# Debris disks: Exploring the environment and evolution of planetary systems

Prospects for submillimeter observational studies in the next decade

A White paper for the Astro2020 Decadal Survey

Thematic area: Planetary Systems

Wayne Holland*, UK ATC, Royal Observatory, Edinburgh, UK
Mark Booth, Astrophysical Institute, Friedrich-Schiller University, Jena, Germany
William Dent, Joint ALMA Observatory, Santiago, Chile
Gaspard Duchêne, Astronomy Department, University of California, Berkeley, USA
Pamela Klaassen, UK ATC, Royal Observatory, Edinburgh, UK
Jean-François Lestrade, Observatoire de Paris, CNRS, Paris, France
Jonathan Marshall, Academia Sinica, Taipei, Taiwan
Brenda Matthews, NRC, Herzberg Astronomy & Astrophysics Programs, Victoria, Canada

## Summary

Recent surveys have shown that exoplanets are near-ubiquitous around main sequence stars, but surprisingly little is known about their properties and the environments in which they reside. Planets and remnant planetesimal belts are produced in the gas- and dust-rich disks around nascent stars. Debris disks provide a unique way to study the demographics of planetary systems and how they evolve from their primordial structures. Observations tell us about the scale of the regions with planetesimals, the possible locations and masses of planets, and the composition and dynamics of the material present. Over the past decade optical/IR surveys have revealed new populations of disks, whilst millimetre-wave interferometers have given the first detailed views of planetesimal belts orbiting other stars. This paper focusses on the prospects for observations of debris disks in the submillimeter region, and outlines the direction the research is likely to take in the next decade.

Major goals include exploring the structure and dynamics of disks surrounding Solar-type stars (“Exactly how unusual is our Solar System architecture?”), investigating disks around low luminosity stars (“Are disks prevalent, and what is the nature of the disks surrounding M dwarfs where there is a known high incidence of terrestrial planets?”), the role of atomic and molecular gas in the evolution of disks (“Are there evaporating comets in these systems, which could have implications for terrestrial planet habitability?”) and the variability of disk features over time (“Can we observe the outcomes of stochastic events related to planetary dynamics and/or collisional events?”) as well as (quasi)periodic events that reveal lumpy structure in debris belts or the presence of stable populations of cometary bodies.

Crucial to this progress is the development of new facilities. Past and present surveys, from the infrared to the millimeter, are strongly sensitivity- and resolution-limited, meaning, for example, that extrasolar analogues to our Solar System simply have not yet been found. Indeed, to date no debris disk system has been detected that is as faint as our own Edgeworth-Kuiper belt. Although interferometers such as ALMA will continue to play a major role in resolving planetesimal belts, there exists an opportunity for a large, single-aperture telescope in the submillimeter to make a significant contribution to our understanding of such systems. The Atacama Large Aperture Submillimeter Telescope (AtLAST), a concept for a 50m-class telescope operating from 350μm to 1mm, will be particularly effective at characterising the cold outer regions in these systems, having the sensitivity to detect thousands of new disks around stars across a wide luminosity range, many to below the fractional luminosity level of the Edgeworth-Kuiper belt in our own Solar System.

*Contact person: Wayne Holland, UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK; e-mail wayne.holland@stfc.ac.uk

## 1. Introduction

When *IRAS* first detected excess far-IR emission around a significant fraction of main sequence (MS) stars the results suggested the presence of belts of cool dust in thermal equilibrium with the star. The remnant mass in such structures was thought to be dominated by planetesimals (i.e. asteroids and comets) that undergo collisional grinding down to smaller and smaller bodies, until particles are eventually removed by radiation pressure. It was concluded that the emission observed must therefore be continuously replenished by ongoing collisions between the planetesimals, since the timescales for removal were significantly shorter than the ages of these mature stars. Such structures were termed “debris disks” and most of those seen towards MS stars are analogous to the Solar System’s Edgeworth-Kuiper (EKB) belt.

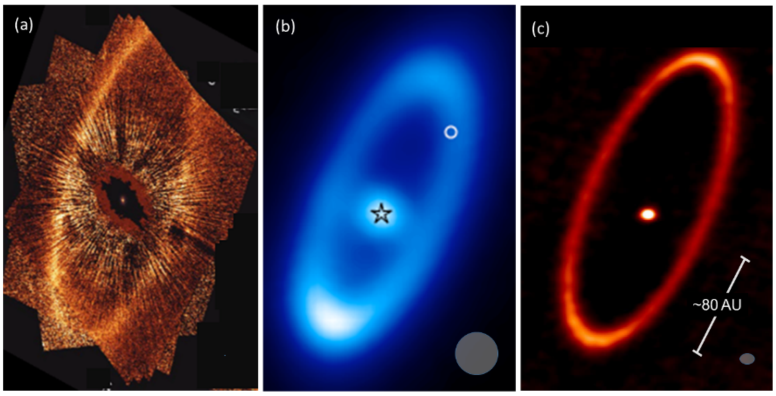


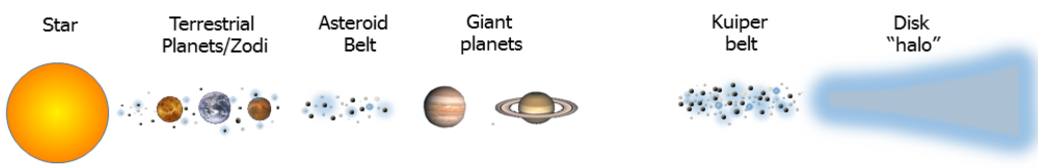

**Figure 1:** Images of the inclined Fomalhaut debris ring from the visible to the millimetre. (a) Optical scattered light using the *HST* (Kalas et al. 2013), (b) Far-infrared emission (70µm) from *Herschel* (Acke et al. 2012), (c) Millimeter emission (1.3mm) from ALMA (MacGregor et al. 2017). The bar shows the approximate diameter of the EKB at the distance of Fomalhaut (7.2pc), and the circle/ellipse represents the angular resolution for each observation (hardly visible

The presence of unseen planetesimals can be inferred through scattered light or thermal emission from micron to millimetre-sized dust grains. Until recently images such as in Figure 1 were impossible to achieve. Indeed, such images are still the exception rather than the norm; facilities such as ALMA are revolutionising the field for individual systems but the number of disks resolved by ALMA is just a few dozen, with considerably smaller number showing a similar level of detail as Fomalhaut. The spectral energy distribution (SED) can also characterise both the fractional excess luminosity of the disk over the stellar emission, as well as the (range of) dust temperatures in the disk. If a disk has multiple components at a range of distances from the star, then observations at different wavelengths probe different components, with, for example, shorter wavelengths generally tracing warmer material, closer to the star (see Figure 2). Conversely, if one component dominates the overall SED (e.g. EKB zone) then observations over a range of wavelengths provide information about dust grain sizes, with longer wavelengths probing larger grains. The SED is therefore a powerful diagnostic and emphasises the importance of multi-wavelength, resolved imaging to separate, for example, the asteroid belt and EKB components.

The Rayleigh–Jeans (R-J) tail of the SED can provide a wealth of information on the radial distribution and size of emitting grains (a test of whether or not the particles in the disk are undergoing a steady-state collisional cascade) as well as a handle on the composition and structure of the dust grains (Ertel et al. 2012). Whilst scattered light observations are sensitive to small grains around a star, the bulk of the dust mass resides in the largest grains most detectable at submm–cm wavelengths, with the mass often estimated from optically-thin observations at submillimeter wavelengths (for grain sizes up to ∼1mm). These grains are likely located in or near the planetesimal belts, which may also show perturbed geometries due to resonances with long-period planets (Wyatt 2006). Hence debris disks can act as pointers to planetary systems with features in the disks potentially highlighting the presence of planets with long orbital periods (e.g. for β Pictoris; Heap et al. 2000), even in cases where the planet is as yet undetected by another method (e.g. Mustill & Wyatt 2009).

## 2. Progress to date

Recent observations of debris disks fall into two main categories: (a) placing disks (and, by implication, our Solar System) into context via statistical samples, providing correlations with, for example, stellar properties such as age, spectral type and metallicity and whether planetary companions are known to exist, and (b) the architecture and properties of individual systems, probed specifically by high angular resolution imaging.



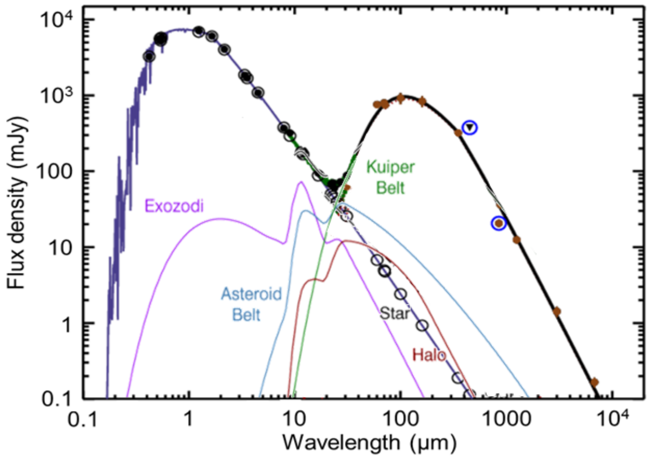




**Figure 2:** Schematic representation of the main components of a debris disk, together with an illustrative spectral energy distribution. The architecture is based loosely on the Solar System, with the planets acting as shepherds to the planetesimal belts (adapted from Hughes et al. 2018). The measured photometric points in the SED is that measured for the Solar-type star HD107146 (Holland et al. 2017).

**2.1 Recent surveys: detection rate and fractional luminosity.** Until the mid-2000's debris disk science relied mainly on photometric fluxes from *IRAS*, *ISO* and a few ground-based telescopes. The true morphology of the disk structure had only been seen for a handful of nearby objects in either scattered light or thermal emission (e.g. Smith & Terrile 1984; Holland et al. 1998). The advent of new satellite observatories changed the field completely with far-IR surveys from *Spitzer* (Meyer et al. 2006) and *Herschel* (Eiroa et al. 2013; Matthews et al. 2014) providing both images (many disks were resolved for the first time with *Herschel*) and much-improved constraints on their SEDs. The detection rates varied by spectral type with A-stars around 30% (Thureau et al. 2014), whilst for FGK (including Solar-types) the rate is more like 15% (Sibthorpe et al. 2018). The disks themselves highlighted a wide diversity of structures: some clumpy, suggesting the presence of perturbing planets.

In terms of limits to the detectable flux, *Spitzer* and *Herschel* achieved fractional dust luminosities (ratio of IR luminosity from the dust to that of the star, $f = L_{IR}/L_{\star}$ ), of $\sim 10^{-5}$ and $\sim 10^{-6}$, respectively. True analogues to the EKB ($f \sim 10^{-7}$; Vitense et al. 2012) are still at least an order of magnitude too faint to have been detected via current surveys, whereas (exo-)Zodiacal dust belts are up to 1000× fainter still. Hence even with a sensitive space telescope neither of the Solar System's debris components would be detectable around a neighbouring star. All disks currently detected are therefore scaled-up versions (in both size and mass) of those found in our own planetary system. It remains conceivable that debris disks are ubiquitous in the galaxy (below current detection thresholds) and at least as common as planetary systems (Winn & Fabrycky 2015).

**2.2 High resolution imaging: resolving planetesimal belts.** The evolution of debris disks, as described by steady-state collisional models, is heavily reliant on knowing the initial location of the planetesimal belt(s) (Wyatt 2008). As a blackbody temperature fit to the SED component tends to underestimate the radius of a belt (the constituent grains are usually hotter than blackbodies) to properly constrain the model requires an accurate measurement of belt radii. The angular resolution of *Herschel* (at best capable of resolving an EKB-sized disk around a star no more distant than 8pc) meant that only a small number of the nearest disks were imaged in any detail. Observations in the mid- and far-IR also do not trace the underlying population of planetesimals, probing instead small dust grains (10–100μm) that are subject to radial migration induced by radiation forces (Burns et al. 1979). Observations at longer wavelengths are therefore more attractive in that the emitting grains are large enough to trace the planetesimals and the often negligible stellar emission makes the system's inner regions more accessible. The advent of interferometers operating in the submm/mm (e.g. SMA, NOEMA, ngVLA and ALMA), means that such observations are now possible (see example in Figure 1).

**2.3 The planet connection.** Given the role of debris disks in the formation and evolution of planetary systems it would not be surprising to find a correlation between the presence of planets and that of disks. Indeed, long-period planets found by direct imaging tend to reside in debris disks (e.g. HR8799; Marois et al. 2008). With the exception of a few systems, however, the planets discovered (via radial velocity or transit methods, which are subject to the observational biases of sensitivity and cadence) tend to be on orbits of just a few AU, having little influence on disks with size scales of 50AU or more. Targeted surveys with Herschel and Spitzer derived detection rates for disks around planet-hosting stars of 20−30% (e.g. Marshall et al. 2014; Matthews et al. 2014). Further studies identified possible trends between low-mass planets and the presence of cool dust (Wyatt et al. 2012; Marshall et al. 2014). However, a study of FGK stars did not find compelling evidence that debris disks are more common (or, indeed, more dusty) around stars harbouring planets (Moro-Martín et al. 2015), although there are also indications that disks are more frequent and more prominent in systems with planets below a Jupiter mass (Matthews et al. 2014). Hence, to date, the results remain somewhat contradictory; constructing large bias-free samples of both planets (e.g. with TESS and PLATO) and disks (in the far-IR/submm) remains a challenge for the future. Indeed, future instrumentation will make it easier to have overlapping samples of exoplanets and disks. For example, the advent of 30m-class optical telescopes will enable the detection of planets around older stars, meaning that many of the current disk hosts surrounding mature MS stars may be revealed as exoplanet hosts.

## 3. Big science questions

Over the next decade a number of important science questions are emerging in the study of debris disks. These are discussed below.

**Q.1 Exploring the structure and dynamics of disks surrounding Solar-type stars**. Exactly how unusual is our Solar System architecture? Being able to reach the fractional luminosity of the EKB around a large sample of stars will help to establish the full distribution of the fractional dust luminosity of the disk population and hence put into context where the Solar System lies. Over the next few years attention will also continue to focus on exploring the architecture and dynamics of individual debris disk systems. Multiple components are now being detected (from direct imaging, as well as inferred from SEDs) and the relationship between these planetesimal belts, and the physical mechanisms that drive their formation and properties (e.g. dust production and migration) will be explored via high angular resolution, multi-wavelength observations. A recent example of this is the disk structure around the Solar analogue HD107146 which appears to show evidence of multiple rings (Marino et al. 2018). In particular, the detection of intermediate regions between separate belts will give a better understanding of the overall system architecture and how close this resembles our own Solar System.

**Q.2 Investigation into the disks around low luminosity stars**. Are disks prevalent, and what is the nature of the disks surrounding M dwarfs where there is a known high incidence of terrestrial planets? Even though the inventory of (reasonably well-characterised) disks now stands at a few hundred increasing the sample size (e.g. for unbiased surveys), particularly around lower luminosity stars, is a major goal. Unfortunately, current observations are severely limited by a lack of sensitivity and confusion noise (e.g. by background sources). Interestingly, the detection of debris around M-stars, given their prevalence in the galaxy and the number of known extrasolar planets around them, has proven more elusive (Lestrade et al. 2009). It is possible that grain removal processes are more efficient in these systems than around more massive stars and so future (sensitive) surveys at longer (submm/mm) wavelengths may be more fruitful in the near term.

**Q.3 The role of atomic and molecular gas in the evolution of disks.** Are there evaporating comets in these systems, which could have implications for terrestrial planet habitability? Debris disks are usually described as gas-poor, and this is true in comparison to earlier disk evolution stages. Recently, there has been a resurgence in the interest of the role of atomic and molecular gas in debris disk evolution, mainly driven by the improved sensitivity of facilities, such as ALMA (Dent et al. 2014, Matrà et al. 2017). Although CO gas and atomic C, probed at longer submm/mm wavelengths, appears to be relatively common particularly around luminous stars, the quantities are unlikely to strongly affect the dust dynamics or planet forming potential. Of more interest is the origin of the gas, which is not clear; it could be either primordial or secondary (Moór et al. 2015), the latter even suggesting that CO could originate from the break-up of a narrow rings of comets that could affect the habitability of any terrestrial planets in a system. Near-term goals include measuring the incidence of gas in more systems, and to detect molecules other than CO thus characterising the composition of the exocometary gas (Hughes et al. 2018). The study of (in particular) molecular gas emission from debris disks is emerging as a major area of research.

**Q.4 The variability of disks.** Time variable phenomena have been observed in the IR spectrum of, for example the β Pic debris disk (Beust et al. 1990) likely due to the presence of exocomets (Kiefer et al. 2014), and in the continuum emission of a small subset of high fractional luminosity "extreme" disks from *Spitzer* (Meng et al. 2015), the latter may have undergone recent collisional events. Younger systems have shown evidence of time variable dust emission on scales of 10AU (e.g. AU Mic; Boccaletti et al. 2015) with the dust generated either by resonance with a parent body, or at the location of a recent giant collision resulting in a swarm of smaller bodies (Jackson et al. 2014). The timescales to observe structural changes for EKB analogues in the far-IR/submm is most likely to be years or decades; tentative evidence has been seen for the rotation of clumps around nearby disks such as ε Eridani over a period spanning 5 years (Greaves et al. 2006). Regular monitoring of disks, particularly those that are well-resolved and show evidence of clumpy structure, could reveal dynamically-induced structural changes perhaps from the movement of planets, or major system environmental events such as collisions between planetesimals.

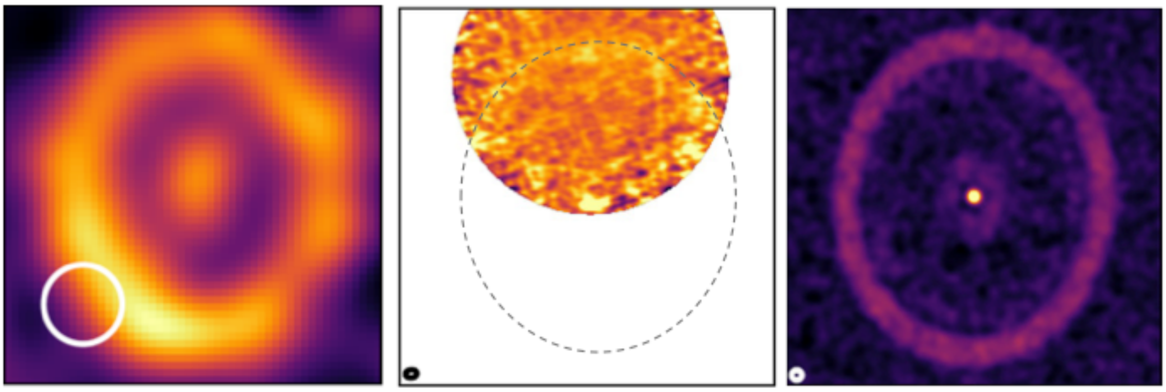


**Figure 3:** The debris disk surrounding ε Eridani, (left) Observed image with the Large Millimeter Telescope (LMT) at 1.3mm (Chavez-Dagostino et al. 2016), (middle) The northern arc of the disk observed with ALMA at 1.3mm (Booth et al. 2017); the dashed ellipse representing an inclined ring of radius 70AU, (right) Modelled image (Booth et al. 2016) from a 50m-class, single-aperture submillimeter telescope at 350µm for the same integration time as used for the ALMA observations. The circles/ellipses represent the approximate angular resolution for each case.

## 4. Prospects over the next decade

To address the questions posed in section 3 requires the development of new facilities, particularly in terms of improving statistical samples, and expanding into debris (both dust and gas) around lower mass and late main sequence (Solar-like) stars. Surveys with existing single-aperture telescopes (e.g. APEX and JCMT) have pushed the limits of detectability and confusion noise. An example is a recent survey with the JCMT which detected debris emission from only 50% of a known (from far-IR observations) disk host sample at submillimeter wavelengths (Holland et al. 2017), clearly struggling for sensitivity for fainter disks. At longer wavelengths (>1mm) the Large Millimeter Telescope (LMT) has also shown potential, with the sensitivity and angular resolution to image nearby disks such as ε Eridani (Chavez-Dagostino et al. 2016; see Figure 3) with the falloff in disk brightness being compensated by an increase in detector sensitivity afforded by a larger dish and more transparent atmosphere. Observations at short submillimetre wavelengths are more effective as they probe the turnover region of the cold dust spectrum (into the R-J regime), offer lower confusion noise per aperture from background sources, and have the advantage terms of better contrast for subtracting contributions to the total flux from the photosphere, chromosphere and coronal emission from the star (MacGregor et al. 2013; Rodríguez et al. 2019). To reach the fractional luminosity of the EKB around hundreds of Solar-type and low luminosity stars ideally needs a large, single aperture telescope operating at short submm wavelengths. Interferometers, such as ALMA and SMA have exquisite sensitivity on small scales, and may undertake "blind" surveys of small number of speculative disk systems. However, it is unlikely that they will ever be used in earnest to find large numbers of new debris disks as it would take far too long and not be an efficient use of such facilities. In addition, ALMA, as is the case for all interferometers, struggles to capture the large-scale structure of extended nearby disks (see Figure 3). Even facilities such as the Atacama Compact array are not sensitive enough to probe to the dust levels of interest.

The Atacama Large Aperture Submillimetre Telescope (AtLAST) is a concept for a 50m-class telescope operating from 350μm to 1mm (http://atlast.pbworks.com/). Such a facility will have the capability to detect thousands of new disks (including those around M-dwarfs and the 500 Solar-type stars within 30pc of the Sun), many to a fractional luminosity level of less than the EKB in our Solar System (see Figure 4). True image fidelity would also be achievable for extended disks (see Figure 3). Surveys could be extended to more distant candidates, and with 2" angular resolution at the shortest wavelengths AtLAST would be capable of resolving structures of smaller than the EKB around stars to a distance of 30pc. Determining the SED from say, 350μm to 1mm can identify multiple disk features (belts) as well as providing a handle on the origin and nature of the material. AtLAST could also carry out high spectral resolution molecular gas observations to tell us whether there are, for example, evaporating comets in these systems (a large number of which could have implications for the habitability of any terrestrial planets). Such a facility would perfectly complement the pointed, high angular resolution capabilities of interferometers such as ALMA, SMA, NOEMA and ngVLA.

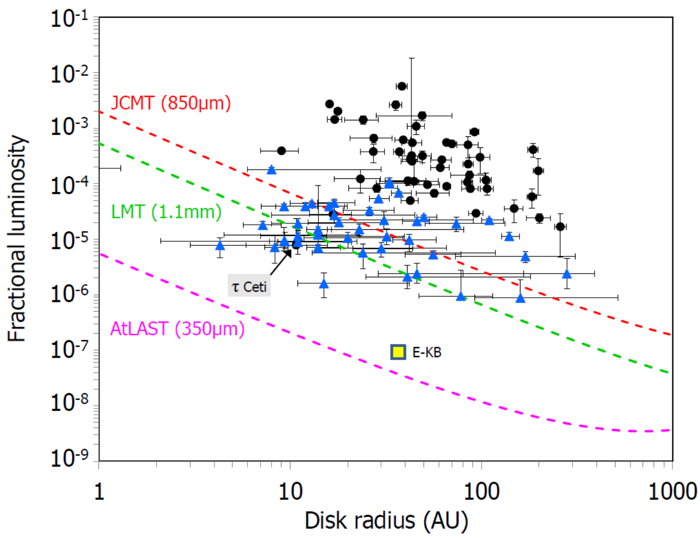



**Figure 4:** The measured fractional luminosity versus disk radius (derived from a modified BB fit to the SED) from surveys of debris disks undertaken of known disk hosts with JCMT (black circles; Holland et al. 2017) and Solar-type stars with *Herschel* (blue triangles; Sibthorpe et al. 2018). The dashed lines represent the detection thresholds (3× the extragalactic confusion limit; Geach et al. 2017) for a number of facilities for a Solar-type star at a distance of 10pc (Wyatt 2008). The yellow box represents the fractional luminosity of the Edgeworth-Kuiper belt in our Solar System (Vitense et al. 2012).

## 5. Summary and recommendations

The study of debris disks has advanced enormously over the past decade. In the White Paper for the 2010 Decadal Review (Holland et al. 2009) it was predicted that ALMA would play a leading role in the study of debris disks towards the end of the decade. This has certainly been the case and future upgrades (such as sensitivity improvements through bandwidth enhancements) will mean that ALMA will continue to provide a unique insight on individual debris systems. One recommendation from the previous paper has not been forthcoming. Given their faintness, there still exists a need for a large single-aperture (50m class), ground-based telescope, operating in the submillimeter region, to improve detection statistics and to crucially investigate disks around low luminosity stars. At short submillimetre wavelengths a facility, such as the proposed Atacama Large Aperture Submillimetre telescope (AtLAST), would be able to detect disks to a luminosity level of the EKB in our Solar System, around thousands of stars in our Solar vicinity. Indeed, a combination of ALMA *and* AtLAST will revolutionise debris disk science. Not only will we vastly increase sample sizes with fainter and more distant populations detected (e.g. disks surrounding M-dwarfs) but also explore the architecture of disks through high angular resolution imaging (placing our Solar System into context with other systems), directly measure dust (and gas) masses to determine the amount of material present, investigate the role of dust and gas in the disk dynamical evolution, and possibly even observe stochastic events related to planets and collisional events.

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