1. Science aim/goal:
Using debris disks to trace the formation and migration history of low-mass ice giants from youth to the age of the Solar System.

2. (i) Scientific Importance:

In roughly two decades, we have progressed from possessing evidence for only one planetary system, our own, to more than 1000 confirmed today. However, our most successful methods for the detection of exoplanets are biased toward the inner zones of mature systems. Most known exoplanetary systems are radically different from the Solar System in ways that make them unlikely abodes for intelligent life. Having giant or ice-giant planets at large orbital distances not only fosters the formation of terrestrial planets but also serves as a shield from influx of small bodies to habitable terrestrial planets. Systems with planets at wide orbits analogous to those of Jupiter, in the critical first few hundred million years of evolution, are virtually unexplored. Studying debris disks offers an alternative method to characterize planetary systems and their evolution. These disks are composed of dust grains ranging from μm- to mm-sized grains continually replenished by collisions of km-sized planetesimals as the byproduct of planet formation. The orbits of these planetesimals are inevitably perturbed by the presence of planets, and hence the disk density distribution can reveal a hidden planetary system.

Debris disks trace a pattern of development similar that of the Solar System: (1) a peak in inner debris disk activity at 10-20 Myr, when terrestrial planets are being built; (2) thereafter a decay for about ~1 Gyr, the expected time dependence for collisional cascades, and matching the time scale out to the Late Heavy Bombardment; and (3) occasional major collisions such as the one that led to the formation of our Moon and Pluto-Charon system. The objective of this proposal is to use resolved disk structures to obtain a general census of these evolutionary steps.

(ii) Measurements Required:

The required spatial resolution is estimated based on the known (unresolved) debris disks with spectral energy distributions (SEDs) measured by existing infrared observatories. The expected disk angular sizes (radius) are estimated by a relationship between the observed dust temperatures and spectral types of stars, derived from a few dozen, marginally resolved disks from Herschel (Pawellek et al. 2014). As shown in Figures 1a and 1b, there are ~150 known disks with radii larger than 1" covering a wide range of ages that can be used to probe the unseen, wide-orbit, low-mass planets in these systems. In order to probe the structures induced by unseen planets, the degree of resolvability is another factor. Figure 1c illustrates how well a simple disk structure can be resolved in units of beams per disk radius (FWHM). In general, resolving by 2 beams is required to measure the belt location and detect modest asymmetry in the disk. More detailed structures, which enable stringent constraints on the shepherding planet, can be probed when the disk is resolved by ≥4 beams. With a beam size of 1" at 60/70 μm, provided by a 10m-size telescope, we can easily resolve nearby ~150 disks by more than 2 beams, and ~50 disks by 10-beam resolution (~10 times more than what Herschel has done). The science return will be amplified if the disk is resolved at multiple wavelengths because different wavelengths trace different size of grains ($\lambda \sim 2\pi a$, Figure 1d). Resolved images at 60/70, 180/200, and 300/350 μm are ideal.

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

SEDs of Kuiper-belt analogs peak in the far infrared (~60-100 μm) with rapidly decreasing brightness at submm/mm. Therefore, resolving a large sample of debris disks at FIR is much more achievable than in the mm wavelengths provided by ALMA. The disk surface brightness is ~150 times fainter at 1.3 mm than at 70 μm. ALMA will only resolve a fraction of the known disks due its limits in sensitivity and sky visibility. Furthermore, the observing efficiency for large disks is low for ALMA since multiple pointings are required to cover the entire disk (see Appendix). Finally, ALMA resolved images are only sensitive to a limited range of grain size (λ~2πa). To fully explore the disk structures, multi-wavelength images at FIR are essential.

(iv) Longevity/Durability:

SOFIA and SPICA do not have adequate resolution at ~60-400 μm to meet the science requirements. Since different wavelengths trace different grain size populations (Figure 1d), FIR disk images have great synergy with future high-resolution images taken by WFIRST, JWST, and ALMA.

3. Figure:

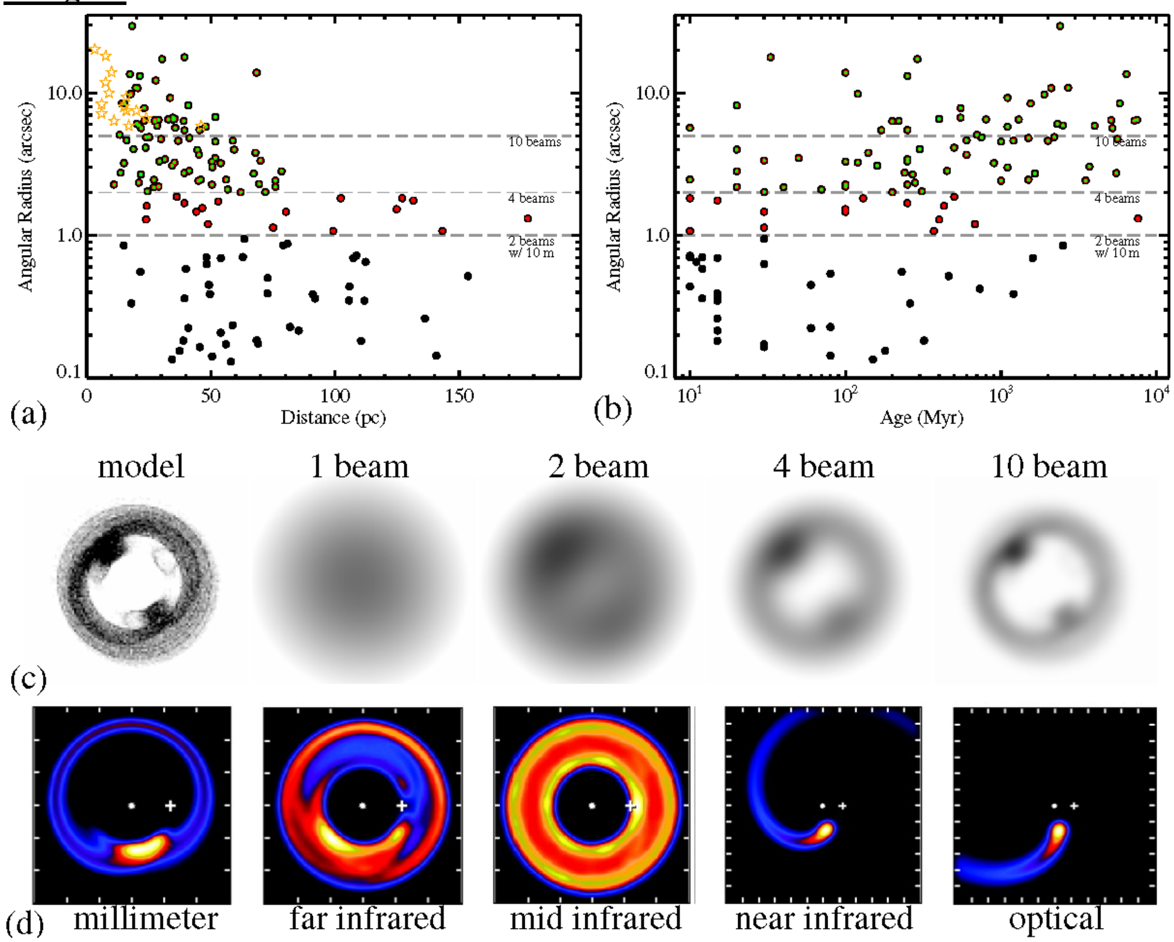

Figure *1*- Expected angular sizes for known debris disks, (dots), as a function of distance (a) and age (b). For a fiducial 10-m size telescope, the beam (FWHM) is 1” at 60/70 μm. The red dots represent the disks that can be resolved at ≥ 2 beams while green dots are the ones that can be resolved at ≥ 4 beams. Orange star symbols are the resolved (at ≥ 2 beams) disks by Herschel. 1” resolution will increase the number of resolved disks by roughly a factor of 10 compared to Herschel. (c) Illustrations of resolvability to probe disk structures. Resolving at ≥ 2 beams can pin point the location of the belt and detect modest asymmetry while detailed structures can be probed at ≥ 4 beam. (d) Wavelength-dependent disk structures, illustrating the need for multi-wavelength observations to put stringent constraints on the unseen planet (figure extracted from Wyatt 2006).

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	µm	60/70	40-400	
Number of targets		~150	~300	lower limit based on currently known debris disks
Angular resolution	arcsec	1.0	0.1	at 60/70 µm. 1” can resolved ~150 disks at ≥ 2 beams, while 0.2” can resolve the same amount of disks at ≥ 10 beams.
Bandwidth		10%	10%	Broadband imaging
Continuum Surface Brightness Sensitivity (1 σ)	µJy/arcsec^2	20		Confusion is not a problem for currently detected debris disks
Signal –to-noise		10		
Field of Regard		4pi		
Any other requirement				

5. Key references:

Wyatt 2008, ARAA review, Matthews et al. 2014, PPVI review.

Appendix

The expected disk sizes are estimated using the SEDs of the disks compiled from existing measurements (mostly from Spitzer, Herschel and WISE). The number of the disks are restricted to the known debris disks, i.e., a lower limit. These disks represent the tip of the iceberg limited by the current FIR sensitivity (see Figure in the proposal of true Solar System Analogs by Kennedy & Wyatt). We expect more disks will be added to the sample once all Herschel and WISE data have been fully mined, and at least one order of mag increase in numbers of cold disks if SPICA (or a mid-size cryogenic telescope) launched prior to FIR Surveyor.

The expected disk angular sizes are estimated by a relationship between the observed dust temperatures (derived from SEDs) and spectral types of stars (Pawellek et al. 2014). We then estimate the minimum surface brightness (SB) by assuming the disk is viewed face on and the flux is uniformly distributed in a ring with a width of 20% of the belt. Figure 2 shows the SB vs. angular size distribution. For reference, we also estimate the expected SB at 1.3 mm by assuming the 1.3 mm flux is ~150 times fainter than the one at 60/100 μm (an optimistic value by assuming the disk emission is blackbody-like up to 200 μm at ~50 K, and follows $\nu^{2.6}$ power law in the submm/mm wavelengths (McGreagor et al. 2016)). Based on the ALMA sensitivity, ~10 hr on-source integration time can reach 1 rms of 5.5 μJy/arcsec^2 with 1" beam, i.e., 55 μJy/arcsec^2 marks the S/N of 10 detection line. At 1" resolution, one single pointing with ALMA at 1.3 mm can cover ~10" extended structure without losing flux; i.e., disks with an angular size larger than ~5" will require multiple pointings for ALMA observations. Based on these numbers and with ~60% of the sky coverage, ALMA could resolve ~20% of the current known debris disk sample with the same resolution of 1".

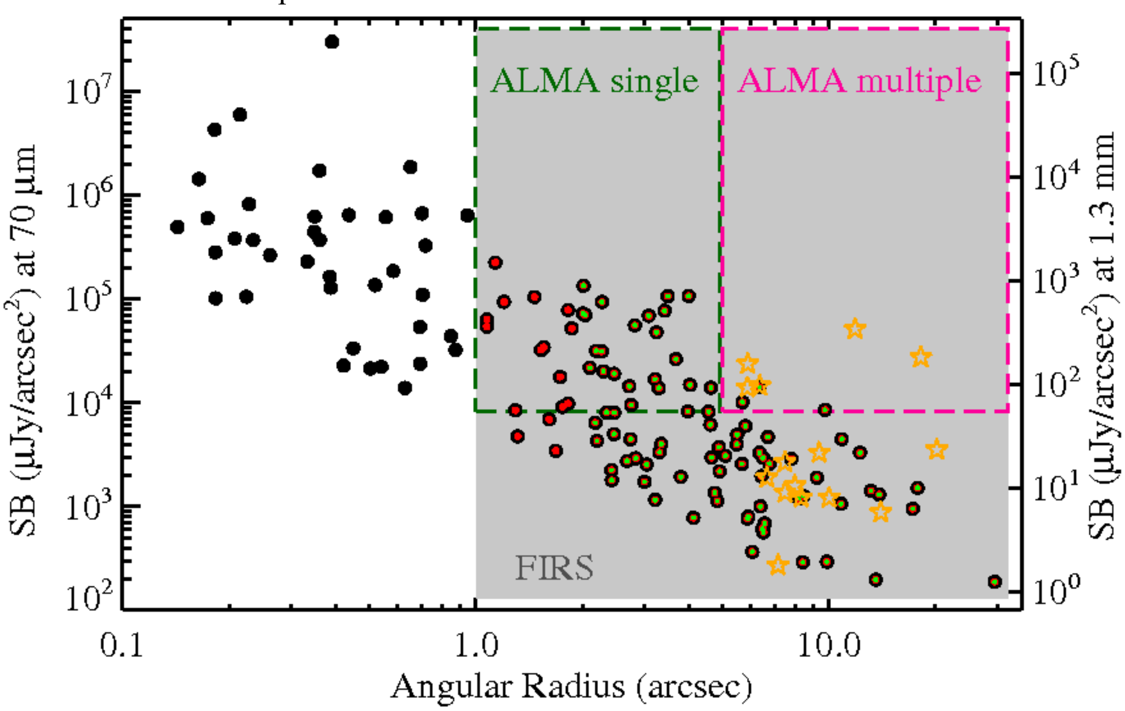

Figure 2 - Minimum expected surface brightness (SB) distribution of the known debris disks. Symbols are the same as Figure 1. The gray area marks the parameter space for a FIR Surveyor with 1" resolution. The right y-axis shows the

corresponding SB at 1.3 mm by assuming the SB is ~150 times fainter than the one at 60/70 μm (an optimistic value). Based on the ALMA sensitivity, ~10 hr on-source integration time can reach 1 rms of 5.5 μJy/arcsec^2 with 1" beam; therefore, 55 μJy/arcsec^2 marks the S/N of 10 detection line for ALMA. At the same 1" resolution, the green box marks the parameter space that can be probed with ALMA with one single pointing, while the pink box requires multiple pointings. Generally, ALMA will be able to resolved ~20% of the FIRS sample (at the same 1" resolution).

Finally, we would like to emphasize the importance of nearby debris disk sample. As illustrated in Figure 1c, the detailed disk structures induced by an unseen planet require the disk to be resolved at ~10 beams. Figure 3 shows a similar SB plot as in Figure 2, but with system's distance in x-axis. The star symbols, in Figure 3, mark the ~50 disks that will be resolved at 10 beams with 1" resolution (mostly are the systems within 50 pc). The average SB for these nearby disks is ~1000 μJy/beam at 70 μm (i.e., ~10 μJy/beam at 1 mm). It will take ~10 days of ALMA integration to reach S/N of 10 detection at 1 mm, but less than one sec to reach the same detection at 70 μm with the FIR Surveyor (based on the continuum sensitivity estimated by Bradford et al.). These nearby ~50 debris disks are the sweet spots for the FIR Surveyor.

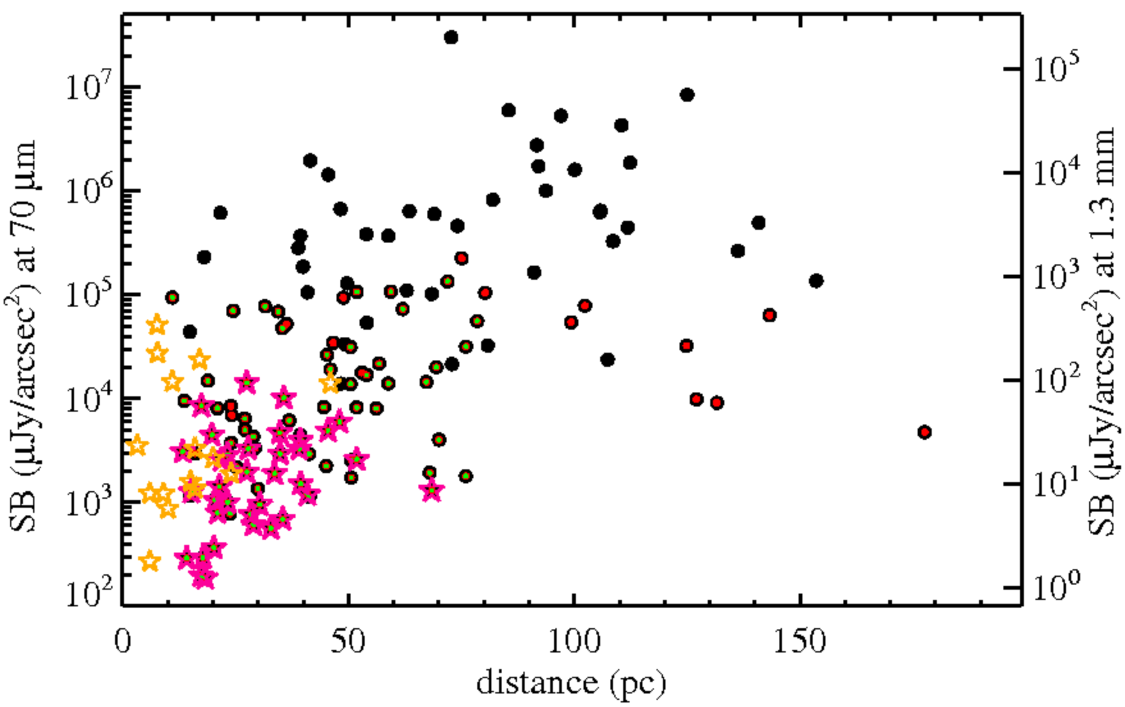

Figure 3 – Similar to Figure 2 but with the x-axis showing the distance rather than angular sizes. The ~50 systems that can be resolved at 10 beams with 1" resolution are marked by star symbols (pink and orange), which are mostly within 50 pc. Due to their proximity, their low surface brightness makes them a unique sample that only the FIR Survey can resolve their disk structures in detail.