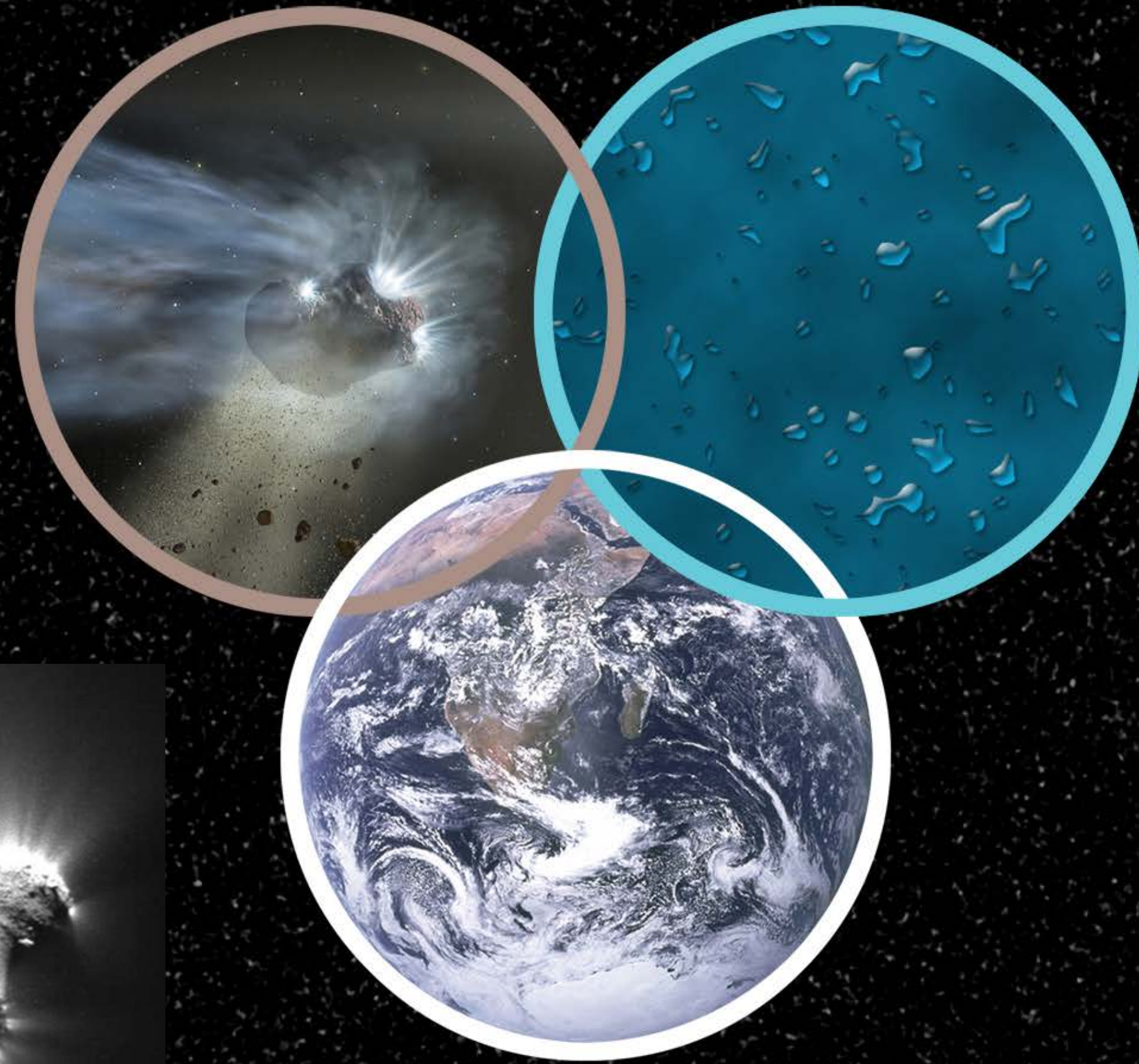


Comets and the Origin of Earth's Water

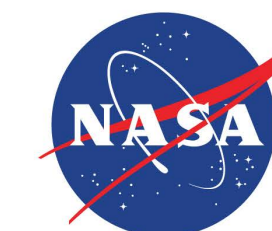


Darek Lis

JPL/Caltech

SOFIA Instrument Roadmap Workshop

June 24, 2020



Jet Propulsion Laboratory
California Institute of Technology

Strategic Significance and Science Goals



Credit: NASA/ESA

Strategic Significance for the NASA Science Mission Directorate

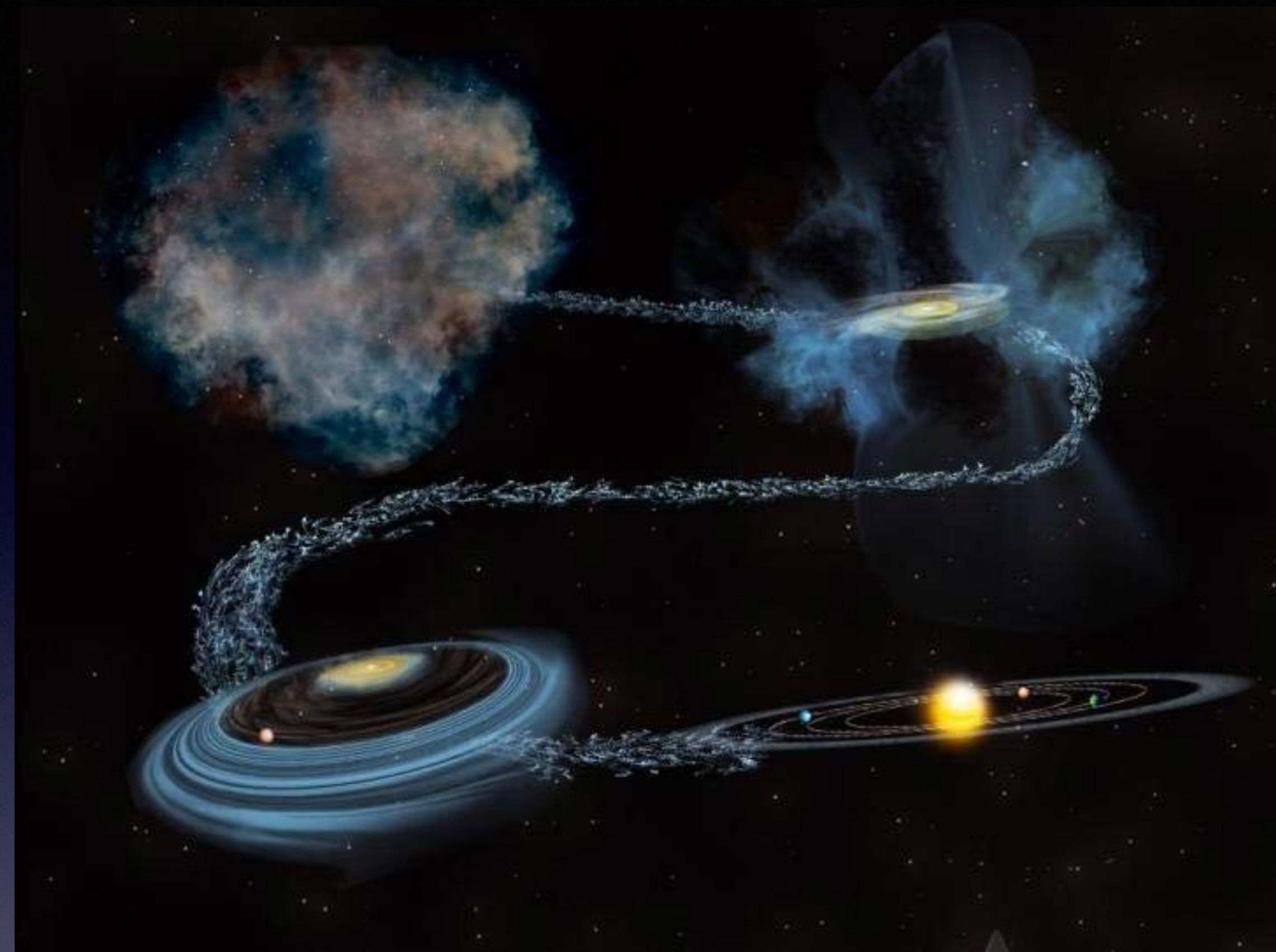
- Understanding how the Earth obtained its water and whether water-rich Earth-like planets are common in the Universe is one of the central themes in NASA's vision
- The 2013 Planetary Decadal Survey *Vision and Voyages* explicitly identified "determining the deuterium/hydrogen and other crucial isotopic ratios in multiple comets" as key measurements for understanding Solar System beginnings

Overarching Science Goals

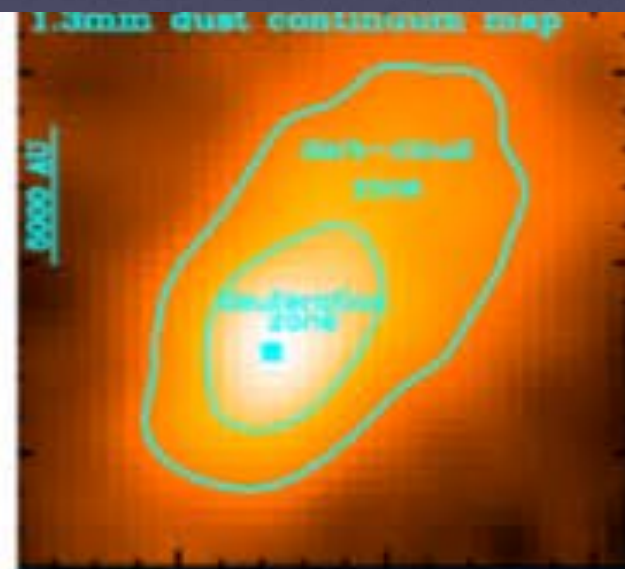
- Understand what governed the accretion, supply of water, and chemistry of the inner planets, and what role did bombardment play
- Understand pre-solar processes recorded in materials of primitive bodies
- Understand what were the initial stages, conditions, and processes of Solar System formation and the nature of interstellar matter that was incorporated

Cosmic Inheritance of Water

- Water, a key ingredient for life, forms efficiently on cold dust grain surfaces and is abundant in interstellar clouds.
- Are there universal pathways leading from this interstellar reservoir of water to forming planetary systems?
- Is the Solar System water content representative of other planetary systems, or has it been shaped by local processes?
- Cold water can be best studied via far-infrared spectroscopy



WATER IN INTERSTELLAR CLOUDS



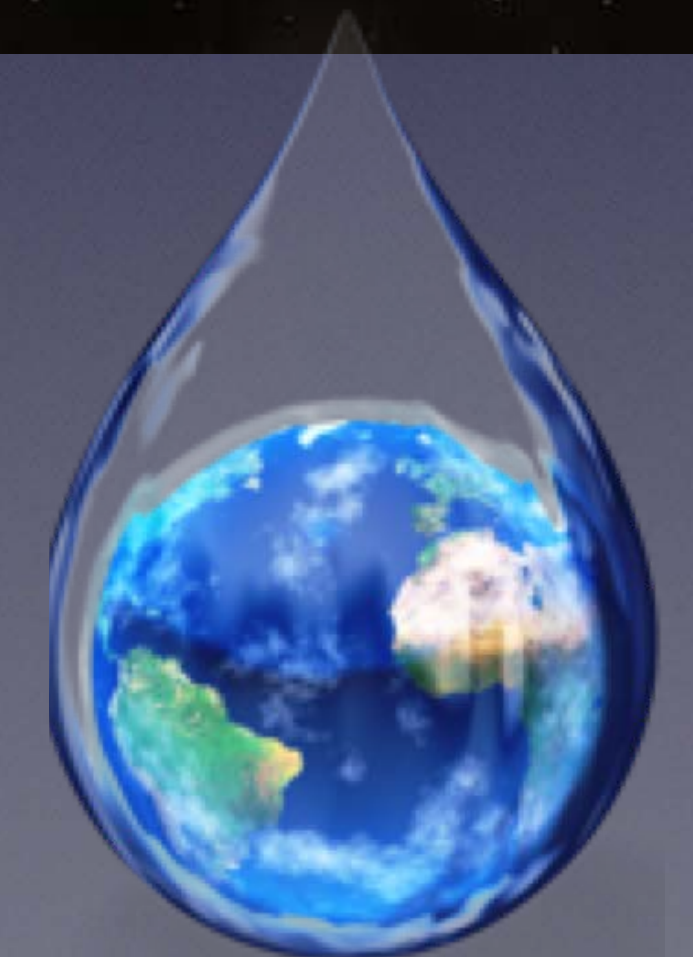
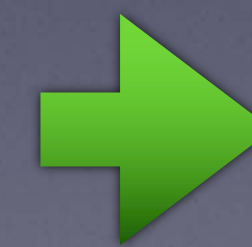
WATER IN CLOUD CORES



WATER IN PROTOSTELLAR DISKS

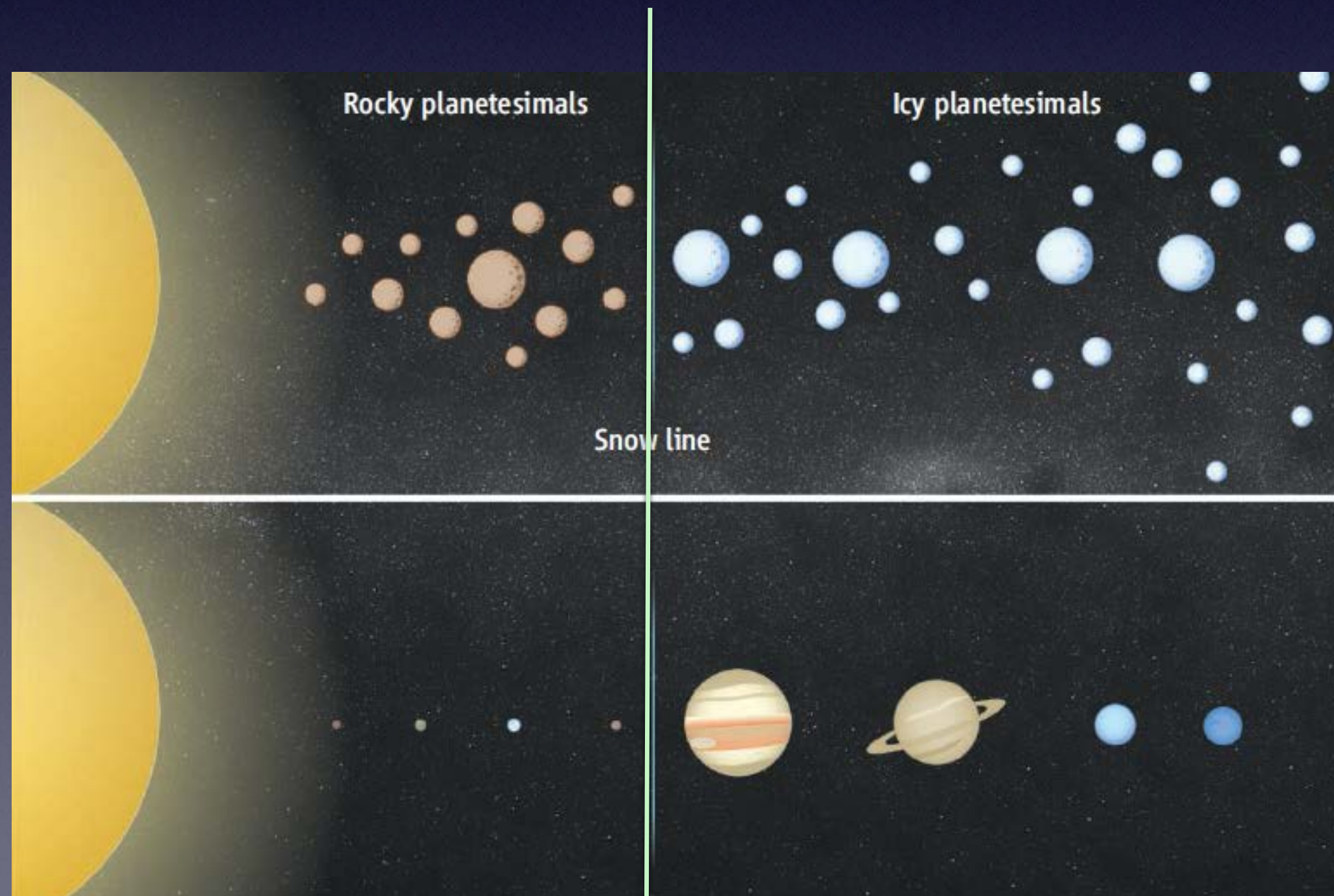


WATER IN THE SOLAR SYSTEM

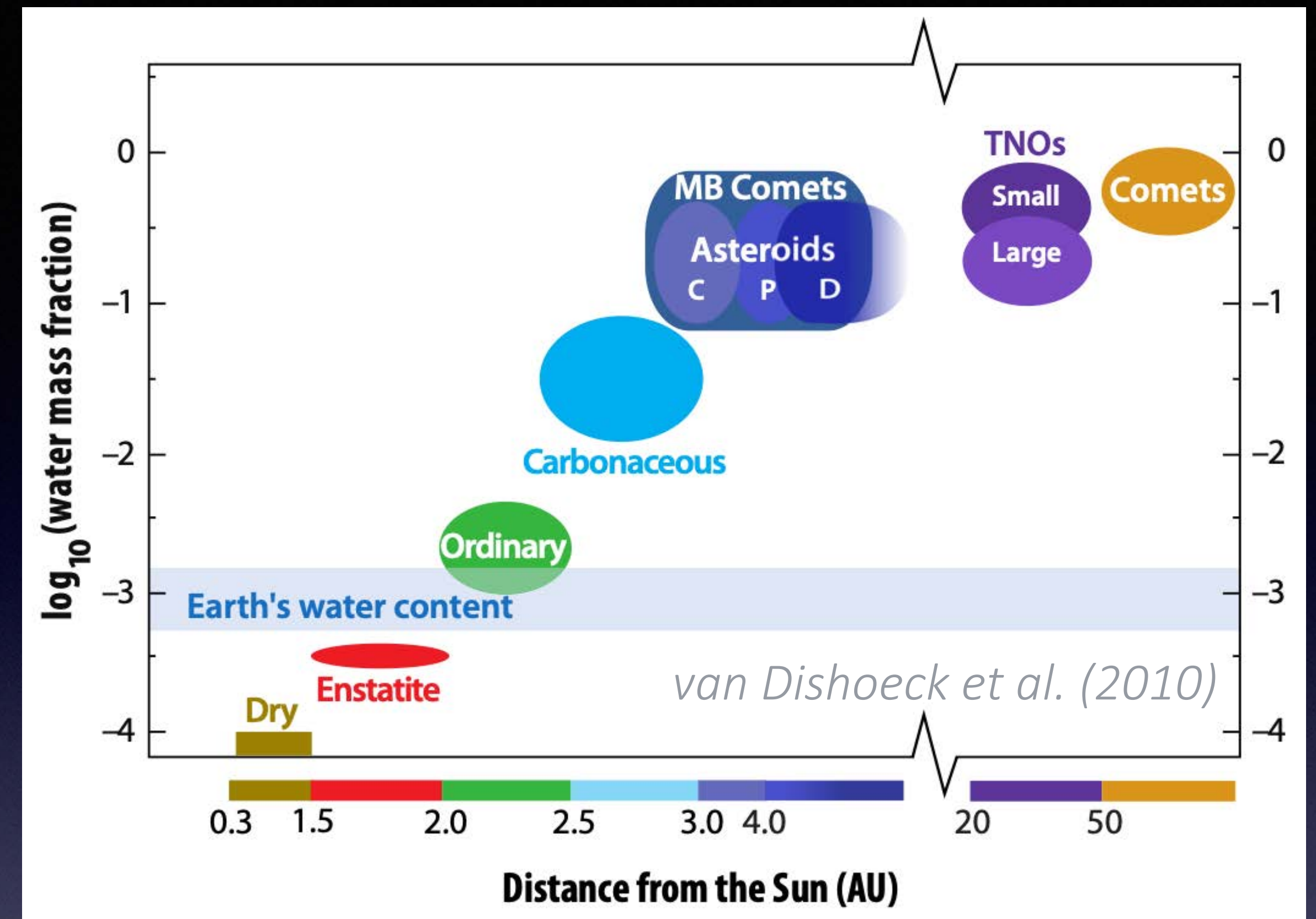


Once upon a time the Earth formed dry

Snow Line

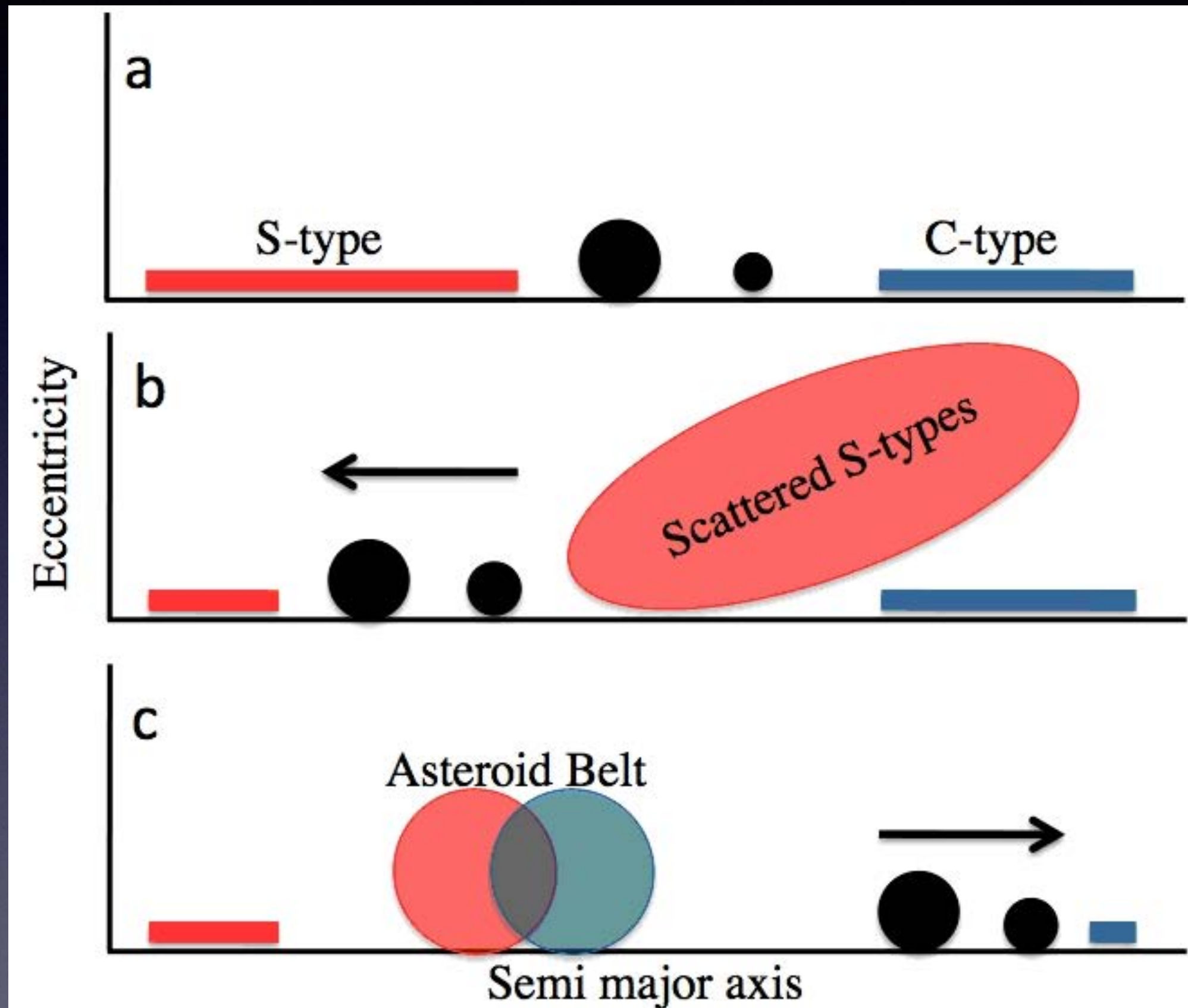


Akeson (2011)

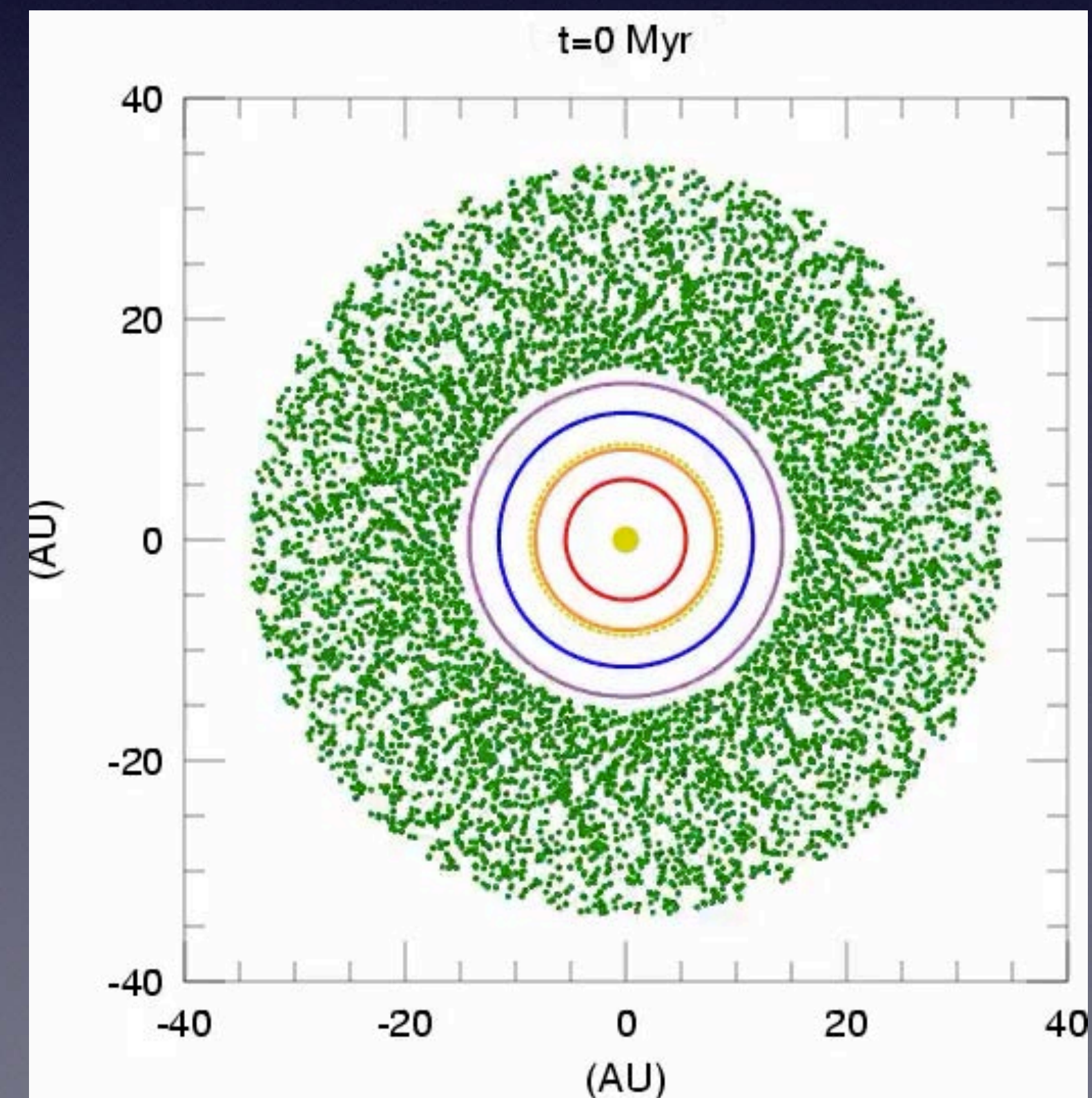


- Water mass fraction increases with distance from the Sun
- “Textbook model”: temperature in the terrestrial planet zone too high for water ice to exist
- Water and organics were most likely delivered later by comets or asteroids
- Alternative: water could have survived, incorporated into olivine grains or through oxidation of an early H atmosphere by FeO in the magma ocean

Complex Solar System Dynamics



- Grand Tack Model: inward then outward migration of Jupiter and Saturn (~5 Myr)
- Nice Model: Saturn's migration into 2:1 orbital resonance with Jupiter — Late Heavy Bombardment (~800 Myr)



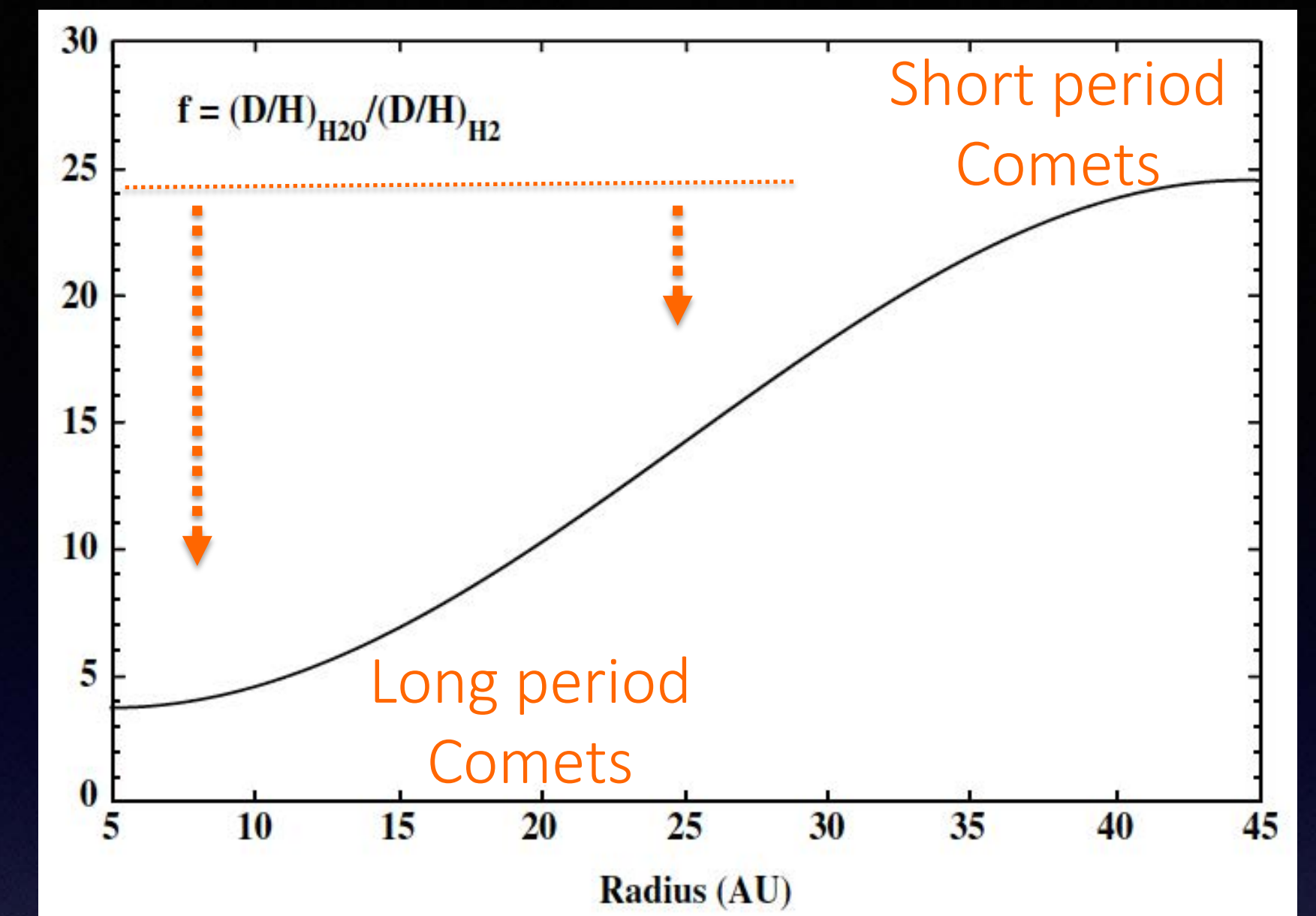
Walsh et al. 2011
Gomes et al. 2005; Tsiganis et al. 2005;
Morbidelli et al. 2005

H. Levison
(SwRI)

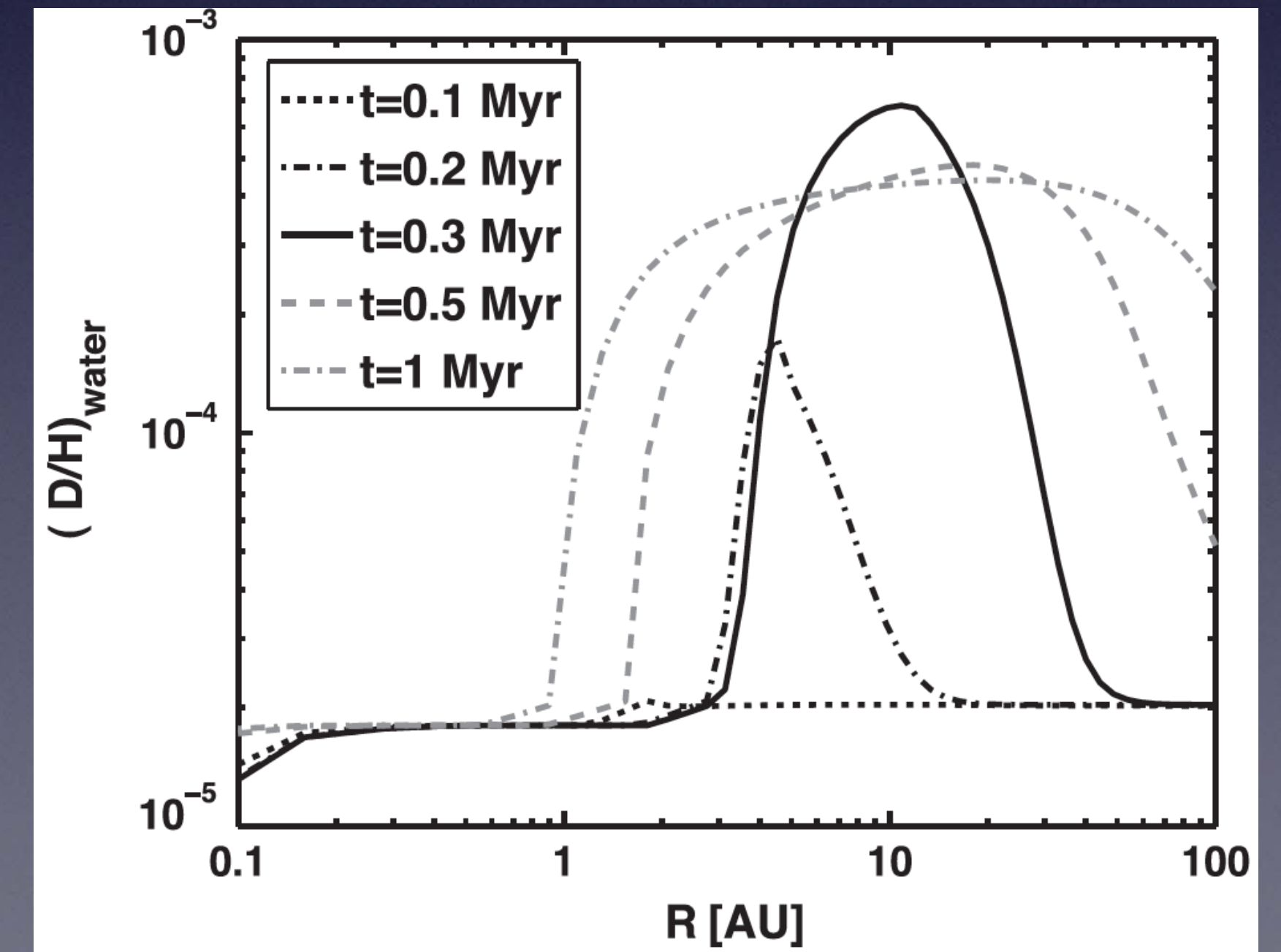
D/H in Water in the Solar Nebula

- Deuteration is a key fingerprint for tracing the origin and history of water
- Water was initially synthesized by interstellar chemistry with a high D/H ratio ($>7.2 \times 10^{-4}$; highest value measured in clay minerals)
- The D/H ratio in the solar nebula then gradually decreased with time
- Turbulent mixing of grains condensed at different epochs and locations in the solar nebula leads to a D/H gradient

- Other models show more complex time dependent behavior
- Need observational data, in particular for the outer Solar System



Horner et al. (2007)



Yang et al. (2013)

Isotopic Ratio Measurements



OSIRIS-REx



Deep Impact/EPOXI



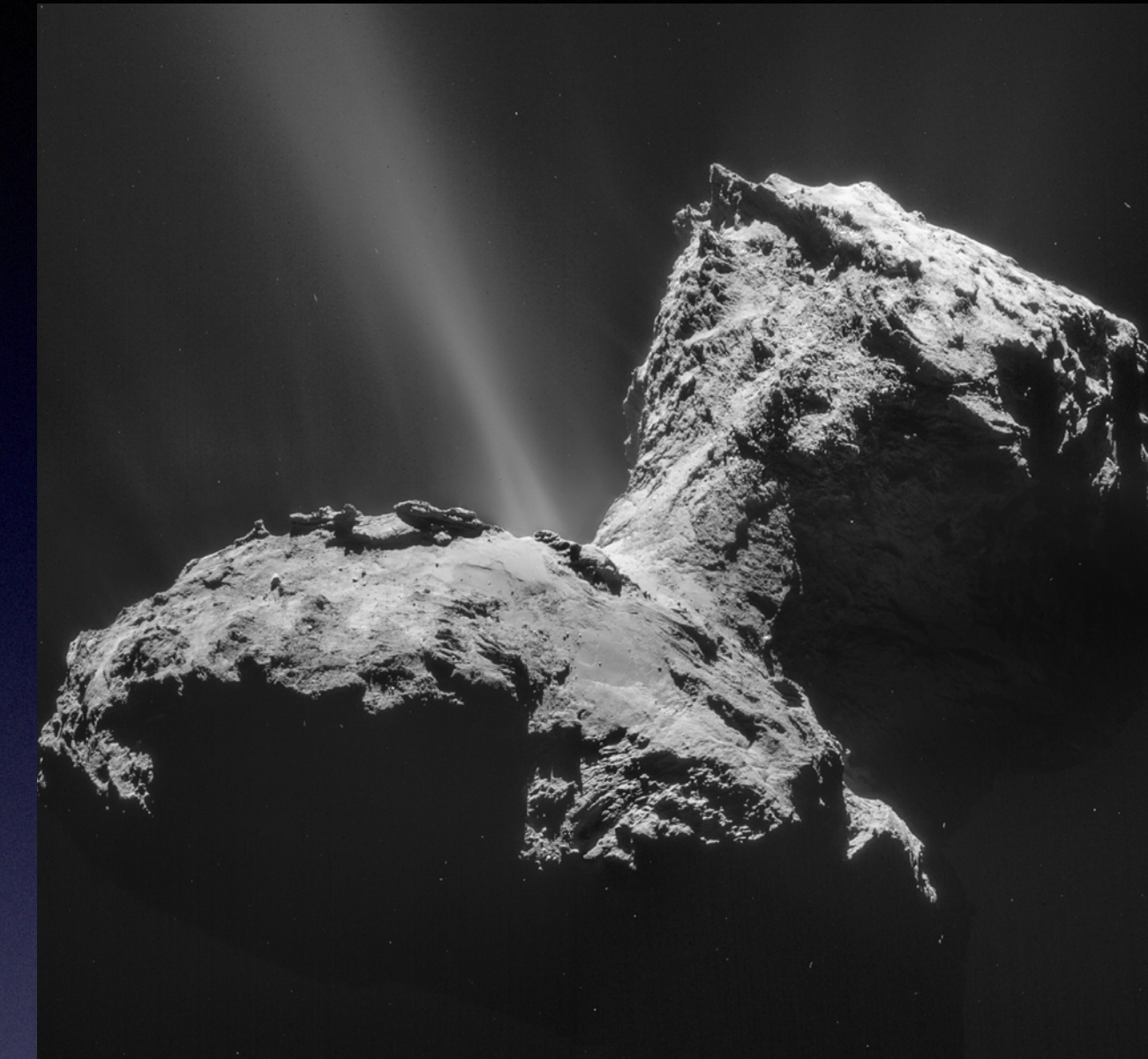
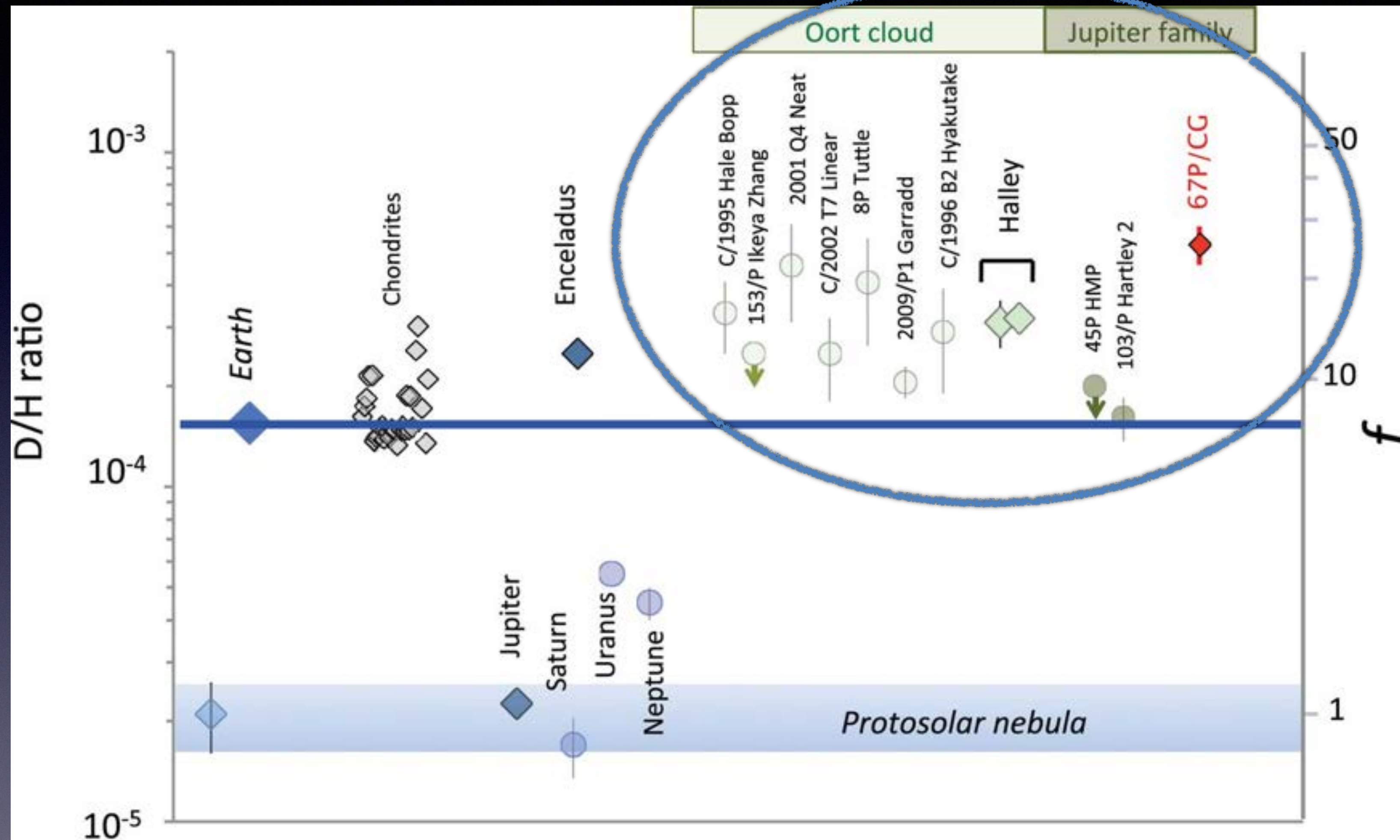
Herschel



Rosetta

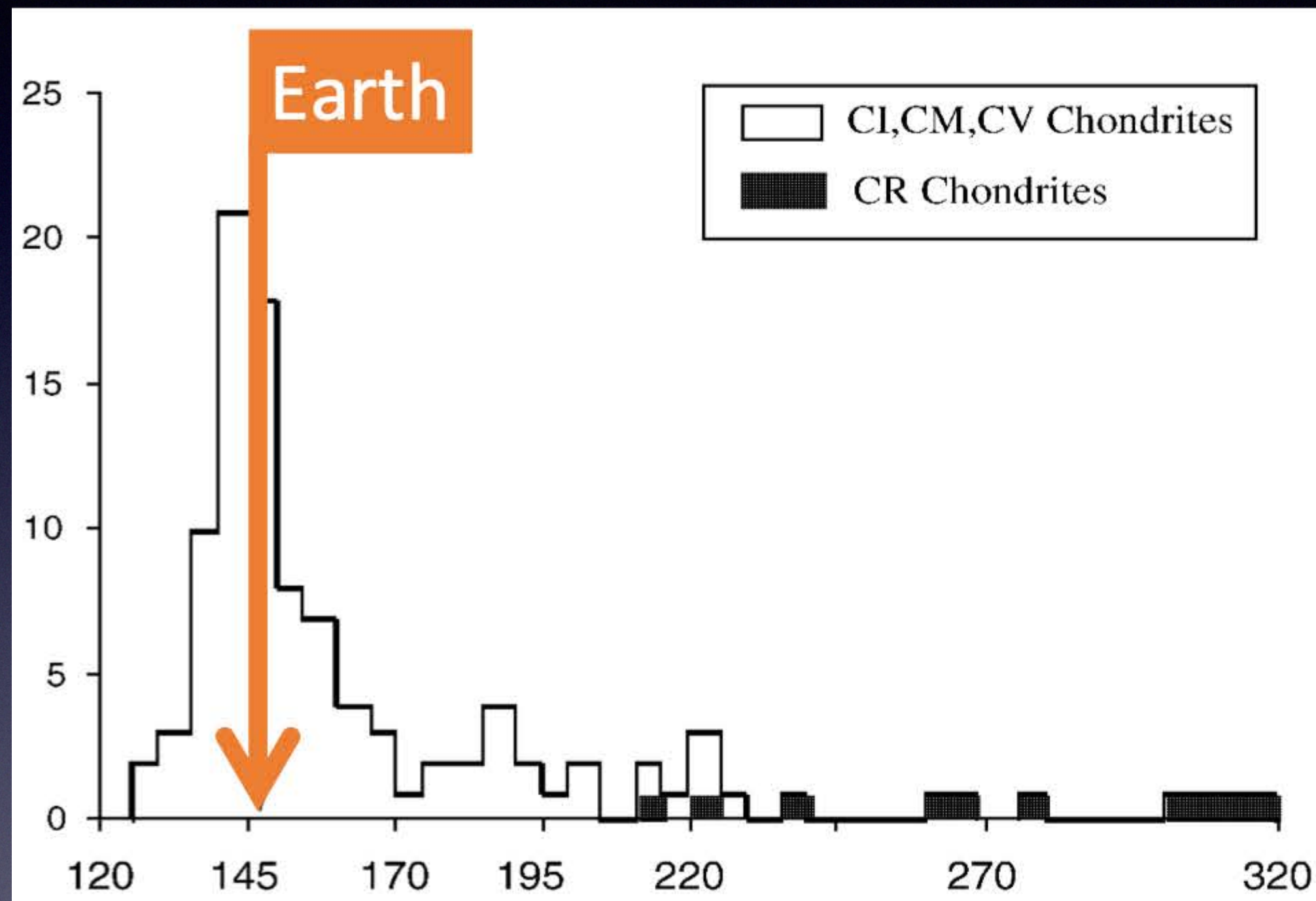
- Remote sensing — statistical studies of objects that have atmospheres
- Sample return or in-situ — detailed studies of individual objects

D/H Observations

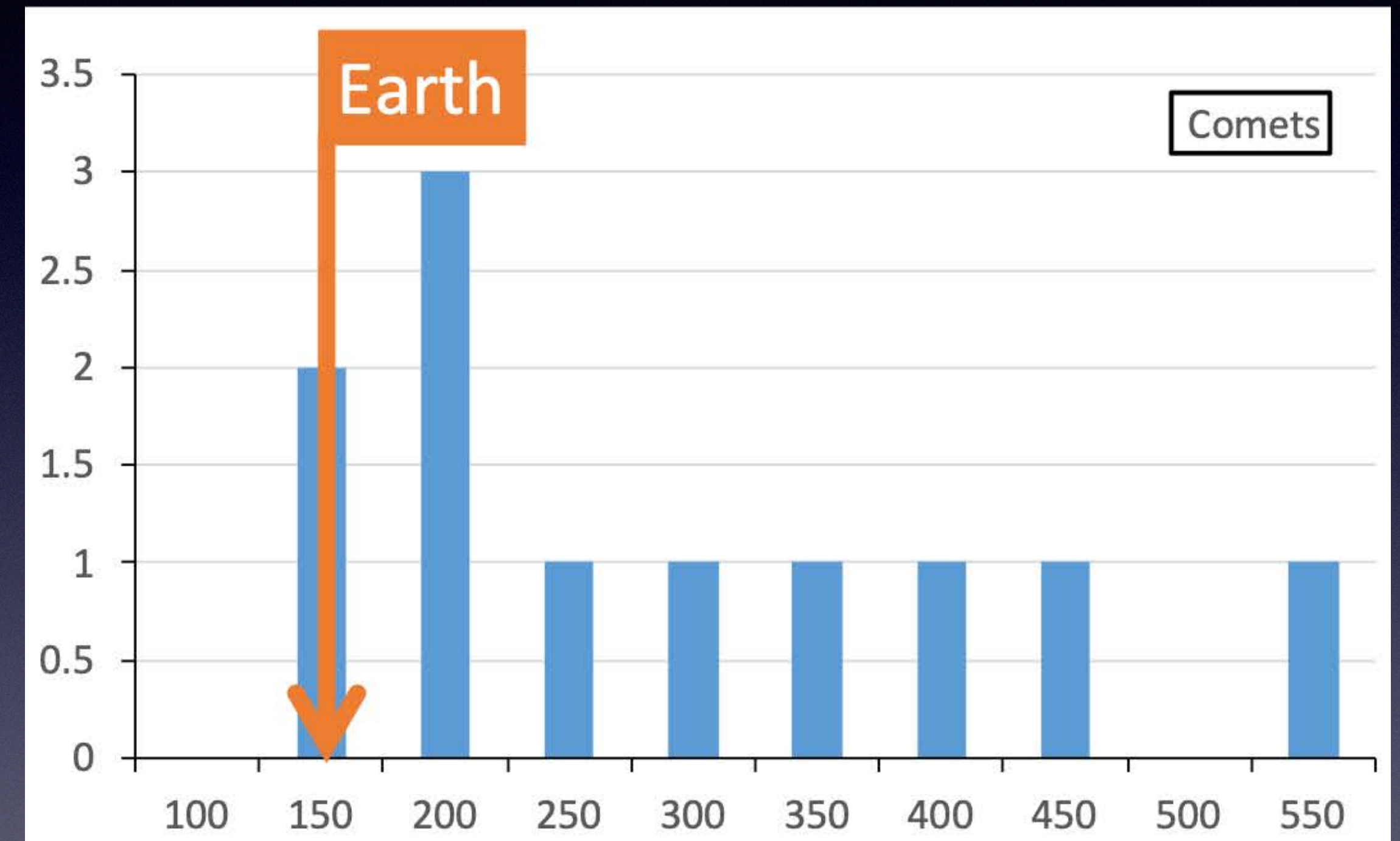


- Comets: variations between one and three times the terrestrial value
- No trends with physical or dynamical parameters

D/H Distribution Inner vs. Outer Solar System



Robert (2006)



- D/H in the inner Solar System relatively well constrained by measurements in meteorites

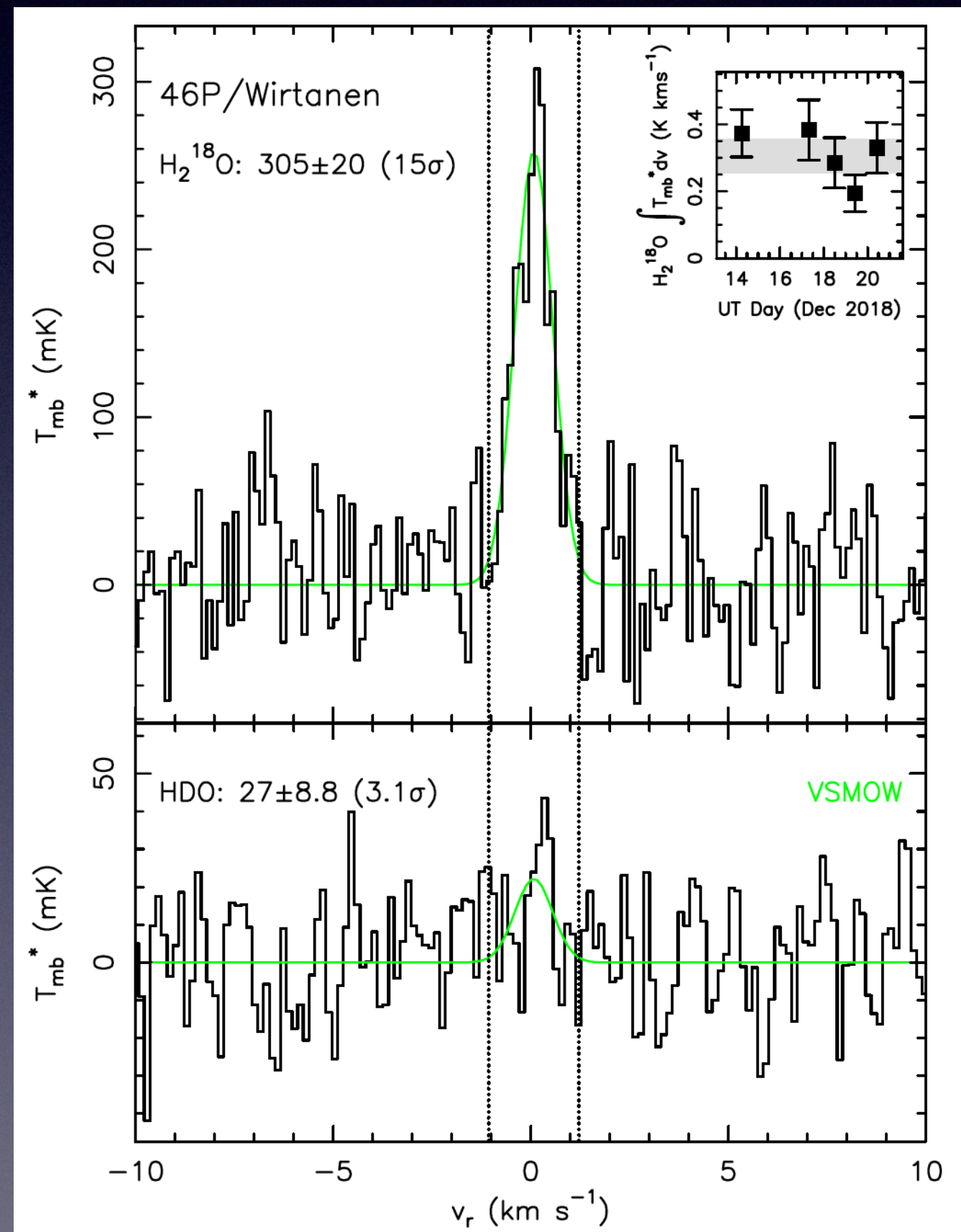
- D/H in the outer Solar System poorly constrained — few measurements with large uncertainties (15-40%, 1σ)
- Need better statistics!

Comet 46P/Wirtanen

SOFIA/4GREAT

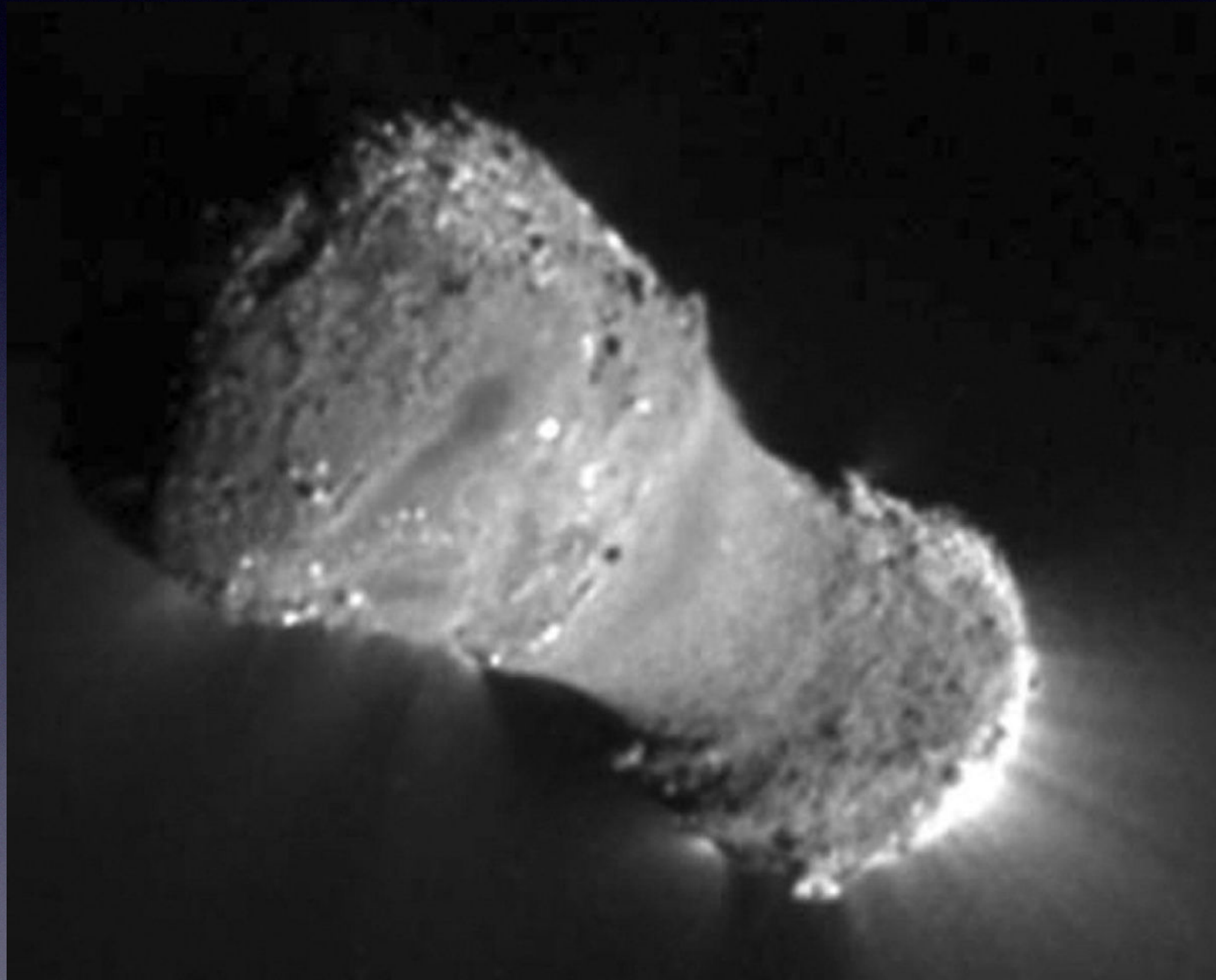


Image: V. Cheng



- Perihelion at 1.06 au from the Sun on 12/12/18
- Closest approach to the Earth at 0.08 au on 12/16/18
- Five SOFIA/4GREAT flights between 12/14 and 12/20 (GT+DDT)
- $D/H = (1.61 \pm 0.65) \times 10^{-4}$ (including statistical, calibration, modeling, and $^{16}\text{O}/^{18}\text{O}$ ratio uncertainties)
- Third Jupiter-family comet with a terrestrial D/H ratio in water
- What is special about these comets?

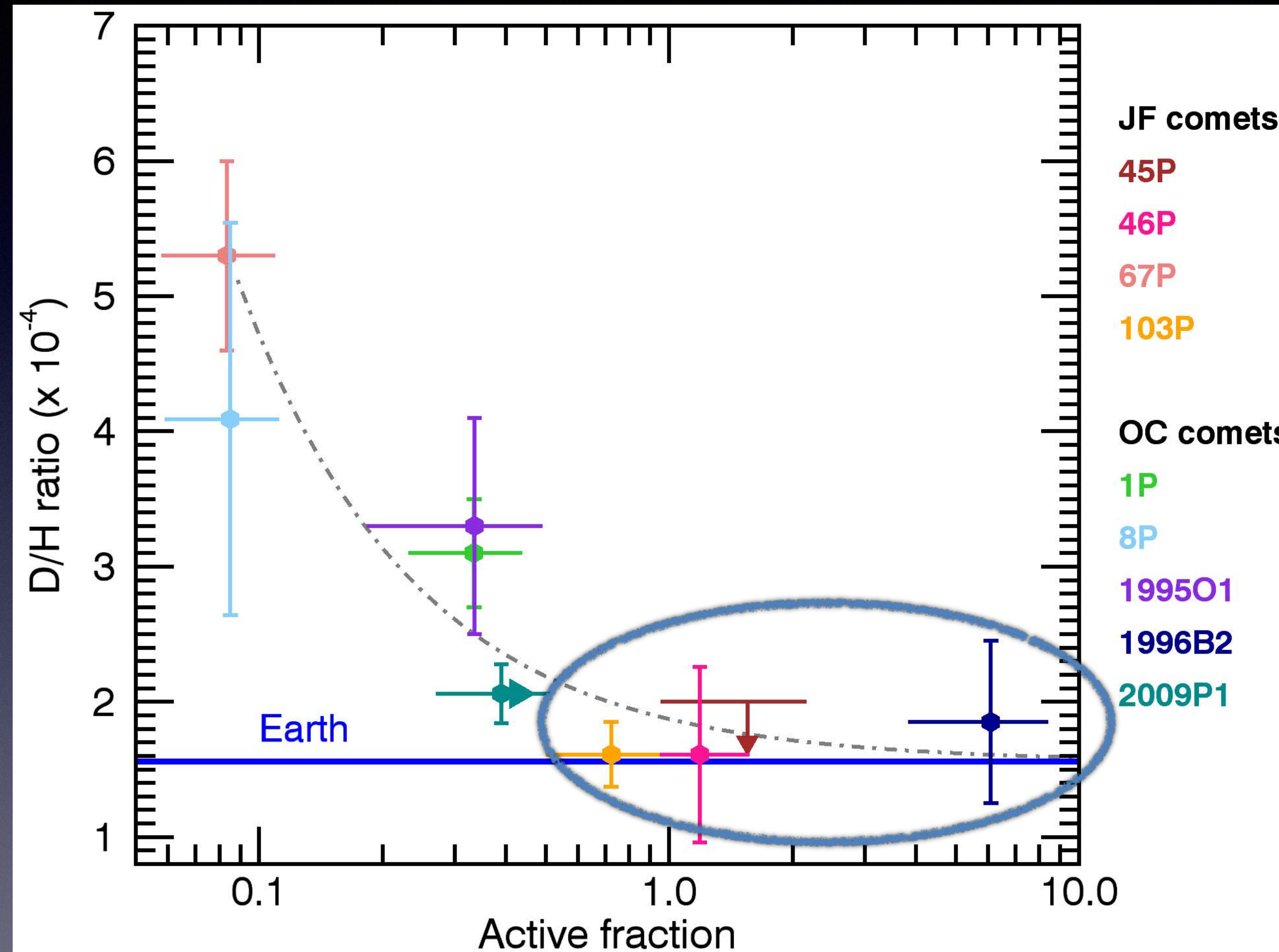
Hyperactive Comets



- Emit more water molecules than can be expected given the size of the nucleus
- Presence of sublimating water-ice-rich particles in the coma
- Archetype 103P/Hartley 2 studied by Deep Impact — both icy grains and water overproduction were observed
- Active fraction: ratio of the active surface area to the total nucleus surface
- A comprehensive set of water production rates from SWAN on SOHO (Combi et al. 2019)

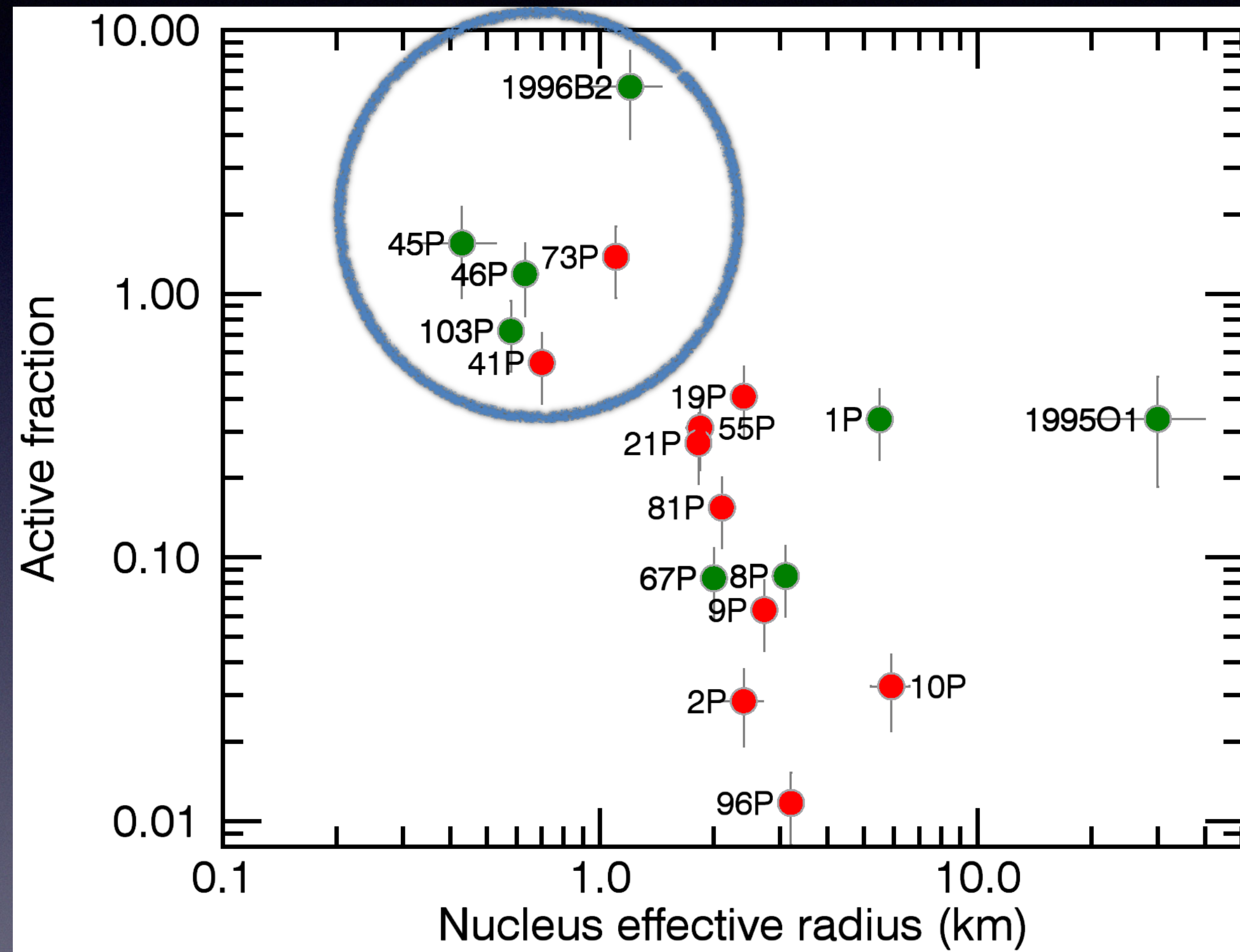
103P/Hartley — Deep Impact/EPOXI

D/H vs. Active Fraction



- Comets with active fraction above 0.5 typically have terrestrial D/H ratios
- Large reservoir of ocean-like water in the outer Solar System

Possible Interpretations?



(1) Hyperactive comets are ice-rich objects that formed just outside the snow line

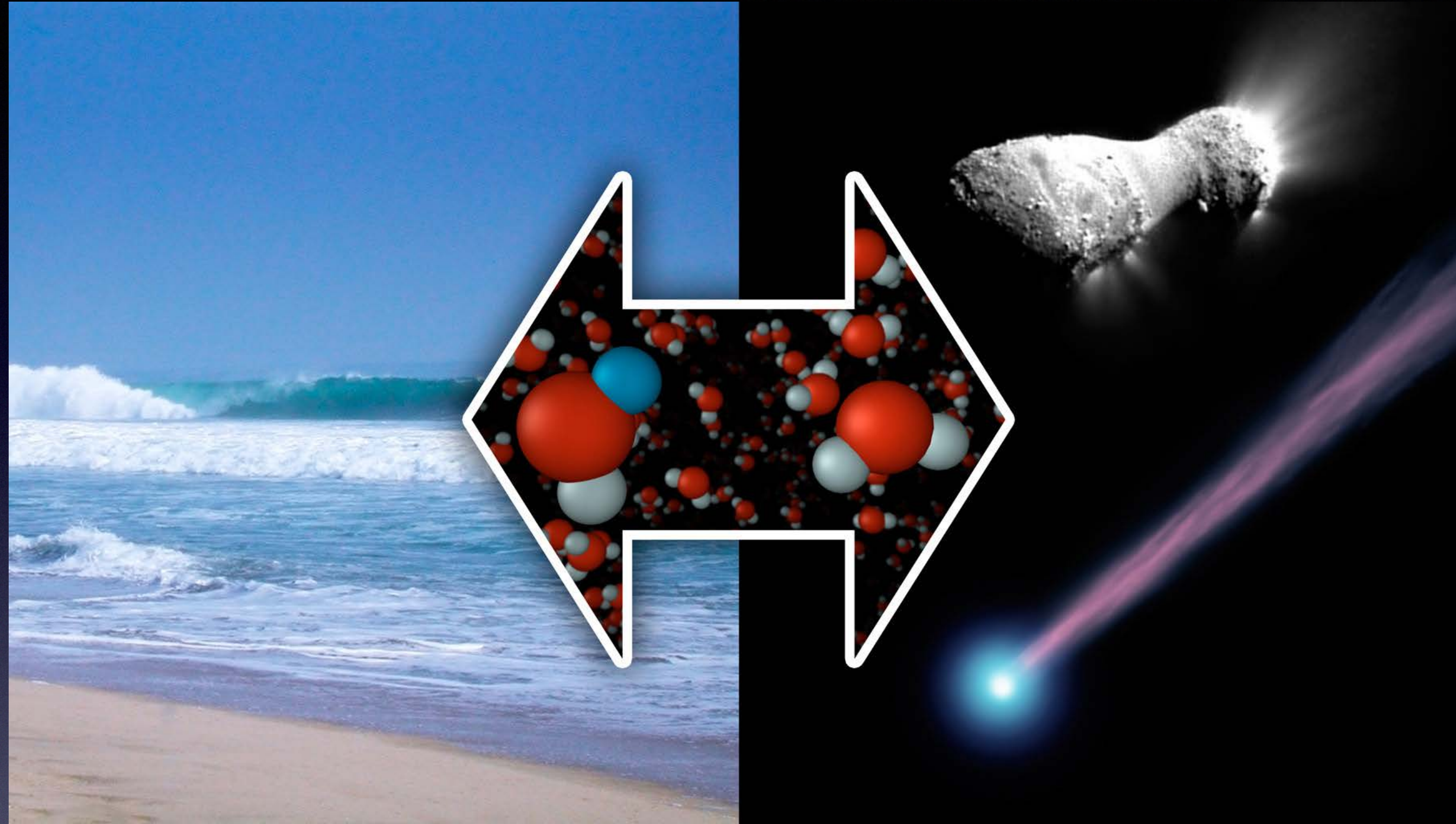
- Observed anti-correlation between active fraction and nucleus size argues against this interpretation
- Planetesimals outside the snow line are expected to undergo rapid growth

(2) Hyperactive comets formed in the outer Solar System from water thermally processed in the inner disk (Yang et al. model)

(3) Isotopic properties of water outgassed directly from the nucleus and from icy grains may be different

- Need laboratory measurements

Summary



- Measurements of isotopic ratios in a large sample of comets, including Main Belt comets, are key for understanding the origin of the Earth's water
- Ultimately, *Origins* or a dedicated Discovery or Explorer class mission is needed to provide a statistically significant sample of measurements to accurately determine D/H in the outer Solar System
- However, with a focused long-term program, SOFIA can significantly increase the number of D/H measurements