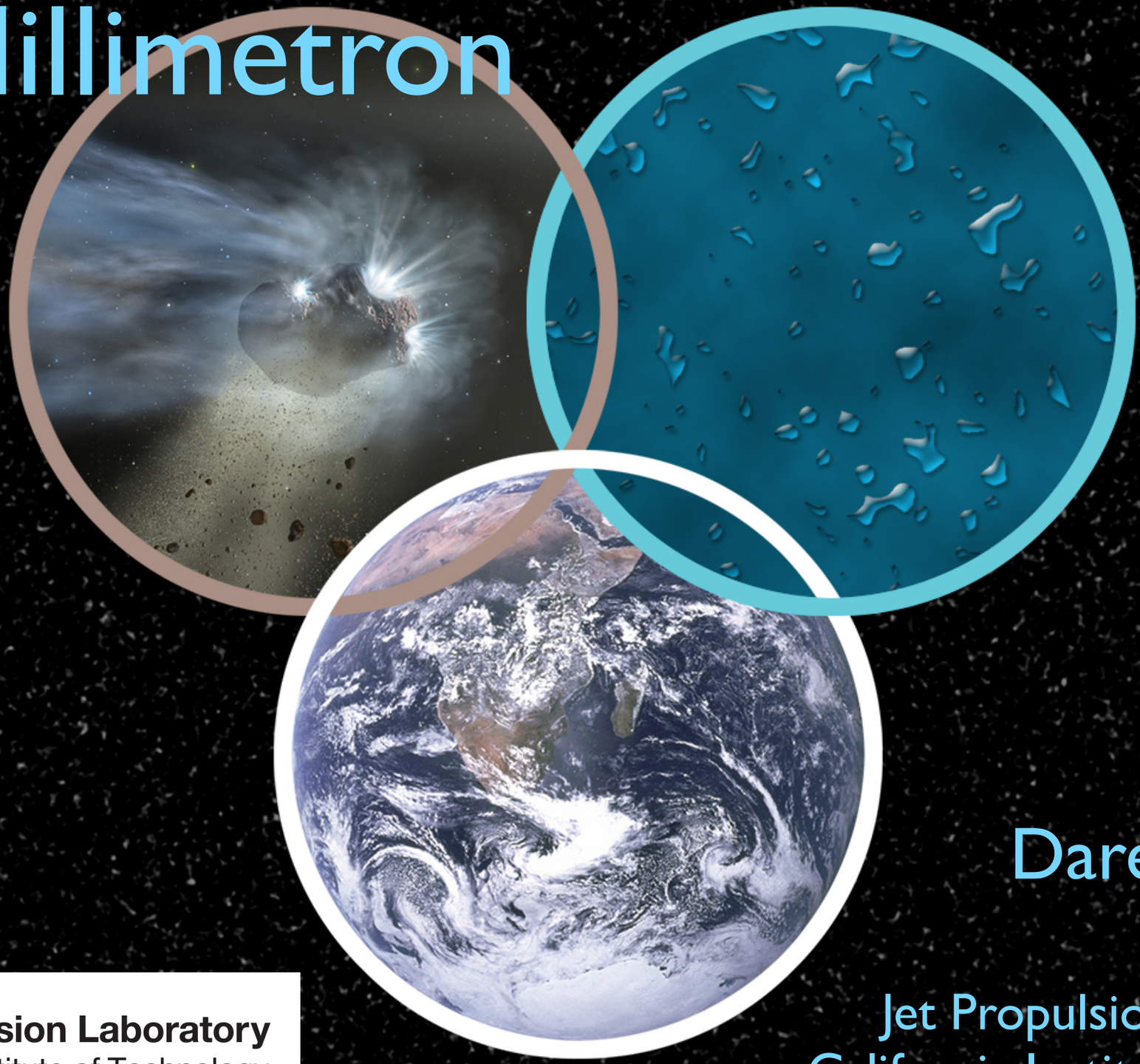
Isotopic Ratios in Cometary Water with Millimetron



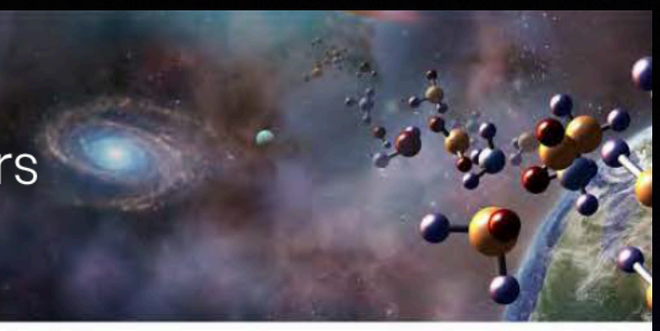
Darek Lis

Jet Propulsion Laboratory
California Institute of Technology

Millimetron Workshop, Sep 2019

Jet Propulsion Laboratory
California Institute of Technology

ORIGINS Space Telescope | From first stars to life



SCIENCE DRIVERS FOR MISSION DESIGN

HOW DOES THE UNIVERSE WORK?

How do galaxies form stars, make metals, and grow their central supermassive black holes from reionization to today?

Using sensitive spectroscopic capabilities of a cold telescope in the infrared, Origins will measure properties of star-formation and growing black holes in galaxies across all epochs in the Universe.

HOW DID WE GET HERE?

How do the conditions for habitability develop during the process of planet formation?

With sensitive and high-resolution far-IR spectroscopy Origins will illuminate the path of water and its abundance to determine the availability of water for habitable planets.

ARE WE ALONE?

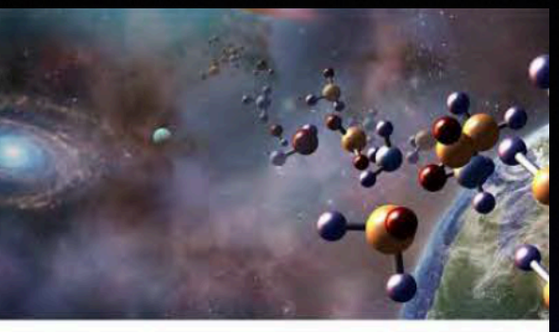
Do planets orbiting M-dwarf stars support life?

By obtaining precise mid-infrared transmission and emission spectra, Origins will assess the habitability of nearby exoplanets and search for signs of life.

NASA/Origins

ORIGINS Space Telescope

From first stars to life



SCIENCE DRIVERS FOR MISSION DESIGN

HOW DOES THE UNIVERSE WORK?

How do galaxies form stars, make metals, and grow their central supermassive black holes from reionization to today?

Using sensitive spectroscopic capabilities of a cold telescope in the infrared, Origins will measure properties of star-formation and growing black holes in galaxies across all epochs in the Universe.

HOW DID WE GET HERE?

How do the conditions for habitability develop during the process of planet formation?

With sensitive and high-resolution far-IR spectroscopy Origins will illuminate the path of water and its abundance to determine the availability of water for habitable planets.

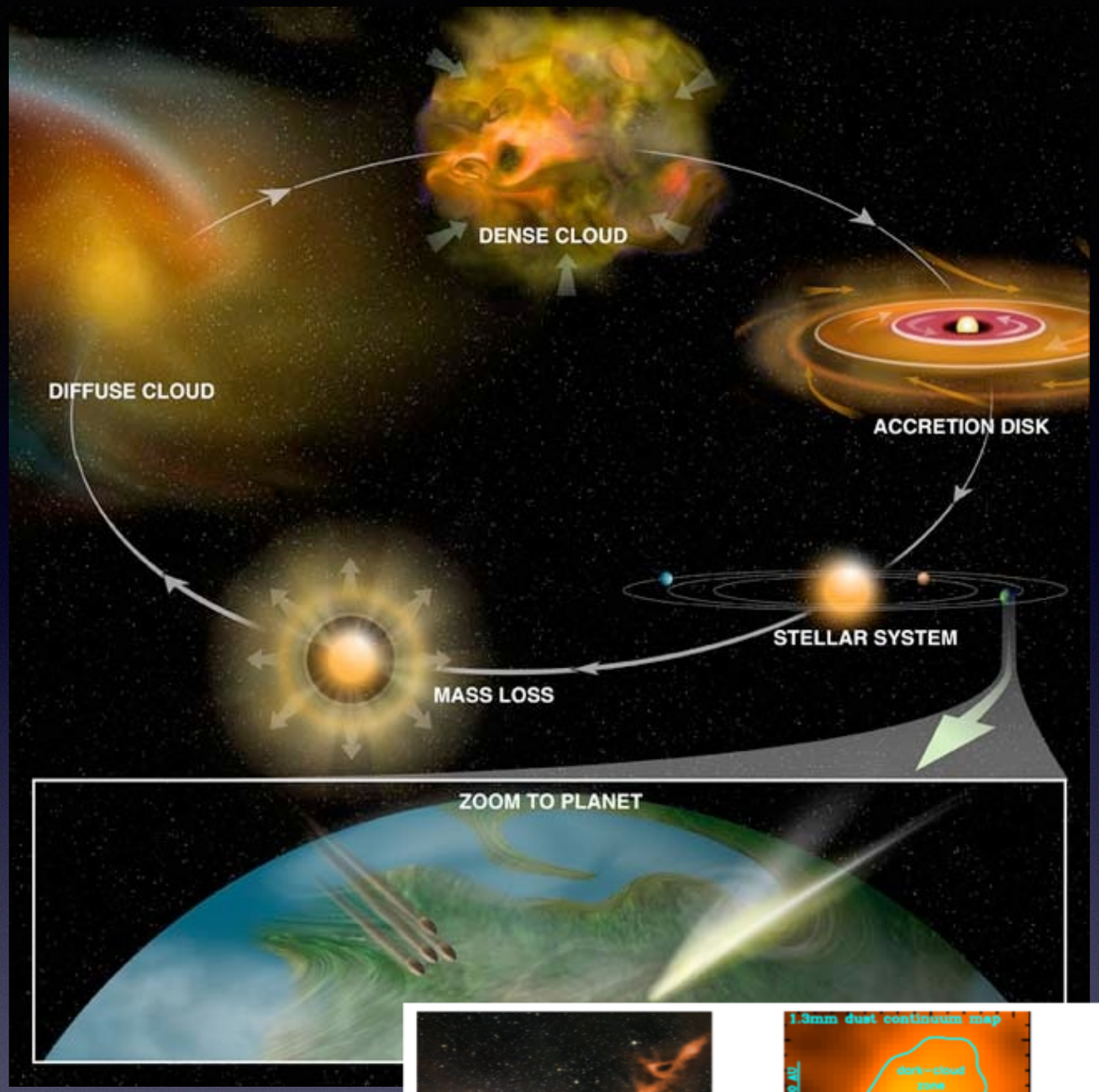
ARE WE ALONE?

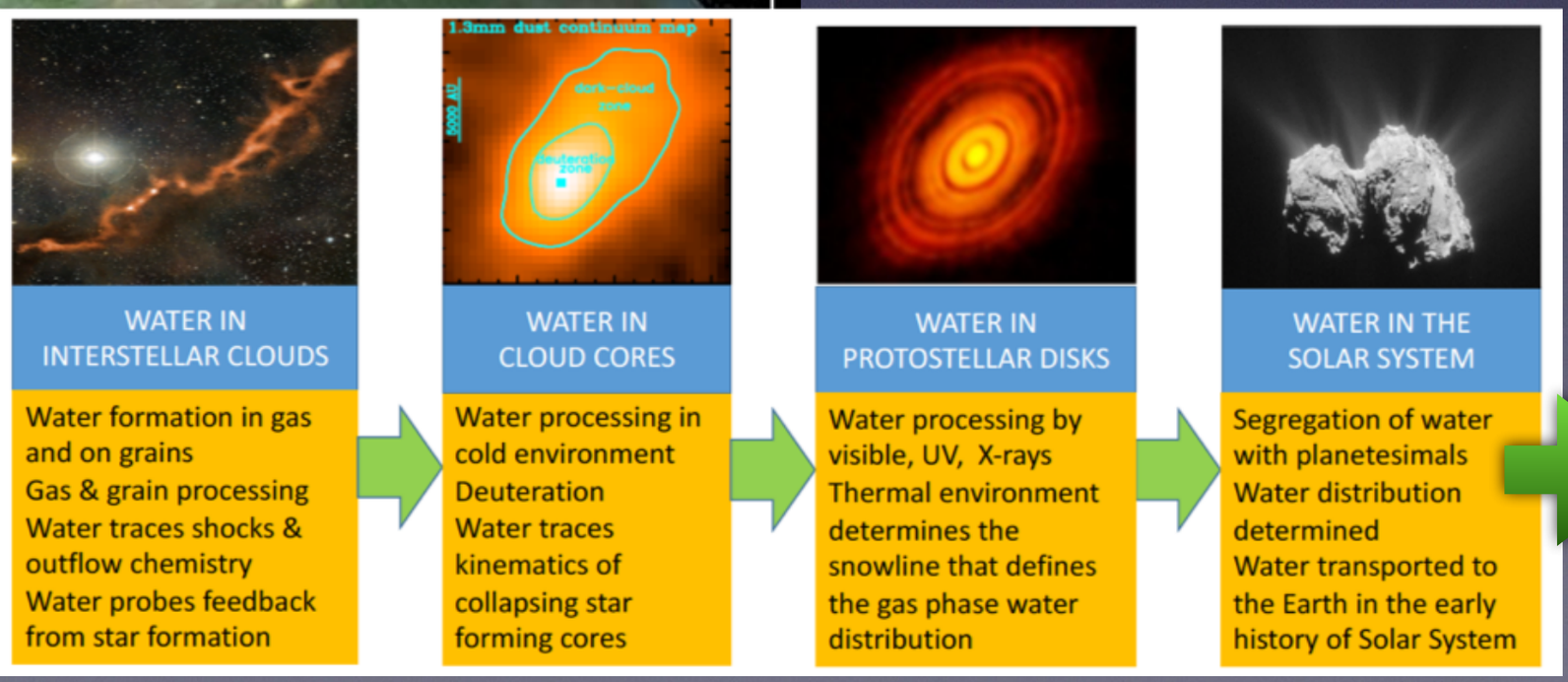
Do planets orbiting M-dwarf stars support life?

By obtaining precise mid-infrared transmission and emission spectra, Origins will assess the habitability of nearby exoplanets and search for signs of life.

NASA/Origins

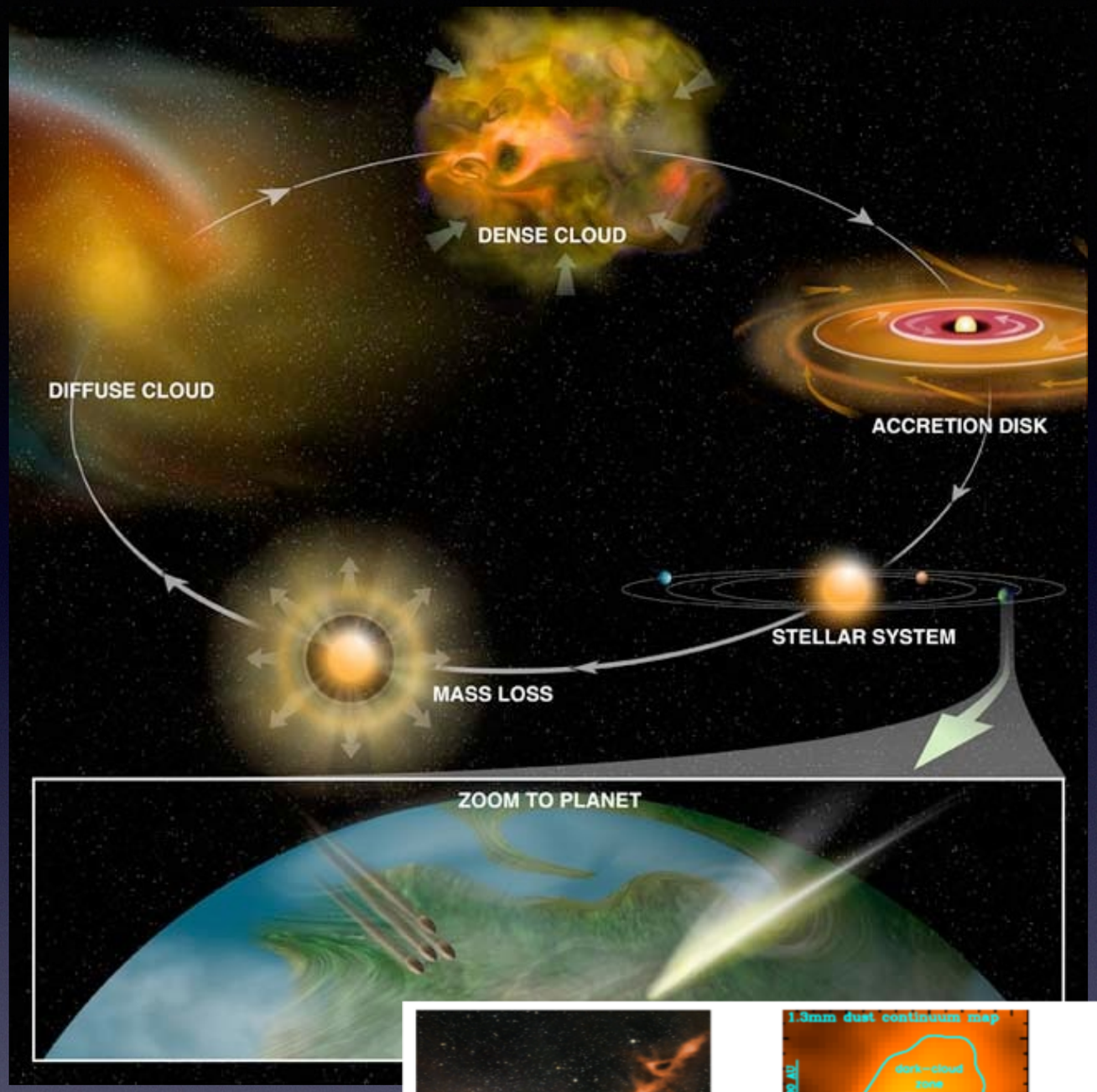
Cosmic Inheritance of Water





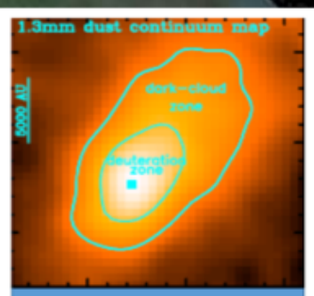
Images: NRAO/NASA

Cosmic Inheritance of Water



WATER IN INTERSTELLAR CLOUDS

Water formation in gas and on grains
Gas & grain processing
Water traces shocks & outflow chemistry
Water probes feedback from star formation

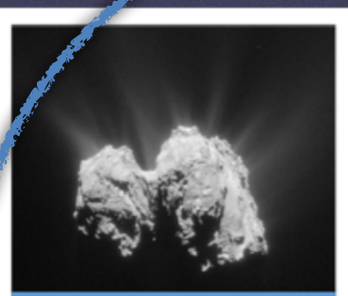


WATER IN CLOUD CORES

Water processing in cold environment
Deuteration
Water traces kinematics of collapsing star forming cores

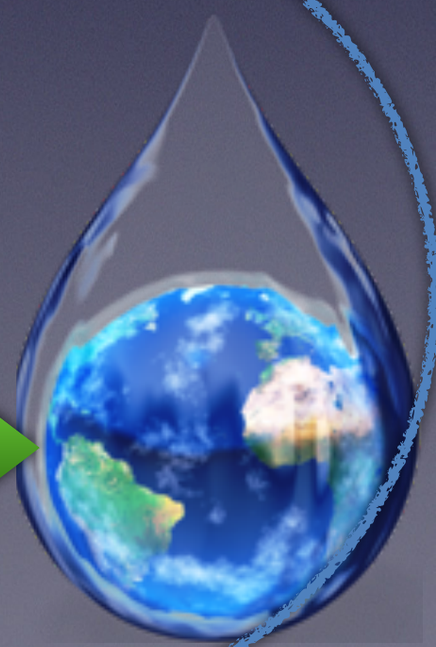
WATER IN PROTOSTELLAR DISKS

Water processing by visible, UV, X-rays
Thermal environment determines the snowline that defines the gas phase water distribution

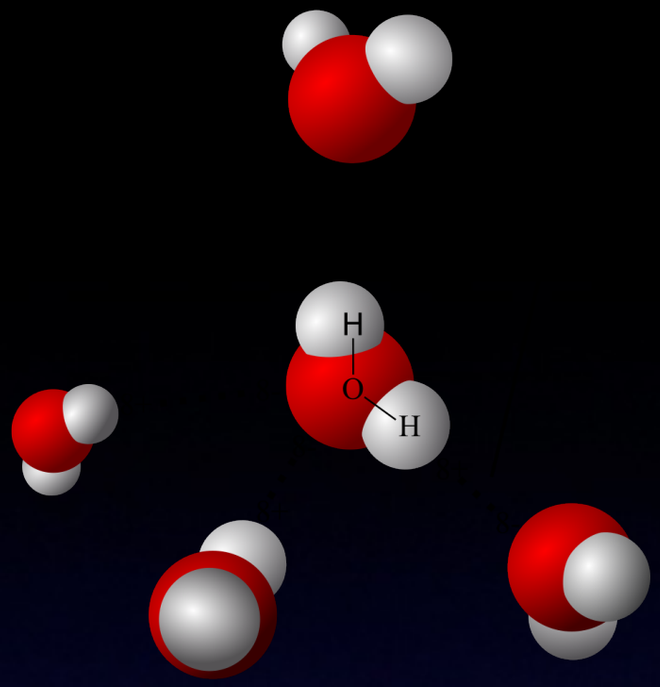


WATER IN THE SOLAR SYSTEM

Segregation of water with planetesimals
Water distribution determined
Water transported to the Earth in the early history of Solar System

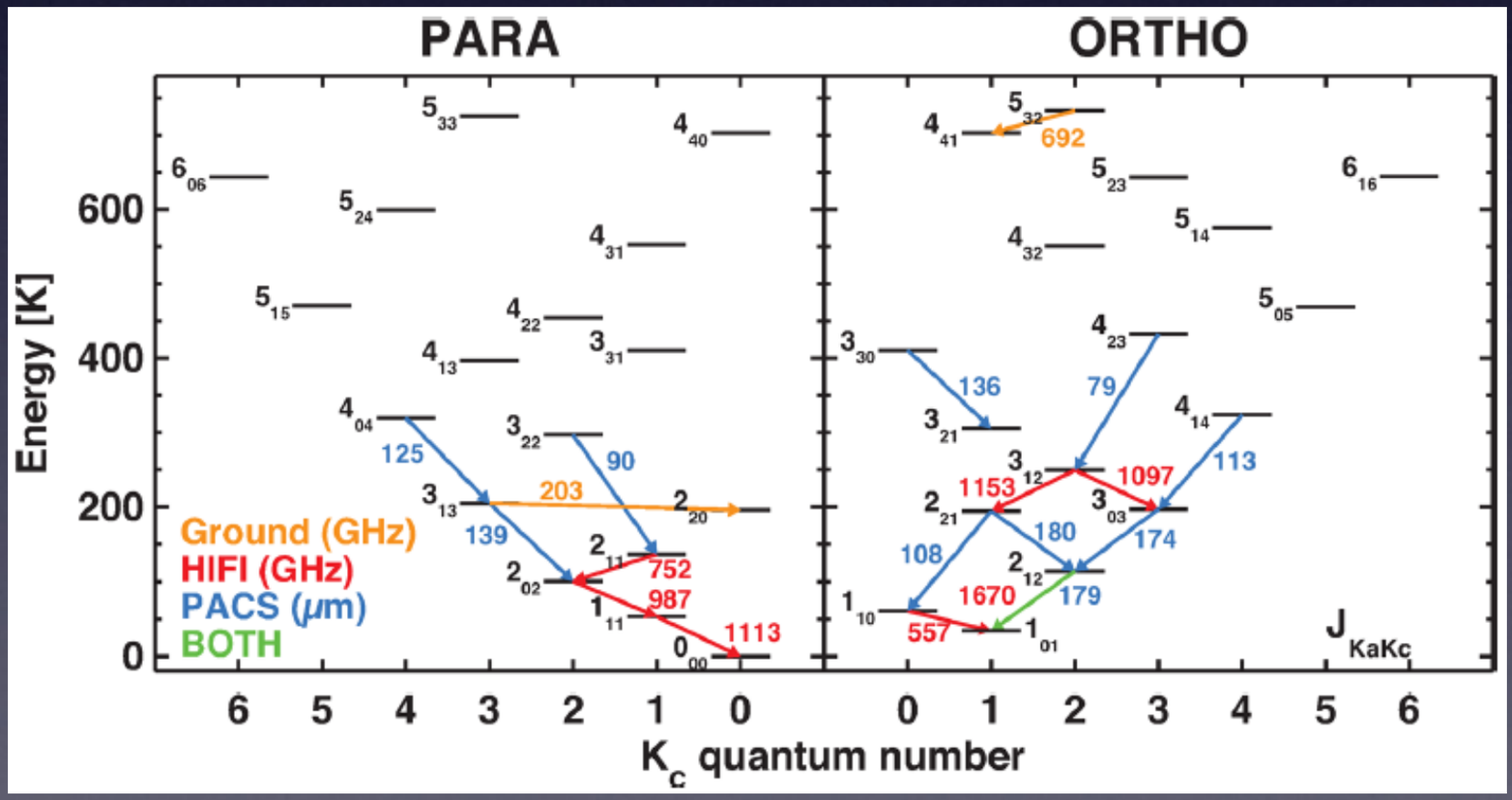


Images: NRAO/NASA

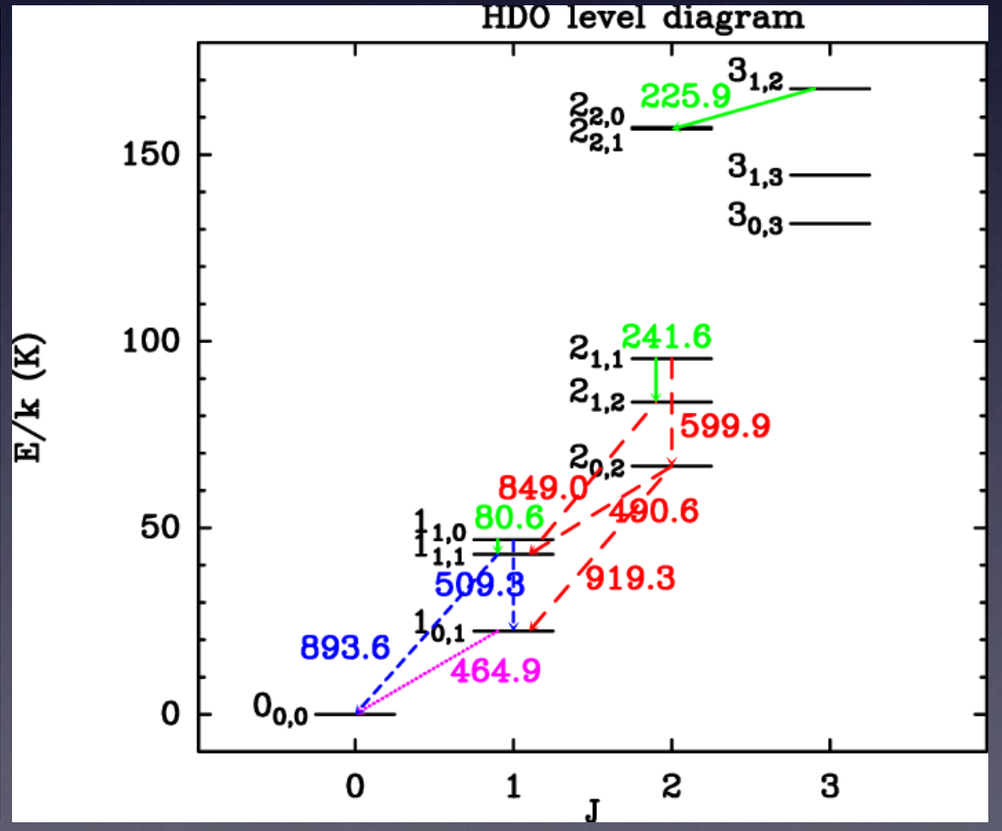


Observations of Cold Water

- Atmosphere opaque at the frequencies of the low-energy water lines
- Even SOFIA cannot observe cold water

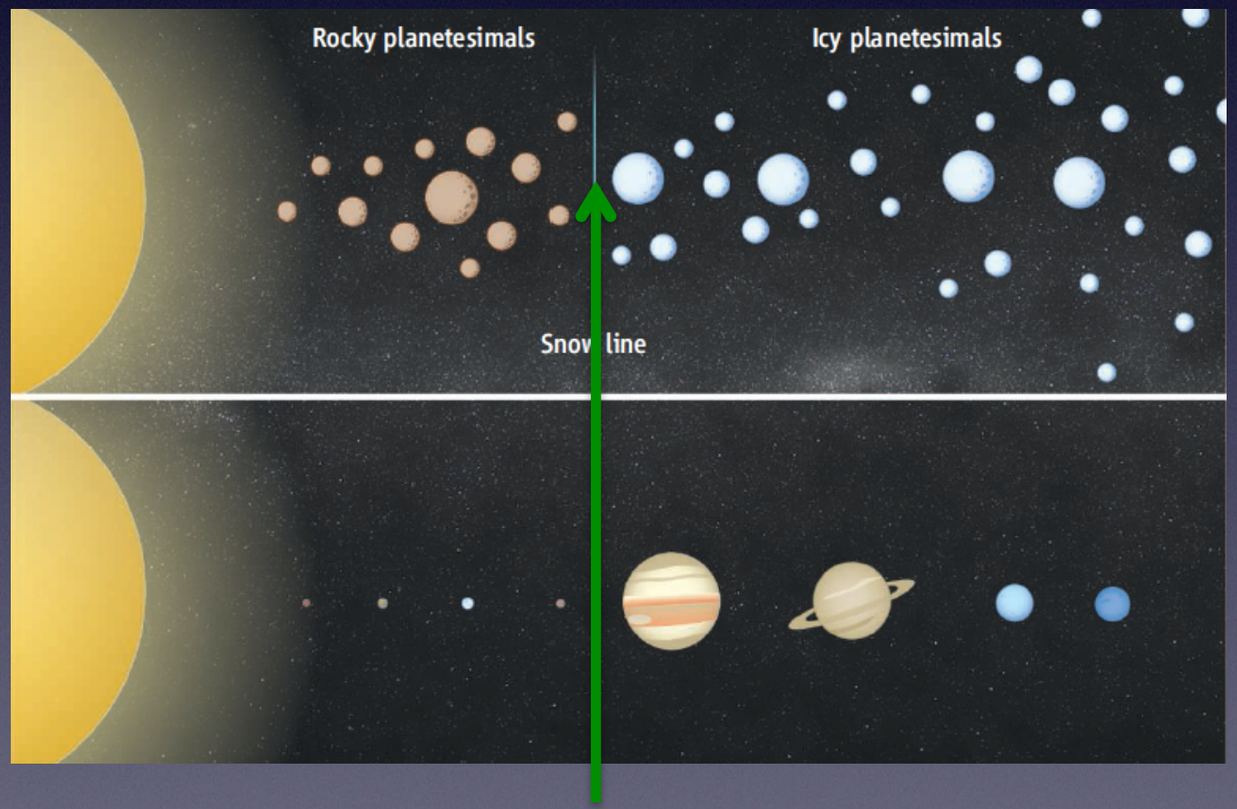


van Dishoeck et al. 2013

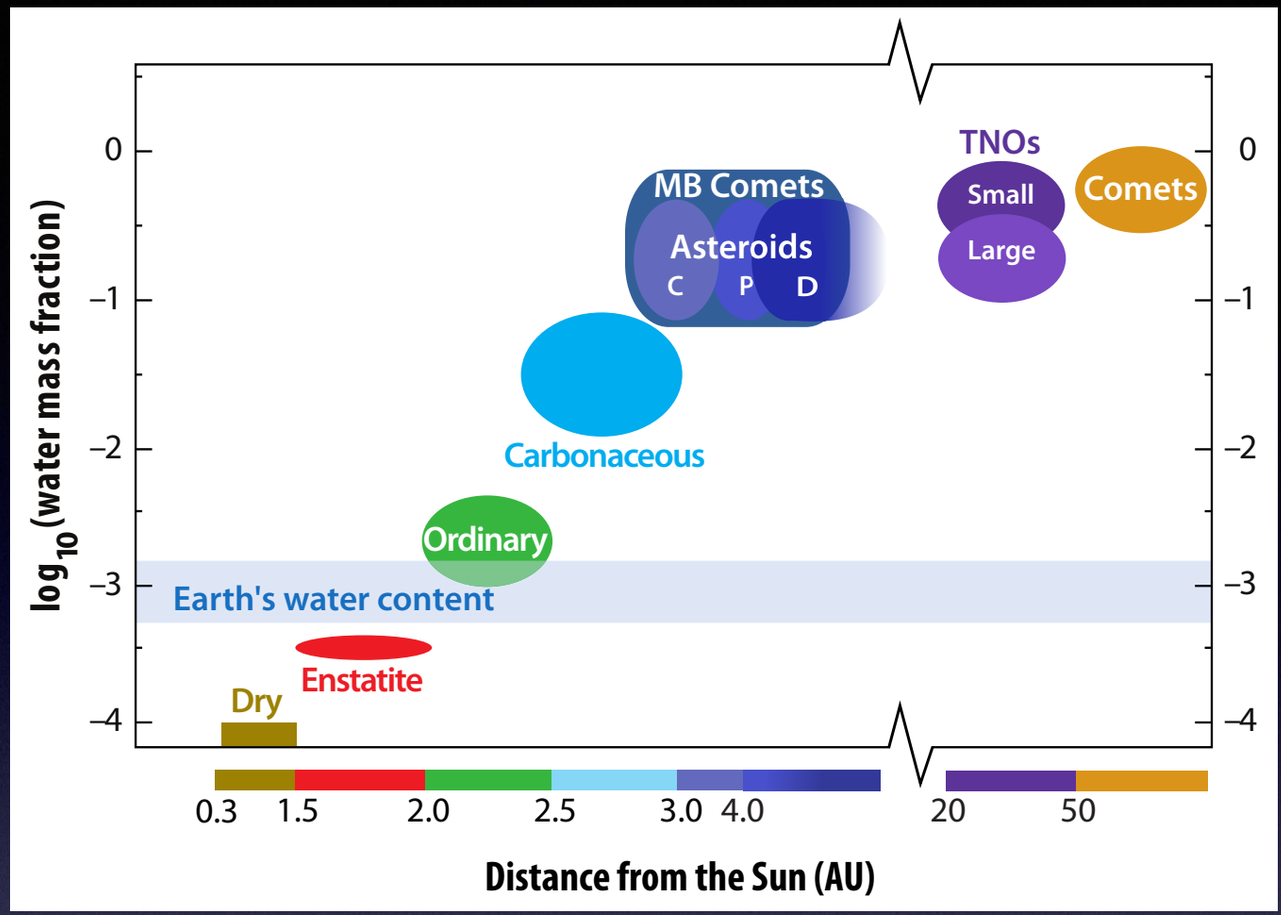


Coutens et al. 2014

Once upon a time the Earth formed dry



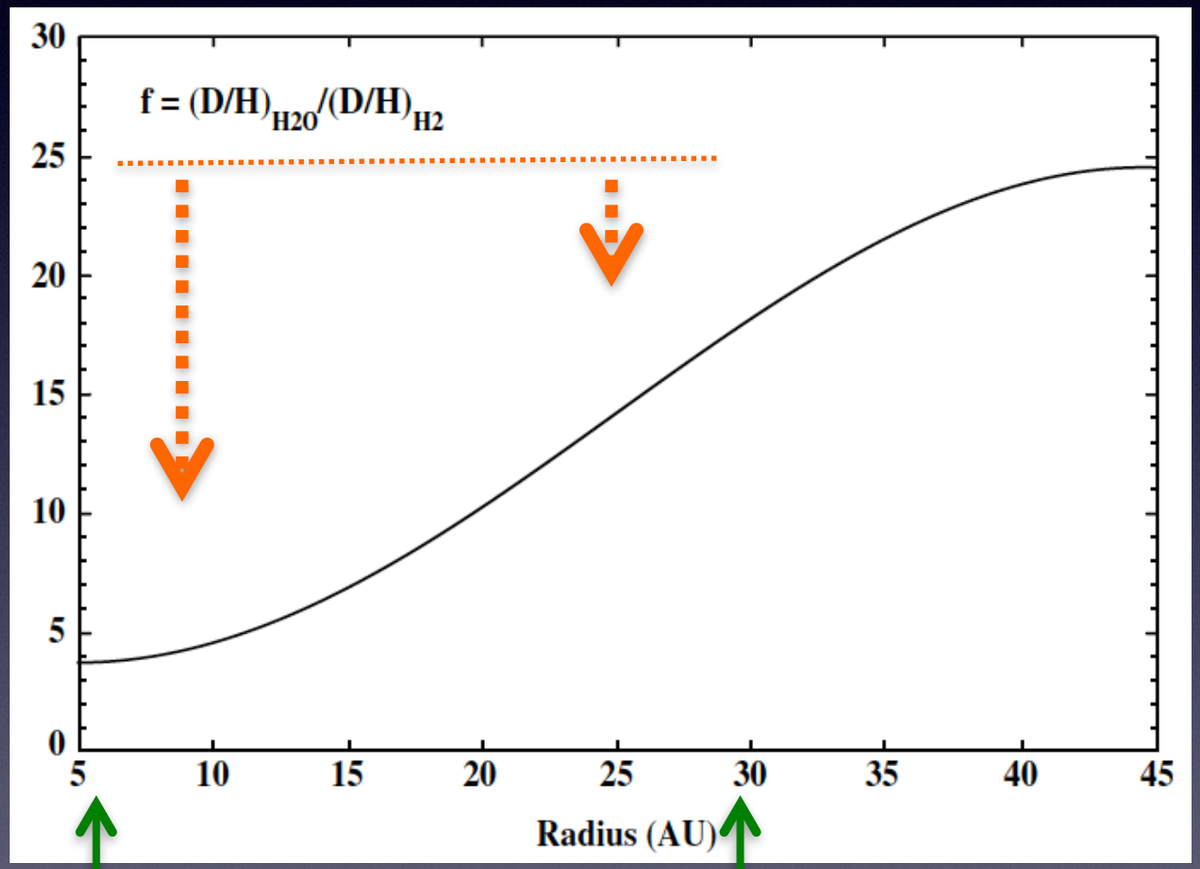
Snow Line



- Temperature in the terrestrial planet zone was too high for water ice to exist
- Water and organics were most likely delivered by comets or asteroids
- Isotopic ratios provide a fingerprint for studying the origin and history of Solar System materials

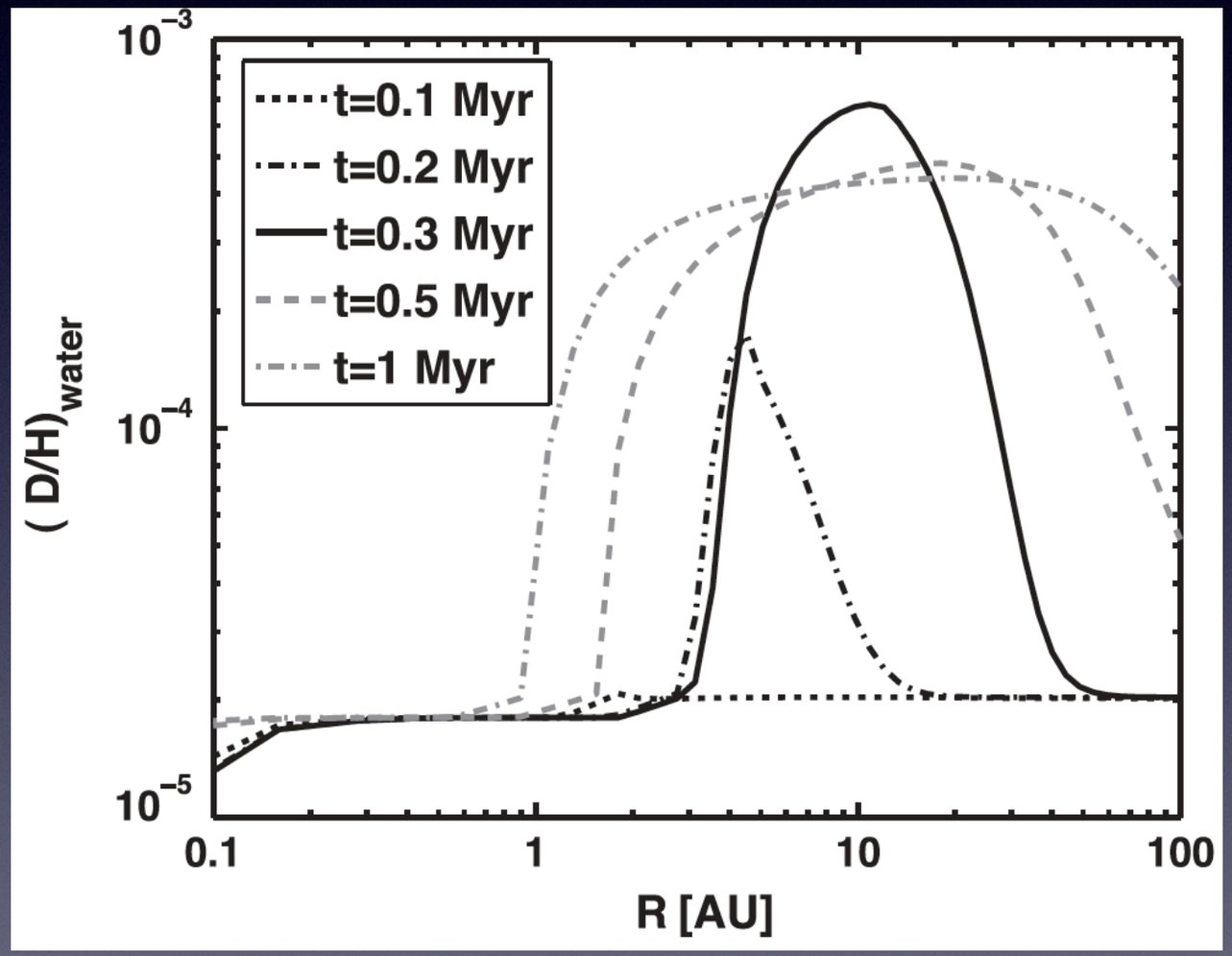
"Textbook" D/H in Water in the Solar Nebula

- Variations in the D/H ratio: progressive isotopic exchange reactions between HDO and H_2
- Water was initially synthesized by interstellar chemistry with a high D/H ratio (>7.2×10^{-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 ➟ D/H gradient



Horner et al. 2007

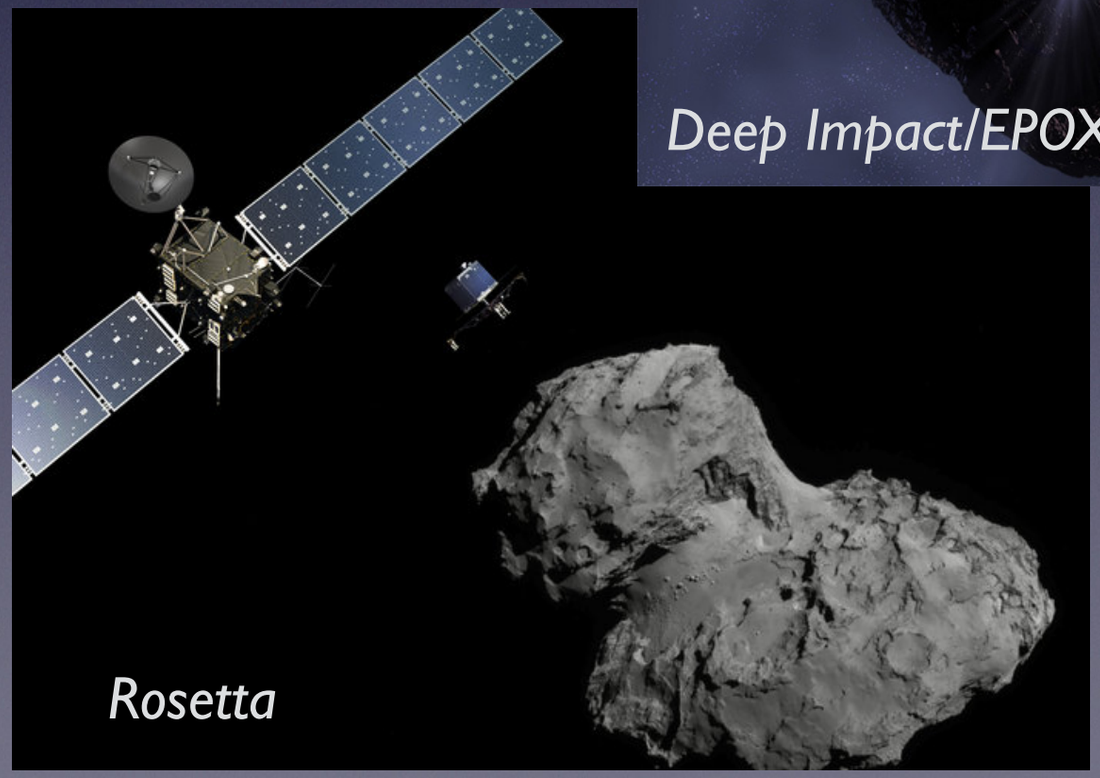
Other D/H Models



- A coupled dynamical and chemical model
- D/H may *decrease* in the outer regions
- Water thermally processed in the inner disk transported outward

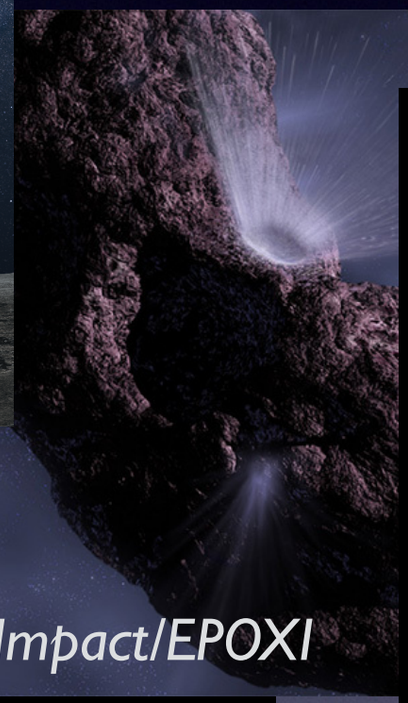
Yang et al. (2013)

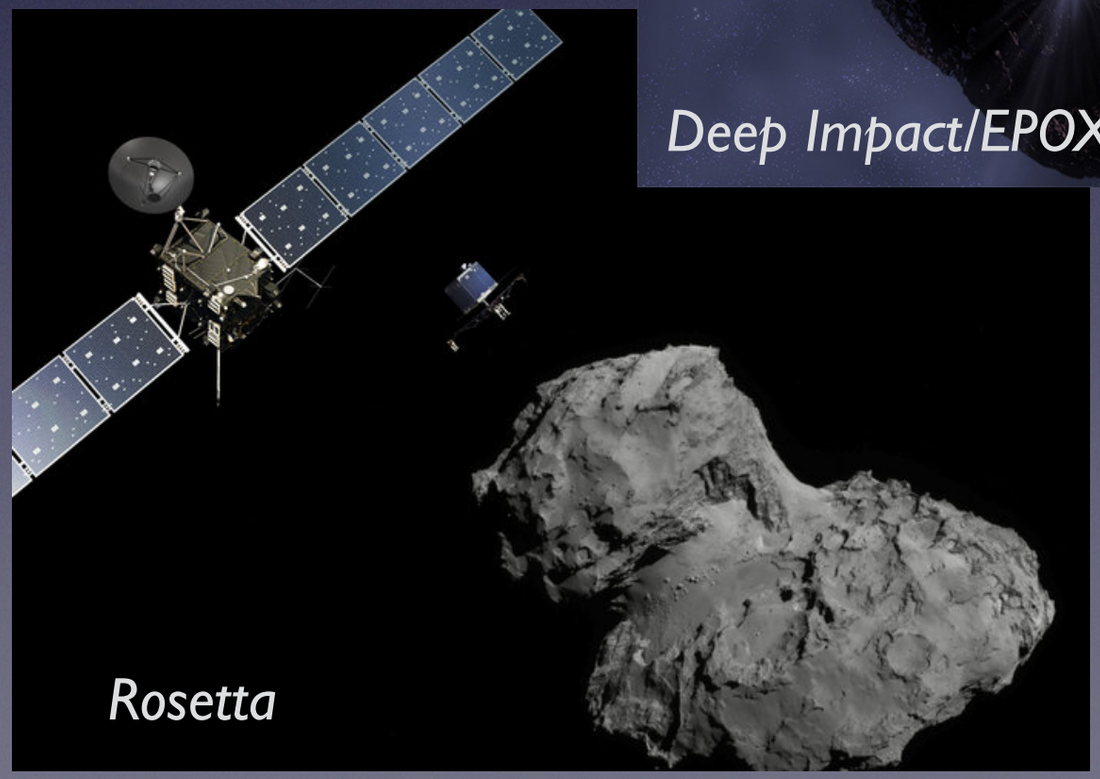
Isotopic Ratio Measurements



- Sample return or in-situ — detailed studies of individual objects

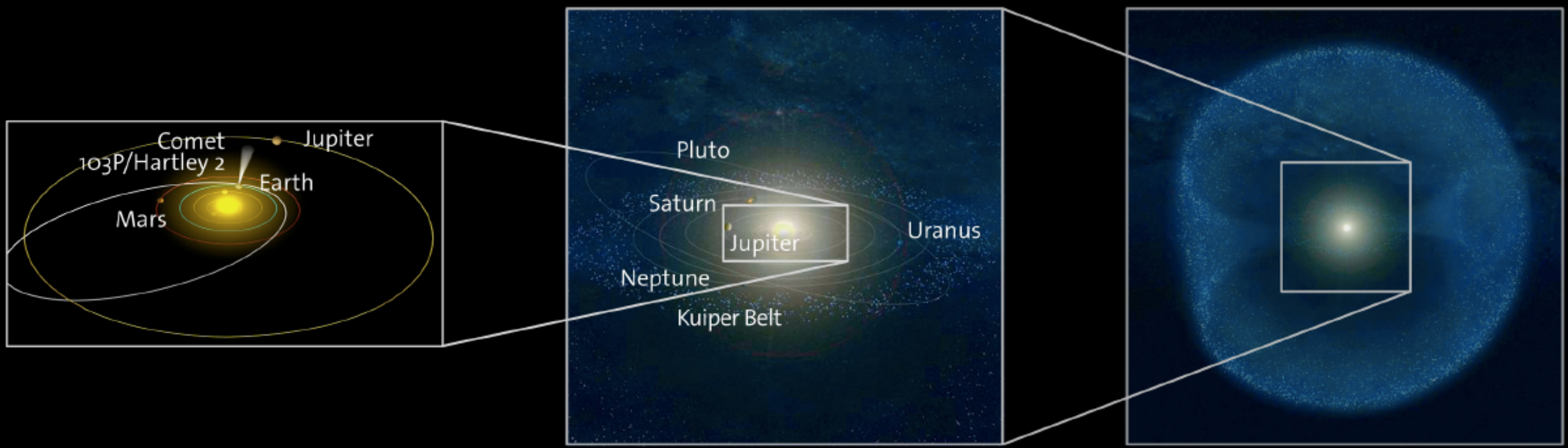
Isotopic Ratio Measurements



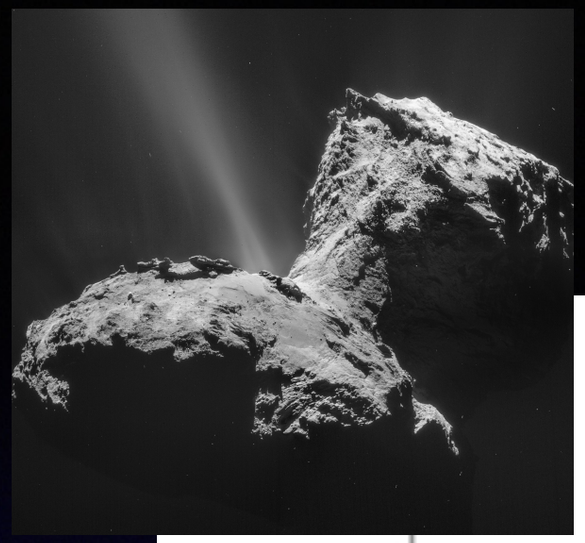


- Remote sensing — statistical studies of objects that have atmospheres
- Sample return or in-situ — detailed studies of individual objects

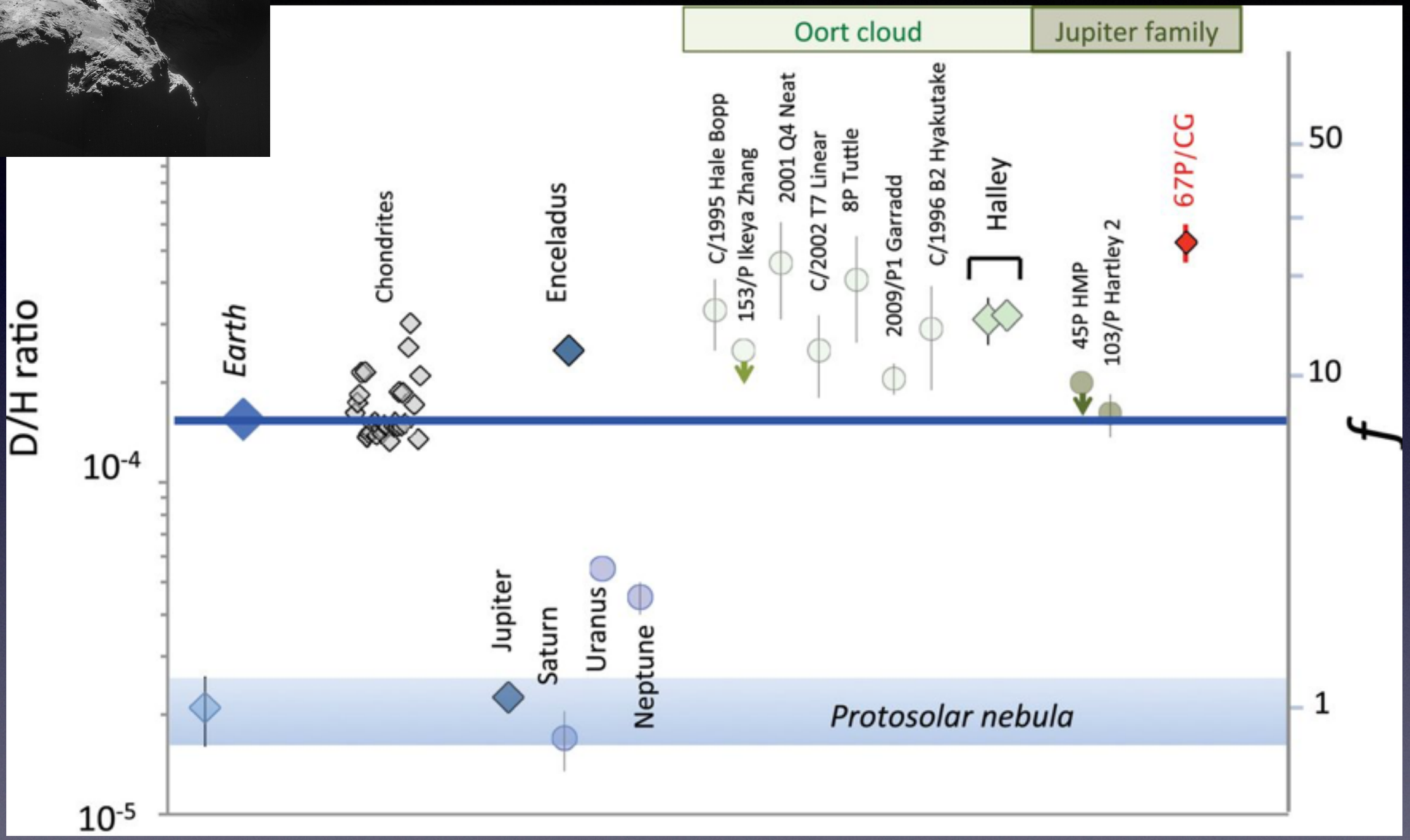
Comets



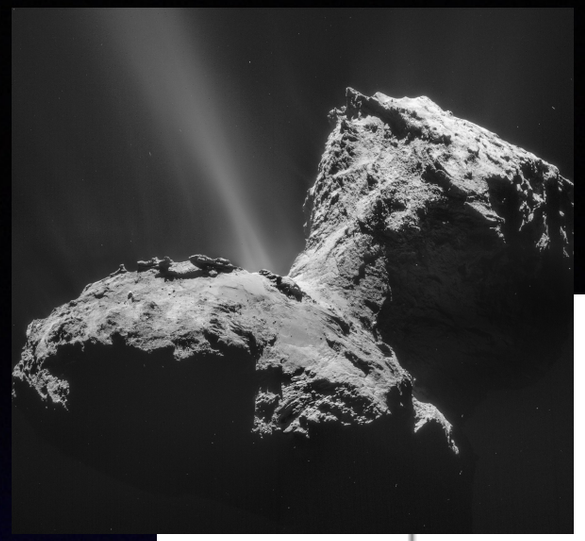
- Comets are among the most primitive bodies formed before planets and asteroids
- *Jupiter Family comets* originate in the Kuiper Belt, or associated scattered disc, beyond the orbit of Neptune
- *Long-period comets* come from the Oort cloud, but formed in the Jupiter-Neptune region
- Sent toward the Sun by gravitational perturbations from the outer planets or nearby stars, or due to collisions



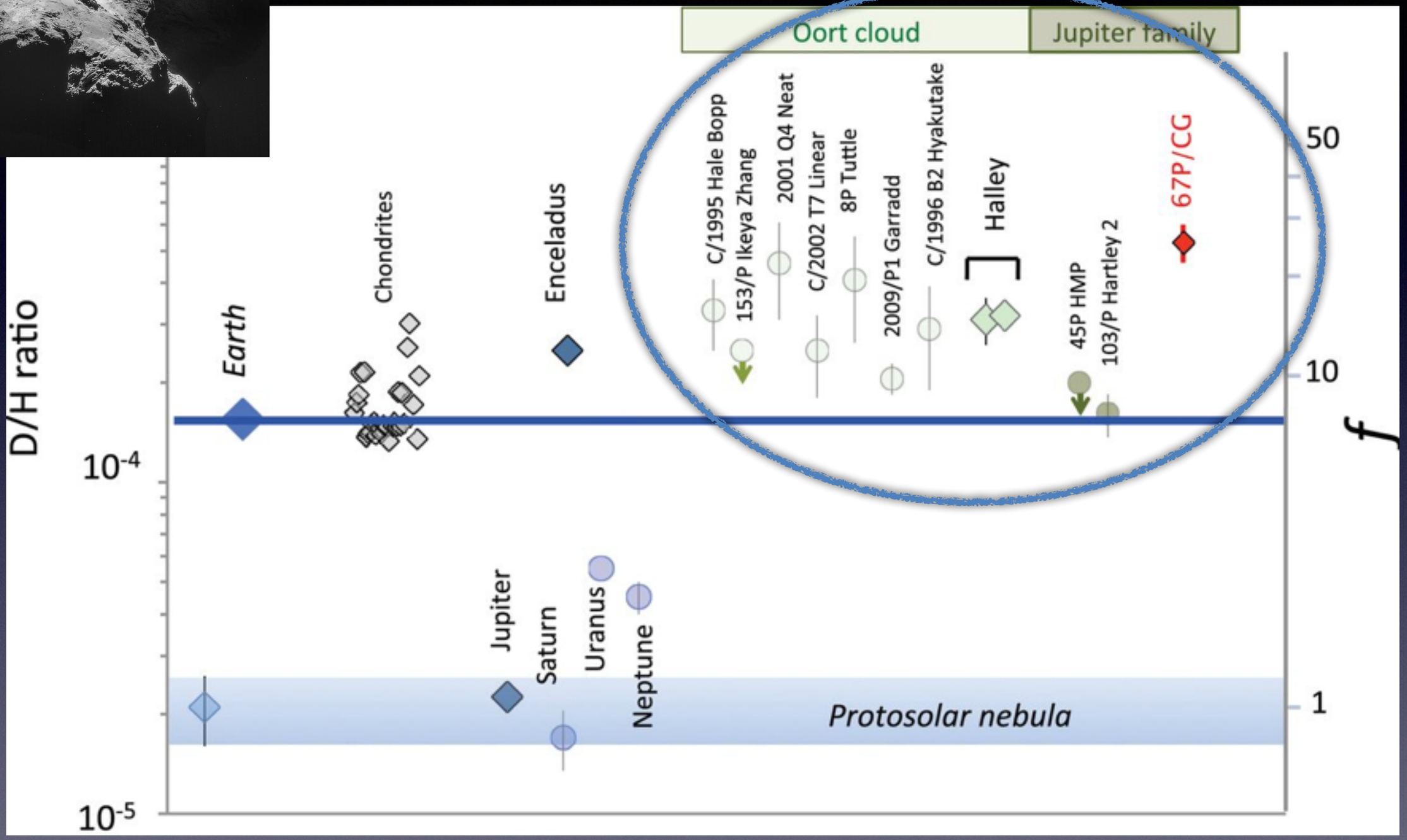
D/H Observations



ORIGINS Space Telescope



D/H Observations



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

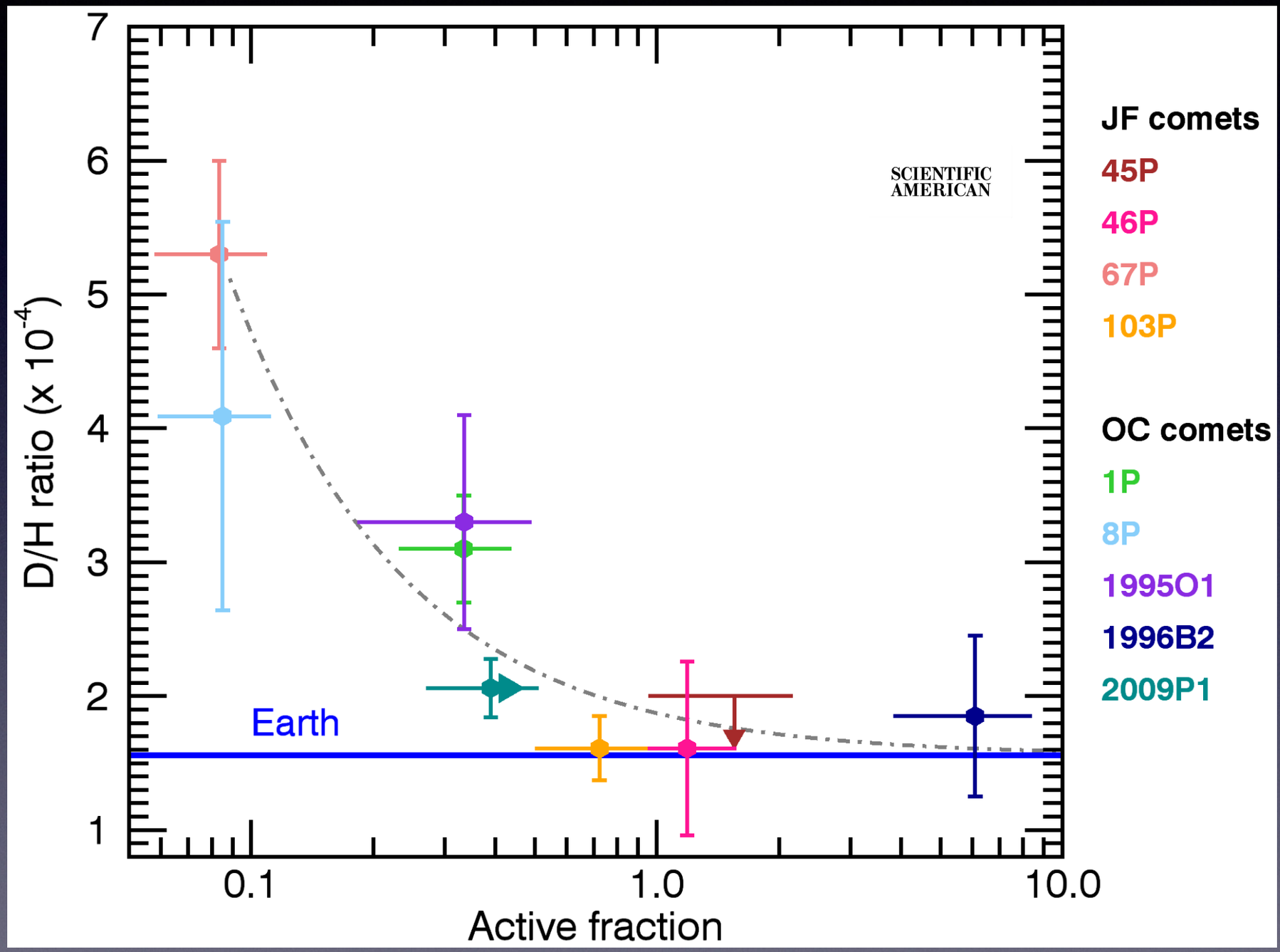
ORIGINS Space Telescope

SPACE

Hyperactive Comets Hint at Origins of Earth's Oceans

A new study suggests primordial seawater may lurk hidden at the hearts of many comets

By Nola Taylor Redd on May 9, 2019

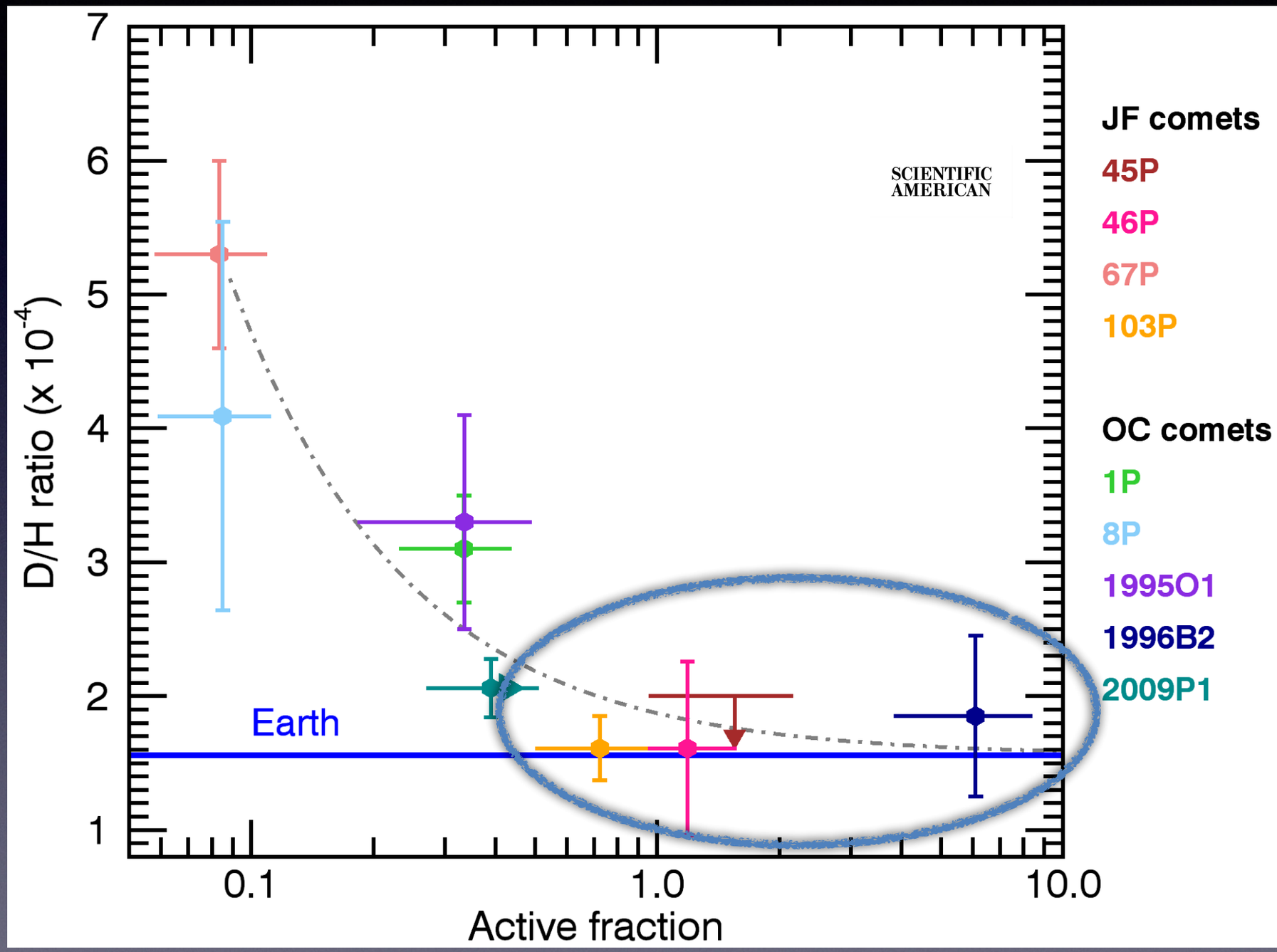


SPACE

Hyperactive Comets Hint at Origins of Earth's Oceans

A new study suggests primordial seawater may lurk hidden at the hearts of many comets

By Nola Taylor Redd on May 9, 2019

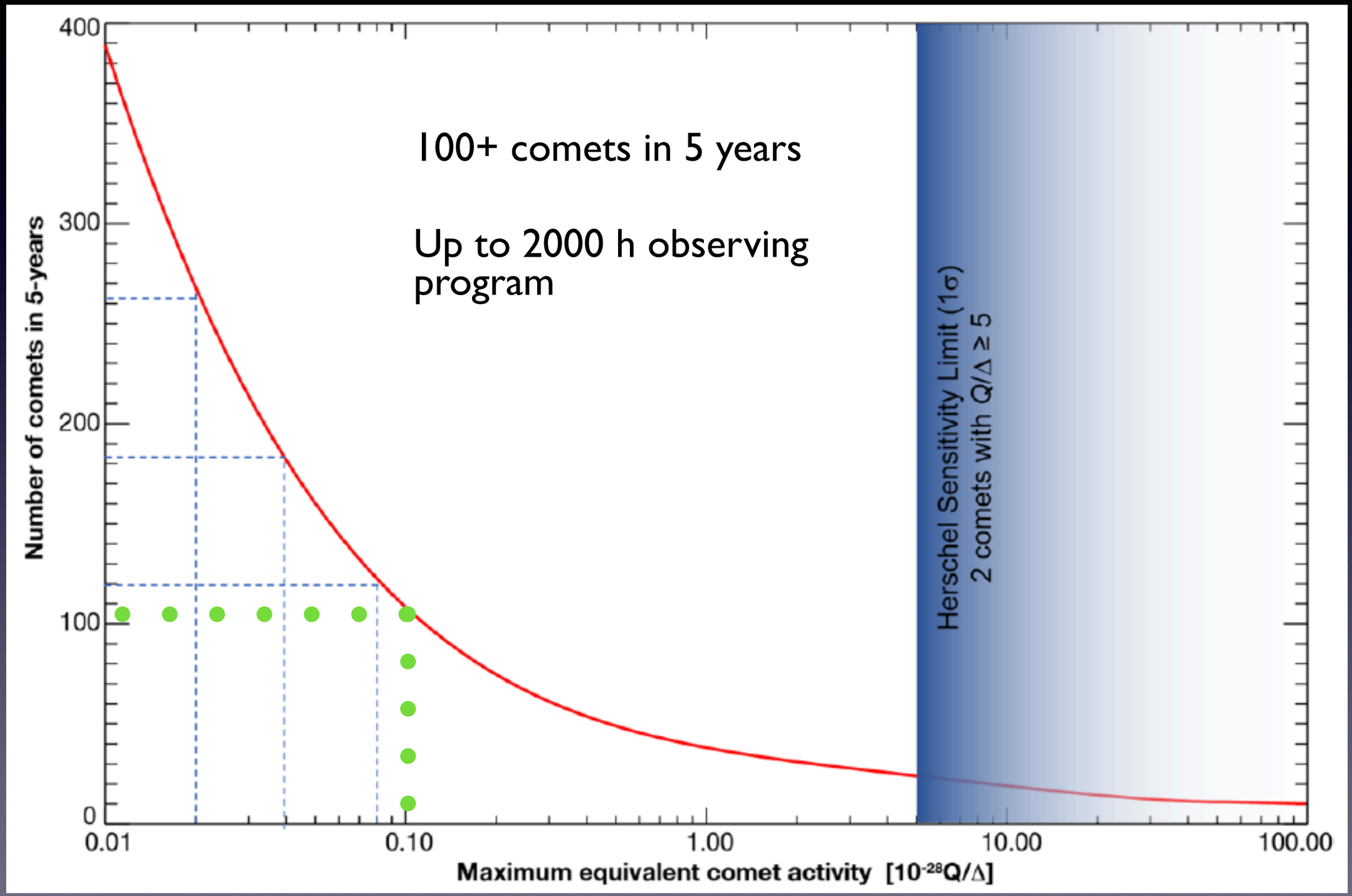


- Hyperactive comets typically have terrestrial D/H ratios
- Large reservoir of ocean-like water in the outer Solar System

Millimetron Sensitivity

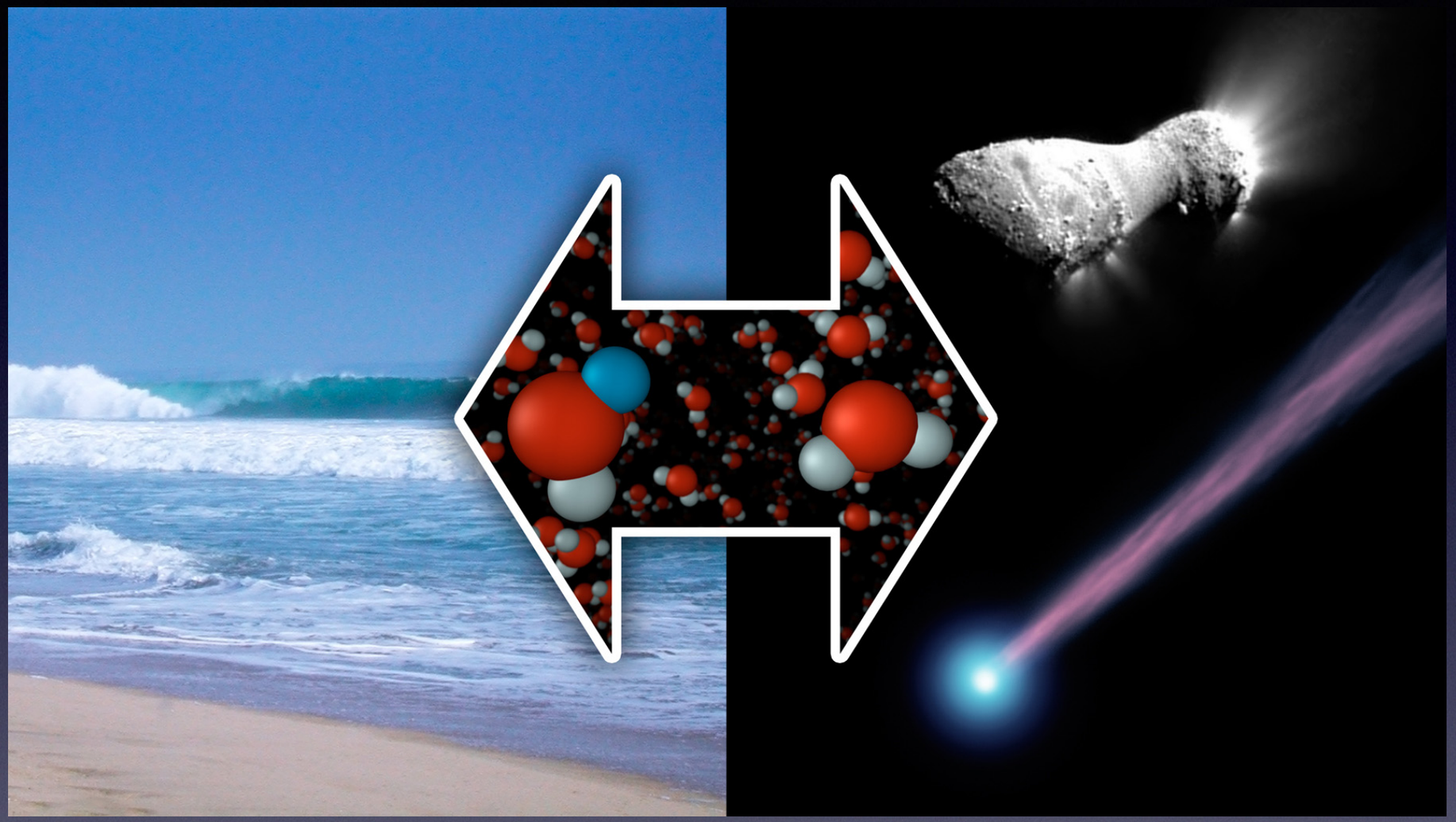
- Herschel/HIFI, comet 103P: Figure of Merit (FOM) $=10^{28}s^{-1}/0.21au=4.8\times10^{28}$
- 10σ detection of the HDO 509 GHz in 320 min
- Expected improvement for Millimetron: × 23
  - Rx sensitivity: 2 (T_{rx} 50 K DSB at 500 GHz demonstrated)
  - Telescope diameter: 10/3.5=2.9
  - Dual polarization: $\sqrt{2}$
  - Two pixels: $\sqrt{2}$
  - 4× longer integration (up to 20 h per source): 2
- Sensitivity limit: FOM = 1.0×10^{27} (for a 5σ detection of HDO)

How Many Comets?



NASA, Origins

Summary



- Measurements of isotopic ratios in a large sample of comets, including Main Belt comets, are key for understanding the origin of Earth's water
- With a long term, focused program, SOFIA can double the number of existing D/H measurements during its lifetime — this is significant, but insufficient
- *Millimetron, Origins* or a dedicated Discovery or Explorer mission needed to provide a statistically significant sample

Jet Propulsion Laboratory
California Institute of Technology