OBSERVATIONS OF COMETS WITH HIRMES

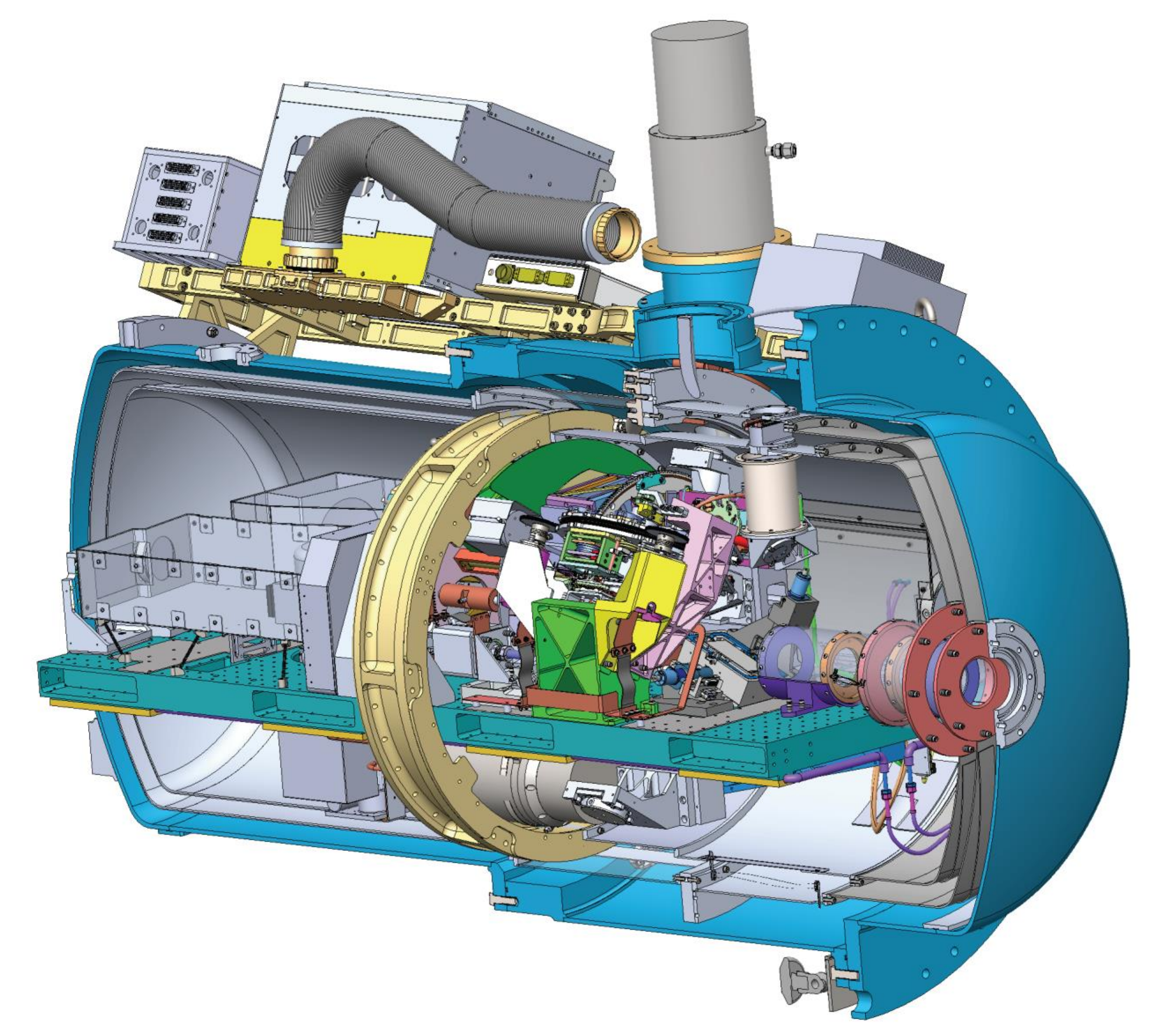
Stefanie Milam (NASA/GSFC), Darek Lis (Caltech) & Silvia Protopapa (SWRI)

https://www.hirmes.org/

HIgh Resolution Mid-infrarEd Spectrometer (HIRMES)

Principal Investigator:
Matthew Greenhouse
NASA Goddard Space Flight Center (GSFC)

Flyer: https://www.sofia.usra.edu/sites/default/files/Instruments/HIRMES/Documents/HIRMES_QG0618.pdf



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HIRMES primary science is to investigate protoplanetary disk physics and addresses the questions:

- How does the disk mass evolve during planetary formation?
- What is the distribution of oxygen, water ice, and water vapor in different phases of planet formation?
- What are the kinematics of water vapor and oxygen in protoplanetary disks?
- *Over riding theme is discover how protoplanetary systems evolve*

SOFIA-HIRMES

- **HIRMES is the 3rd-generation, facility class instrument on SOFIA, planned to be commissioned in early 2021.**
- **High spectral resolving power:**

  R=50,000-100,000 (or 3-6 km/s) over the full 25-122 µm range.
- **Unprecedented sensitivity**:

  At least matching that of Herschel-PACS.
- Low (R=300-600) resolution spectroscopy, including the **wavelength region between 35-55 µm.**

  This region is not covered by Spitzer, JWST, or Herschel, and has not been explored since ESA's Infrared Space Observatory.
- **High spectral mapping speed:**

  R~2000 in selected fine-structure lines.

The Instrument

Mode	Wavelength range	Resolving power	Field of View
High-resolution Fabry-Perot	25-122 µm	50,000-100,000	Long slit
Medium-resolution Fabry-Perot	25-122 µm	12,000	Long slit
Low-resolution grating	25-122 µm	300-600	Long slit
Spectroscopic imaging	51.8, 57.3, 63.2, 88.4, 121.9 µm	2,000	113"x106.8"

THE HIRMES LEGACY SCIENCE PROGRAM (LSP)

- First 2-3 years of HIRMES science operations a Legacy Science Program (LSP) will be observed.
- The HIRMES LSP is designed to reach ambitious science goals as soon as possible after commissioning as part of a large, coherent survey in the context of the original HIRMES science themes.
- Community participation will be essential, and the HIRMES legacy data will be made public as soon as they are observed and processed.

https://www.hirmes.org/legacy-program

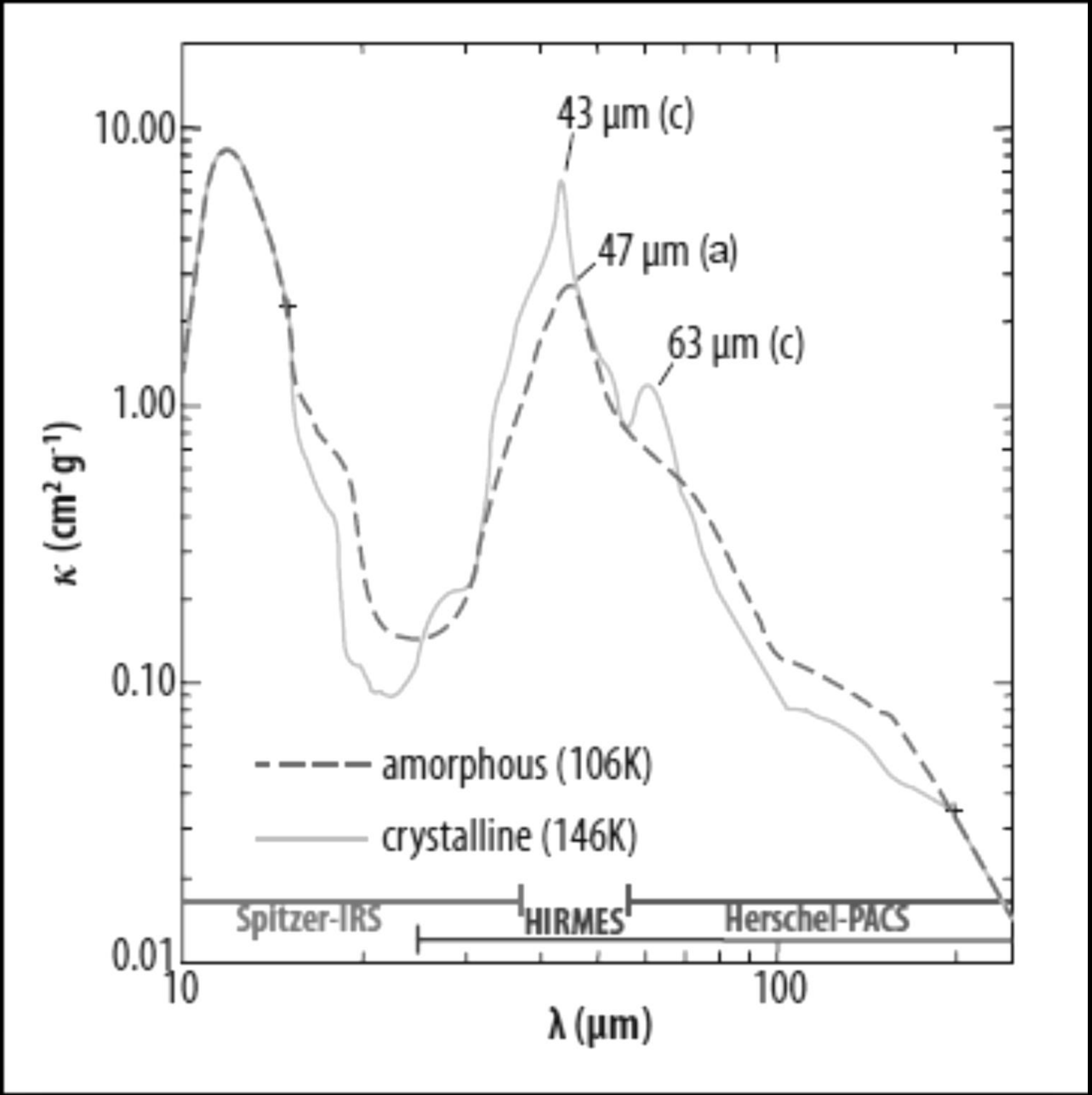
Key Questions for Cometary Ices

How and where can direct, observational evidence for amorphous ice in the outer Solar system be found? What is the best way to do this (via remote sensing)?

Water-ice particle size across several contexts is an important question. Can we remotely determine the purity and size of these grains?

Amorphous vs. Crystalline

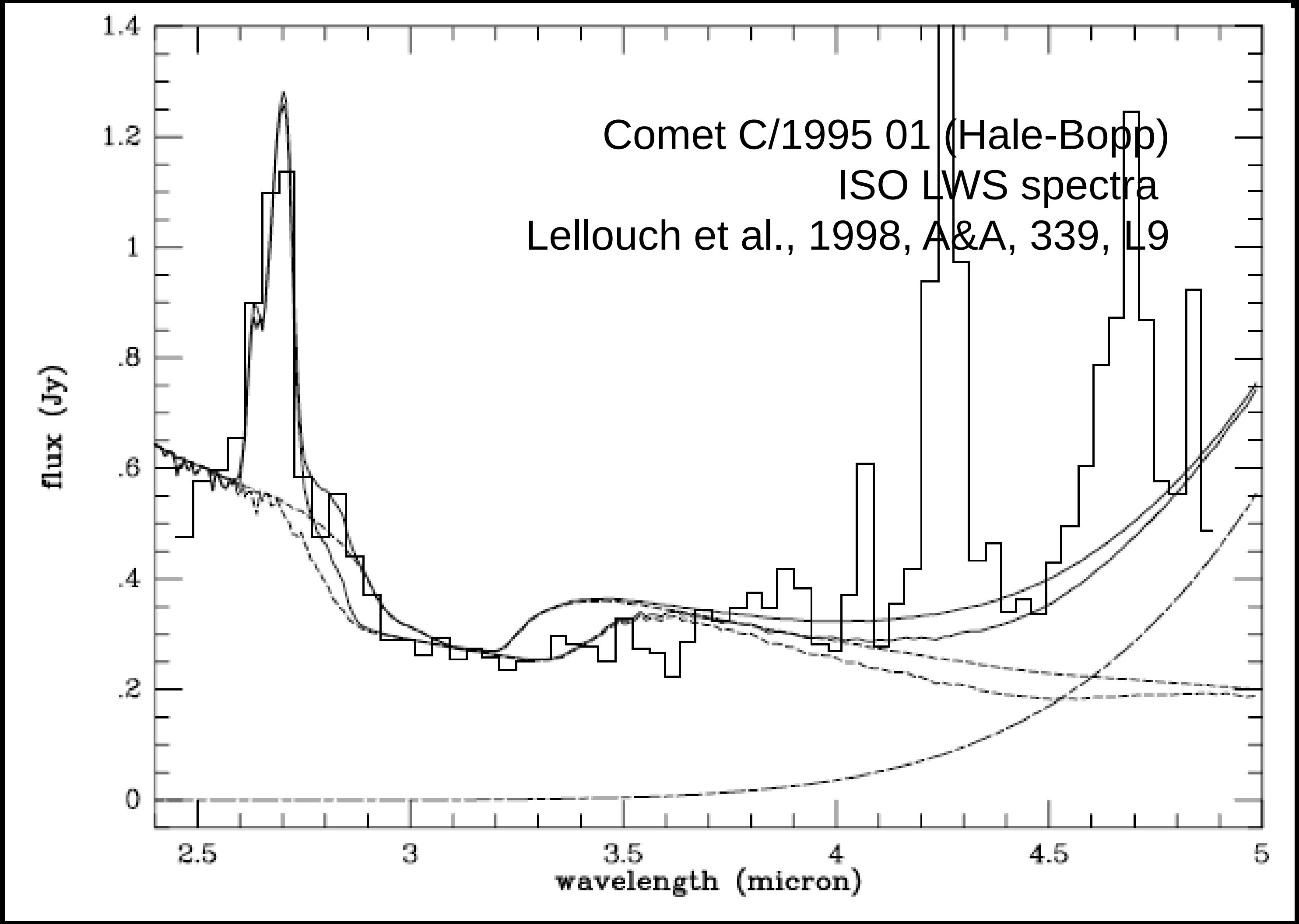
- Amorphous ice can have an intricate physical structure with a large specific area that can be a very effective sponge for other molecules of cometary relevance (Bar-Nun et al. 2007).
    - Understanding the compositions of the comets and related bodies in the source reservoirs.
- Crystallization of ice is exothermic and acts as a heat source in ice
    - Can crystallize other nearby ices
    - Release trapped volatiles
    - → alter pristine nature of comet



Mastrapa et al. 2009

Previous detections of water ice towards comets

- ISO detection towards Hale-Bopp at 2.9 au.
- LWS spectra (R ~200)
- Modeled grain size → r~15 micron
- Dust production rate (100 micron) ~ 4e4 kg/s
- NIR consistent with crystalline ice



Comet C/1995 01 (Hale-Bopp)
ISO LWS spectra
Lellouch et al., 1998, A&A, 339, L9

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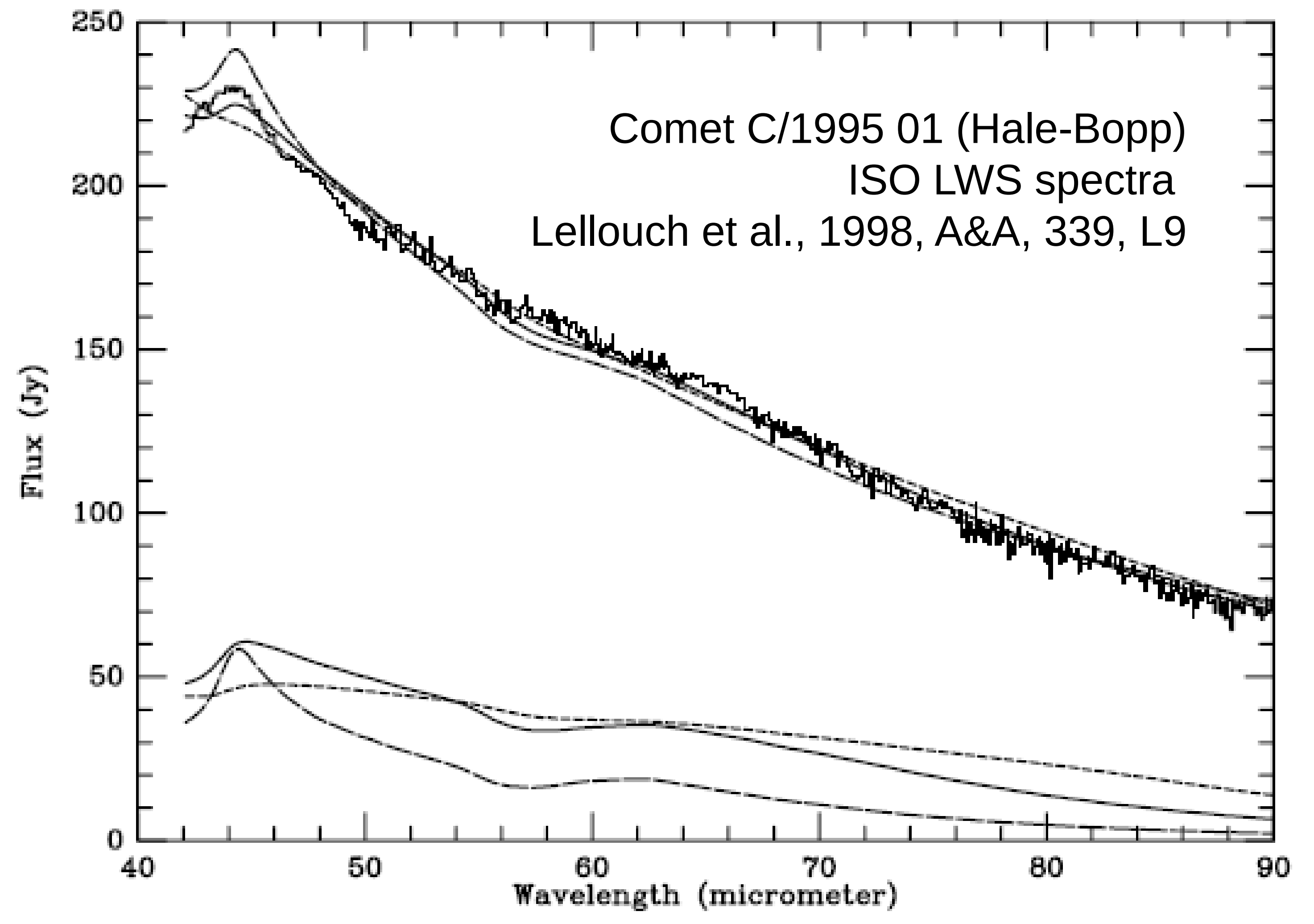
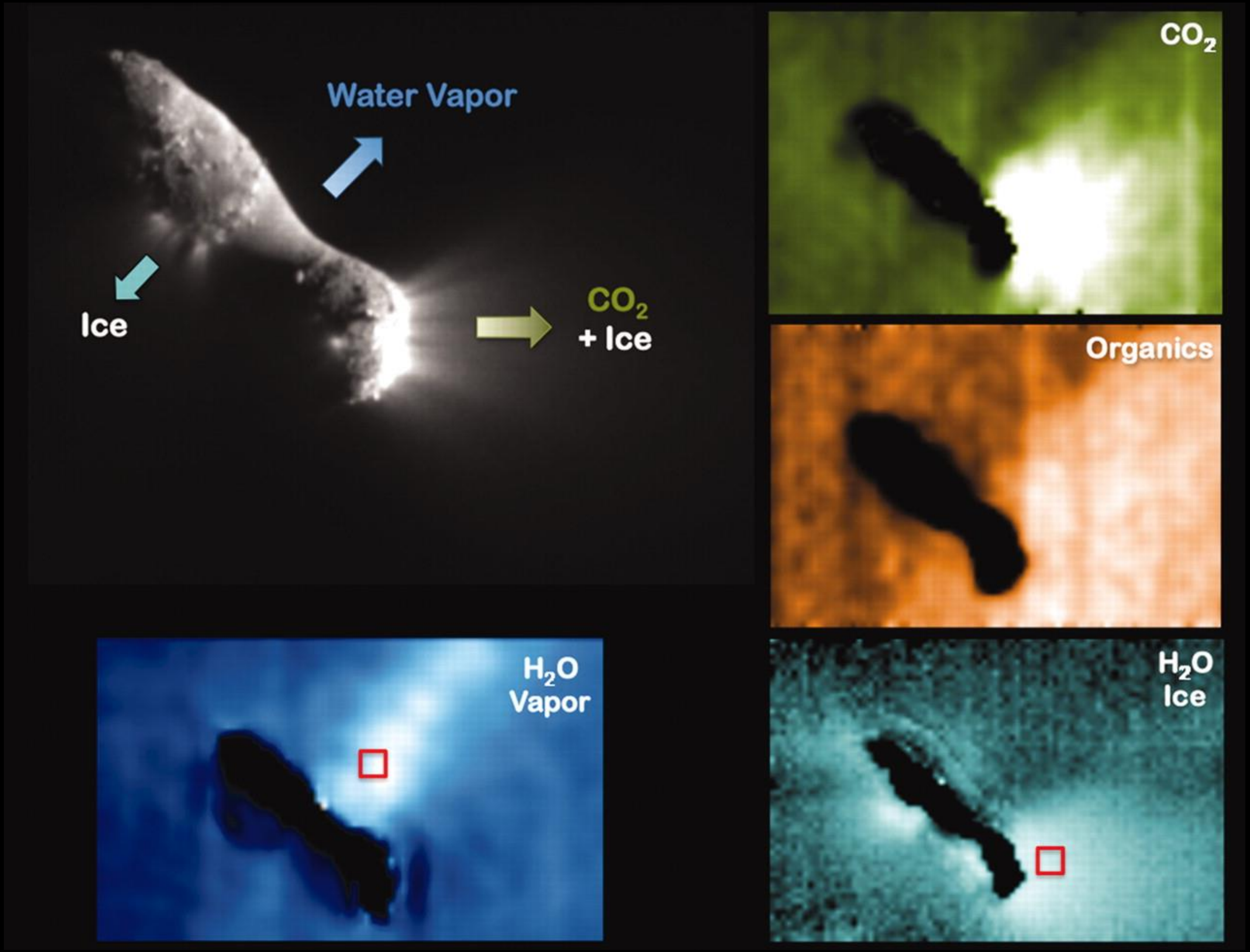


Comet C/1995 01 (Hale-Bopp)
ISO LWS spectra
Lellouch et al., 1998, A&A, 339, L9

Deep Impact and EPOXI

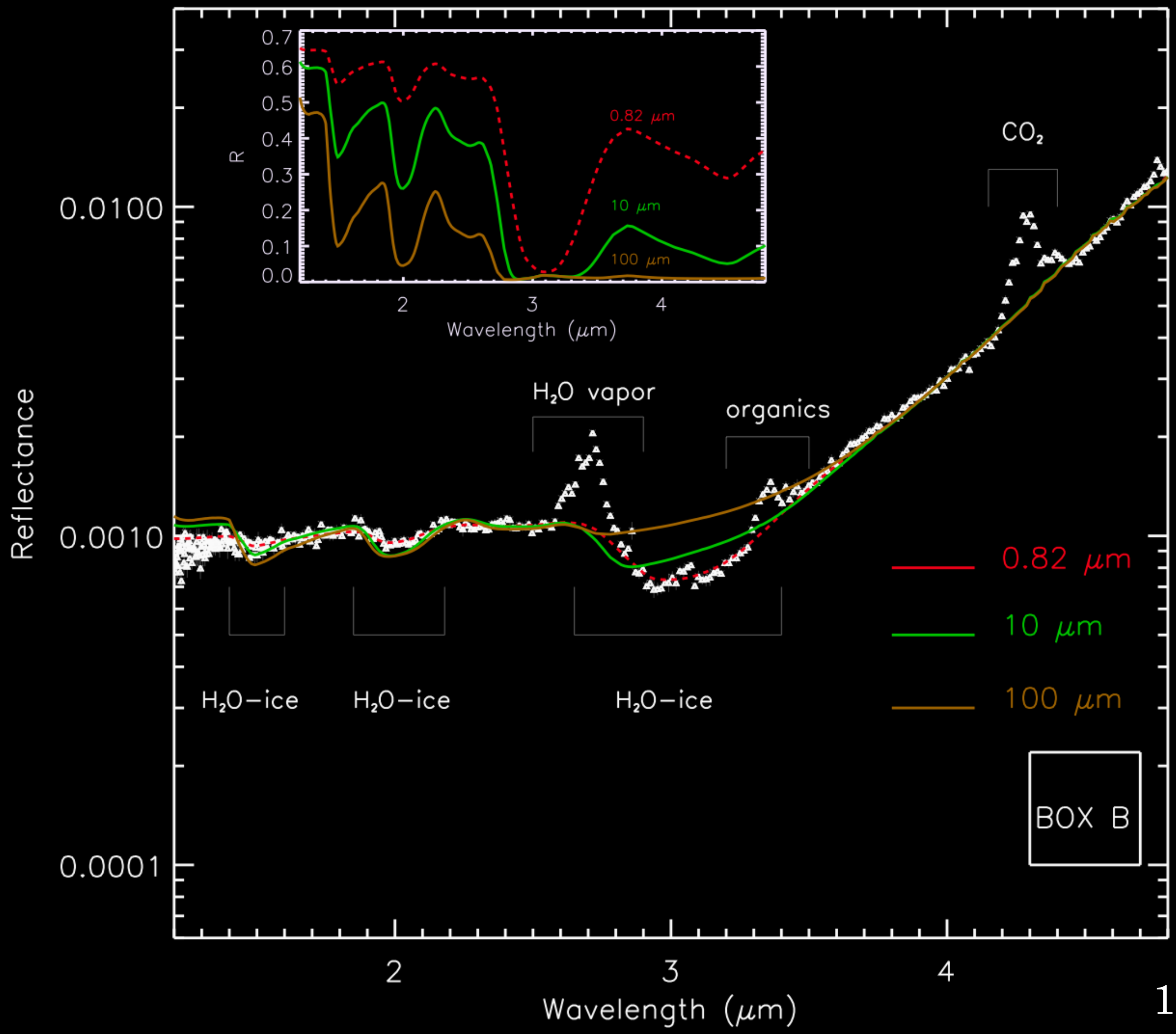
- The panel labeled H_2O Ice is a map of the depth of the ice absorption feature at 3 μm.



A’Hearn et al., 2011, Science, 332, 1396

Grain Size: Water-ice grains in comet 103P/Hartley 2

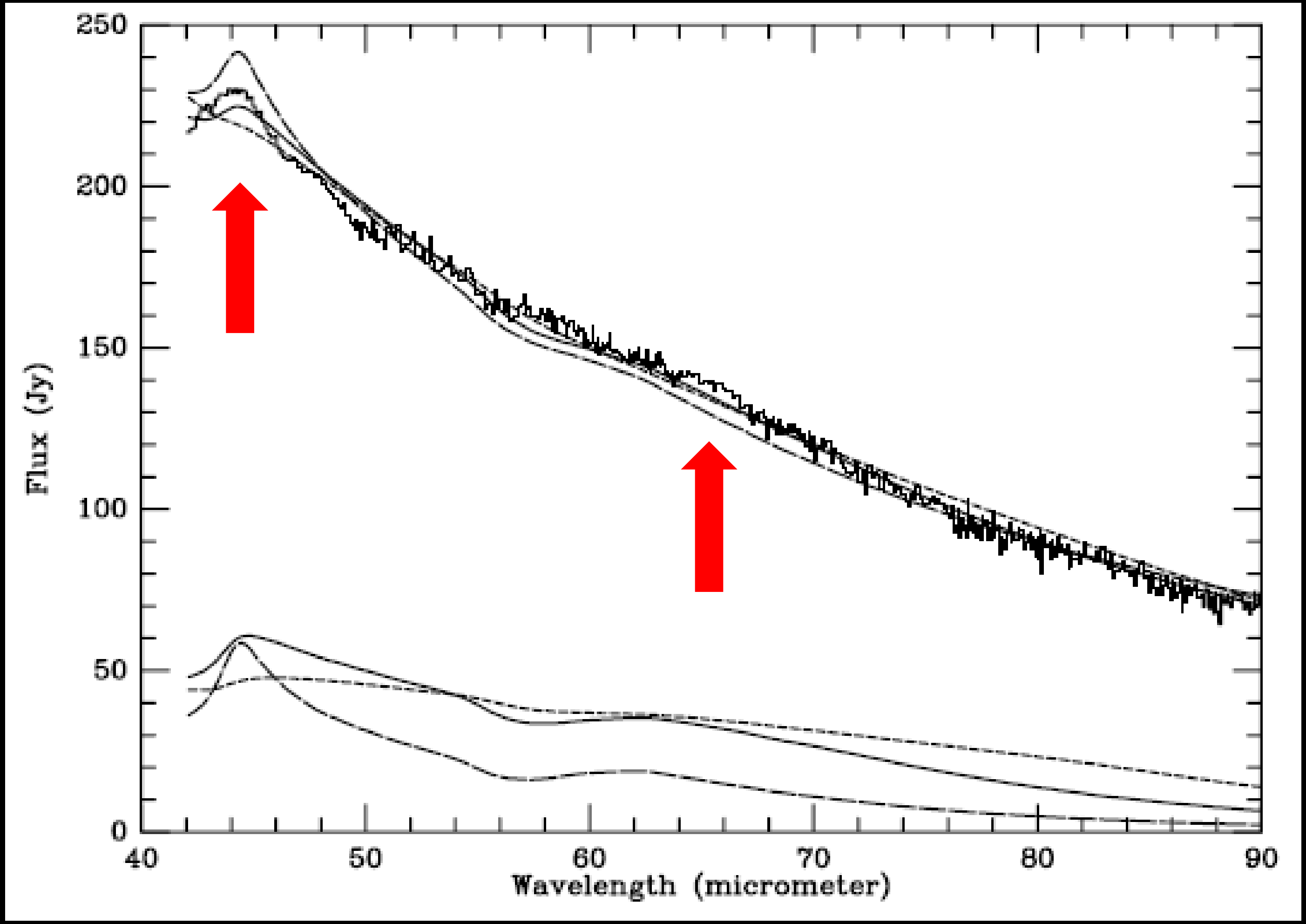
- By studying the physical properties of the major constituent water ice, such as phase, purity, and particle size, we can further constrain the composition of cometary nuclei and their origins and/or processes they may have occurred.
- Protopapa et al. (2014) concluded that the three absorption features observed at 1.5, 2.0, and 3.0 micron are consistent in bandwidth and strength with the presence of water ice grains of size <5 micron in the coma.



Protopapa et al. 2014, 2018

SOFIA-HIRMES LSP – Comet ice

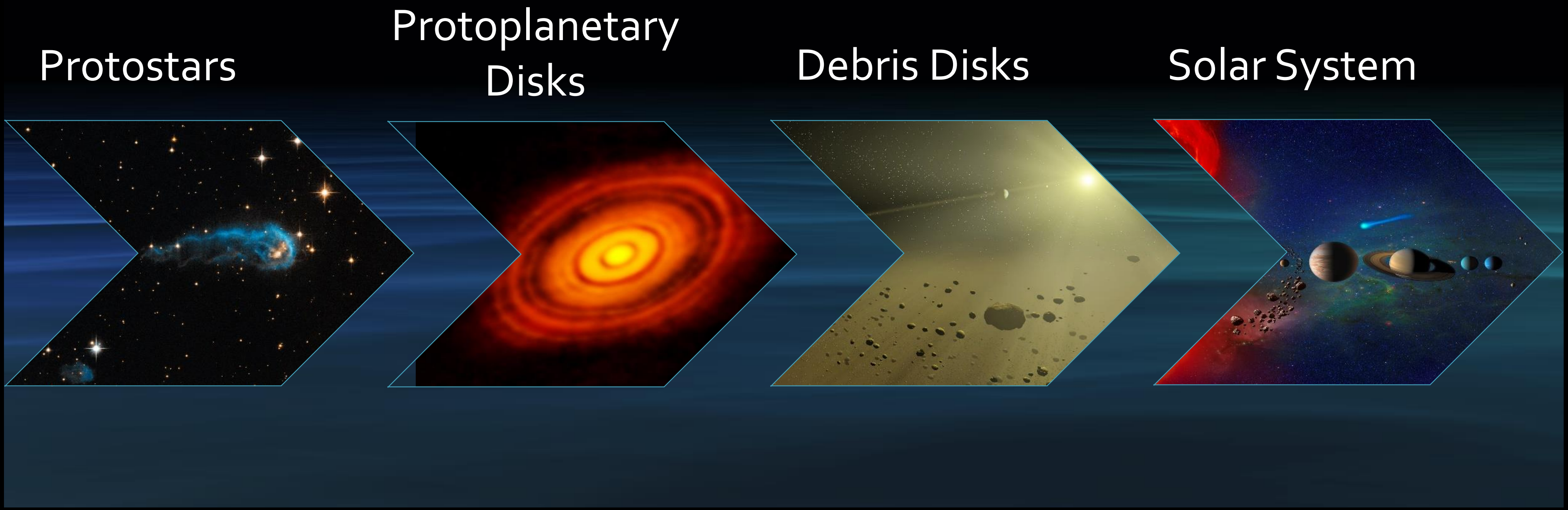
- Need moderately bright comet at >3au (FOM>0.1)*.
- Aim to observe 10% contrast between dust and ice features near 44 and 65 microns.
- Plan for 1 Target of Opportunity



HIRMES is unique by offing high enough spectral resolution to decipher a crystalline to amorphous abundance ratio in comets, as well as the bandwidth to help determine the dust size.

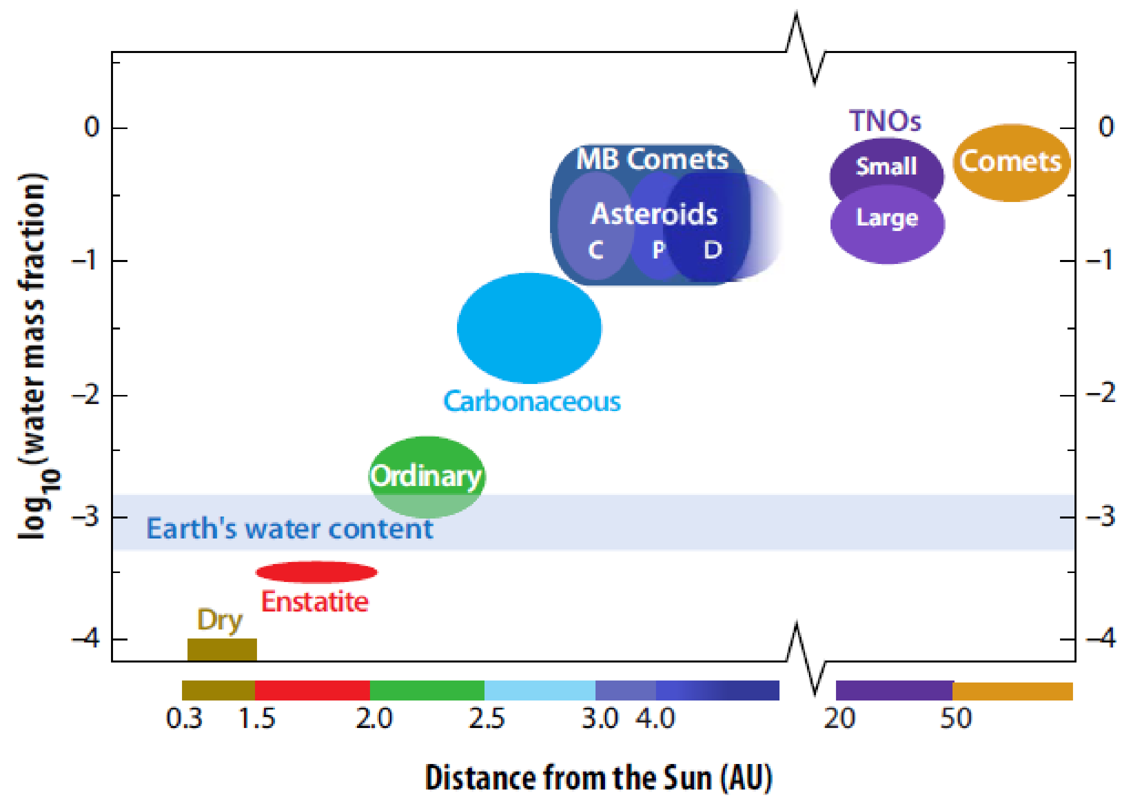
*Figure-of-merit (FOM), defined by the water production rate, Q, (s^{-1}) and heliocentric distance (rH) divided by geocentric distance (Δ in AU), FOM = $Q(H_2O)rH/\Delta[10^{28}]$.

Cosmic Inheritance of Water?



- Water is a key ingredient for life and a central theme of NASA’s vision
- Water trail can be best studied via far infrared spectroscopy

Why is Earth Wet?



- 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

Origin of Solar System water

- 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 (>7.2×10-4; 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

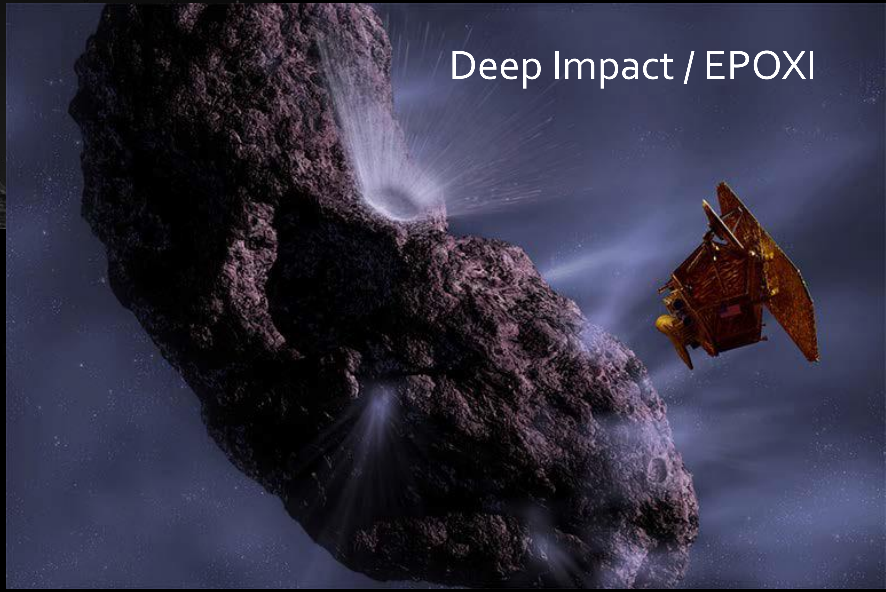
➢ Other models show more complex time dependent behavior

➢ Need observational data, in particular for the outer Solar System

Horner et al. 2007; Yang et al. (2013)

Isotope Ratios in Comets

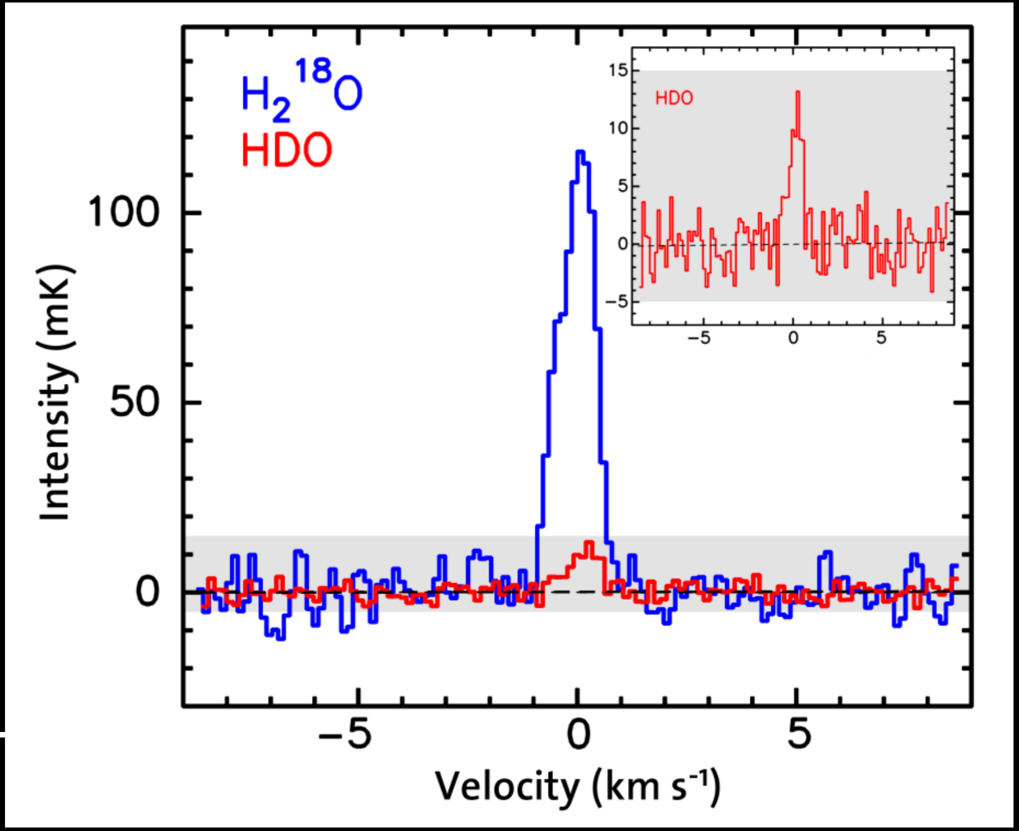
- Sample return or *in-situ* — detailed studies of individual objects.
- Remote sensing — statistical studies of objects that have atmospheres


Deep Impact / EPOXI

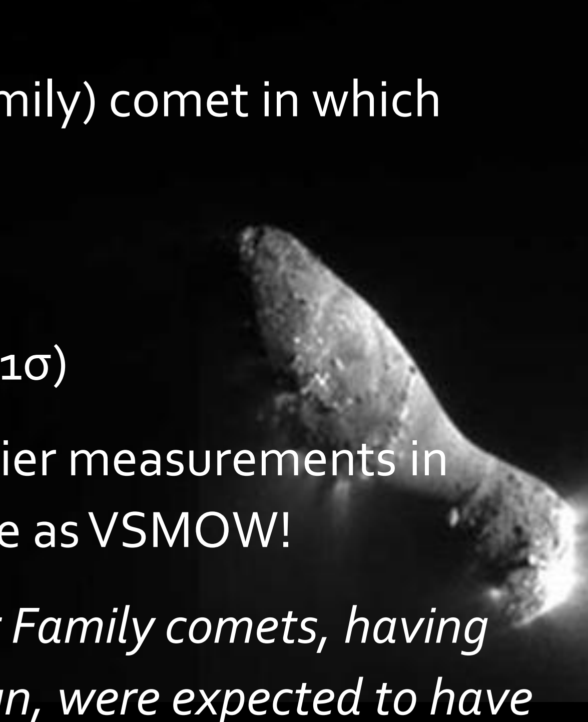

Herschel

Ocean-like water in the Jupiter-family comet 103P/Hartley 2

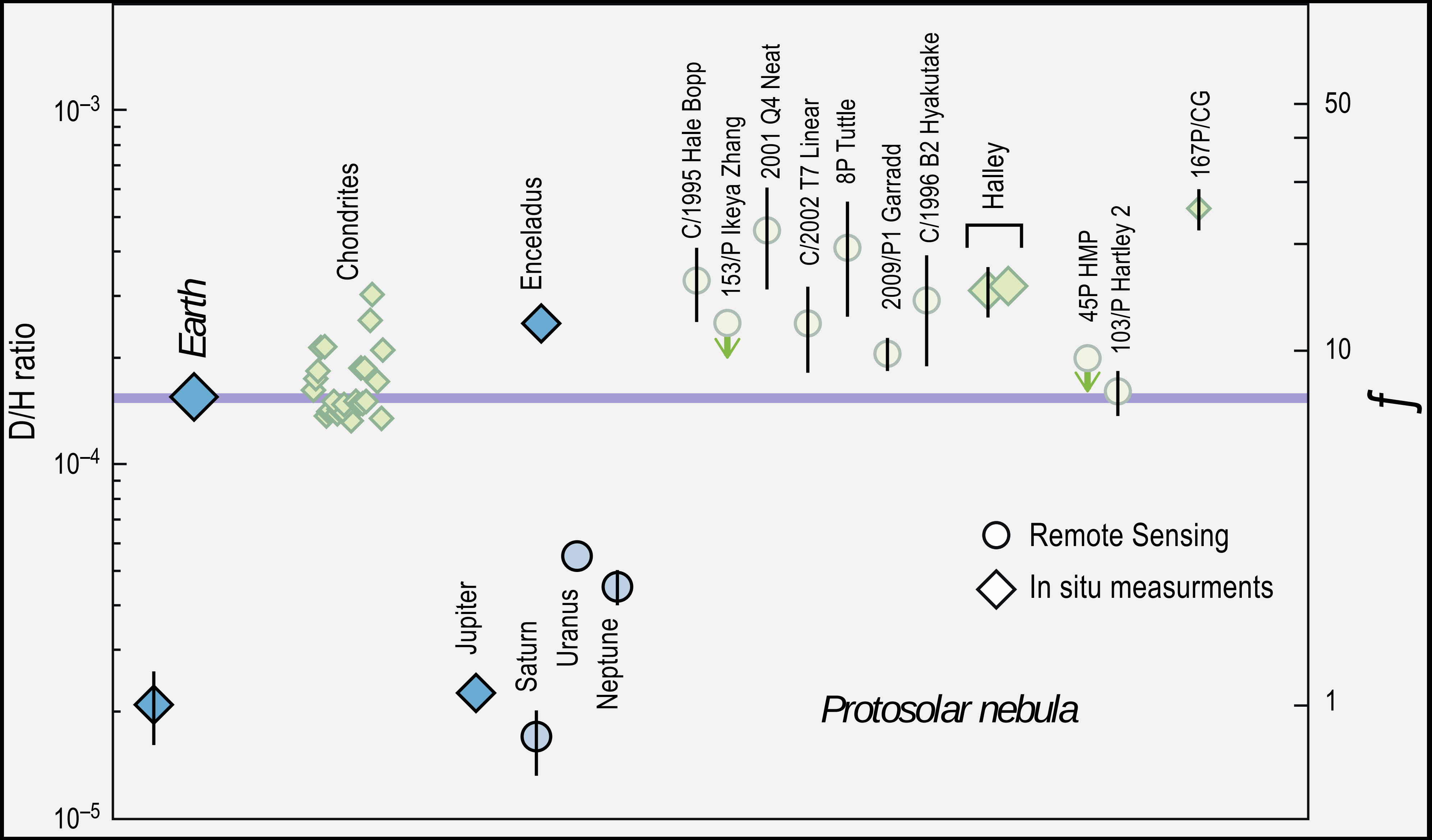
Paul Hartogh[1], Dariusz C. Lis[2], Dominique Bockelée-Morvan[3], Miguel de Val-Borro[1], Nicolas Biver[3], Michael Küppers[4], Martin Emprechtinger[2], Edwin A. Bergin[5], Jacques Crovisier[3], Miriam Rengel[1], Raphael Moreno[3], Slawomira Szutowicz[6] & Geoffrey A. Blake[2]



- Using HIFI on Herschel
- The first Kuiper Belt (Jupiter Family) comet in which D/H was measured
- HDO clearly detected (11σ)
- D/H in water (1.61+/-0.24)x10^{-4} (1σ)
- A factor of 2 lower than the earlier measurements in Oort cloud comets and the same as VSMOW!
- *Surprising result, because Jupiter Family comets, having formed farther away from the Sun, were expected to have higher D/H values than Oort cloud comets!*



How did Earth get its water?

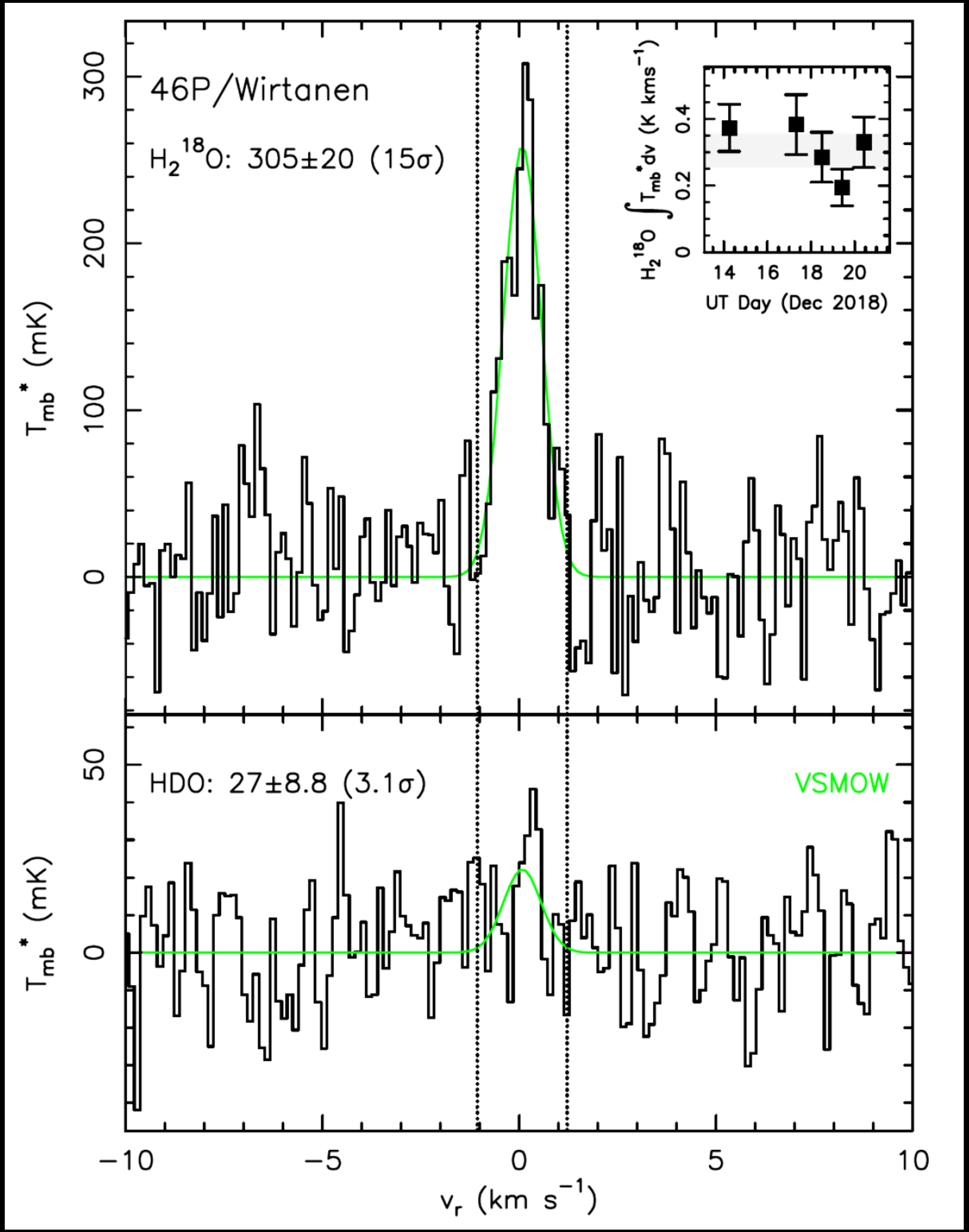


From Altwegg++2015

CURRENT SOFIA: Comet 46P/Wirtanen

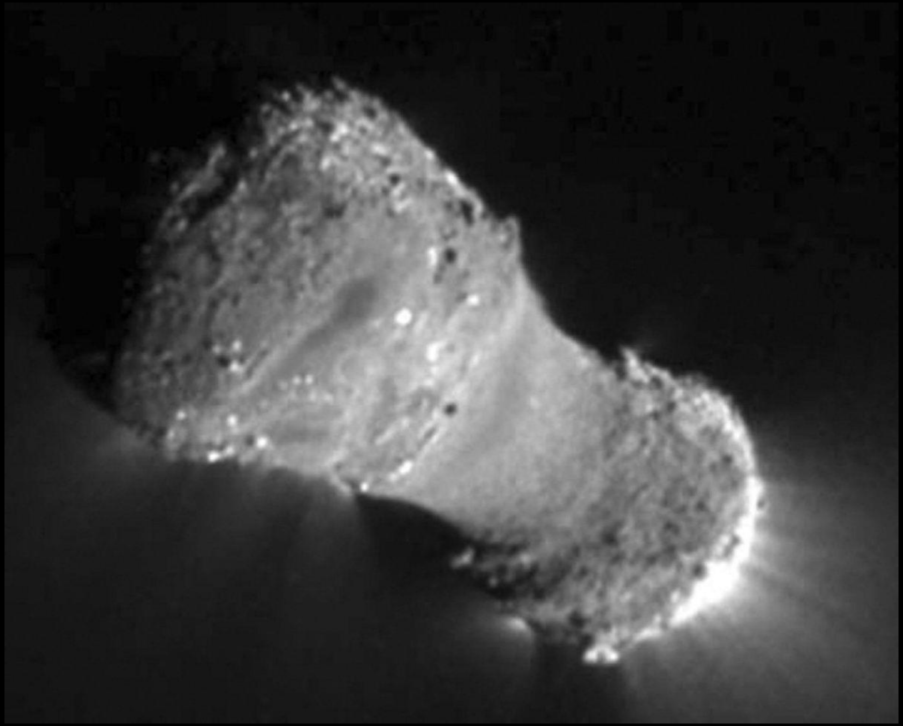
- Perihelion on 12/12/18 at 1.055 au from the Sun
- Closest approach on 12/16/18 at 0.08 au from the Earth
- Five **SOFIA/4GREAT** flights between 12/14 and 12/20 (GT+DDT)
- **D/H = $(1.61 \pm 0.65) \times 10^{-4}$** including statistical, calibration, modeling, and 16O/18O ratio uncertainties
- Third Jupiter-family comet with a D/H ratio consistent with the Earth's ocean value

What is special about the comets with a low D/H ratio?



Lis et al. (2019)

Hyperactive Comets

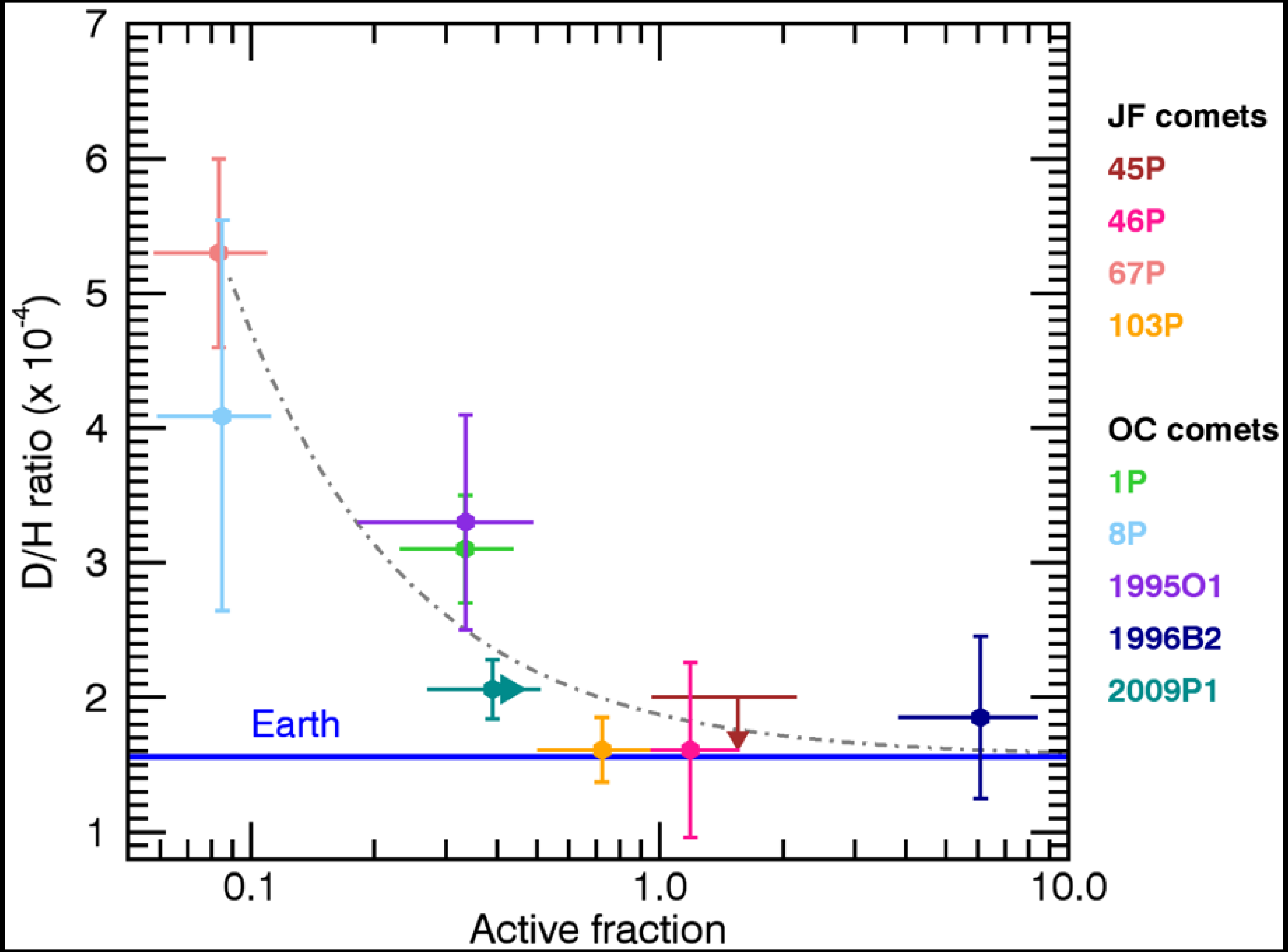


103P/Hartley — Deep Impact/EPOXI

- 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)

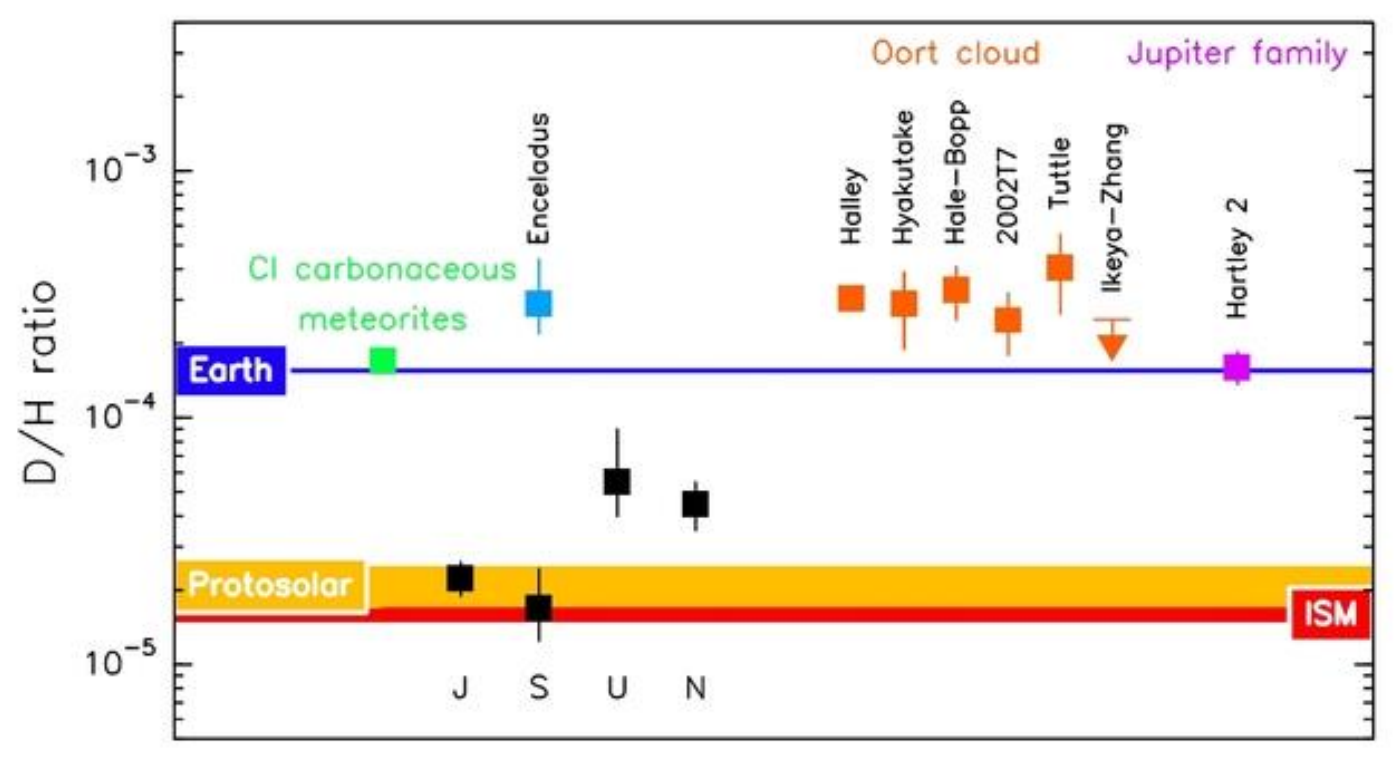
D/H *vs* Active Fraction

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



SOFIA-HIRMES LSP – D/H

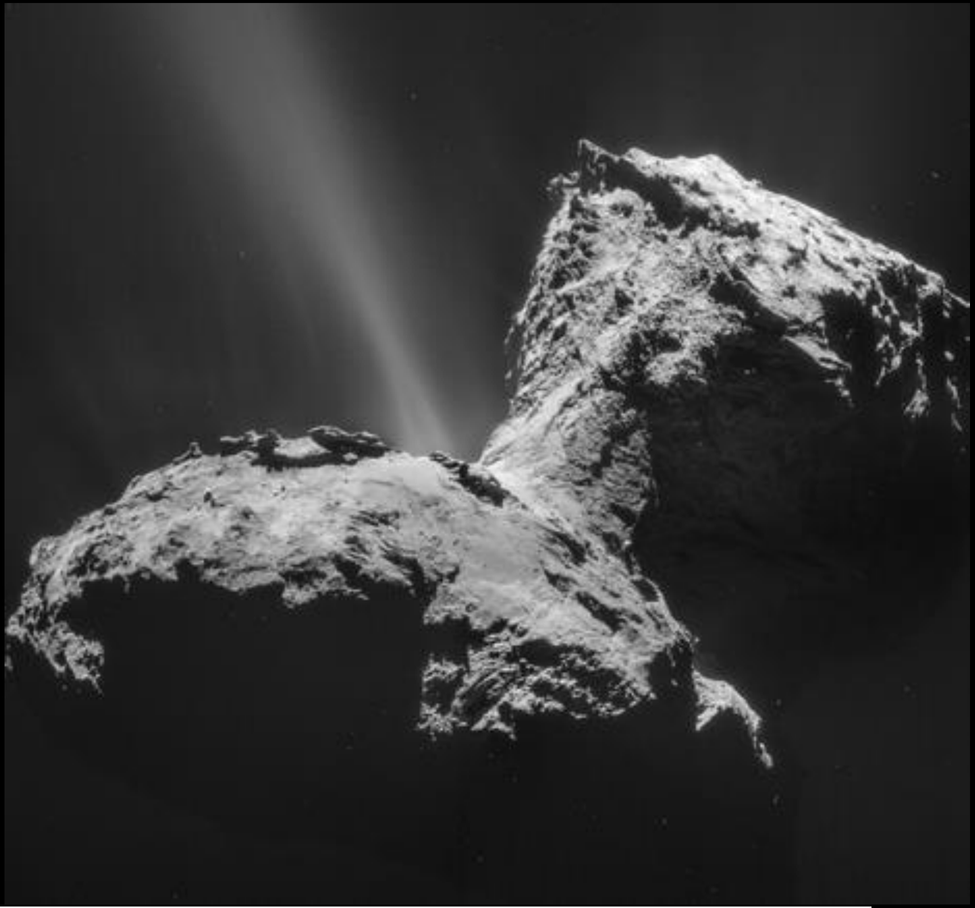
- Need moderately bright comet (FOM ~ 1).
- High-resolution spectra of the HDO and $H_2{}^{18}O$ lines at 112.1 and 109.3 µm, respectively.
- Plan for 1 Target of Opportunity



SOFIA's GREAT instrument acquired the D/H ratio, with 5 flights and two instrument settings (880 minutes of observing time) for a comet with a FOM~1.

With HIRMES, we can acquire a comet D/H ratio with the same S/N within 5 hours, one spectral setting, and a comet with the same FOM.

Comets and HIRMES



- By gaining a better understanding of the A/C water ice abundance, as well as the ice particle size and purity, we will gain new insights into the water and organic preservation in cometary bodies that may either preserve, or alter the pristine nature of the volatile material observed.
- 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
- With a long term, focused program, SOFIA can double the number of existing D/H measurements (4GREAT+HIRMES)

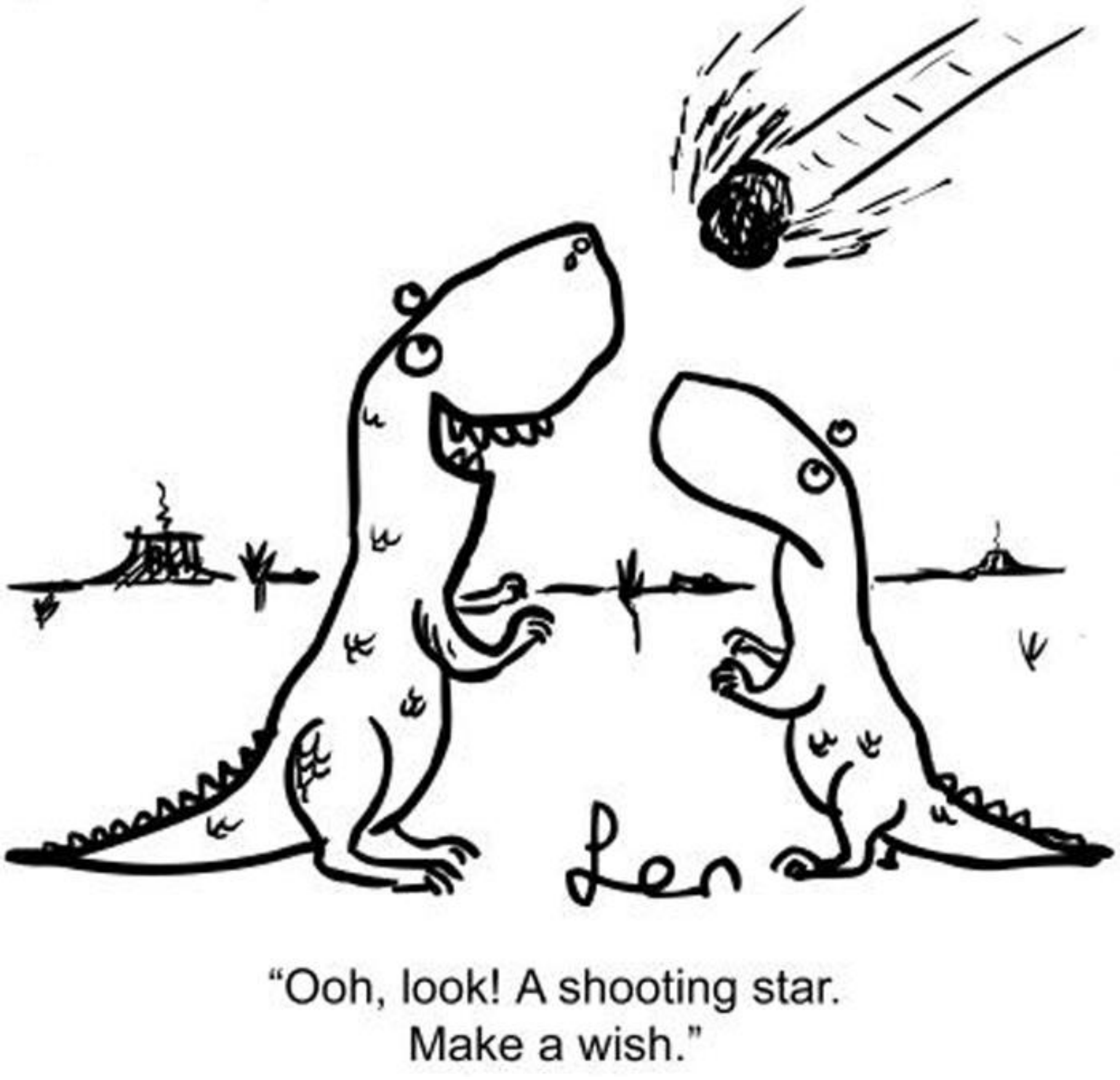
PREPARING FOR SOFIA-HIRMES SCIENCE

JUNE 22-24, 2020
STSCI

The HIRMES Science Working Group invites the astronomical community to a workshop June 22-24, 2020 at Space Telescope Science Institute on the campus of Johns Hopkins University. The goal of the workshop is to raise the community's awareness to the upcoming availability of HIRMES, discuss the science that could be enabled by this new capability, and provide technical support for attendees interested in submitting HIRMES proposals.

Thanks to Darek Lis and Silvia Protopapa for contributions AND Geronimo Villanueva for incorporating HIRMES into PSG.

https://psg.gsfc.nasa.gov/



"Ooh, look! A shooting star. Make a wish."