1. Science aim/goal:

Create a comprehensive Galactic census of the water content in >1000 planet-forming disks around young stars of all masses at disk radii of 1-100 AU. This goal will definitively answer the question of whether water is universally abundant and available as an ingredient for habitable planets.

2. (i) Scientific Importance:
We do not know whether protoplanetary disks are universally able to seed their planets with water and other volatile species critically for origin of life, as we know it. In order to measure the abundance and distribution of water in gas and dust actively being incorporated into planetesimals and planets, access to far-infrared lines of water vapor is required. Further, to understand the full diversity of planet-forming disks and their connection to exoplanetary composition and the availability of water to potential biospheres, it is critical to obtain a census of the content of water in large samples of protoplanetary disks around stars of all masses, and for a wide variety of environments. Indeed, Spitzer observations suggest that there are strong chemical differences in disks around stars of different masses, with water being abundant around solar-mass stars, but much less pronounced around both low-mass and intermediate-mass stars (Pontoppidan et al. 2010, Pascucci et al. 2009). A full census will finally place the Solar Nebula into a broad Galactic context. Is water equally common in disks around low-mass and high-mass stars, near young OB clusters in environments, and in low-metallicity regions? Is the Solar System chemically typical or unusual (Pontoppidan et al. 2014, Bergin et al. 2015)?

Herschel was able to detect water from the planet-forming region (1-10 AU) in a few disks, but was sensitivity-limited (Riviere-Marichalar et al. 2012, Podio et al. 2013, Blevins et al. 2016). At the end of the Herschel mission, we essentially lost the ability to observe water vapor from gas with temperatures in the 50-500 K. It is water at these temperatures that uniquely trace the planet- and comet-forming regions at 1-50 AU, including the location of the snow line.

The broad wavelength range needed to efficiently observe water vapor also includes strong transitions from many other chemically important molecular species unique to the mid- to far-infrared, including HDO and NH_3. These can generally be observed using the same requirements as those needed to observe water.

(ii) Measurements Required:
This goal requires intermediate resolution spectroscopy (R~25,000) from 15-200 micron to measure line fluxes and widths of water lines tracing gas temperatures from 50-500 K. Constructing empirical distributions of the water content throughout protoplanetary disks around brown dwarfs, low-mass stars to solar-mass and massive stars requires the ability of the observatory to acquire spectra of at least 1,000 disks, and ideally more. This sets constraints on line sensitivity as well as multiplexing and operational efficiency.

(iii) Uniqueness to 10μm to few mm wavelength facility:

Cold and warm water vapor can only be efficiently, consistently and comprehensively observed in the far-infrared. No current facility is be able to observe water vapor from gas at temperatures of 50-500 K around large numbers of protoplanetary disks out the distances of the nearest massive star-forming regions (e.g., Orion at 415 pc), and spectrally resolve the lines.

(iv) Longevity/Durability:

In the 2025-2030 time frame, we will have exquisite data sets revealing the physical structure of dust and gas in perhaps ~100 nearby protoplanetary disks, as observed with ALMA. We will have a census of the amount of water vapor in the surfaces of a similar number of inner disks at 1 AU from lines tracing hot gas as observed with JWST. JWST will also provide measurements of the composition of a range of exoplanetary atmospheres, and their complement of water and other volatile species. All of these data sets will raise fundamental questions requiring knowledge of the distribution and amount of water beyond 1 AU: How do planets generally acquire their water? Is the water formed in the disk or does it have a primordial origin? Does water play a fundamental role in the ability of disks to form planets?

Warmer water can be observed from the ground and will be observed by JWST at wavelengths below 28 micron. Additionally, a small number of warm-water lines may be observed by ALMA, under very favorable circumstances and for a few bright disks. A broad census of water in large samples of disks requires a space-based, highly sensitive observatory operating at wavelengths of, at least, 30-200 micron.

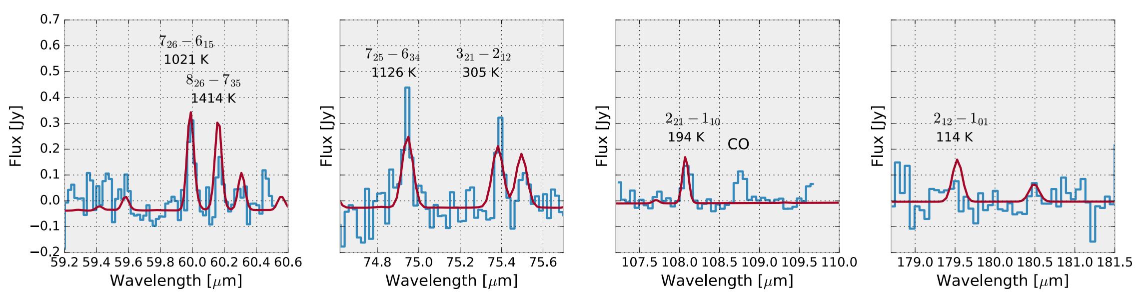

Figure 1: Continuum-subtracted water lines from a protoplanetary disk around solar-mass stars, as observed with Herschel-PACS (Blevins et al. 2016. The red curve is a two-dimensional radiative transfer model, including the effect of a snow-line. Note that the lines are under-resolved with PACS by a factor ~20; fully resolved lines would in this case have peak fluxes of 5-10 Jy.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	28-180	15-600	

Number of targets		1,000	10,000	
Survey area	deg.^{2}	N/A		
Angular resolution	arcsec	0.5"@30 micron	0.5"@180 micron	The required value will resolve many typical wide binaries at 150 pc at the shortest wavelengths. The desired value will resolve typical binaries across the waveband.
Spectral resolution	$\lambda/\Delta\lambda$	25,000	100,000	
Bandwidth		2%	5%	Required value will typically span 2-10 water lines in one setting.
Continuum Sensitivity (1 σ)	μJy	N/A		
Spectral line sensitivity (1 σ)	W m^{-2}	10^{-21}		Detect water in disks around low-mass stars in Orion.
Signal –to-noise		>50	>200	Line-to-continuum ratios of HDO and H2 18O lines are a few %
Dynamic range		1e4 x σ		Must be able to observe nearest disks as well as a large sample of more distant disks.
Field of Regard		Galactic plane +/- 20degrees		
Cadence		N/A		
Any other requirement				

5. Key references:

Pontoppidan et al. 2014, PPVI, 363
Riviere-Marichalar et al. 2012, A&A, 538, 3
Podio et al. 2013, ApJ, 766, 5
Blevins et al. 2016, ApJ, 818, 22
Bergin et al. 2015, PNAS, 112, 8965

Appendix

The mid- to far-infrared spectrum of protoplanetary disks is often dominated by emission from millions of water vapor lines, of which a few hundred are currently detected. The corresponding transitions span a very wide range of excitation, or upper level, energies, from less than 100 to 1000s of Kelvin. This allows for a mapping of the distribution of water vapor in objects with a strong temperature gradient, such as protoplanetary disks. Essentially, each line will trace gas in a relatively restricted temperature range, and the combination of many water lines with an appropriate model can map the abundance of water vapor as a function of radius, and even height, in the disk. Up until now, this has been done for a few disks using unresolved line spectroscopy with Spitzer and Herschel (Zhang et al. 2013, Blevins et al. 2016). However, the analysis of such unresolved spectroscopy will always be model dependent. One powerful way to break model degeneracies is to spectrally resolve the lines and use Keplerian motion of the disk to obtain an independent measure of the spatial distribution of the emission for each line. Figure 2 shows the distribution of line widths (indicating the dominant radius traced by the line) as a function of wavelength and upper level energy of the line. It is seen that the snow line is traced by lines beyond ~20 micron. The area beyond the snow line, where water vapor is exceedingly rare, is measureable in only a few lines, the strongest of which is the 179.5 micron line. The ground state line at 538 micron traces the outermost disk beyond 20 AU, but is also relatively weak, and requires the highest spectral resolution. The figure shows that to resolve the snow line a resolving power of R=25,000 is required, while to resolve the outer disk, and to obtain details on the line profiles, R=100,000 is required for typical disks.

A transformative component of this science case is the potential for the far-infrared, with the greatly enhanced sensitivity of a large, cold telescope, is to survey a large number of disks around stars with masses down to the brown dwarf limit, and at least to the distance of Orion, the nearest massive star forming region. The Orion cluster is thought to be similar to the environment in which the Sun formed (REF). In Figure 3, we show the predicted water line flux for known protoplanetary disks in Orion (a few thousand). This demonstrates the feasibility of conducting a complete census of water for at least 1000 disks around stars across the mass spectrum, if line sensitivity is as high as $\sim 10^{-21}$ W/m^2.

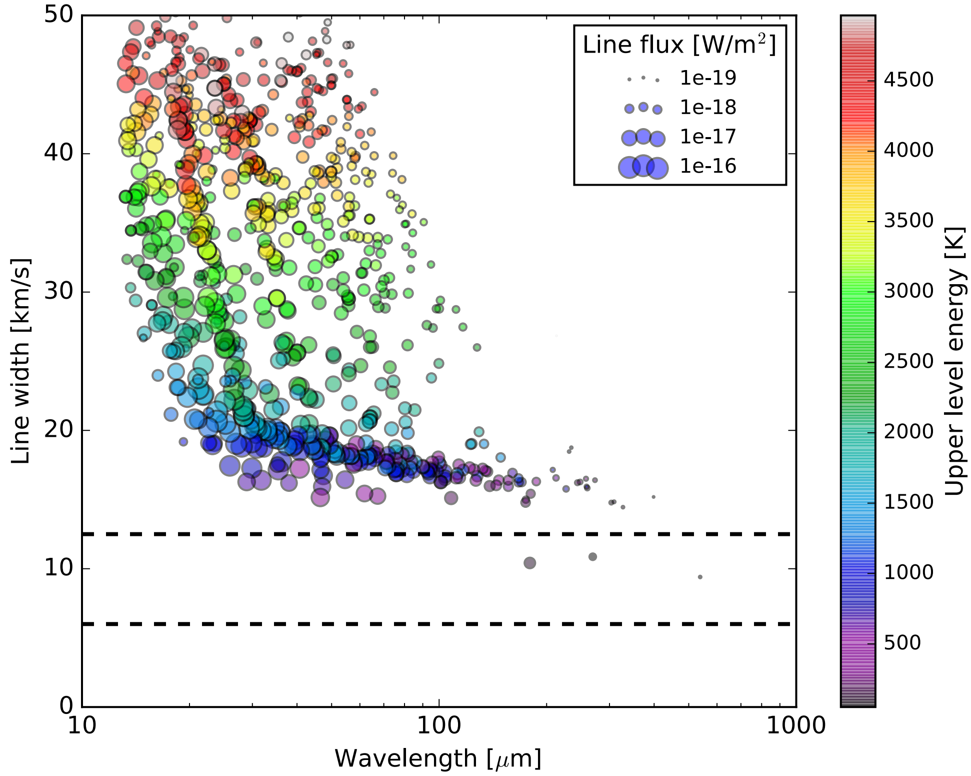

Figure 2: 2D model distribution of water vapor lines from a typical protoplanetary disk around a solar-mass young star at an intermediate inclination. This model has been fitted to Spitzer and Herschel spectra of RNO 90 (Blevins et al. 2016). The line width on the y-axis is a tracer of the disk radius traced by the line (due to Keplerian rotation). The presence of a snow line leads to a cutoff at line widths of ~15 km/s in this case. Note the relative weakness of the 557 GHz (538 micron) ground-state water line, which is due to freeze-out of water vapor in the outer disk. The size of the symbols indicate the integrated line flux, and the color indicates the upper level energy (the effective gas temperatures traced are a factor 2-3 lower than the upper level energy). The two dashed lines indicate line widths corresponding to resolving powers of R=25,000 and R=100,000.

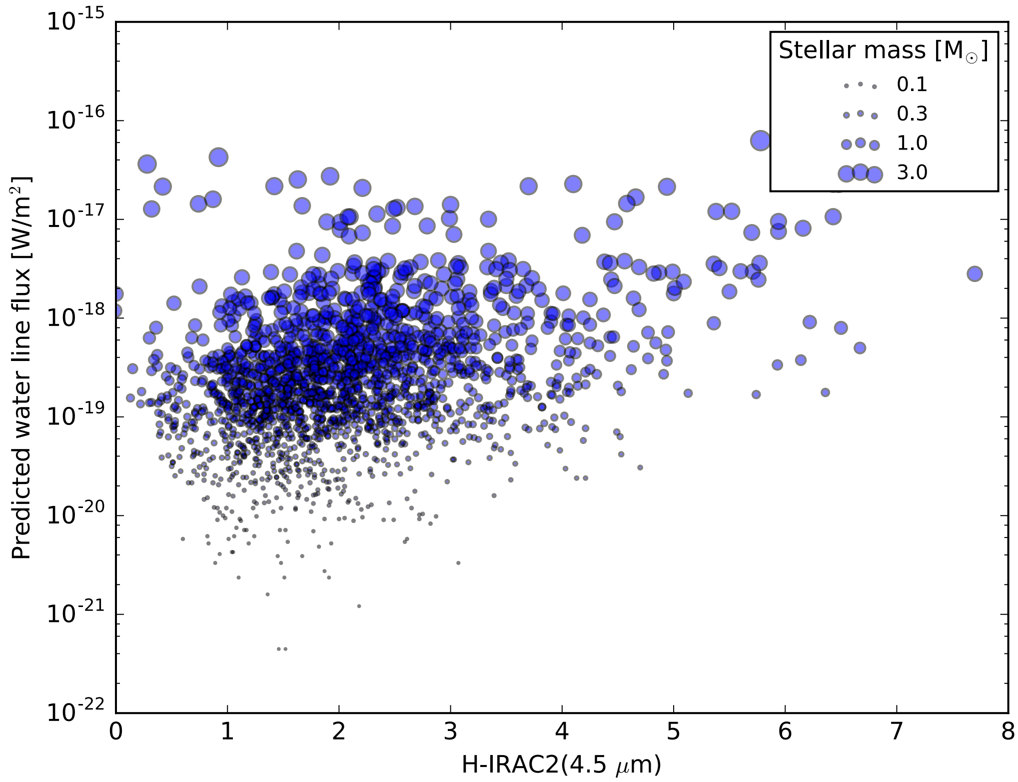

Figure 3: Predicted line fluxes for the Orion cluster for a representative far-infrared water line (321-212) at 78.4 micron. The line flux from RNO90 are scaled by luminosity and distance to match observed infrared photometry (Megeath et al. 2012). The stellar masses are estimated using the evolutionary tracks of Siess et al. 1997. It is seen that sensitivity to lines in the 10^20-10^21 W/m2 range will allow for complete water inventories of disks out to 500 pc.