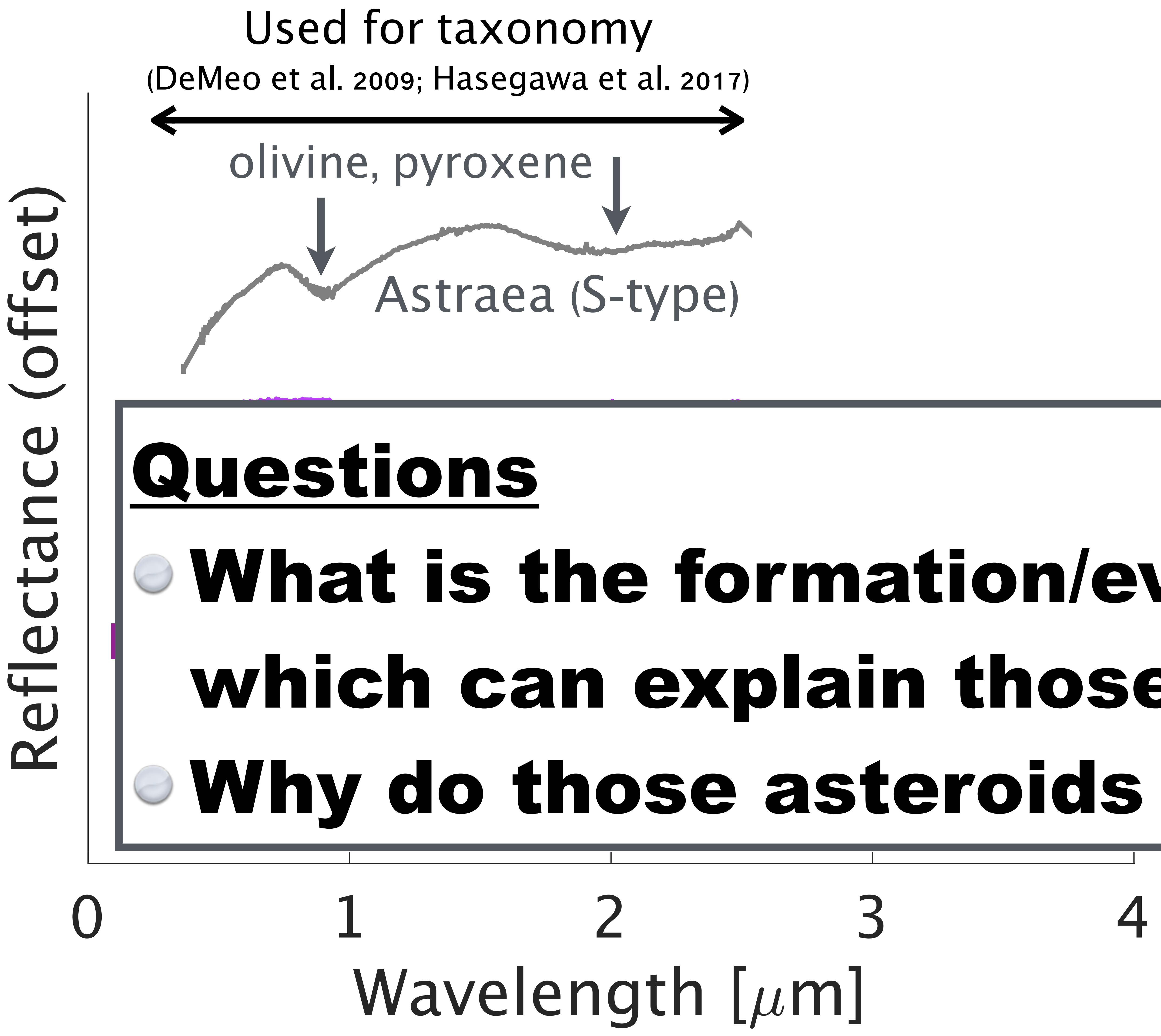
C-type
= Carbonaceous chondrites (CCs)?

S-type (Itokawa)
= Ordinary chondrites (Hayabusa samples)
(Nakamura et al. 2011)

and more

Asteroids in the outer SS are volatile rich and record the origins of planetary water

Infrared reflectance spectra



AKARI satellite detected characteristic absorption features on large (> 100 km) C- and D-type asteroids

2.7 μm abs.

-Hydrous minerals (OH)

-Carbonates (CO_3)

-NOT abundant in CCs

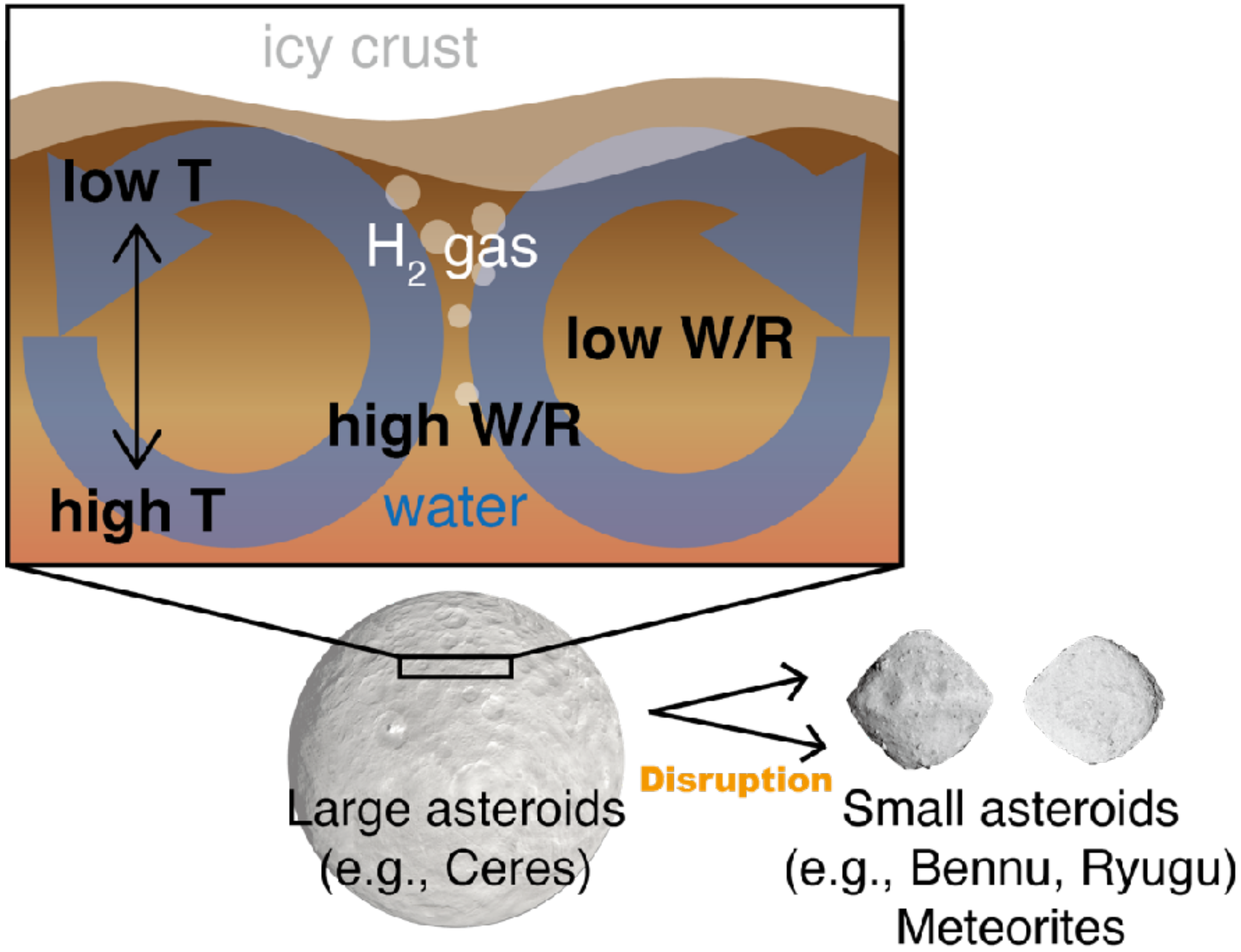
Questions

- **What is the formation/evolution history which can explain those features?**
- **Why do those asteroids look differently from CCs?**

Modeling water-rock reactions in asteroids

Purpose

- Constrain their initial bulk compositions
- Discuss the formation history of asteroids and the origin of Earth's water



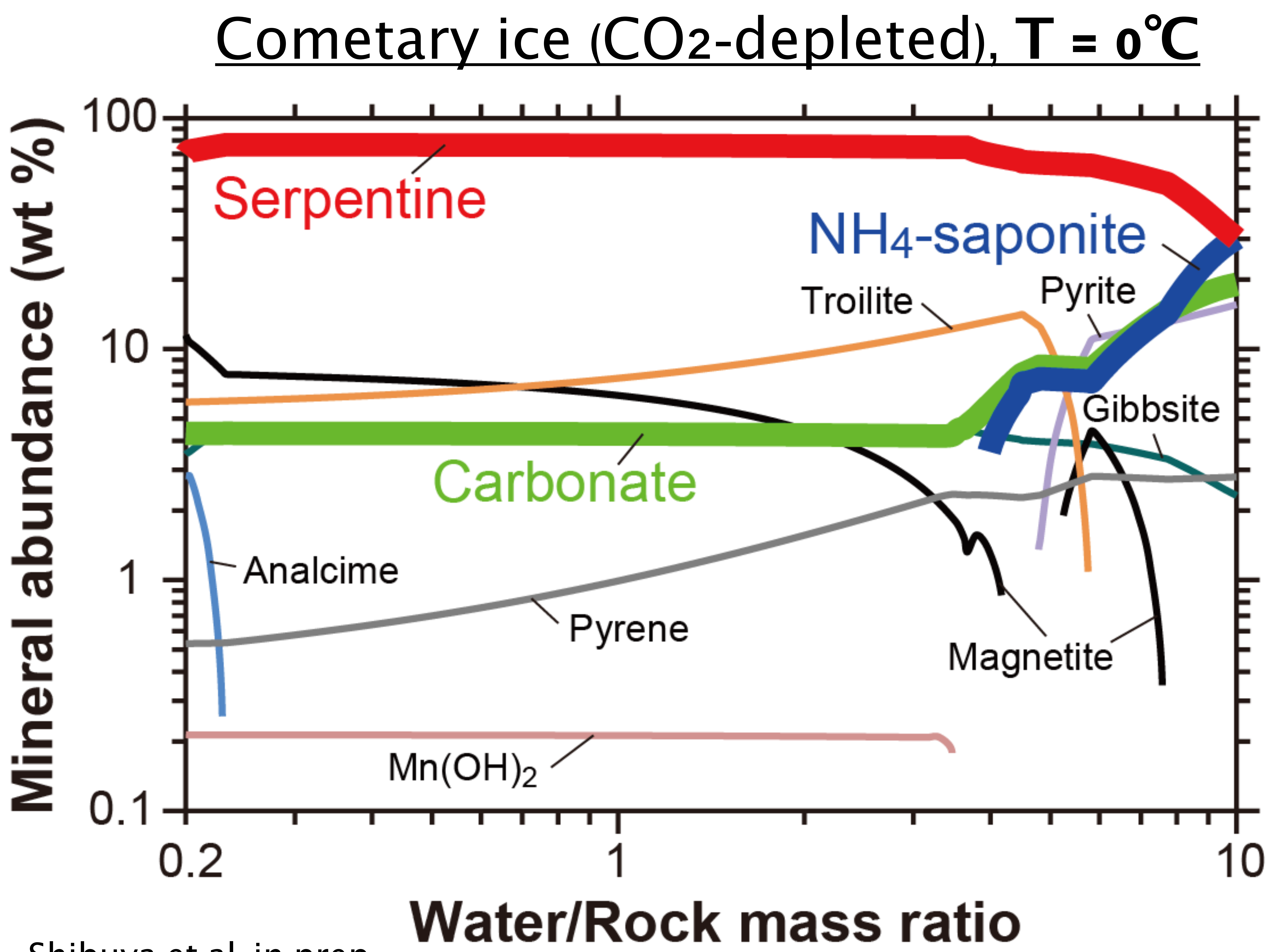
Chemical equilibrium calculations

- CV chondrite + H_2O + NH_3, H_2S, & CO_2
- Parameters: water-rock ratio (W/R),
  temperature,
  CO_2 abundance

Synthetic spectra calculations

- Parameter: grain size
- Compare to AKARI observations

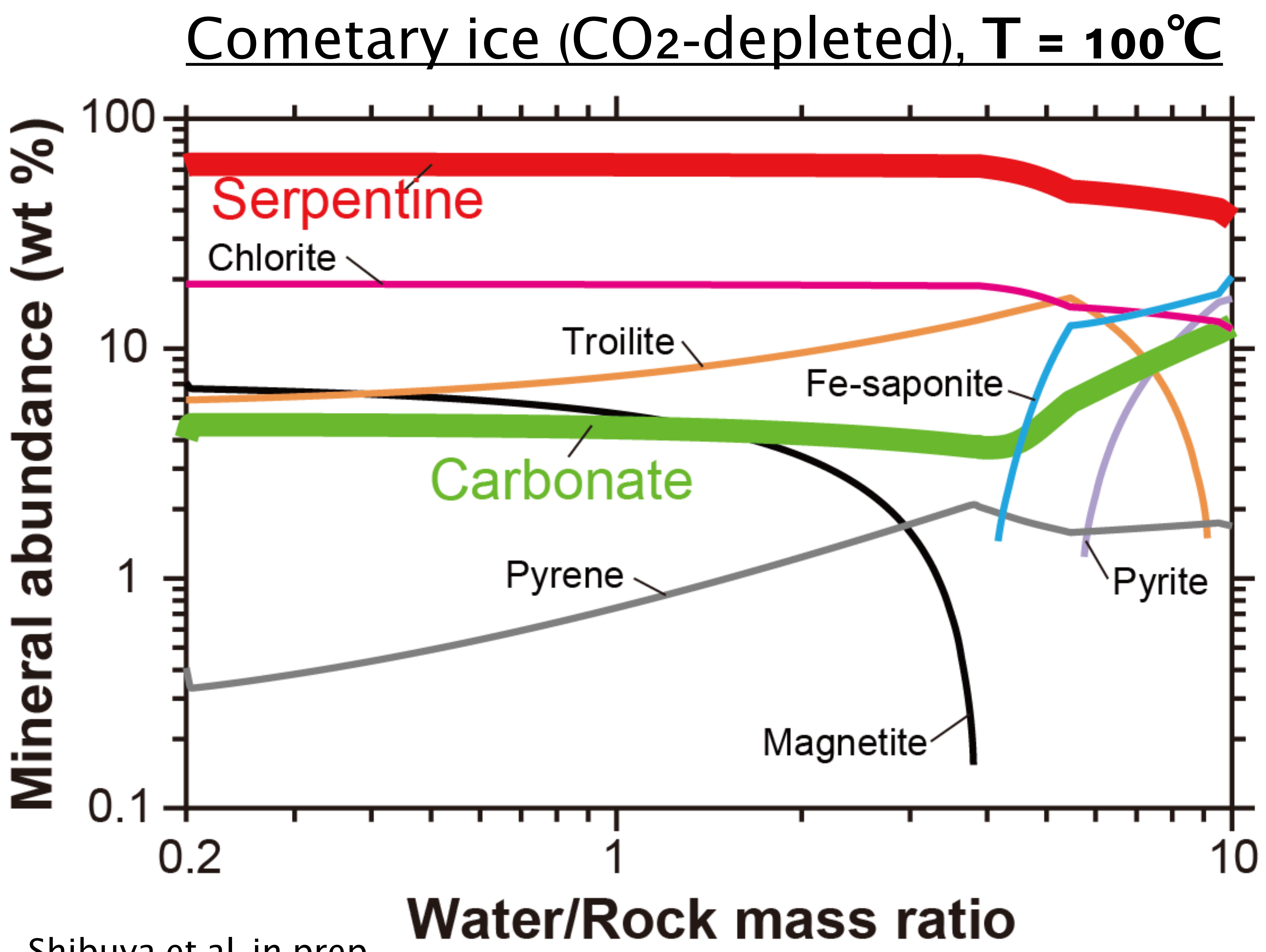
Results: mineral abundance



Shibuya et al. in prep.

- **Hydrous minerals** dominate for the wide range of W/R & T(< 350℃)
- **NH_4-saponite** forms at high W/R & T ~ 0℃
- **Carbonates** become abundant at high W/R

Results: mineral abundance



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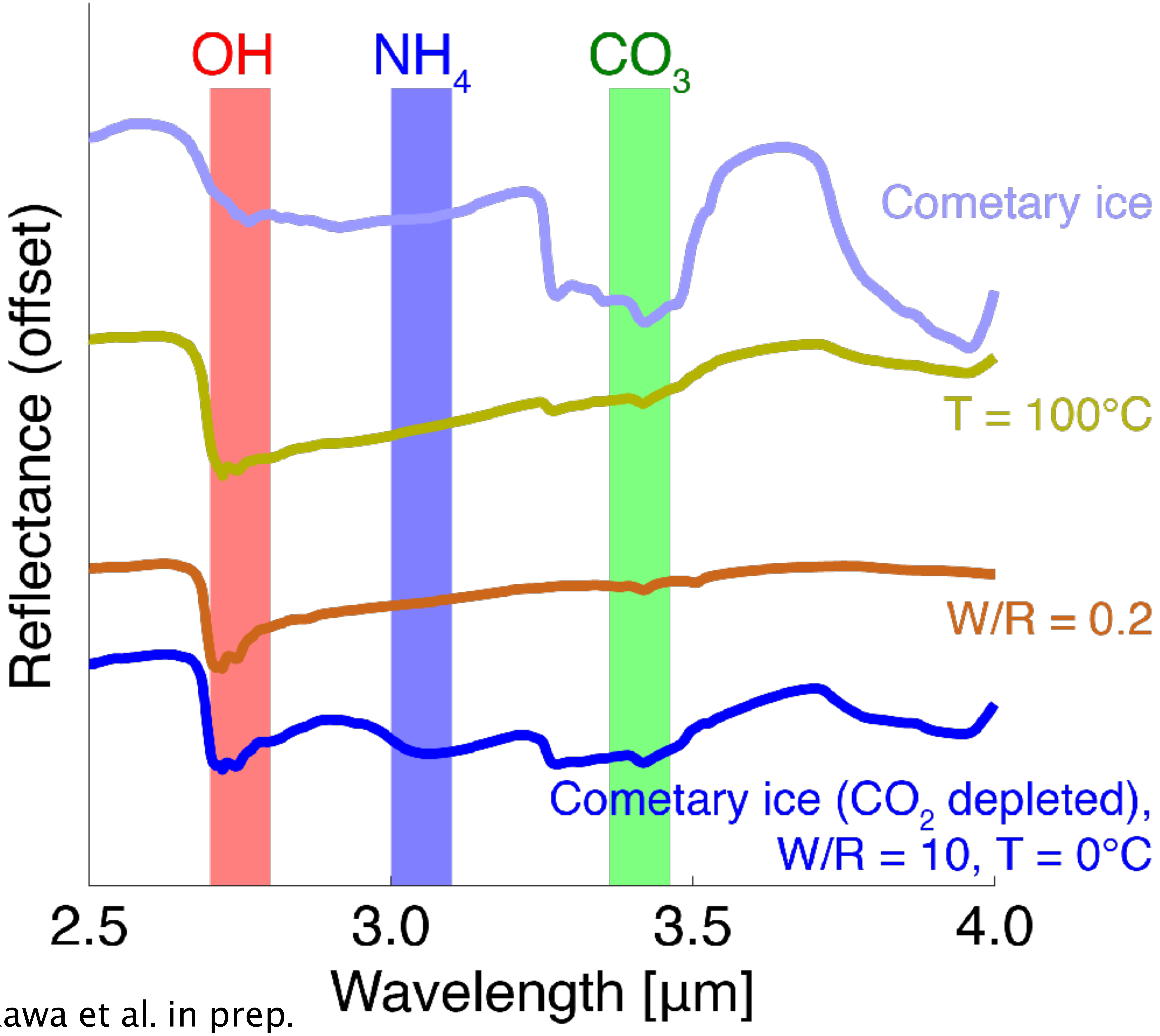
Results: reflectance spectra



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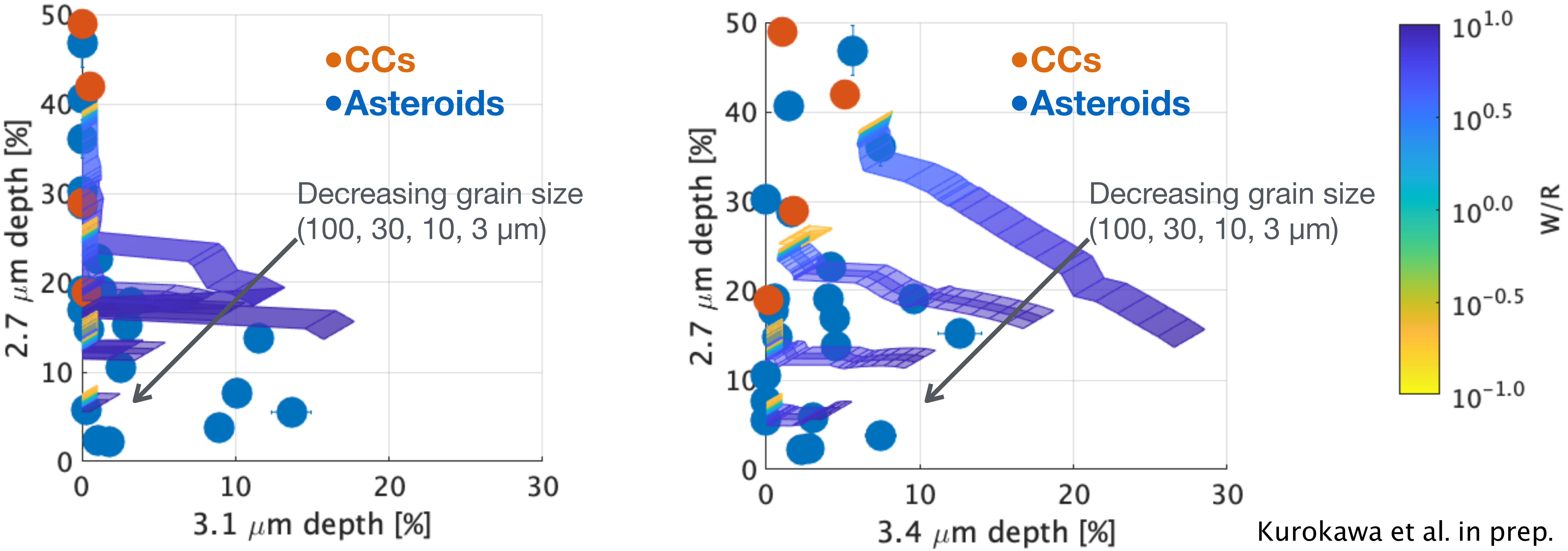
Comparison to observations

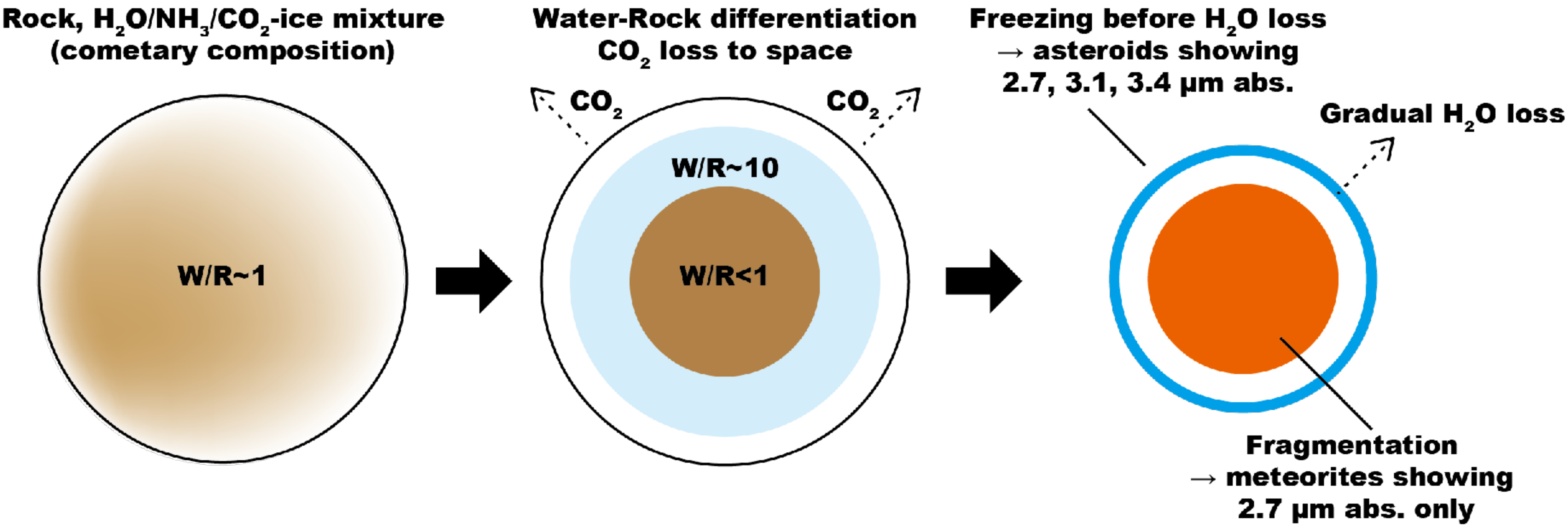
Cometary ice (CO_2-depleted), T = 0℃



Kurokawa et al. in prep.

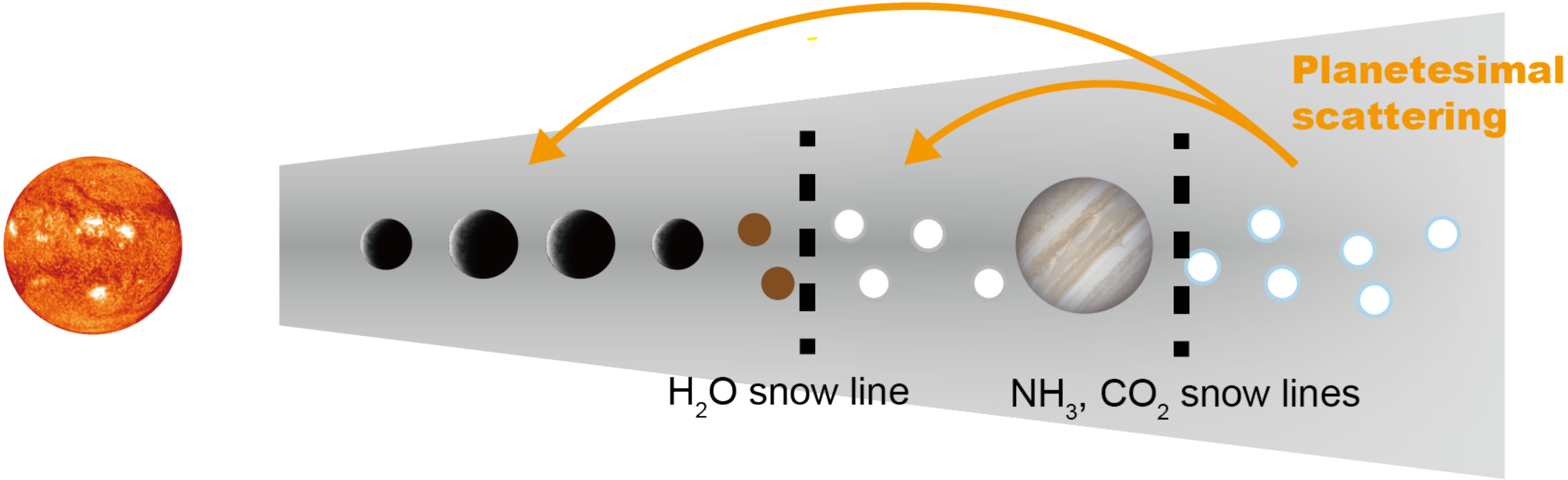
- Asteroids and CCs can be explained by W/R>1 and W/R<1, respectively
- Variation in abs. depths reflects variation in parameters such as grain size

Scenario for asteroid formation & evolution



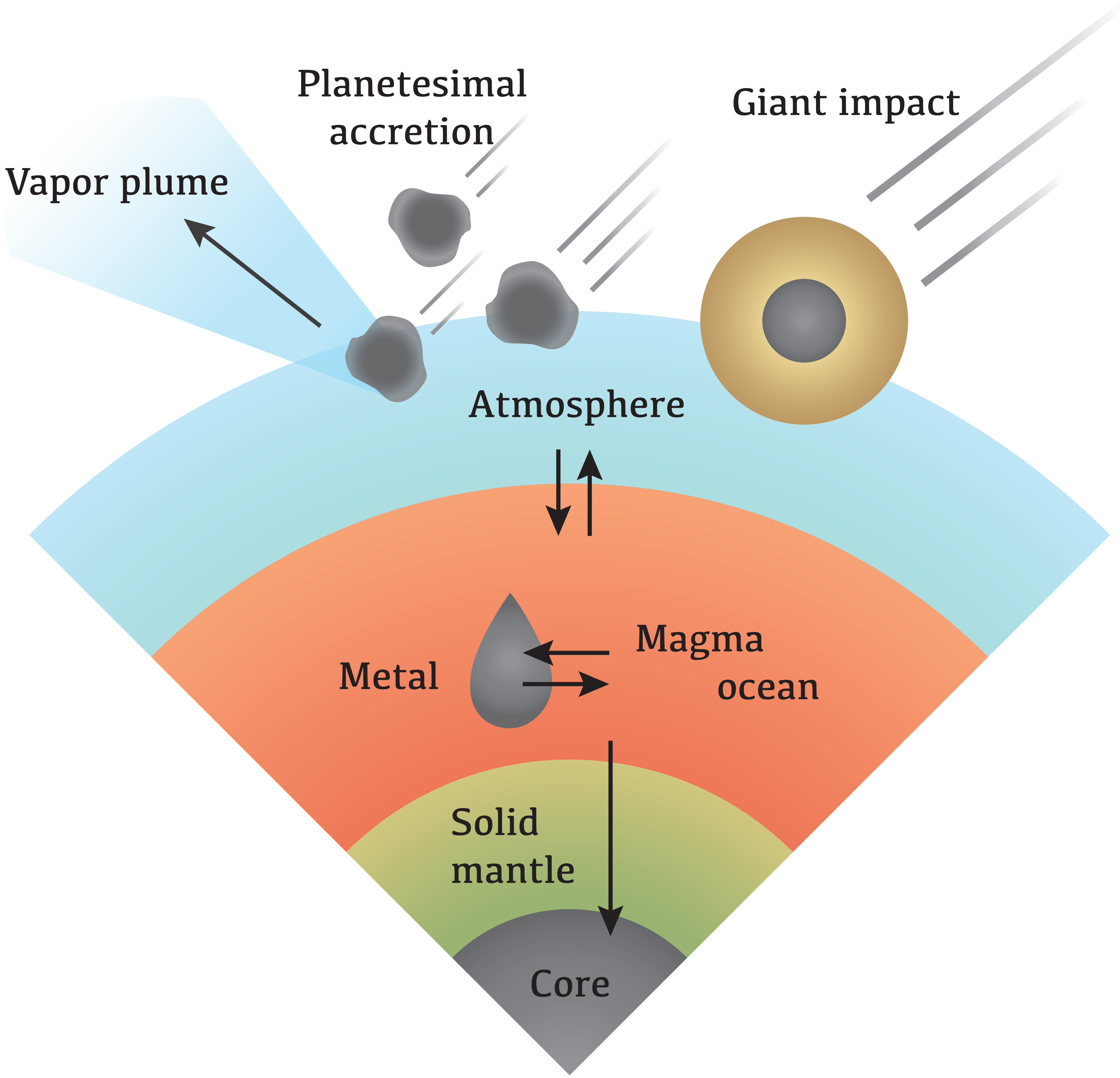
- C- & D-type formed as rock and $H_2O/CO_2/NH_3$ ice mixtures
- Differentiate to outer high W/R (asteroid surface) and inner low W/R (meteorites)
- Quenching at 0℃ suggests H_2O loss is slow (> heating period ~10^7 years)

Implications for planet formation



- C- and D-type asteroids formed beyond NH_3 and CO_2 snow lines
- They were scattered to the main belt by giant planets
  - -Grand Tack (Walsh et al. 2011)
  - -Inward migration of Jupiter formed beyond N_2 snow line (Öberg & Wordsworth 2019)

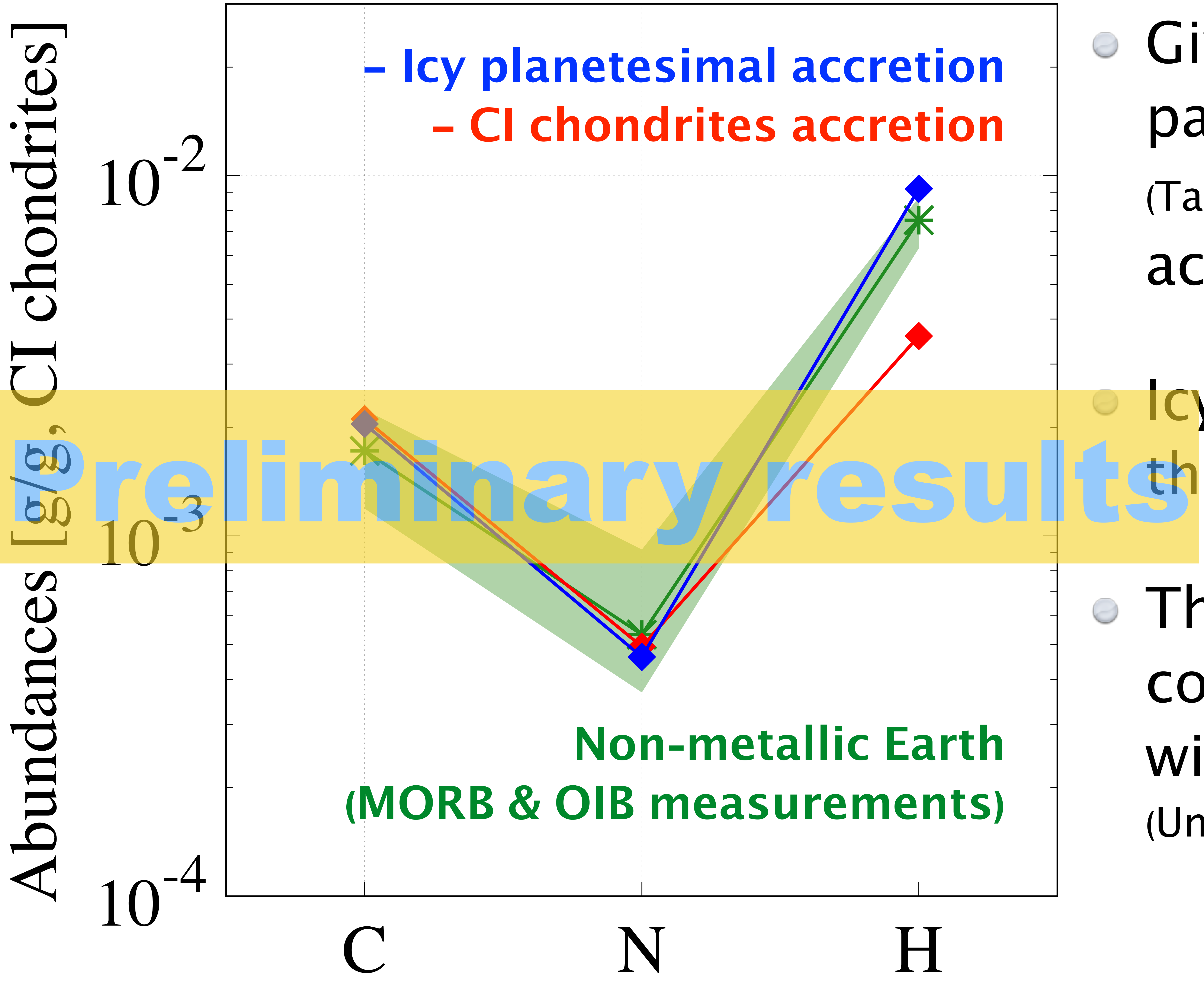
Early volatile delivery



- Planetesimal scattering due to giant planets' migration led to volatile delivery during Earth's accretion
- Partitioning of H into core-forming metal removes a large amount of water from non-metallic Earth
(Okuchi 1997; Tagawa et al. submitted)

Sakuraba, Kurokawa et al. submitted
Sakuraba & Kurokawa in prep.

Icy planetesimals solve water budget



- Given a recent estimate of H partitioning coefficient into metal (Tagawa 2020 PhD thesis), CI chondrites accretion results in water deficit
- Icy planetesimal accretion solves the water deficit problem
- The resulting H abundance in the core is 1 wt.% (~ 100M_{EO}), consistent with the geophysical constrains (Umemoto & Hirose 2015; 2020)

Sakuraba, Kurokawa et al. submitted
Sakuraba & Kurokawa in prep.

Implications for exploration missions

- **Revisit asteroid taxonomy with further telescopic observations**
  (C-type asteroids have already been shown to be diverse in NIR!)
  - Twinkle, JWST, ground telescope in near infrared
  - SPICA in mid infrared
  - LUVOIR in ultraviolet
- **Understand asteroids-meteorites relation**
  - Hayabusa2, OSIRIS-REx to C/B-types
  - MMX, OKEANOS, and Lucy to D/P-types
- **Test the layered model hypothesis for large asteroids**
  (Surface covered by high W/R products!)
  - e.g., future Ceres lander

Summary

- The presence of 3.1 and 3.4 μm absorption features on many C- and D-type asteroids suggests their formation beyond CO_2 and NH_3 snow lines, water-rock differentiation, and retention of H_2O for a long time
- Accretion of the ice-rich asteroids onto proto-Earth can explain low C/H and N/H ratios in non-metallic Earth as well as possible huge H content in the core