1. Science aim/goal: *To measure accurate isotopic ratios and abundances of trace gases, to constrain models and inform understanding of solar system origin and evolution.*

2. (i) Scientific Importance: Far-infrared space telescopes such as ISO, Herschel and Spitzer have made important advances in measurements of trace gases and isotopes for cold outer solar system objects, including HD on the four giant planets, water abundance on Titan, and HDO in comets. In addition, the stable isotopic ratios $^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$ provide valuable information about both planetary formation and evolution, for example the large differences seen in $^{14}N/^{15}N$ from Jupiter (450) to the Earth (272) to Titan (167) may indicate both differences in original constituents but also fractionation by escape. However, our knowledge of these critical tracers of solar system formation and evolution remains meagre, with no far-IR space telescopes currently active. The measurements of D/H in hydrogen on the giant planets have large errors, so we are uncertain as to the degree of enrichment versus the protosolar nebula. The D/H is an important indicator of core/envelope fraction, which is needed to discriminate between models of planetary formation (Owen and Encrenaz 2003). The far-IR region provides a rich hunting ground for the signatures of isotopologues of small molecules, and the detection of complex molecules, such as benzene at 14.8 μm, which can be measured to constrain models of photochemistry.

(ii) Measurements Required: Spectroscopy from 10-1000 μm is a key capability of a far-IR space telescope. This will enable a sensitive study of HD lines at 28-112 μm, and rotational lines of HCN, CO, NH_3 and PH_3 and isotopes at 50-500 μm. Many trace gases also have vibrational bands in the mid-infrared (10-20 μm), including HCN, C_2H_2, C_2H_6 and more. The strong CO_2 v_2 band at 15 μm, inaccessible even to SOFIA, would be accessible from space, including nearby isotopic emissions from $^{13}CO_2$ and $CO^{18}O$. Spectral resolution should equal or exceed those of previous telescopes to improve S/N, while an aperture size of 10-20 m is desirable for S/N, and less so for spatial resolution.

(iii) Uniqueness to 10μm to few mm wavelength facility: The measurements possible in the far-IR will permit unique science. Small molecules such as HD (rotational lines) and H_2 (quadrapole lines) are only visible in this spectral region, and water lines including isotopes are for the most part not observable from the Earth due to atmospheric water. In addition, isotopes of CO and HCN will be observable. The amount of objects that can be sampled in situ (e.g. Galileo probe, Rosetta, OSIRIS-REx) is much smaller than needed, therefore remote sensing with a far-infrared facility to determine isotopic ratios on many solar system bodies is crucial to determining a complete inventory.

(iv) Longevity/Durability: A far-IR telescope will complement rather than compete with other large facilities that will exist in 2025 to 2030. Ground-based optical facilities in the 30-40m class will provide revolutionary capability at optical and near-infrared wavelengths. The JWST instrument range extends only to 28 μm, while ALMA commences at ~300 μm, leaving a significant gap in the far-infrared. After the expected end of JWST operations around ~2028, no mid- to far-infrared telescope is currently scheduled to be operational, leaving an even wider gap between near-IR and sub-mm capabilities. A large far-IR telescope will provide unique and critical science addressing key questions of solar system formation and evolution.

3. Figure:

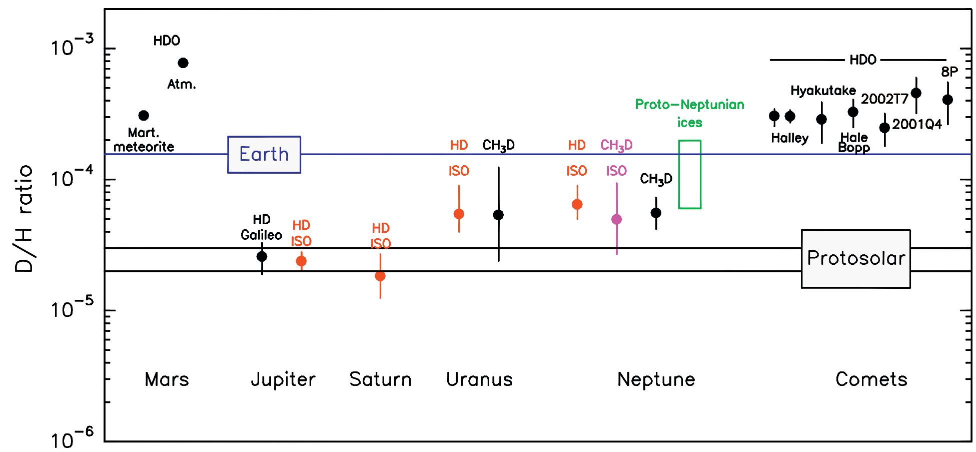

Figure 1: measured D/H ratios in solar system objects (Hartogh et al. 2009). The origin of volatiles supplied to the inner solar system from beyond the snow line – including the Earth's water- is currently uncertain.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	µm	10-300	10-900	A 30 K object has Planck peak at 96 µm
Number of targets		20	100	Includes outer planets and moons with detectable atmospheres, KBOs and comets.
Survey area	deg.^{2}	4π sr	4π sr	All but Mercury, Venus, Moon should be observable, as with JWST.
Angular resolution	arcsec	1.0 @ 50 µm	1.0 @ 100 µm	Requires 12.5 (25.0) m telescope
Spectral resolution	Δλ/λ	10^4	10^7	Grating is required, heterodyne preferred in addition
Continuum Sensitivity (1 σ)	µJy	100	10	
Spectral line sensitivity (1 σ)	W m^{-2}	10^{-5}	10^{-4}	
Signal –to-noise		1000	10000	
Dynamic range		5000	50000	ALMA is 10^3. Solar system planets can be bright compared to astrophysical targets, depending on bandwidth (spectral resolution), spatial resolution.

5. Key references:

Hartogh, P. et al.: "Water and related chemistry in the solar system. A guaranteed time key programme for Herschel," Planetary and Space Science 57 (2009) 1596–1606

Owen and Encrenaz, "Element abundances and isotopic ratios in the giant planets and Titan", Space Sci. Rev., 106, pp121-138, 2003.