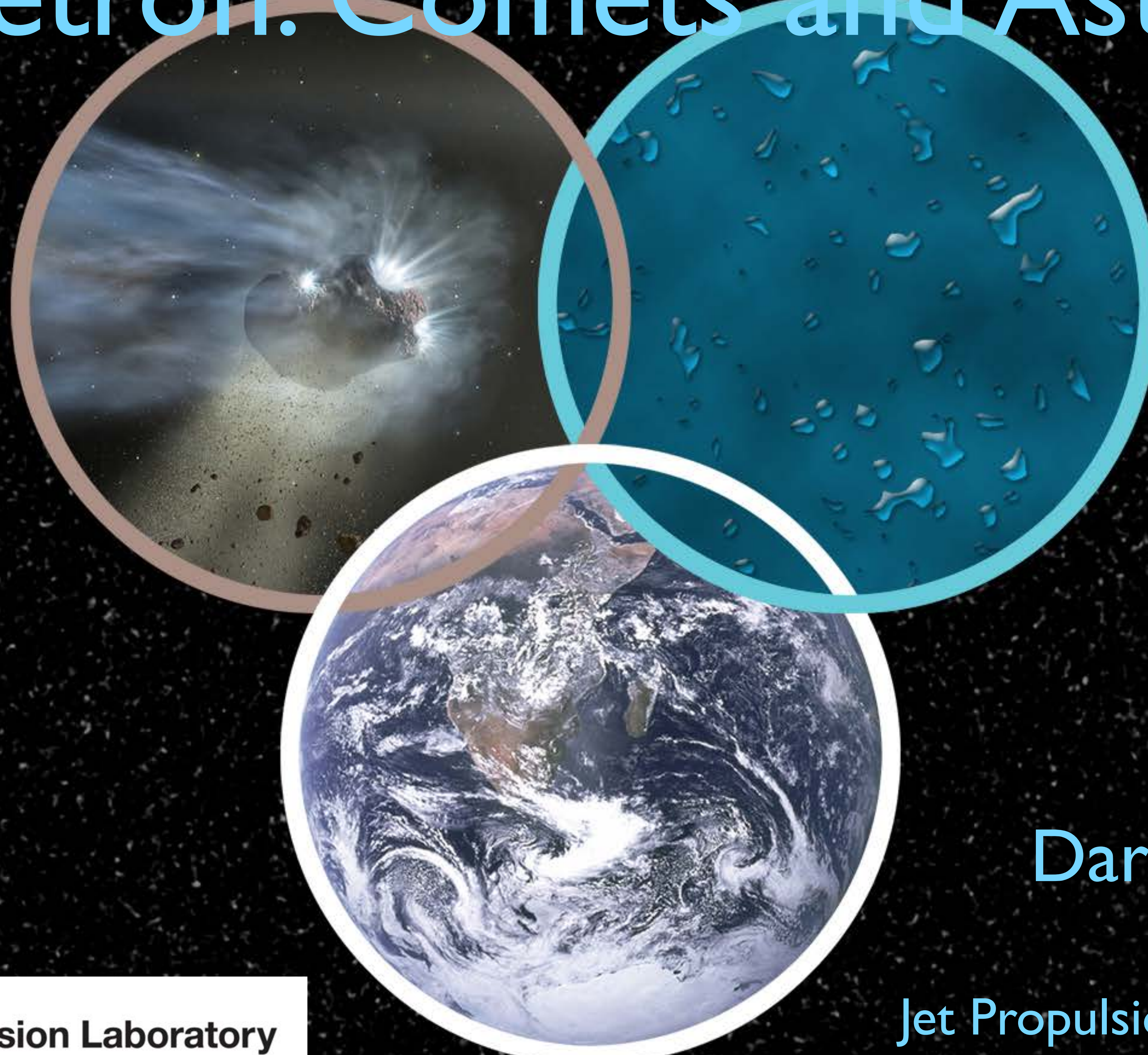
Solar System Spectroscopy with Millimetron: Comets and Asteroids



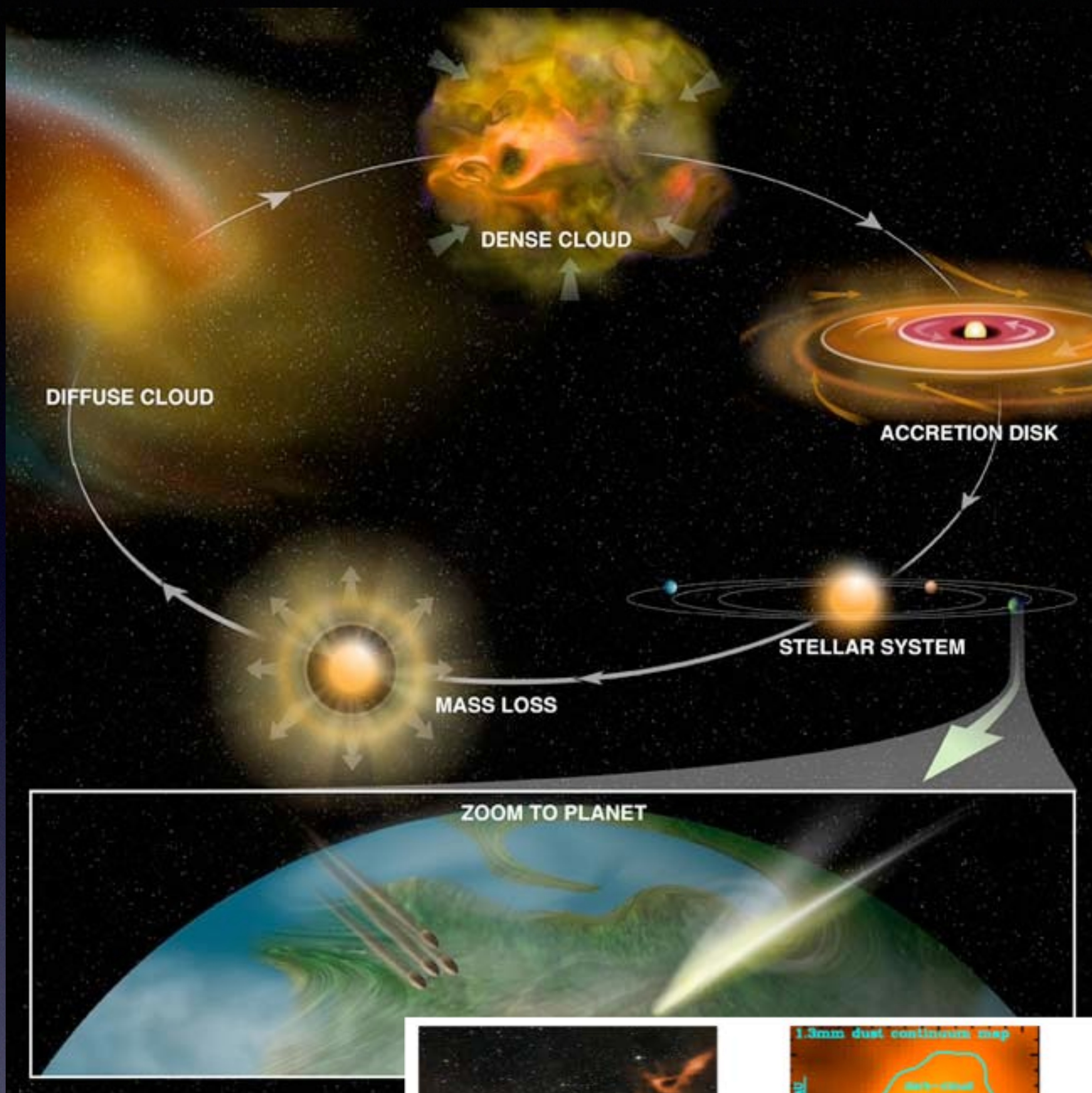
Darek Lis

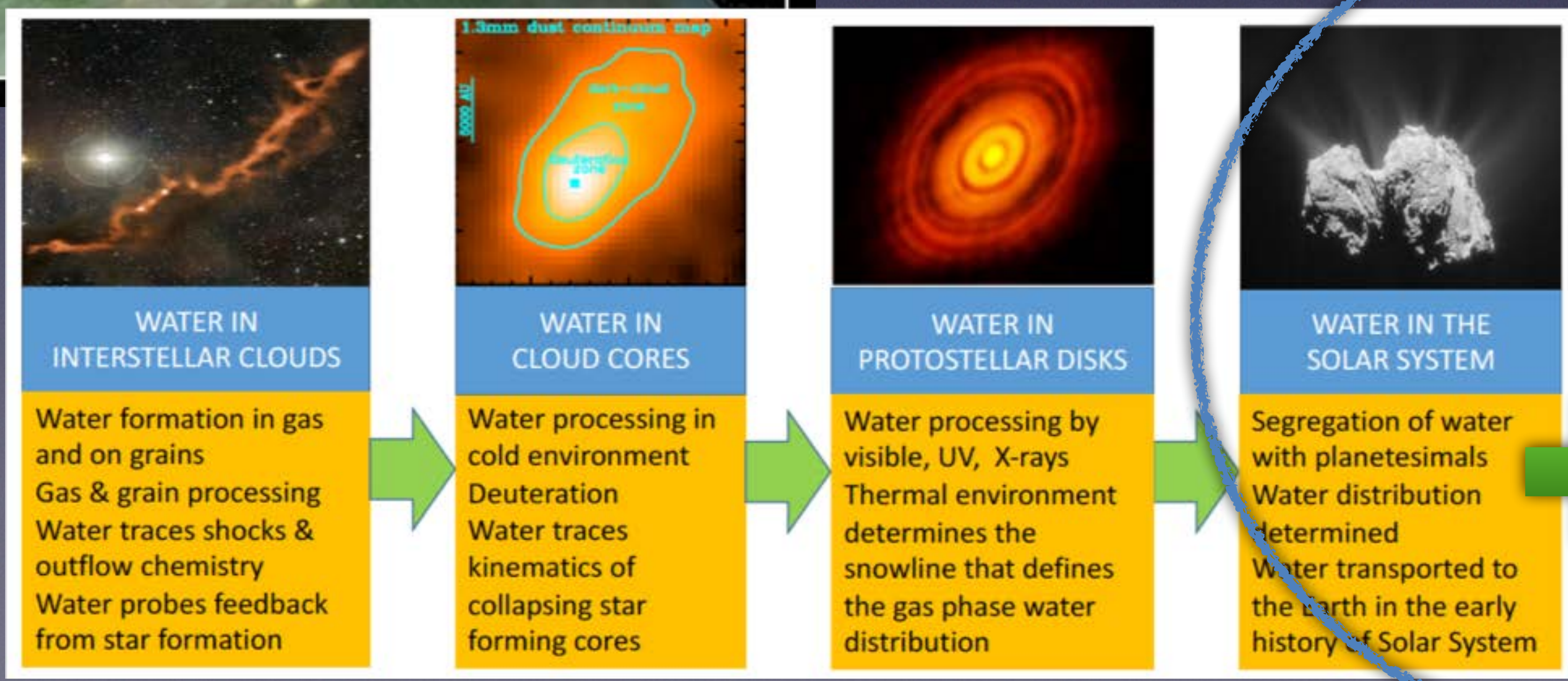
Jet Propulsion Laboratory
California Institute of Technology

Millimetron Workshop, Sep 2019

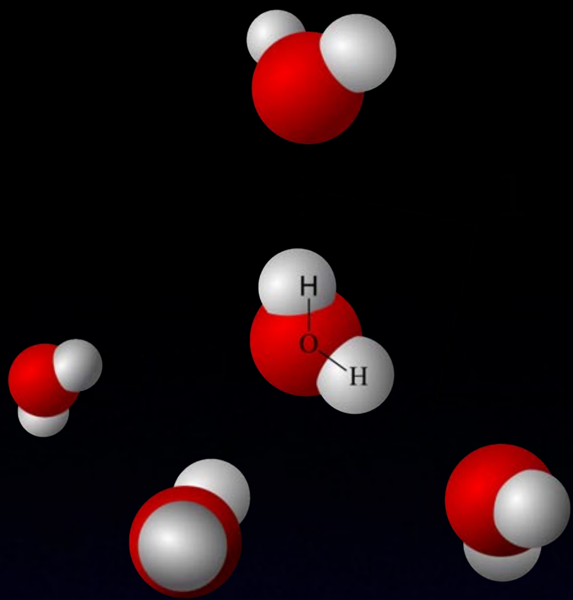
NASA/Origins

Cosmic Inheritance of Water



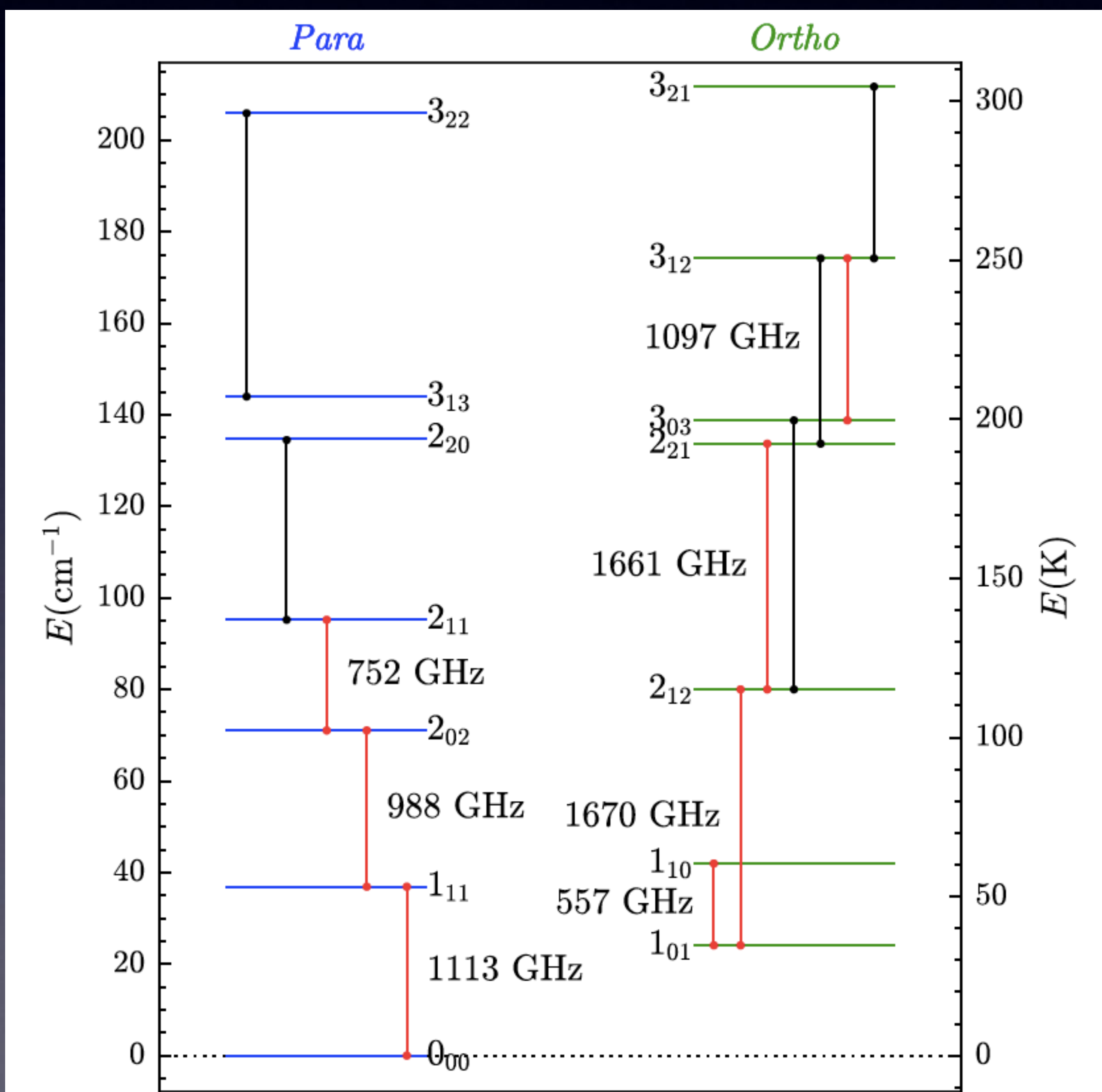


Images: NRAO/NASA

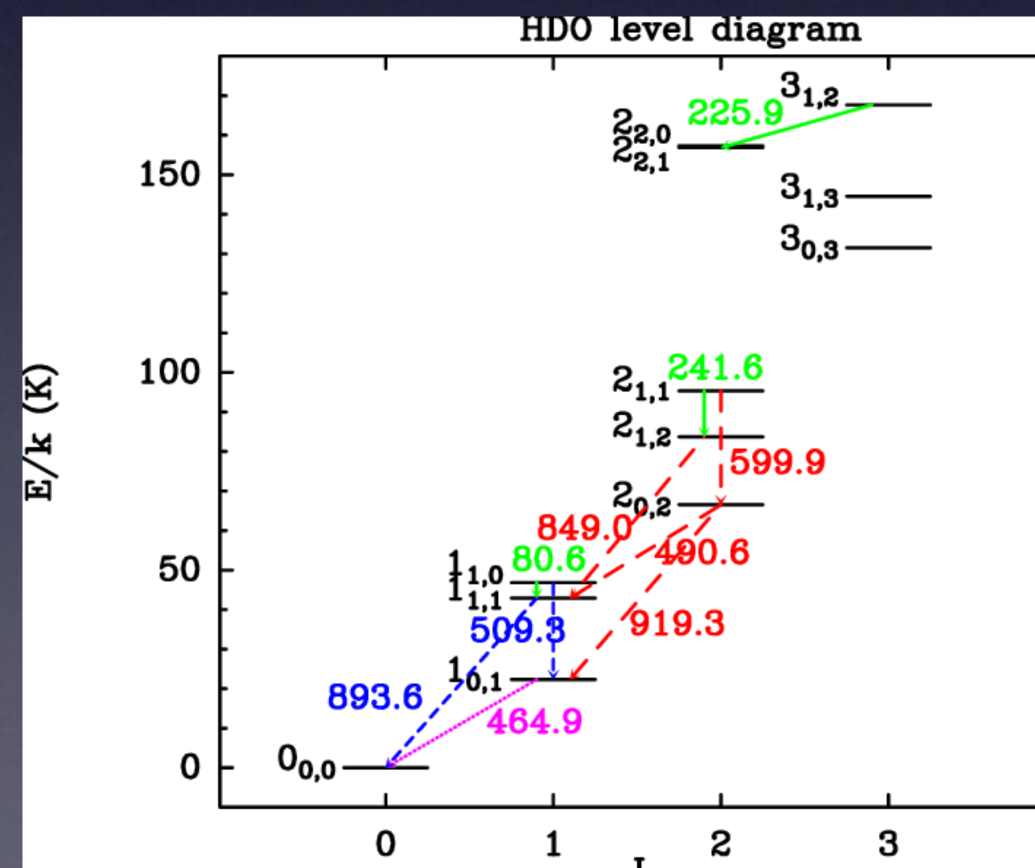


Observations of Cold Water

- Key low-energy water I lines between 500 and 1700 GHz
- Atmosphere often completely opaque
- Even SOFIA cannot observe cold water

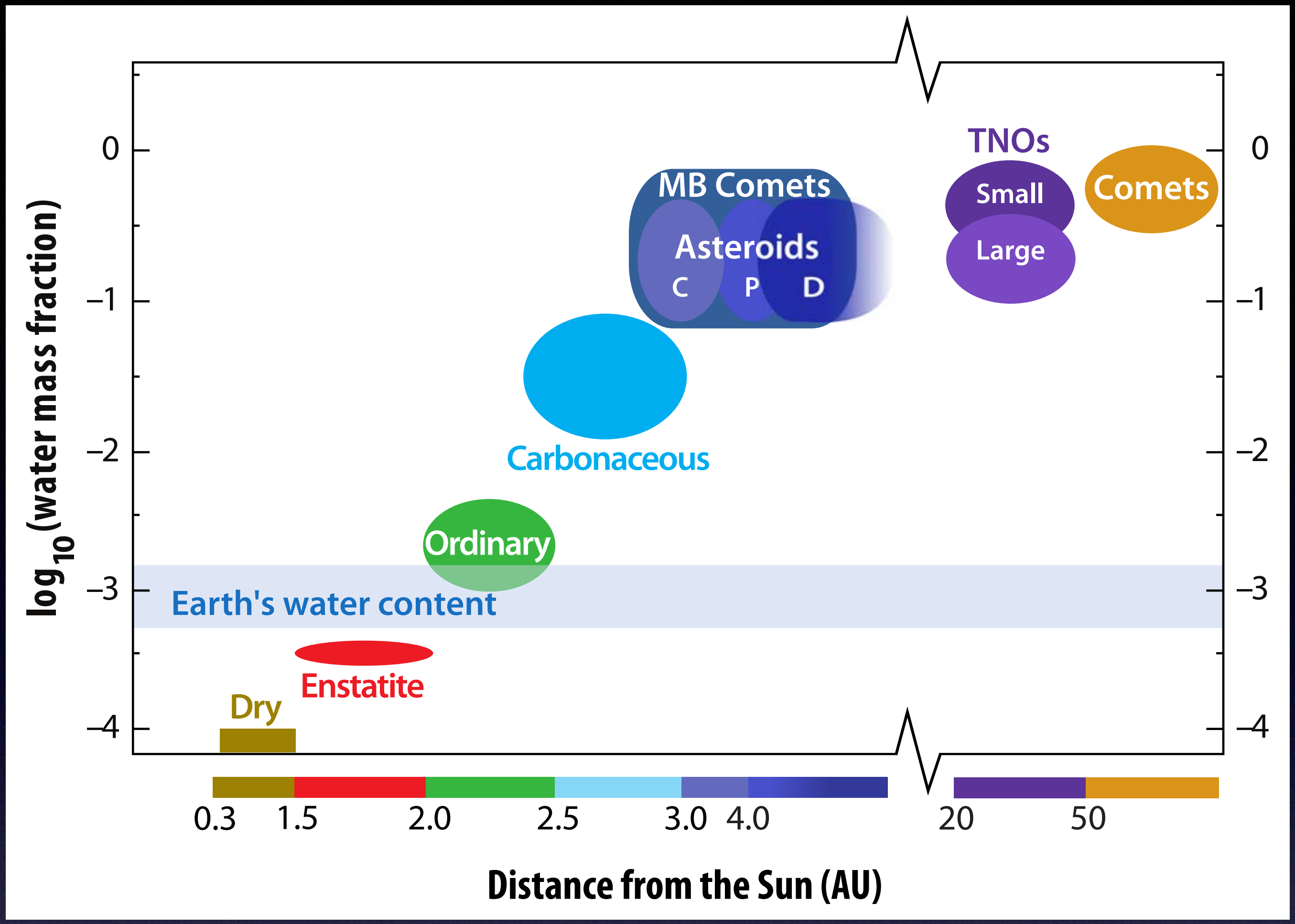


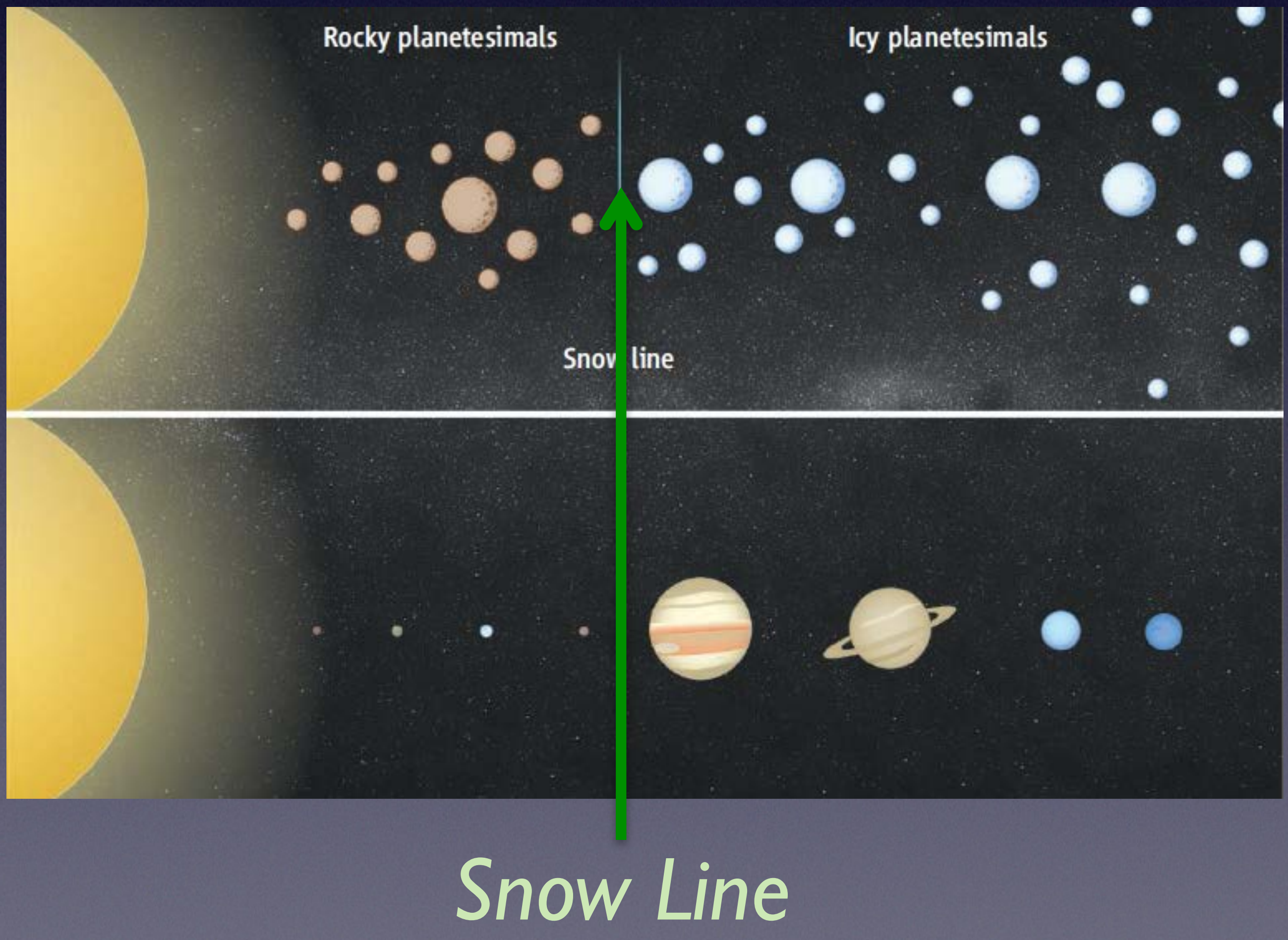
Putaud 2019



Coutens et al. 2014

Once upon a time the Earth formed dry

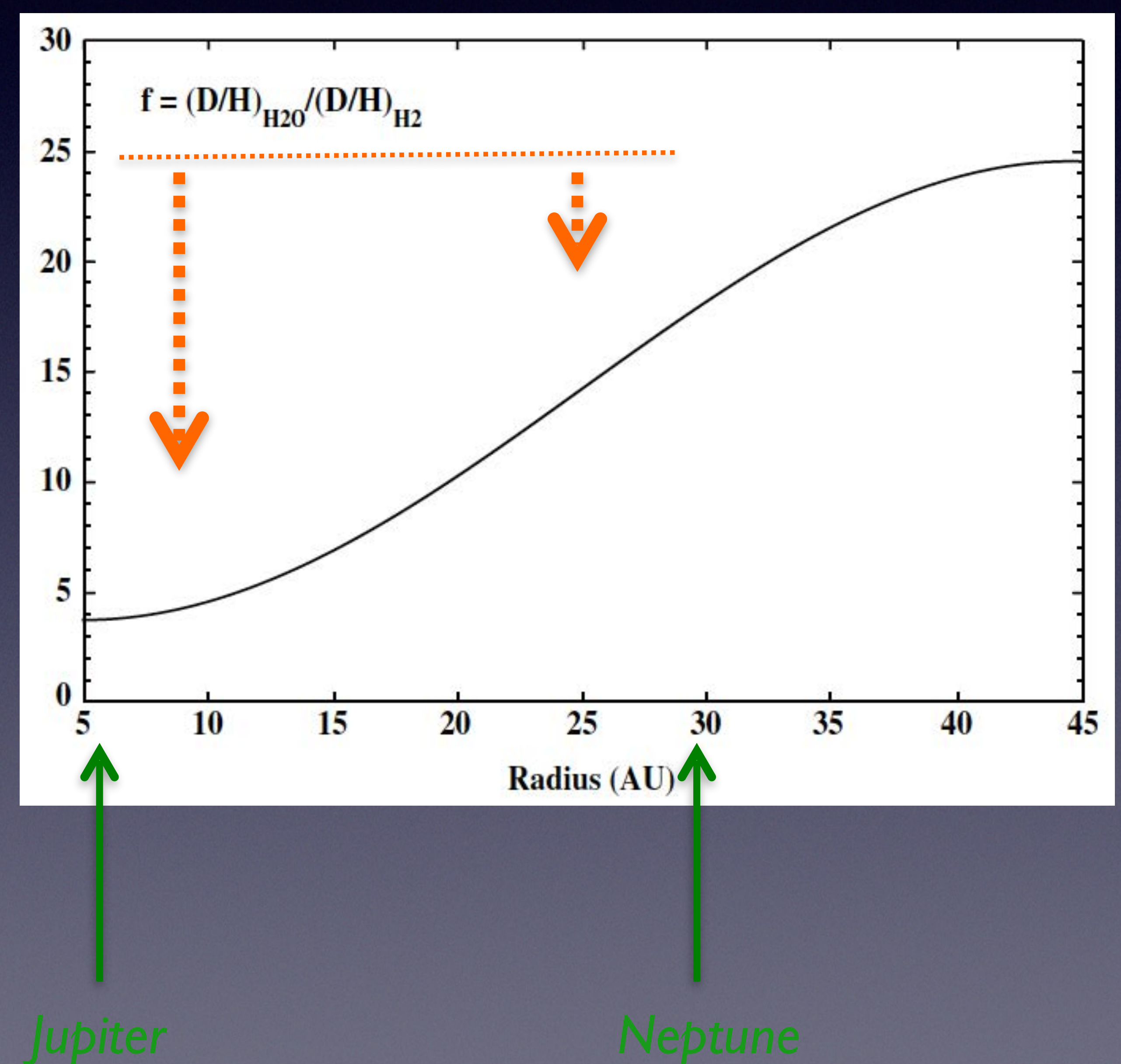




- Water mass fraction increases with heliocentric distance
- “Textbook model”: temperature in the terrestrial planet zone was too high for water ice to exist
- Water and organics were most likely delivered by comets or asteroids
- Alternative: water could have survived, incorporated into olivine grains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

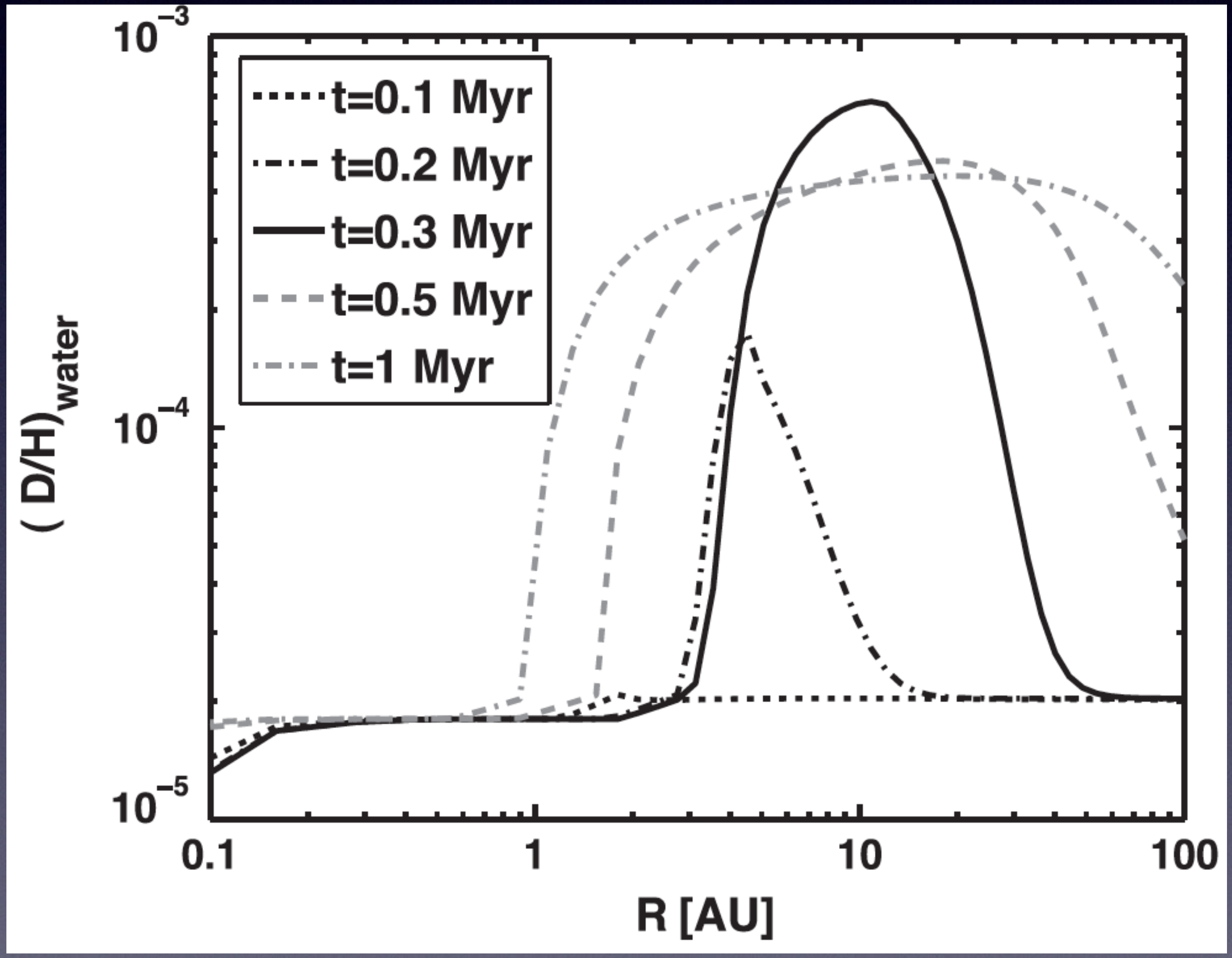
"Textbook" D/H in Water in the Solar Nebula

- 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

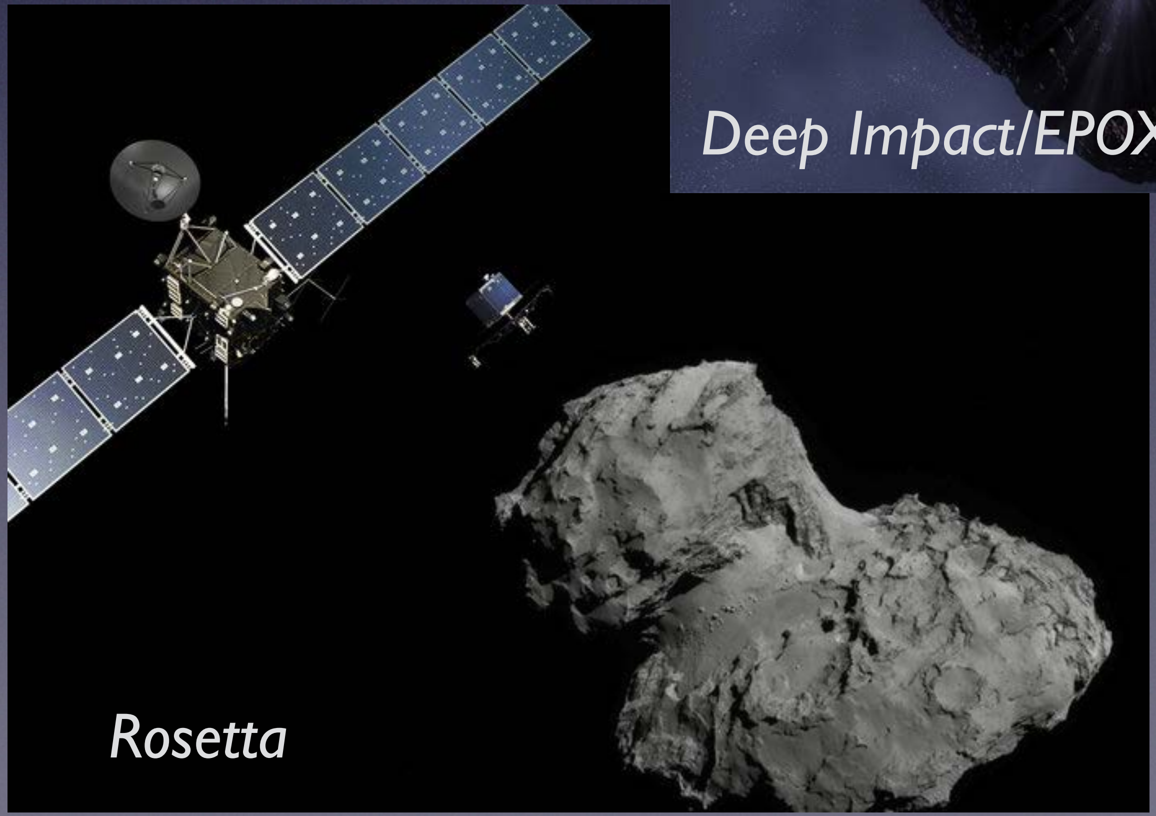
Yang et al. (2013)

Isotopic Ratio Measurements

OSIRIS-REx

Deep Impact/EPOXI

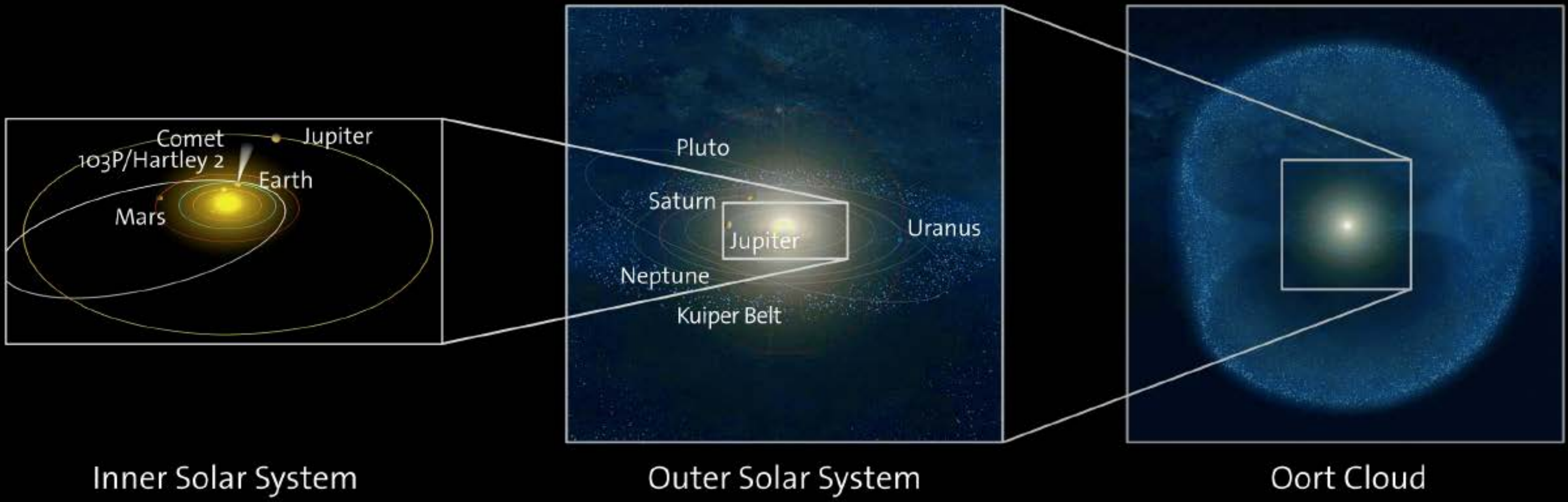
Herschel



Rosetta

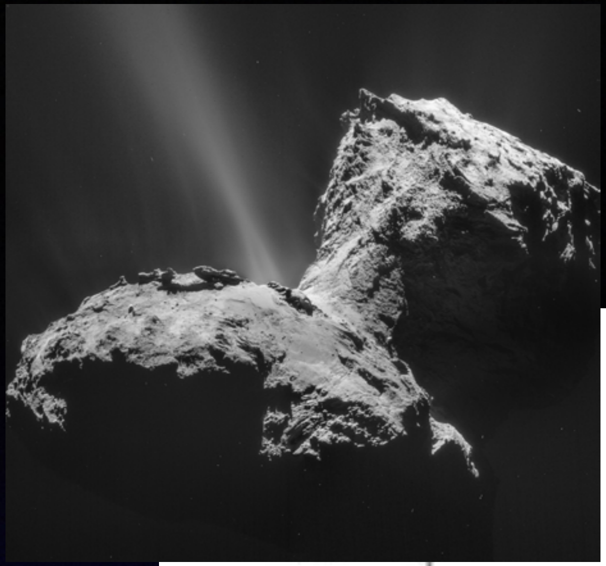
- Remote sensing — statistical studies of objects that have atmospheres
- Sample return or in-situ — detailed studies of individual objects — H, O, N, noble gases

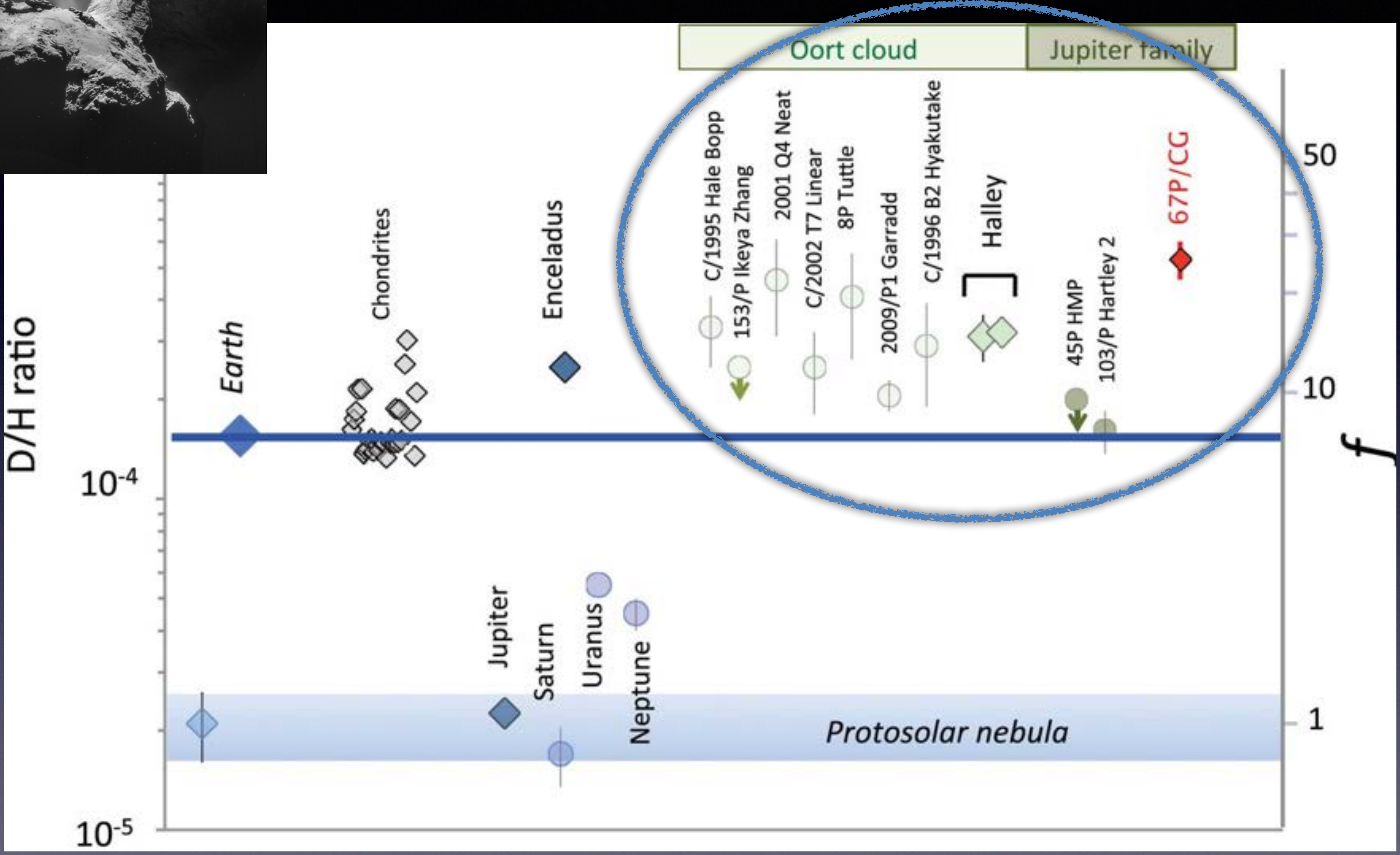
Comets



- 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





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

ORIGINS Space Telescope

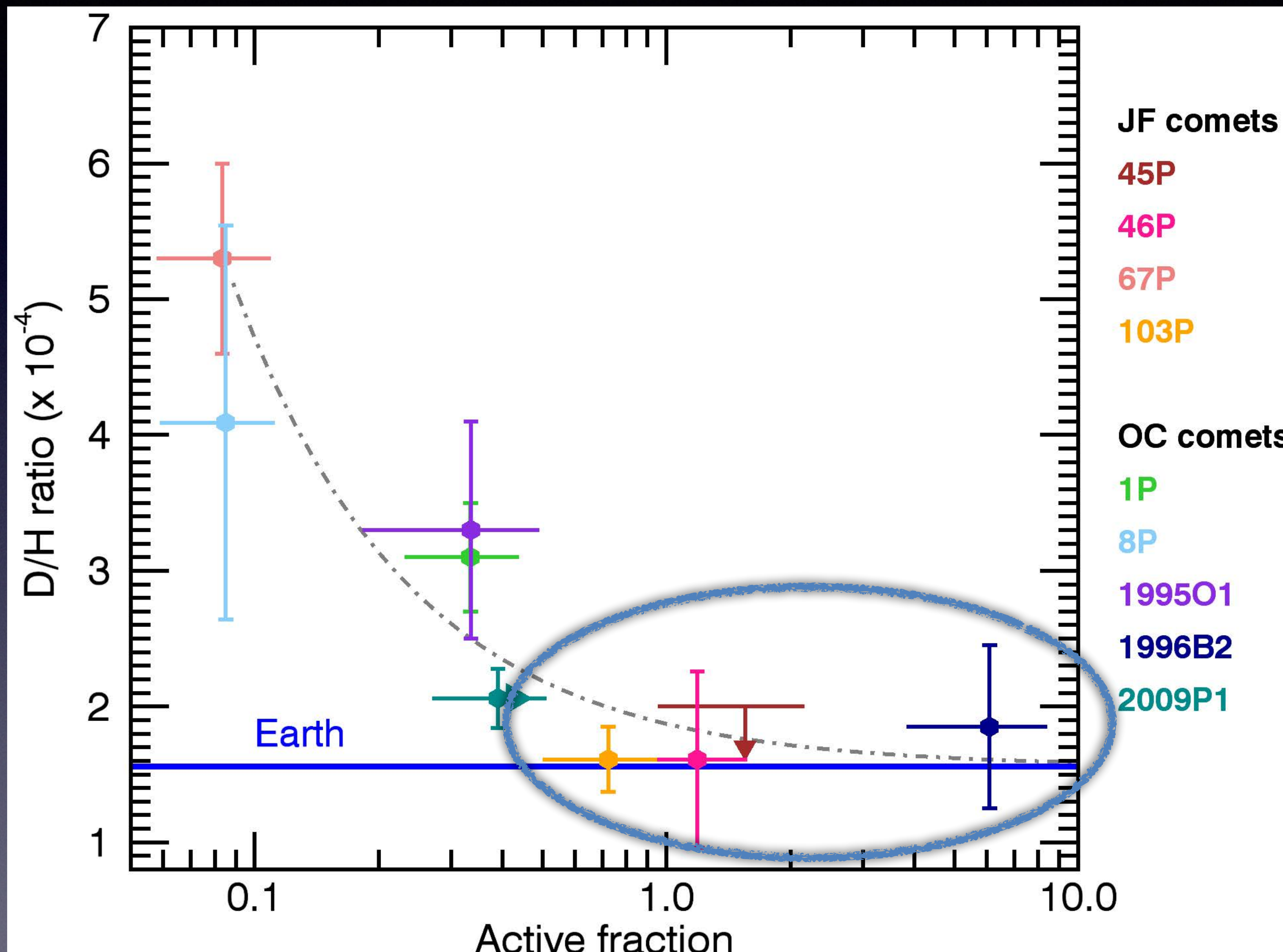
SPACE

Hyperactive Comets Hint at Origins of Earth's Oceans

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

SCIENTIFIC AMERICAN

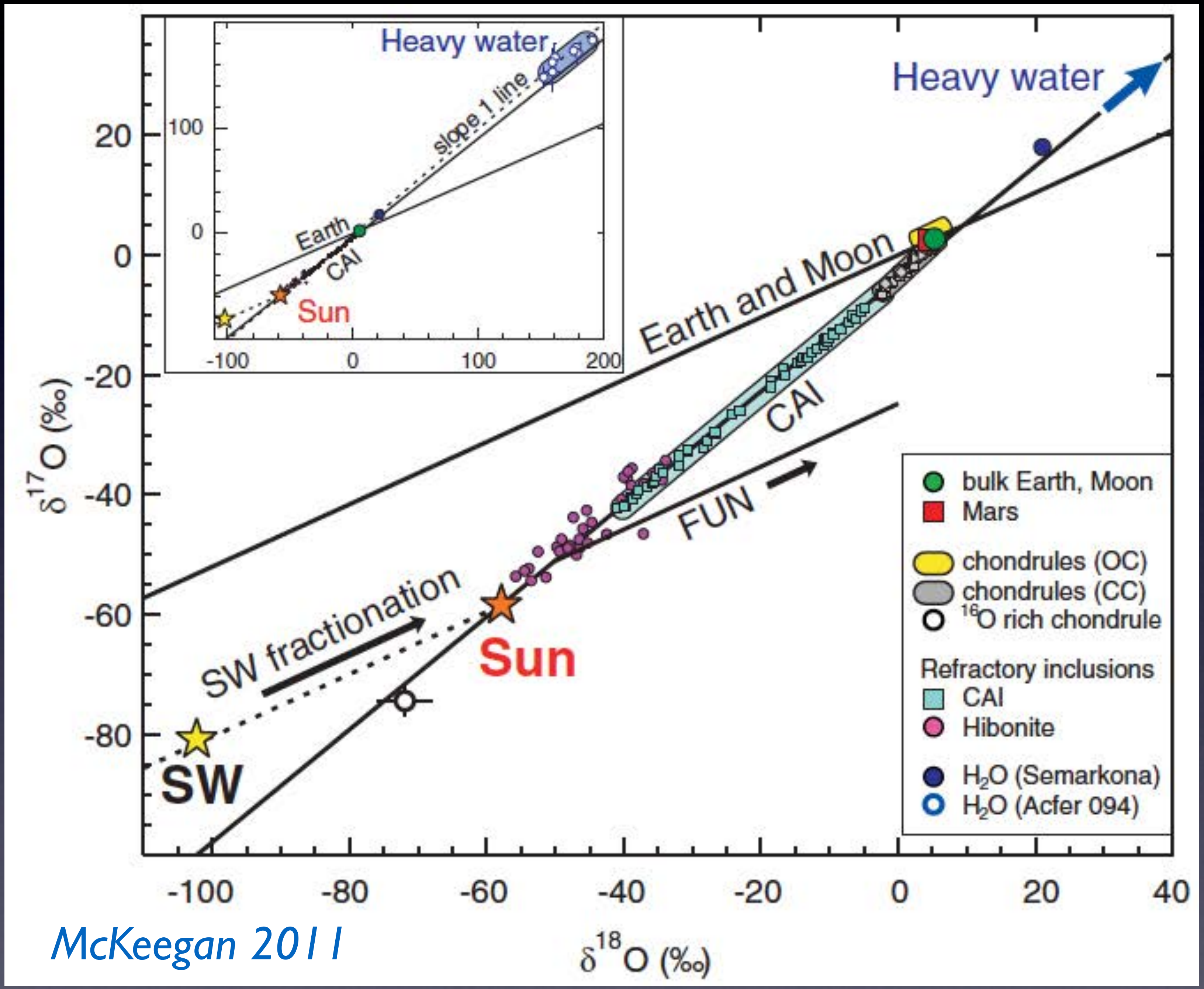
By Nola Taylor Redd on May 9, 2019



Lis et al. 2019

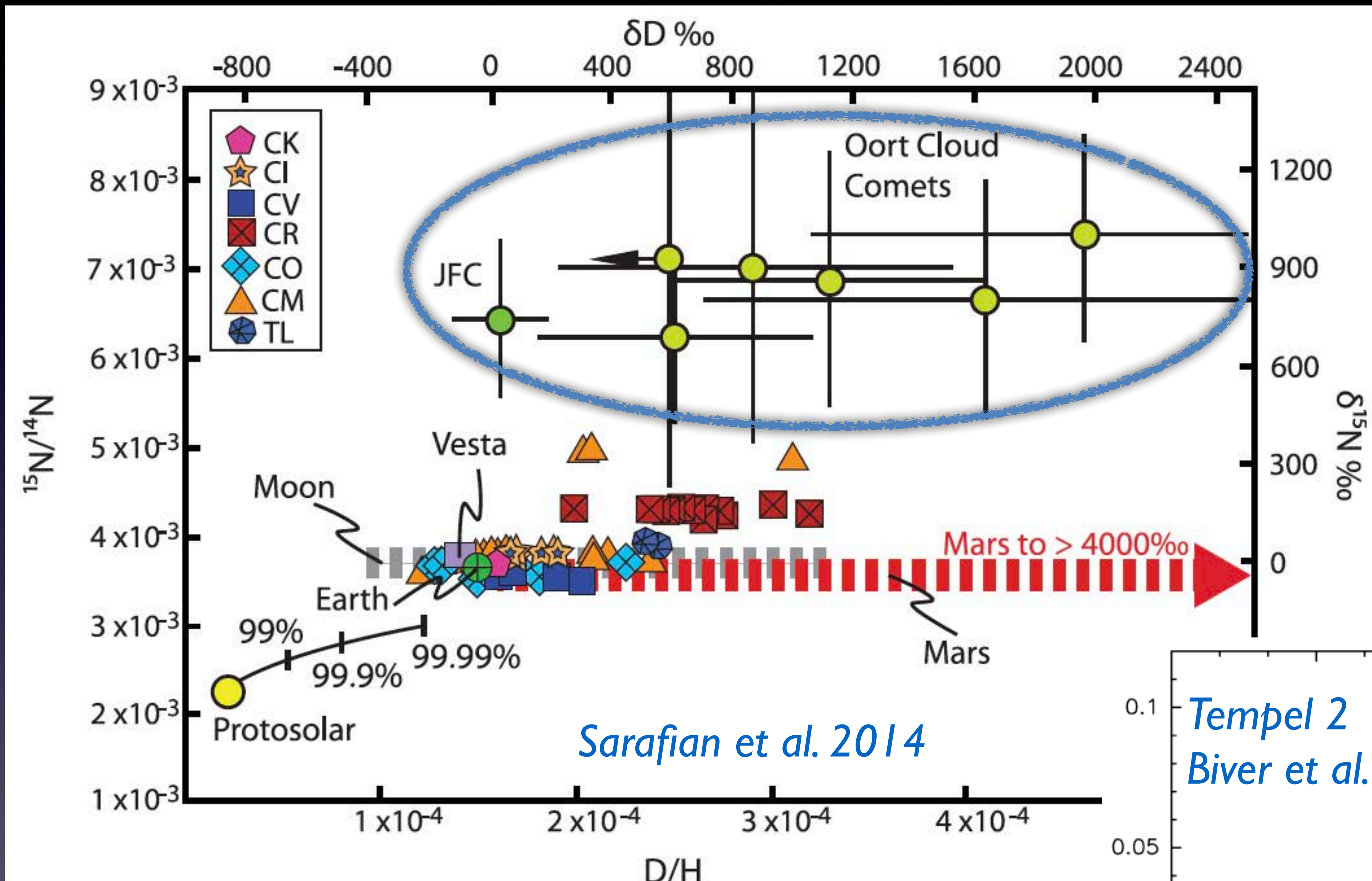
- Hyperactive comets typically have terrestrial D/H ratios
- Large reservoir of ocean-like water in the outer Solar System

Oxygen Isotopic Ratios

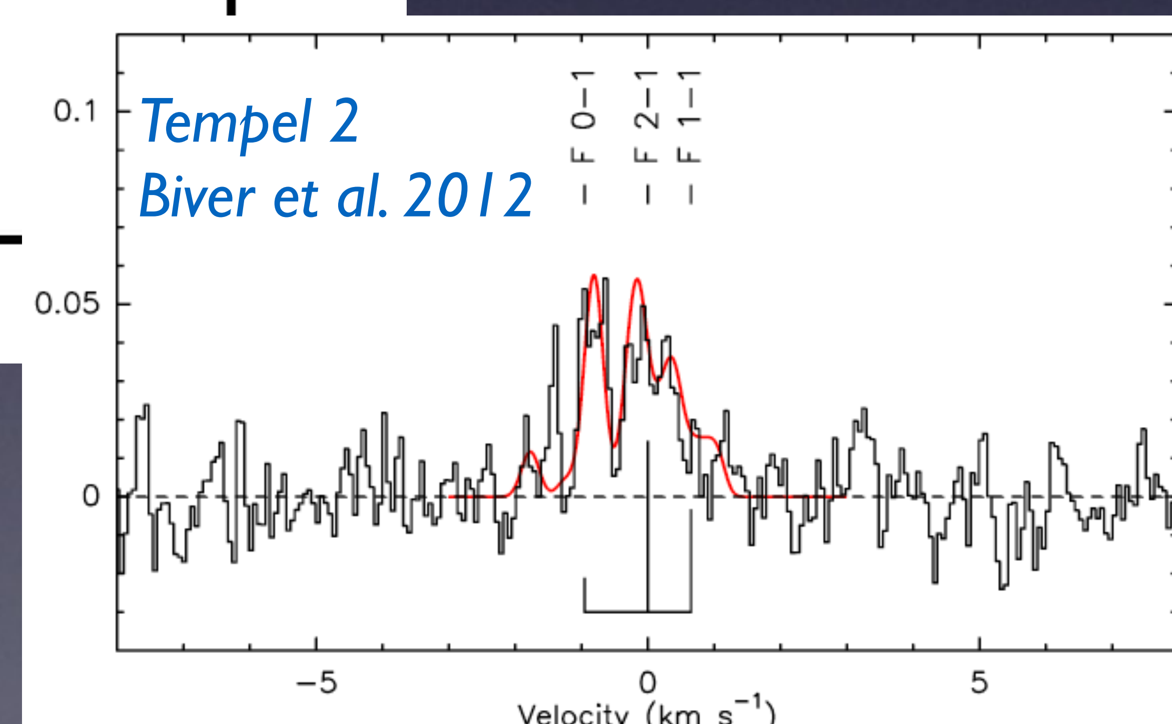


- Expect mass dependent fractionation: fractionation of $^{17}O/^{16}O$ half of that of $^{18}O/^{16}O$
- Mass independent fractionation observed — why?

Nitrogen Isotopic Ratios



- Comets enriched in ^{15}N?
- Cometary measurements mostly in CN and HCN
- Rosetta: ammonia 4.7 times more abundant than HCN
- Ammonia may not be isotopically equilibrated with CN and HCN



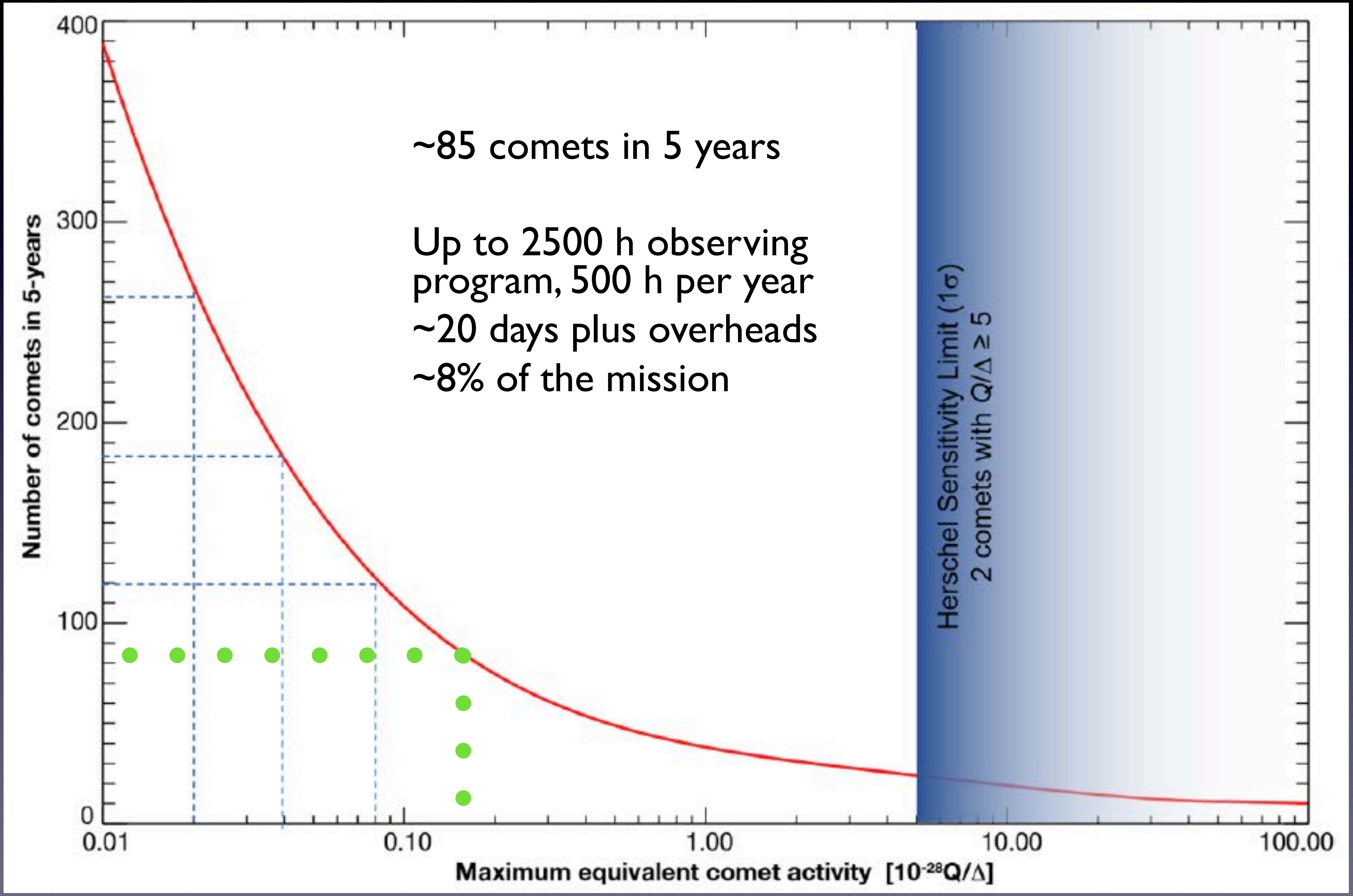
- Fundamental NH_3 line at 572 GHz detected with Herschel, but not $^{15}NH_3$

Millimetron Sensitivity

- Herschel/HIFI observations of comet 103P/Hartley — heterodyne spectroscopy
- Figure of Merit (FOM) $=10^{28}s^{-1}/0.21au=4.8\times10^{28}$
- 10σ detection of the HDO 509 GHz in 340+82 min (7 h)
- Expected improvement for Millimetron: × 16
  - Rx sensitivity: 2 (T_{rx} 50 K DSB at 500 GHz demonstrated)
  - Telescope diameter: 10/3.5=2.9
  - Two pixels: $\sqrt{2}$
  - 4 × longer integration (up to ~30 h per source): 2
- Sensitivity limit: FOM = 1.5×10^{27} (for a 5σ detection of HDO; SOFIA~1.5×10^{29})

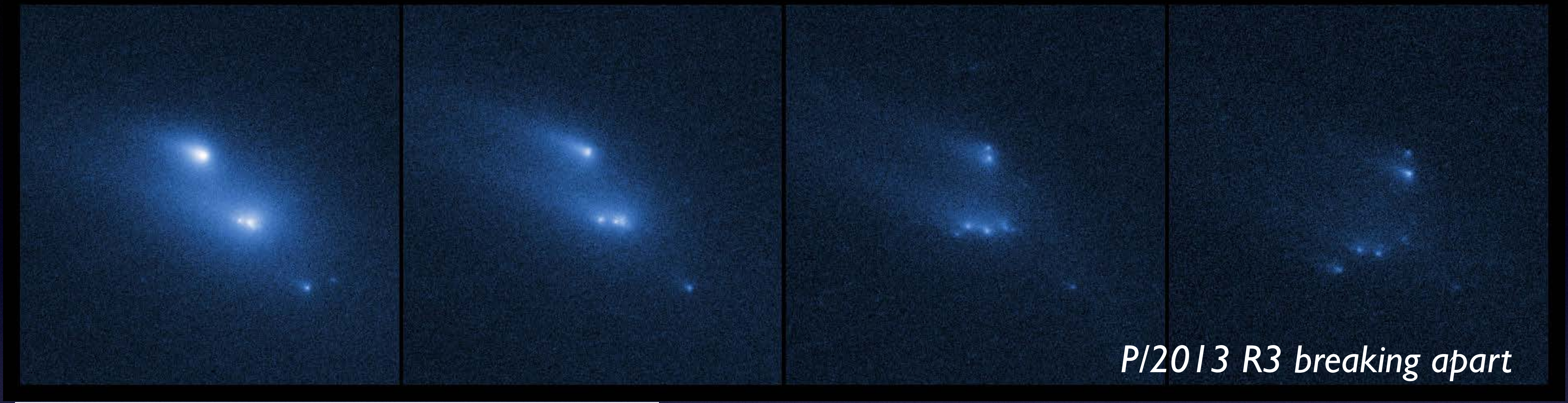
- Frequency settings:
  - D/H and O — Ch 1: HDO 509.3 GHz, $H_2{}^{18}O$ 547.7 GHz / $H_2{}^{17}O$ 552.0 GHz + Ch 2: $H_2{}^{16}O$ 1097.4 (or 1153.1, 1162.9, 1228.8 GHz — modeling required)
  - N — Ch 1: NH_3 572.5 GHz / $^{15}NH_3$ 572.1 GHz (with $H_2{}^{16}O$ 556.9 GHz) + Ch 2: HDO 894 GHz

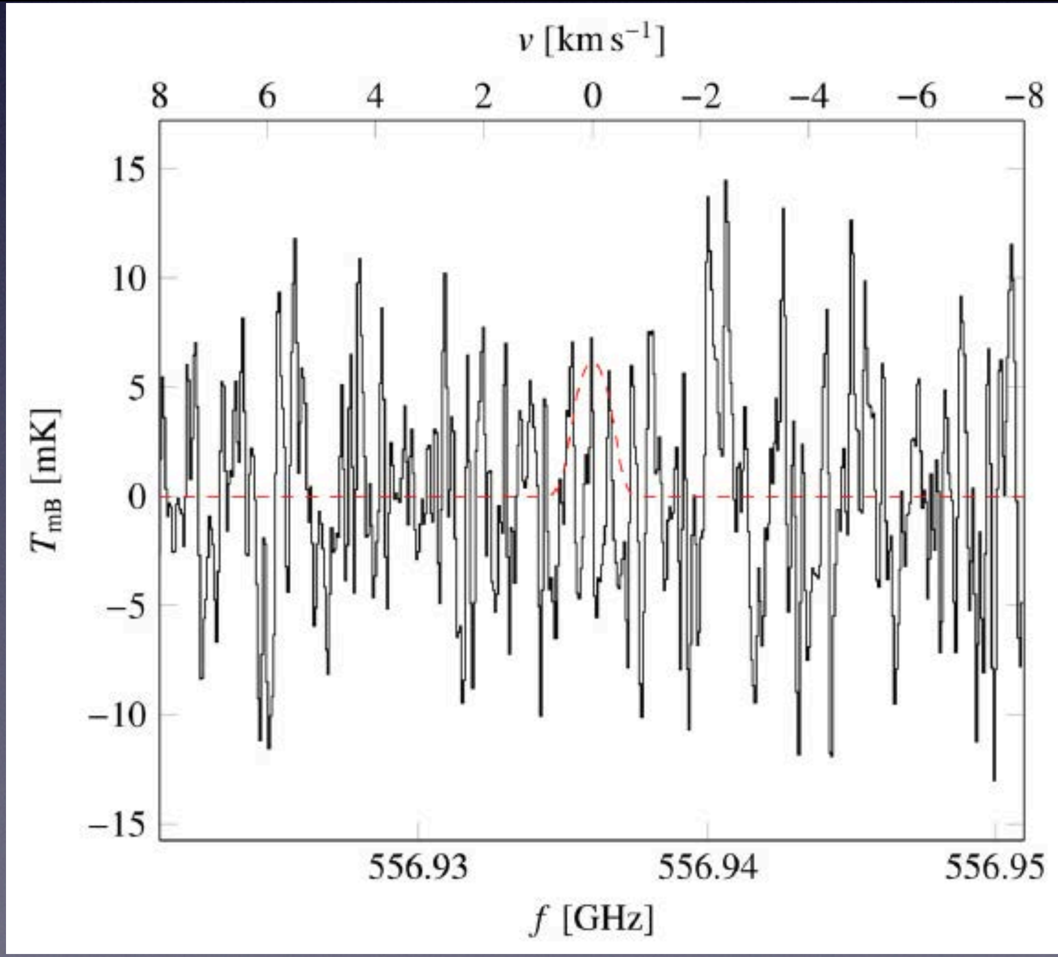
How Many Comets?



NASA, Origins

Main Belt Comets/Active Asteroids

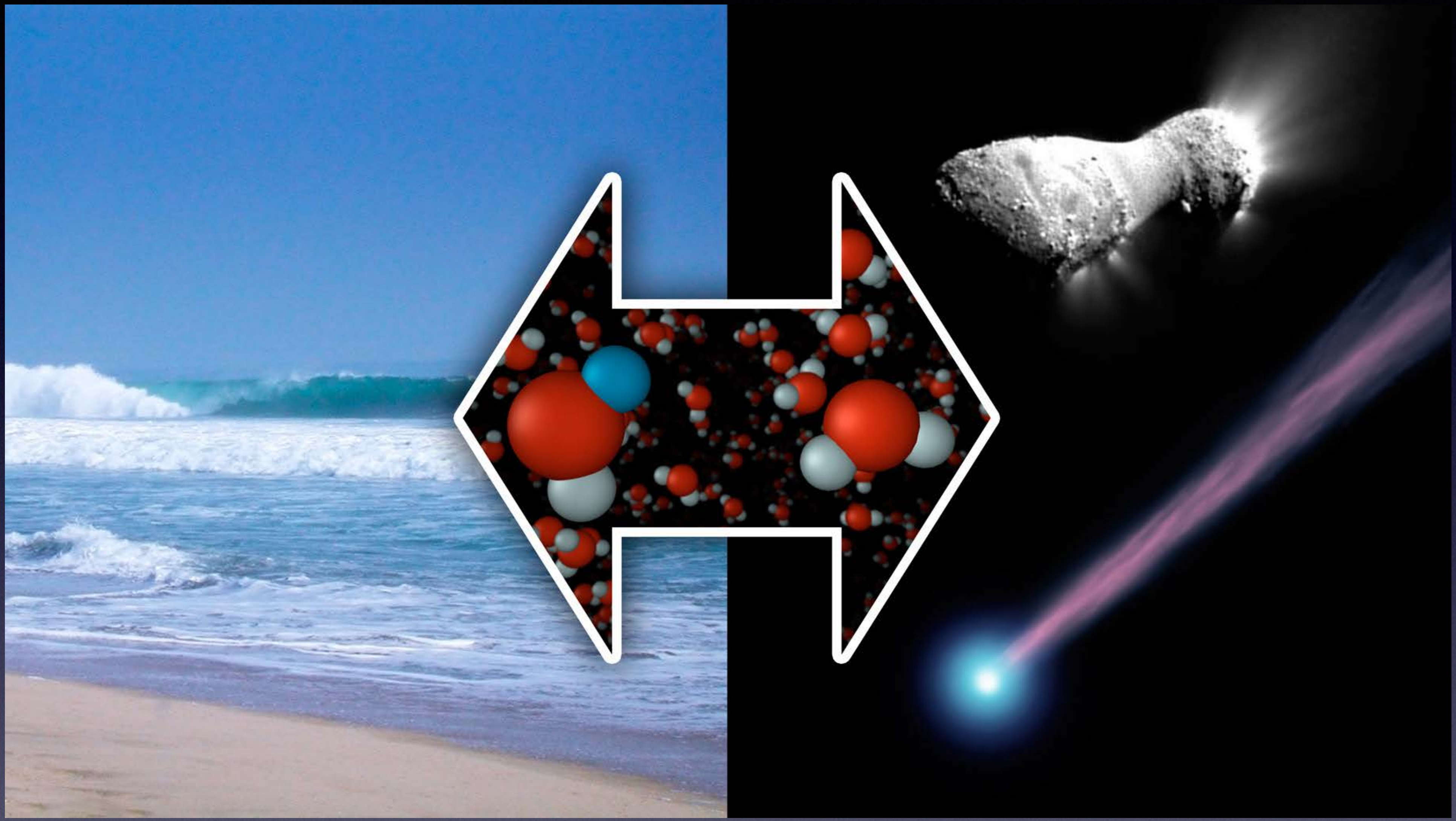

P/2013 R3 breaking apart



176P/LINEAR — de Val-Borro et al. 2012

- Intrinsically icy bodies on asteroidal orbits in the Main Belt
- Observed to eject dust — satisfy the observational definition of a comet — no water outgassing detected
- Formed and remained at their current location — not captured
- Herschel: $Q(H_2O)<4\times10^{25}$ s^{-1} (3σ, 5h)
- DGR=1 expect: $Q(H_2O)<2.3\times10^{24}$ s^{-1} (highly uncertain)
- *Millimetron* would detect water emission, but is unlikely to measure isotopic ratios

Summary



- *Vision and Voyages* explicitly identified *"determining the deuterium/hydrogen and other crucial isotopic ratios in multiple comets"* as key measurement for understanding Solar System beginnings (D/H, but also O and N isotopic ratios)
- Observations of water emissions in active asteroids provide information about water content of the asteroid belt and are of key importance for future in situ missions under consideration
- Important for understanding habitability of other planetary system

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