The Statistics of Extended Debris Disks Measured with Gaia and Planck

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Abstract

Thermal emission from debris disks around stars has been measured using targeted and resolved observations. We present an alternative likelihood-based approach in which temperature maps from the Planck cosmic microwave background (CMB) survey at 857 and 545 GHz are analyzed in conjunction with stellar positions from Gaia to estimate the fraction of stars hosting disks and the thermal emission from the disks. The debris disks are not resolved (or even necessarily detected individually), but their statistical properties and the correlations with stellar properties are measured for several thousand stars. We compare our findings with higher sensitivity surveys of smaller samples of stars. For dimmer stars, in particular K and M dwarfs, we find that about 10% of stars within 80 pc have emission consistent with debris disks. We also report on 80 candidate disks, the majority of which are not previously identified. We have previously constrained the properties of Exo-Oort clouds using Planck data— with future CMB surveys, both components can be measured for different stellar types, providing a new avenue to study the outer parts of planetary systems.

Unified Astronomy Thesaurus concepts: Debris disks (363); Circumstellar disks (235); Cosmic background radiation (317); Submillimeter astronomy (1647)

1. Introduction

Many stars are known to be surrounded by orbiting disks of dust and debris. The sizes of these debris disks range from tens to hundreds of astronomical units. Their presence is thought to proceed from the protoplanetary disk phase of a newly formed star, with dust grains originating primarily from the collisional cascade of planetesimals (Wyatt 2008). Absorption of optical light from the parent star by the debris disk heats the disk to temperatures on the order of tens to a hundred Kelvin, depending on the stellar type and the distance from the star. Given their temperatures and large surface areas, debris disks can be strong emitters in the infrared and submillimeter. Observations in the infrared probe the inner hotter parts of the disks and small grains. Observations in the submillimeter, however, are better suited to studying extended debris disks and larger grains. Submillimeter observations of debris disks have been somewhat limited but serve as a powerful probe to understanding debris disk properties around low-luminosity stars (Lestrade et al. 2006). In this work, we focus on observations in the submillimeter because of the availability of deep, large-area submillimeter maps from Planck (Planck Collaboration et al. 2018). However, the methodology that we develop could in principle be applied to observations at any frequency.

Targeted, high-resolution observations of debris disks in the submillimeter have long been used to study these objects. Observations with ALMA at 223 GHz, for instance, can resolve the structure of nearby disks such as that of Fomalhaut (MacGregor et al. 2017).

In this analysis, we take a complementary approach to studying debris disks, using low-resolution, but large-area, data from Planck. Using the measured positions and distances of Gaia-detected stars (Gaia Collaboration et al. 2018b, 2018c), we constrain the parameters of simple disk models. While the Planck observations cannot resolve features in individual debris disks, they can be used instead to constrain the statistics of the emission from these objects and correlations with, for instance, stellar properties. Open questions in this area include the incidence of debris disks around stars of different spectral types and the number of dim, low-mass stars hosting cool debris disks (Lestrade et al. 2009; Binks & Jeffries 2017; Hughes et al. 2018).

Several previous works have studied the statistics of debris disk populations. For instance, Patel et al. (2014, 2017) used infrared observations with the all-sky Wide-field Infrared Survey Explorer (WISE) survey to identify stars with excess thermal emission beyond the stellar photosphere. Studies of debris disks with wide-field surveys provide measurements of a substantially larger number of potential debris-disk-hosting stars than pointed observations. Other all-sky surveys used in previous debris disk analyses include IRAS, 2MASS, and AKARI, all observing at shorter wavelengths compared to Planck (Rhee et al. 2007; Ishihara et al. 2017).

Our analysis is unique in several respects relative to previous analyses. For one, we use submillimeter observations from Planck, relying primarily on the 545 and 857 GHz bands. We are therefore more sensitive to colder debris disks, the outskirts of debris disks, and larger grains. An ancillary advantage of these low-frequency observations is that the signal from the stellar photosphere is expected to be negligible. For observations with, e.g., WISE, on the other hand, emission from the star itself may be non-negligible (Patel et al. 2014). Another novel feature of our analysis is that we do not require any individual debris disk to be detected in the Planck maps. Because we combine constraints from many possible debris disks, disks with signals too weak to be detected individually in the Planck maps can still contribute to our constraints.

We note that our analysis is sensitive to other sources of emission correlated with stars in addition to that from debris disks. For instance, protoplanetary disks (Williams & Cieza 2011) or exo-Oort clouds (Baxter et al. 2018) could also source similar emission signals. Our results should in some sense be viewed as constraining all of these potential sources.
However, for the present analysis, we expect debris disk emission to dominate over other sources.

The paper is organized as follows. In Section 2, we describe the ingredients of our debris disk model; in Section 3, we describe the data from Planck and Gaia that we use to constrain this model; in Section 4, we describe how we process the data; in Section 5, we describe the application of our analysis to simulated data sets; in Section 6, we present our results on actual data; and we conclude in Section 7.

2. Modeling

We use Planck data to constrain the parameters of a model describing the population of extended debris disks around stars detected by Gaia. We do not require that any individual disk be detected in the Planck maps.3

Debris disk temperatures are typically in the range of 30–100 K toward the outskirts of the disk, depending on the distance from the parent star. These temperatures correspond to Wien peaks at roughly 1800 and 6000 GHz, beyond the frequency range probed by Planck. We therefore rely on the highest frequency channels from Planck, namely those at 545 and 857 GHz. Relative to debris disk observations with, e.g., WISE or CHARA (Nuñez et al. 2017), we expect our analysis with Planck to be more sensitive to extended disks or disks around less luminous stars.

The Planck 545 and 857 GHz channels have approximate beam sizes of 4.7 and 4.3 FWHM, respectively. Because the typical debris disk radius ranges from ~30 to 300 au (Pawellek et al. 2014), essentially all debris disks beyond a few parsecs from Earth will be unresolved by Planck. Therefore, to a very good approximation, we can measure only one number for each disk, namely the amplitude of its emission signal. We refer to the amplitude measurement for the $i$th star as $d_i$, which we measure as a surface brightness with units of Jy sr$^{-1}$ (i.e., the units of the Planck 545 and 857 GHz maps). We will discuss how $d_i$ is obtained from the Planck maps in Section 4.1.

Our model for $d_i$, which we denote with $\hat{d}_i$, is the sum of a (possibly zero) debris disk contribution and a term accounting for background emission from other sources:

$$\hat{d}_i = \alpha_i \frac{L_i}{A_{eff} 4 \pi r_i^2} + B_i,$$

The quantity $\alpha_i$ controls the presence or absence of a debris disk, with $\alpha_i = 1$ if the star has a debris disk and $\alpha_i = 0$ otherwise. $L_i$ is the luminosity of the debris disk signal in the Planck band of interest and $r_i$ is the distance to the $i$th star. $A_{eff}$ is an effective sky area (in steradians) that captures both the impact of the Planck beam and impact of the chosen map pixelization; we will discuss this factor in more detail in Section 4.2. Finally, $B_i$ describes the contribution of backgrounds and noise sources to the measurement of $d_i$. We simplify our notation by defining

$$s \equiv \frac{L_i}{4 \pi A_{eff}},$$

so that Equation (1) becomes

$$\hat{d}_i = \alpha_i \frac{s}{r_i^2} + B_i,$$

At the frequencies of interest and for the majority of stars, emission from a possible debris disk will completely dominate over any emission from the stellar photosphere because of the much larger solid angle subtended by the disk relative to the star. We therefore ignore possible photospheric emission from the star for the majority of this analysis, but discuss this possible contribution in Section 7.

Assuming contributions to $B_i$ from the star itself are negligible, $B_i$ is then dominated by extragalactic backgrounds and galactic dust. It is therefore reasonable to assume that the background distribution is independent of the signal distribution. However, this assumption could be broken if debris disks are more likely to form in places in the galaxy with significant nearby dust, for example.

Given the assumption of independent signal and backgrounds, we can write the likelihood of the data in the case where $\alpha_i = 1$ as

$$P(d_i|\theta, \alpha_i = 1) = \int ds \, P_i(s) P_B(d_i - s/r_i^2),$$

where $\theta$ represents the model parameters describing the debris disk emission, $P_i(s)$ characterizes the probability distribution of $s$, and $P_B(B)$ characterizes the probability distribution of the backgrounds. On the other hand, in the absence of a debris disk (i.e., $\alpha_i = 0$), the probability of measuring $d_i$ is just given by the background distribution:

$$P(d_i|\theta, \alpha_i = 0) = P_B(d_i).$$

Because we do not expect to get many high signal-to-noise detections of debris disks, we are most interested in the case where we cannot determine whether $\alpha_i = 0$ or $\alpha_i = 1$ at high significance. We therefore marginalize over $\alpha_i$ to obtain the likelihood:

$$P(d_i|\theta) = \int P_B(d_i - s/r_i^2) P_i(s) P(\alpha_i = 1) ds + P_B(d_i) P(\alpha_i = 0).$$

We will return to the possibility of measuring $\alpha_i$ for individual stars in Section 6.6.

We suppose for simplicity that all stars (after imposing some selection criteria to be discussed below) have the same probability of hosting a debris disk. Under this assumption, we define the disk fraction

$$f_{\text{disk}} \equiv P(\alpha_i = 1).$$

It follows that $P(\alpha_i = 0) = 1 - f_{\text{disk}}$.

In order to compute the likelihood defined above, we must assume some form for the background distribution $P_B(B)$ and the signal distribution $P_i(s)$. As we discuss in more detail in Section 4.1, we find that we can accurately model the background fluctuations in the Planck maps with a Gaussian model with mean $\mu_{B,i}$ and variance $\sigma_{B,i}^2$, where these two parameters vary from star to star (with index $i$ labeling the

Note that some nearby disks, such as that of Fomalhaut, can be detected with signal-to-noise greater than one in the Planck maps; see, e.g., Baxter et al. (2018).
different stars). Equation (6) then becomes
\[
P(d_i|\theta) = f_{\text{disk}} \int_0^\infty \mathcal{N}(d_i - \frac{s}{r'_i} | \mu = \mu_{r,i}, \sigma^2 = \sigma^2_{r,i}) P_i(s) ds + (1 - f_{\text{disk}}) \mathcal{N}(d_i | \mu = \mu_{r,i}, \sigma^2 = \sigma^2_{r,i}),
\]
where \( \mathcal{N}(x|\mu, \sigma^2) \) is the normal distribution.

We now consider the signal distribution, \( P_i(s) \), for which we will explore two models. Perhaps the simplest possible model is that all debris disks have the same luminosity so that
\[
P_i(s) = \delta(s - s_d),
\]
where \( \delta \) is a Dirac \( \delta \) function, and \( s_d \) describes the luminosity of all disks. In this case, the model parameters are \( \theta = \{ f_{\text{disk}}, s_d \} \). We will refer to this as the constant luminosity model.

While the constant luminosity model has the advantage of simplicity, it is unlikely to reflect the true distribution of debris disk properties in nature. For instance, recent collisional events of planetesimals are thought to result in an extended tail of strong emitters (Bryden et al. 2006). A common choice for modeling the distribution of debris disk luminosities is a log-normal model (e.g., Bryden et al. 2006). Because the total debris disk luminosity can be reasonably expected to scale with the luminosity of the parent star, it is common in the literature to work with the fractional luminosity, i.e., the ratio of the bolometric disk luminosity to that of the parent star. For simplicity, we will instead adopt a log-normal model for \( s \) itself. In this case, we have
\[
P_i(s|\mu_{ln,i}, \sigma^2_{ln,i}) = \frac{1}{s\sqrt{2\pi} \sigma_{ln}} \exp \left[ \frac{- (\ln s - \mu_{ln,i})^2}{2\sigma_{ln,i}^2} \right].
\]
For this model, the parameters are \( \theta = \{ f, \mu_{ln,i}, \sigma^2_{ln,i} \} \).

Finally, we assume that the \( d_i \) measured for each star is independent of the measurements for other stars, allowing us to write the total likelihood as
\[
\mathcal{L}(|d_i|\theta) = \prod_i P(d_i|\theta),
\]
where \( \{d_i\} \) represents the set of measurements for all stars and the product runs over all stars. The assumption of independent measurements may be invalidated by correlated background fluctuations for nearby stars. However, our tests on simulated data suggest that this effect does not lead to a bias in our constraints (see Section 5). The likelihood in Equation (11) is computed by substituting either Equation (9) (constant luminosity model) or Equation (10) (lognormal model) into Equations (8) and (11).

3. Data

3.1. Planck Data

The Planck satellite observed the full sky in nine frequency bands from 30 to 857 GHz (Planck Collaboration et al. 2018). Our analysis relies on the 545 and 857 GHz bands, as these frequencies are most well matched with the emission of possible debris disks and are also the highest resolution bands. We use the publicly available maps at https://pla.esac.esa.int/. These maps are downgraded to a Healpix (Górski et al. 2005) resolution of \( N_{\text{side}} = 1024 \) for the final analysis in order to better match the pixel size to the beam size.

3.2. Gaia Data

The stellar positions and distances used in this analysis are taken from the Gaia DR2 release (Gaia Collaboration et al. 2018a). This data release contains parallaxes for stars down to a limiting magnitude of \( G = 21 \). The Gaia satellite also obtains low-resolution spectroscopy, from which broadband photometry is extracted and stellar parameters are estimated (Andrae et al. 2018). We use the Gaia color measurements to impose various cuts on the stellar catalog (see Section 4.3) and focus on nearby stars with \( d < 100 \) pc. The Gaia data set is virtually complete for main-sequence stars in this volume, and the expected parallax errors are essentially negligible for our purposes.

3.3. Masking

Galactic backgrounds and non-debris-disk point sources are a potential challenge for our analysis. The high density of Gaia stars across the sky means that it is not unlikely to have a chance alignment between a star and a bright background fluctuation or extragalactic source. We reduce the impact of such background fluctuations by imposing a conservative sky mask. The mask is derived from a map of H I column density by Lenz et al. (2017), which has been shown to correlate strongly with thermal emission from galactic cirrus at low H I column density. In our fiducial analysis, we leave unmasked any pixels whose column densities are in the bottom 10th percentile of this map (see Figure 1). Additionally, we use the PSCz catalog from Saunders et al. (2000) to mask IRAS-detected galaxies with an aperture of \( 5' \) and NGC objects with a radius of \( 15' \).

4. Methodology

4.1. Measurement of \( d_i \) and Background Model

Because Planck does not resolve the debris disks, we can only measure a single amplitude value for each star, \( d_i \). In the interest of simplicity, our estimator for \( d_i \) is just the pixel value of the Planck map at a resolution \( N_{\text{side}} = 1024 \) for the pixel in which the star resides. Such a pixel is roughly \( 3'/4 \) on a side, which can be compared to the \( 4'/3 \) FWHM of the Planck beam at 857 GHz. Consequently, for a debris disk located in the center of a pixel, the pixel will contain a majority of the debris disk flux. We correct for missing flux due to the beam and pixelization as described in Section 4.2.

In principle, one could construct an estimator for \( d_i \) that uses the known position of the star inside the pixel and the beam shape to obtain a more optimal estimate of the signal from the star. However, we find that the simple technique adopted here performs well in simulations and is significantly simpler and faster than fitting a beam template or applying a matched filter to the maps. We postpone a more optimal analysis to future work.

The distribution of the backgrounds in the Planck 545 and 857 GHz maps varies significantly across the sky, as these maps receive large contributions from galactic cirrus and other nonisotropic sources. To form an estimate of the local background distribution for each star, we draw an annulus around the star—from \( \theta_{\text{min}} \) to \( \theta_{\text{max}} \)—and measure the mean, \( \mu_{r,i} \), and variance, \( \sigma^2_{r,i} \), of the map within this annulus. Our estimate of the background contribution to \( d_i \) is simply a normal distribution with this mean and variance.
4.2. Effective Area, $A_{\text{eff}}$

We now describe the computation of the effective area, $A_{\text{eff}}$ in Equation (1). This factor effectively measures the relation between flux from a point source and surface brightness measured in the Planck maps. By definition, a point source with flux $X$ Jy will on average lead to a pixel with surface brightness $(X/A_{\text{eff}})$Jy sr$^{-1}$. $A_{\text{eff}}$ therefore includes both the impact of the instrument beam and the impact of pixelization of the beam-smoothed map. We estimate $A_{\text{eff}}$ with a Monte Carlo procedure, where we first choose random positions in an $N_{\text{side}} = 2048$ map, add a signal with known flux to the pixel containing the random position, convolve the resultant map with the Planck beam (using a Gaussian approximation to the beam), and downgrade it to the $N_{\text{side}} = 1024$ resolution of the actual data analysis. Finally, the surface brightness values in the pixels of the degraded map centered on the input positions are computed, and the ratio is taken relative to the input signal. We repeat this process many times to build statistics. We find $A_{\text{eff}} = 31.6 \pm 0.003$ arcmin$^2$.

4.3. Star Selection

Debris disks have been measured around a wide variety of stars, though they have been most commonly detected in spectral classes A–K (Krivov 2010). Because of this, we focus our analysis on main-sequence stars in spectral classes A–M. We choose not to omit M stars from our baseline analysis, given that submillimeter surveys such as Planck are well suited to measuring debris disks around a cooler sample of stars (Lestrade et al. 2006). We do, however, remove giant stars from our sample as they can be strong emitters in the wave bands of interest due to gas and dust ejecta (Ventura et al. 2018). Additionally, we remove possible white dwarfs, as they have been found to have low debris disk detection rates (Barber et al. 2012). These selections are accomplished with several magnitude and color cuts:

I. We remove stars with absolute magnitude in the Gaia $G$ band, $M_G$, greater than 10.
II. Stars with $M_G < 4$ and color $BP - RP > 0.9$ are removed as possible giants.
III. Stars with $M_G > 4 \times (BP - RP) + 3$ are removed as possible white dwarfs.

Our baseline cuts are illustrated by the orange points in the bottom panel of Figure 2 and leave roughly $2.5 \times 10^9$ stars across the full sky out to 330 pc. The roman numerals in the shaded regions correspond to the three cuts described above, while the green points indicate stars in our fiducial sample (see Section 5.3). We include a main-sequence isochrone (Valcarce et al. 2012, 2013) to aid in visually distinguishing a star from the main sequence.

A unique feature of our stellar population compared to that of previous debris disk analyses is the higher density of dim, low-mass stars in our sample. The top panel of Figure 2 illustrates the distribution of Gaia $G$-band absolute magnitudes after performing the main-sequence selection described above. The step falloff in the number of stars at $M_G \sim 9$ is a consequence of Gaia’s stellar selection. While we explore removing dim stars from our analysis in Section 6.5, our baseline stellar population is clearly dominated by stars with $M_G > 7$. As illustrated in Appendix C.1, we find that $\sim 75\%$ of the main-sequence stars in our sample are in spectral classes K–M for varying distance cuts.

5. Analysis of Simulated Data

5.1. Generating Simulations

We test our analysis pipelines and model assumptions by generating and analyzing simulated Planck maps with mock debris disk signals.

To generate these simulated data sets, we start by randomly generating mock debris disk luminosities using either the constant luminosity or log-normal models. The amplitude of the signals in either case is chosen to roughly match (on average) measurements of Fomalhaut’s debris disk at 857 GHz by Acke et al. (2012). For the constant-luminosity model, we set $s_d \approx 2.96 \times 10^{40}$ W Hz$^{-1}$Sr$^{-1}$. We note that Fomalhaut is a mid- to large-size debris disk. We assume $f_{\text{disk}} = 0.15$ following Krivov (2010), who found that approximately 15% of stars in spectral classes A–K host debris disks. The mock debris disk emission is then randomly turned off with probability $1 - f_{\text{disk}}$. Next, the mock disks are assigned distances drawn from the true distribution of distances to Gaia stars and inserted into Healpix maps at randomly located pixels of an $N_{\text{side}} = 2048$ map. This map is then convolved
with the Planck beam and degraded to a resolution of \( N_{\text{side}} = 1024 \). In order to increase the statistical precision of the simulation tests, we generate the simulations using a density of stars five times greater than found in the actual data.

The background contributions in the simulated maps are generated either as Gaussian noise or by using the Planck maps themselves. In the Gaussian case, we choose a noise level comparable to the variance of the Planck maps over the unmasked region. This model is a poor imitation of the highly non-Gaussian galactic backgrounds, but it is useful for our purposes because in this case, we can know the background distribution perfectly. On the other hand, using the Planck maps themselves as an estimate of the background is justified as the debris disk emission is expected to make a small contribution to these maps. When using the Planck maps as background estimates, we only place simulated debris disks within pixels that do not host actual Gaia stars out to three times the maximum distance.

5.2. Gaussian Simulation Results

We now discuss the results of analyzing the simulated Planck maps, starting with the Gaussian simulations. Given that the Gaussian simulations are very unlike the real data, they are most useful for the purposes of validating our pipelines; we therefore relegate most discussion of these results to Appendix B. For the Gaussian background case, our model is a complete description of the data and should therefore recover an unbiased estimate of the input parameters. The results of this analysis are shown in Figure B1. We find that the input parameters are recovered to within the uncertainties.

As the distance cut is increased, the number of stars increases. At the same time, however, the average flux from a star will decrease as the distance cut is increased. Consequently, if the background model is correct, one expects the constraints to asymptote to a constant level of uncertainty as the distance cut is increased (see Appendix A for a more detailed justification of this point). This behavior in the limit of a large distance cut is illustrated by the dashed contours in Figure B1, where we use a 250 pc maximum distance cut.

Using the Gaussian simulations, we find that if there are multiple disks in the same pixel, the parameter constraints can be biased. Additionally, neighboring pixels containing disks also lead to bias in simulations, because, when convolving with the Planck beam, the signal from nearby sources combine. Our modeling does not account for these features, so we impose the restriction that no star in a pixel can be within three times the maximum distance cut of another star in the same pixel, and no star included in the analysis can be within \( 3\alpha \) of another star in the catalog. This restriction eliminates bias in the simulations, but could conceivably impose a selection bias in the actual analysis, as stars with nearby neighbors may have differing debris disk properties. For a maximum distance cut of less than 100 pc, these restrictions typically remove about 20%–30% of stars that survive the H1 masking (see Section 3.3).

5.3. Planck Simulation Results

We next analyze the simulations in which the background model is the Planck maps themselves. Unlike the Gaussian background case, using the Planck maps means that our Gaussian approximation to the local background distribution near a disk is not necessarily accurate. The Planck-based simulations therefore enable us to test the extent to which our background model can yield accurate parameter constraints.

The results of analyzing the Planck background simulations are shown in Figure 3 for the constant luminosity model and Figure B3 for the log-normal luminosity model. In the case of the constant luminosity model, we choose the same input parameters as used in the Gaussian simulations (Section 5.2). For the log-normal luminosity model, we choose a fiducial value of \( \sigma_{\mu_{\text{Lum}}} = 1 \) and select the value of \( \mu_{\text{Lum}} \) that corresponds to our earlier choice of \( s_{\text{G}} \) in the Gaussian simulations. As before, we set \( f_{\text{Disk}} = 0.15 \).

For both tests, we consider three types of variations around our fiducial analysis choices: (1) using different stellar distance cuts, (2) using different annulus sizes for the purposes of estimating local backgrounds, and (3) using different masking
thresholds for the HI mask. Our fiducial choices include a distance cut of 65 pc, an annulus size of $\theta_{\min} = 5'$ and $\theta_{\max} = 10'$, and a HI mask of 10%

For distant stars, for which the expected signal will be less than the backgrounds, inaccuracies of our background model can lead to parameter biases. Because the number of stars increases rapidly with distance cut, using a large distance cut could conceivably lead to a bias in the recovered constraints. We therefore ensure that reasonable variations around our fiducial distance cut do not lead to biases in the simulations. The results for this test are shown in the left panel of Figure 3 and in Figure 4 for the constant luminosity and log-normal models, respectively. We find that small variations around the fiducial distance cut do not lead to biases. In the limit of a large distance cut, however, the inaccuracies of our Gaussian background model become apparent.

Next, we consider the impact of varying the annulus sizes used to estimate the background distribution near each star. The middle panels of Figures 3 and B3 show that for reasonable variations around our fiducial choice, the size of the annulus does not significantly impact our results. We find, however, that if the annulus size is increased significantly beyond the fiducial choice, the variance estimate of the background will also increase (as the annulus will then sample regions with different levels of galactic dust). In this case, the uncertainties on the model parameters increase, and the estimate of the signal flux will be driven to zero. This is illustrated by the dashed contours in the middle panel of both figures.

The impact of varying the HI mask is shown in the right panel of Figures 3 and B3. More conservative masks reduce the impact of nonisotropic and non-Gaussian backgrounds, at the cost of decreasing the number of stars. Significantly less conservative HI masks are found to lead to potential biases, as emission from non-debris-disk sources becomes more common.

We also consider the bias that can result from a mismatch between the true and assumed debris disk luminosity distributions. In particular, we analyze simulations for which the disks have been generated assuming the log-normal model, but which we analyze using the constant luminosity model. The results of this test are shown in Figure B2. The constant luminosity model returns increasingly biased results as the width of the log-normal distribution is increased. We also overplot a curve corresponding to fixed total luminosity, i.e., fixed $f_{\text{disk}}L_\nu$. As the width of the log-normal is increased, the model fits the high brightness fluctuations by increasing $L_\nu$, while decreasing $f_{\text{disk}}$, keeping the total luminosity fixed to match the fixed mean brightness of the log-normal distribution.

6. Results with Data

We now present the results of our analysis applied to the Planck data, using the maps at both 545 and 857 GHz.

6.1. Null Test

We first consider the results of our analysis applied to pixels on the sky that are not hosts to Gaia-detected stars. This test should yield no detection of signal (i.e., be consistent with $f_{\text{disk}} = 0$). The results of the null tests are shown in Appendix C. For both the constant luminosity and log-normal models, the null tests yield nondetections given our fiducial analysis choices.

We note that prior to applying our conservative HI mask, null tests would occasionally fail. Inspection of the data points leading to the failing null tests revealed that these were often driven by extended patches of dust emission, or by apparent extragalactic sources. After imposing the conservative HI mask and the extragalactic source mask discussed in Section 5.3, we find that the null tests pass across many realizations. The imposition of the conservative masks effectively ensures that the backgrounds are more closely described by the Gaussian background model that we have adopted.

6.2. Constant Luminosity Model Results

We first consider the results of analyzing the data assuming the constant luminosity model. As noted above, if the underlying debris disk population follows a log-normal distribution of luminosities (as we suspect it does), assuming a constant luminosity model can result in significant biases. We
therefore relegate the constant luminosity model results to Appendix C.3.

6.3. Log-normal Model Applied to Known Debris Disks

As motivated above, the log-normal luminosity model is likely a good description of the underlying debris disk luminosity distribution. We test this model by applying it to a catalog of 75 known debris disks.\textsuperscript{4} In this case, we expect to recover $f_{\text{disk}} = 1$. The result of this analysis is shown in Figure C4. We find that the constraints are indeed consistent with $f_{\text{disk}} = 1$. Fixing $f_{\text{disk}}$ to 1 and marginalizing over $\mu_{\ln s}$, we find the 68% confidence interval on $\sigma_{\ln s}$ to be $[1.29, 2.95]$.

6.4. Log-normal Luminosity Model Results

We now apply the log-normal analysis to the full catalog of Gaia-detected stars.

As before, our fiducial analysis choices are to use a 65 pc maximum distance cut and a H I mask leaving 10% of the sky uncovered, and to remove all stars with a Gaia measured $G$-band absolute magnitude, $M_G$, less than 10. We explore how the debris disk constraints vary as a function of $M_G$ in Section 6.5.

Given the fairly low signal-to-noise ratio of our measurements, we fix $\sigma_{\ln s} = 1.5$ in the subsequent analysis. This value is consistent with the results obtained from our analysis of known debris disks in Section 6.3. We fix $\sigma_{\ln s}$ for two primary reasons. First, for small values of $\sigma_{\ln s}$, the log-normal luminosity model converges to the constant luminosity model, which we find is prone to biases if the true luminosity distribution has significant spread. This is a probable scenario, as a population of debris disks is likely to have an extended tail of strong emitters due to recent collisional events (Bryden et al. 2006). Second, for large values of $\sigma_{\ln s}$, the log-normal model is more susceptible to fitting background fluctuations in the Planck maps.

Results for the log-normal luminosity model with $\sigma_{\ln s} = 1.5$ are shown in Figure 5. For the fiducial analysis choices, we find

\textsuperscript{4} https://www.circumstellardisks.org
constraints (95% confidence level):

\[ \mu_{\ln s} = 92.5 \pm 1.04 \]

\[ f_{\text{disk}} = 0.10 \pm 0.17 \cdot \]

We determine the statistical significance of our measurements by using a likelihood ratio test to compare the best-fit model to the model consistent with no excess signal \( f_{\text{disk}} = 0 \). For our fiducial analysis choices, we find a detection at 4.2\( \sigma \) with the 857 GHz channel. For the 50 pc and 80 pc distance cuts also presented in Figure 5, we find 6.0\( \sigma \) and 5.2\( \sigma \) detections, respectively. In the 545 GHz channel, we find even higher statistical significance at 6.6\( \sigma \) for the fiducial 65 pc maximum distance cut, and 5.6\( \sigma \) and 8.8\( \sigma \) for the 50 and 80 pc distance cuts, respectively.

The vertical lines in each plot of Figure 5 represent the expected shift in spectral luminosity between frequency channels for a blackbody emitter well approximated by the Rayleigh–Jeans law. The position of the blue vertical line is determined by taking the \( L_n \) corresponding to the best-fit \( \mu_{\ln s} \) in the 857 GHz channel and multiplying by the square ratio of the frequencies, \((545/857)^2\). The position of the dashed lines are determined in a similar way, but by using the best-fit \( \mu_{\ln s} \) from the 545 GHz channel, then applying the appropriate Rayleigh–Jeans scaling. We find that this scaling matches the results in both frequency channels, suggesting that our constraints are dominated by thermal emitters. This differs from the results found in Section 6.2 with the constant luminosity model, where the Rayleigh–Jeans approximation consistently overestimates the shift in \( L_n \) between frequency channels. This suggests that the constant luminosity model results may indeed be biased, as expected.

To the authors’ knowledge, no submillimeter debris disk survey has included such a large and unbiased sample of main-sequence stars in spectral classes A–M as we have included here in our analysis. For this reason, a direct comparison of the baseline results presented in Figure 5 with constraints from the literature is not straightforward. Observations from the Herschel DEBRIS (Disk Emission via a Bias-Free Reconnaissance in the Infrared/Submillimeter) survey, however, include stars with spectral types that are most closely matched to the sample used in this analysis. The DEBRIS survey observed a total of 446 stars in spectral classes A–M and detected 77 debris disks for an incidence rate of \( 17\% \) (Holland et al. 2017). For reference, our constraint on \( f_{\text{disk}} \) for the fiducial star sample is \( f_{\text{disk}} = 10\% \pm 4\% \) at 68\% confidence. Indeed, our constraint on \( f_{\text{disk}} \) is consistent with measurements from the DEBRIS survey, but also allows for the possibility of a larger population of debris disks at 95\% confidence. In Section 6.5, we explore how our constraint on \( f_{\text{disk}} \) varies as a function of spectral type.

Our constraint on \( \mu_{\ln s} \) is also reasonable, preferring slightly lower values than measurements with Herschel of the debris disk surrounding Fomalhaut. For reference, Acke et al. (2012) measure an integrated flux over the Fomalhaut debris disk of 1.1 Jy, corresponding to a \( \mu_{\ln s} \) of 93.3. In this section, we expect to find \( \mu_{\ln s} \) preferring somewhat lower values than this measurement, given that Fomalhaut has a particularly bright debris disk. Indeed, we find this to be the case. In Appendix C.6, we measure thermal emission from Fomalhaut’s debris disk with Planck 857 GHz and find constraints in agreement with measurements from Herschel.

### 6.5. Debris Disk Constraints as a Function of Stellar Magnitude

We now consider how the debris disk constraints change as the stellar selection is varied. Using the fiducial H I mask with 10\% of the sky left uncovered and a 80 pc maximum distance cut, we explore the dependence of the parameters \( f_{\text{disk}} \) and \( \mu_{\ln s} \) on the maximum G-band absolute magnitude of stars included in our sample. Results for this test are shown in Figure 6. We note that for all distance cuts explored on data with \( M_G < 10 \), the sample is most heavily dominated by spectral classes K–M (see Appendix C.1 for more discussion).

Generally, we find that adding cool, dim stars to our analysis pushes the constraints on \( f_{\text{disk}} \) to lower values. In particular, for \( M_G < 4 \), our stellar population comprises stars in spectral classes A–F. For this subset of stars, we find \( f_{\text{disk}} = 21\% \pm 3\% \). For \( M_G < 8 \), we measure spectral classes A–K, for which
increases. This is somewhat surprising, as less-luminous stars are expected to have cooler and smaller debris disks. One possible explanation for this finding is that $\sigma_{\ln s}$ increases for fainter stars; as we have seen, this could bias the results to low $f_{\text{disk}}$ and high $\mu_{\ln s}$. For these reasons, it is possible that the true $\mu_{\ln s}$ is lower than our results show in Figure 6, while the true $f_{\text{disk}}$ is higher for the faint end of our sample. We illustrate this behavior by overplotting the best-fit $\mu_{\ln s}$ and $f_{\text{disk}}$ for $\sigma_{\ln s} = 2.0$ in Figure 6, for the two lowest luminosity bins (our choice of $\sigma_{\ln s} = 1.5$ is motivated by a somewhat brighter sample of stars; see Figure C4). These measurements are represented by the orange and blue stars, corresponding to the best fits from the 545 and 857 GHz channels, respectively.

6.6. Candidate Stars

Although our analysis is not aimed at detecting individual debris disk candidates, we can identify candidates using the individual likelihoods that we have computed. We utilize the log-normal luminosity model with $\sigma_{\ln s} = 1.5$, as in the previous sections, to identify individual stars that contribute significantly to the total model likelihood. In particular, we use a likelihood ratio to compare two models for each star: in one model, $f_{\text{disk}}$ is set to 1 in Equation (8), with $\mu_{\ln s}$ set to the best-fit value from the fiducial run on data. In the other model, $f_{\text{disk}}$ is set to 0 in Equation (8). We then define the log-likelihood difference between the two models:

$$\Delta \log P(d_i) \equiv \log P(d_i|f = 1, \mu_{\ln s}) - \log P(d_i|f = 0),$$

where $\mu_{\ln s, 0}$ is the best-fit value from our fiducial result on data (Section 6.4). Stars with large $\Delta \log P$ are better described by a model with a debris disk emission signal than one without, so we rank all stars according to their respective values of $\Delta \log P$ and report the top contributors as possible debris disk candidates.

In Table 1, we present the top 80 debris disk candidate stars with the highest $\Delta \log P$. Our choice of including 80 stars is not entirely arbitrary; on simulated data, we rank all mock stars, some with an added debris disk signal, by their respective $\Delta \log P$. We find that below a certain threshold value, the false-positive rate begins to rise significantly. This threshold corresponds to a cutoff at approximately 80 stars on real data.

To construct Table 1, we use the fiducial choice of a 10% H I mask, but include stars out to 80 pc for a larger sample size. We utilize the highest resolution channel available at 857 GHz.

Our approach for identifying candidates is sensitive to non-debris-disk fluctuations in the Planck maps. These fluctuations tend to be easily differentiated from possible debris disk signals in the data by their extended profiles. Due to their radial extent and the size of the Planck beam, debris disks, on the other hand, are not expected to have a significant amount of flux in regions surrounding the central-star-hosting pixel in an $N_{\text{side}} = 1024$ Healpix map. We therefore place an asterisk in the “Visual” column for possible debris disk signals that appear to satisfy this condition. We identify these stars as particularly strong candidates. We also include a column indicating whether or not a star is listed as a debris disk candidate in previous analyses. In order to determine the status of this column for each star, we use the publicly available SIMBAD astronomical database (Wenger et al. 2000) to mark stars with associated papers containing the keyword “Debris Disk(s)” in the
| Rank | Name/ID       | Type   | Dist. (pc) | Visual | Prev. Candidate |
|------|--------------|--------|-----------|--------|-----------------|
| 0    | 36 UMa       | F8V C  | 12.9      | *      | Y               |
| 1    | CD-49 424   | K5-V C | 39.4      | ...    | Y               |
| 2    | LP 221-55   | M0.5Ve | 41.5      | *      | N               |
| 3    | TYC 7501-1011-1 | M1 D | 33.6      | ...    | N               |
| 4    | CD-53 694   | M0.5Ve C | 51.0    | *      | N               |
| 5    | Ross 917    | L      | 39.4      | ...    | N               |
| 6    | LP 768-488  | G      | 33.5      | *      | Y               |
| 7    | HD 87141    | F5V D  | 51.9      | ...    | Y               |
| 8    | CD-28 1030-Flare Star | M1Ve | 19.6      | *      | N               |
| 9    | HD 120004   | F8 E   | 55.7      | *      | Y               |
| 10   | phi Gru     | F4V C  | 34.1      | *      | N               |
| 11   | G 267-3     | ...    | 32.4      | *      | N               |
| 12   | CD-47 277   | M0V(e) | 42.0      | ...    | N               |
| 13   | CD-27 470   | ...    | 76.0      | *      | N               |
| 14   | G 56-19     | ...    | 40.7      | *      | N               |
| 15   | BD+62 1259  | G5 D   | 65.3      | *      | Y               |
| 16   | HD 129499   | G5 E   | 53.9      | *      | Y               |
| 17   | LP 768-488  | ...    | 51.4      | *      | N               |
| 18   | NLTT 1733   | ...    | 50.6      | ...    | N               |
| 19   | HD 8406     | G3V C  | 37.7      | ...    | Y               |
| 20   | Gaia DR2 2310240437249834496 | ... | 35.2      | ...    | N               |
| 21   | TYC 3034-841-1 | ... | 68.1      | *      | N               |
| 22   | UCAC2 11235167 | ... | 26.7      | *      | N               |
| 23   | HD 11112    | G3V C  | 44.4      | *      | Y               |
| 24   | UCAC4 526-056995 | ... | 45.5      | *      | N               |
| 25   | G 60-2      | K7 D   | 59.0      | ...    | N               |
| 26   | BD+14 2695  | K3V C  | 15.8      | ...    | N               |
| 27   | UCAC4 784-023772 | ... | 57.0      | ...    | N               |
| 28   | UCAC4 514-055849 | ... | 26.6      | *      | N               |
| 29   | V* BK CrB   | K7V C  | 52.8      | ...    | N               |
| 30   | LP 88-47    | ...    | 68.6      | *      | N               |
| 31   | LP 99-246   | M3 D   | 37.5      | *      | N               |
| 32   | HD 219122   | G1/2V D | 77.4    | *      | Y               |
| 33   | NLTT 32168  | ...    | 69.9      | *      | N               |
| 34   | HD 19545    | A3V C  | 54.2      | *      | Y               |
| 35   | 35 LMi      | F3V D  | 46.3      | *      | Y               |
| 36   | HD 91312    | A7IV C | 33.5      | *      | Y               |
| 37   | LTT 9738    | ...    | 60.3      | ...    | N               |
| 38   | 2MASS J03013462-5743097 | ... | 56.7      | *      | N               |
| 39   | L 175-9     | ...    | 35.6      | ...    | N               |
| 40   | HD 211369   | K2.5Vc:| 25.9      | ...    | Y               |
| 41   | SiKM 1-902  | M1.0Ve C | 41.3    | *      | N               |
| 42   | BD+15 1323  | K2V C  | 39.0      | *      | N               |
| 43   | HD 11608    | K1/2V D | 43.2    | *      | Y               |
| 44   | 2MASS J04593244-2924122 | ... | 30.8      | ...    | N               |
| 45   | WISEA J010746.74-525505.9 | ... | 79.5      | ...    | N               |
| 46   | BD+47 2312  | G5 D   | 39.6      | ...    | Y               |
| 47   | HD 223171   | G2V C  | 41.4      | ...    | Y               |
| 48   | HD 151044   | F8V C  | 29.3      | *      | Y               |
| 49   | HD 116956   | G9V E  | 21.7      | *      | Y               |
| 50   | G 146-18    | ...    | 40.7      | ...    | N               |
| 51   | V* EK Dra   | G1.5V E | 34.4    | *      | Y               |
| 52   | HD 149026   | G0IV C | 76.0      | *      | Y               |
| 53   | V* AT CrB   | K3V C  | 23.2      | *      | Y               |
| 54   | UCAC4 730-050199 | ... | 37.7      | ...    | N               |
| 55   | HD 111631   | M0V C  | 10.7      | *      | Y               |
| 56   | UPM J2145-4145 | ... | 76.6      | ...    | N               |
| 57   | G 116-59    | ...    | 50.4      | ...    | N               |
| 58   | SiKM 1-970  | K5 D   | 44.2      | ...    | N               |
| 59   | LP 1032-111 | K4 D   | 58.7      | *      | N               |
| 60   | CD-28 1222  | ...    | 59.2      | ...    | N               |
| 61   | BD+40 27900 | K0 D   | 42.0      | ...    | N               |
| 62   | HD 95175    | K3 D   | 32.2      | ...    | N               |
title. Stars possibly associated with debris disks under this criterion are marked with Y, while stars not satisfying this criterion are marked with N. The ordering of the stars in Table 1 is determined by the Rank # of each star. This number specifies the ranking of each star’s $\Delta \log P$ in the entire sample. A star with a Rank # of 0 corresponds to the highest $\Delta \log P$, while subsequent Rank #’s correspond to increasingly lower values of this metric.

Of the 80 stars with the top $\Delta \log P$, 24 are identified as previous debris disk candidates according to our criterion, while 43 are identified as particularly strong candidates from visual inspection.

### 7. Discussion

#### 7.1. Summary

We have presented constraints on the debris disk population around stars within roughly 100 pc of the Sun, using a combination of Planck and Gaia data. While the Planck survey has lower resolution and sensitivity compared to other surveys used for debris disk analyses, it is an all-sky survey and thus enables comprehensive studies of a large sample of stars. Furthermore, the Planck wavelength coverage makes it well suited to studying the cold extended disks around dim stars.

In our analysis, individual debris disks are not necessarily detected, so we use a likelihood approach that enables us to fit for the fraction of stars with disk-like emission and for the disk luminosity. We apply different models for the disk luminosity distribution and select a log-normal distribution with fixed width as our fiducial choice. Our main result is shown in Figure 5 and includes an 8.8$\sigma$ detection for the 80 pc distance cut in the 545 GHz frequency channel. The constraint on the fraction of main-sequence stars that host debris disks, in a sample dominated by K and M-dwarf stars, is $f_{\text{disk}} = 0.10^{+0.16}_{-0.07}$ at 95% confidence. This constraint is consistent with analyses using Herschel and Spitzer. Sibthorpe et al. (2017), Eiroa et al. (2013), and Trilling et al. (2008), for instance, have measured hundreds of debris disks around a sample of typically brighter stars using such surveys and find $f_{\text{disk}}$ in the range of 10%–30%.

We also place constraints on $f_{\text{disk}}$ as a function of the absolute magnitude of the stars in our sample. Stars with large absolute magnitudes, i.e., dim K and M stars, are especially interesting for present-day studies of debris disks and planetary systems, as there are limited submillimeter observations of these systems (Binks & Jeffries 2017). In Figure 6, we find a preference for lower disk fractions as we allow fainter stars to enter our sample. At the 80 pc distance cut with $M_G < 10$, $\sim$75% of the stars in our sample are in spectral classes K–M. For this set of stars, we find $f_{\text{disk}} = 0.09^{+0.11}_{-0.05}$. It is not uncommon for analyses focusing on the detection of debris disks around M-dwarf stars to report detection rates as low as ours. Binks & Jeffries (2017), for instance, report detection rates for young M-dwarf stars $\sim$13%, falling below 7% for older M dwarfs. Detection rates for K-type stars, while slightly higher than those for M dwarfs, are found to be lower than the more luminous spectral classes (Sibthorpe et al. 2017).

We test for thermal emission by comparing measurements in the 857 and 545 GHz channels with the expectation from the Rayleigh–Jeans regime $\nu^2$ scaling. We find consistency with the Rayleigh–Jeans relation for the full sample of Gaia stars (see Figures 5 and C3). For the dimmest stars in our samples, the flux in the 545 GHz channel shows hints of departures from the Rayleigh–Jeans scaling, consistent with colder debris disks.

Because our analysis is carried out in submillimeter wavelengths, it is well suited to constraining the properties of cold/extended disks, especially around dim M-dwarf stars. In fact, there has been mounting evidence for a substantial population of debris disks too cold to make the detection thresholds of shorter wavelength surveys such as WISE and IRAS (Lestrade et al. 2006, 2009; Holland et al. 2017; Luppe et al. 2019). Submillimeter debris disk surveys differ from their shorter wavelength counterparts, as they probe cooler disks and have stronger constraining power in the disk outskirts, which are expected to have larger dust grains and more massive planetesimals. At 857 GHz, our analysis is sensitive to such cool systems, and our results are suggestive of the possibility

| Rank # | Name/ID     | Type  | Dist. (pc) | Visual | Prev. Candidate |
|--------|-------------|-------|------------|--------|-----------------|
| 64     | G 178-24    | ...   | 79.9       | s      | N               |
| 65     | HD 235600   | K0 E  | 40.0       | ...    | N               |
| 66     | HD 108944   | F9V C | 50.0       | s      | Y               |
| 67     | TYC 8082-471-1 | 43.2  | ...       | N      |
| 68     | LEHPM 6585  | ...   | 66.1       | s      | N               |
| 69     | 2MASS J2323554-4451522 | ... | 50.0    | s      | N               |
| 70     | BD-14 363   | G5V D | 64.8       | ...    | N               |
| 71     | 2MASS J01182472-2611189 | ... | 71.6       | s      | N               |
| 72     | HD 148-61   | M1.5Ve C | 25.9   | s      | N               |
| 73     | G 148-61    | M1.5Ve C | 25.9   | s      | N               |
| 74     | G 148-61    | M1.5Ve C | 25.9   | s      | N               |
| 75     | V′ DQ Tuc  | M2V C | 29.1       | ...    | N               |
| 76     | HD 212038   | K2.5V C | 27.0   | ...    | N               |
| 77     | LSPM J1055+2455 | ... | 68.4       | s      | N               |
| 78     | G 122-8     | M3.5Ve C | 23.2   | ...    | N               |
| 79     | WISEA J21643.04+322830.9 | ... | 69.1       | s      | N               |

Note. Stars with lower rank numbers have a greater $\Delta \log P$ and are thus considered better candidates. Stars that pass a visual inspection in the data are identified as especially promising candidates, marked by *. The Prev. Candidate column indicates whether or not the star of interest has been included in previous debris disk analyses according to the Simbad astronomical database.

### Table 1
(Continued)
seen with Herschel (Lestrade et al. 2009), that debris disk systems around dim stars could in fact be escaping detection by shorter wavelength surveys (Luppe et al. 2019).

7.2. Validation of Our Analysis and Candidate Debris Disks

While the main goal of our analysis is to provide constraints on the number of stars with debris disks, our approach is easily applied to a small subset of stars, or even measurements around individual stars. In Figure C4, we verify that our analysis, applied to a set of well-studied debris disks, yields measurements on $f_{\text{disk}}$ consistent with 100%. In Figure C5, we show the agreement of our flux measurements for two well-studied debris disks to measurements from Herschel.

We also identify like debris disk candidates by ranking each star according to its likelihood of hosting a debris disk. See Table 1 for the 80 most promising candidate stars, most of which have not been identified as debris disk candidates previously.

7.3. Caveats

A potential source of bias in our measurements could stem from the luminosity distribution model we adopt. Our fiducial analysis relies on modeling the debris luminosity distribution as log-normal, with a fixed width based on our analysis of a population of known debris disks (Section 6.3). We choose to keep the width of the log-normal distribution fixed in order to avoid possibly fitting background fluctuations in the maps. With higher resolution and higher signal-to-noise data from future surveys, we expect to be able to treat $\sigma_{\text{ln}}$ as a free parameter.

Another caveat for our analysis concerns our extensive masking of the sky. By excluding regions of the sky with high H I column densities, we ensure that our analysis is more robust to contamination from galactic backgrounds. However, it is possible that this masking leads to a selection of stars whose debris disk properties differ from the global average. For instance, debris disks are more likely in star-forming regions and the H I mask preferentially excludes these regions, we could bias the constraints on $f_{\text{disk}}$ low relative to the true, all-sky value. Our constraints should therefore be viewed as applying only to stars in the unmasked region of our analysis. Additionally, foreground extinction could potentially impact the measured signal, though this scenario is unlikely given that we do not include stars past 80 pc in our sample.

While our analysis is meant to provide constraints on a population of debris disks, our approach is potentially sensitive to other sources of thermal emission. Three possibilities are protoplanetary disks, nebular emission seen in young stars, or a halo of particles ejected from a disk by radiation pressure or stellar winds (see Planck Collaboration et al. 2015; Wyatt et al. 2015; Chiang & Fung 2017, for example). The ages of the hot stars in our sample are typically larger than 100 Myr, so the former two explanations appear unlikely. Distinguishing a particle “halo” appears challenging, as the emission in both cases is dominated by small grains. Interestingly, in Table 1, our list of 80 candidate sources includes one flare star.

7.4. Prospects with Cosmic Microwave Background Data Sets

The present analysis is in some sense a proof of principle; we have demonstrated that one can use wide-field cosmic microwave background (CMB)-focused data to constrain debris disks. It is worth considering how future CMB observations could be used to place tighter constraints on debris disks, and what we could hope to learn from such studies in the future.

Measurements from Planck are hindered by a large beam size relative to the angular scale of the typical debris disk. Higher angular resolution data would be beneficial to an analysis like ours by reducing the impact of background sources contaminating the debris disk signals. Galactic dust in particular has less power on very small scales.

A central concern of this analysis is placing constraints on a population of debris disk systems surrounding cool K–M-type stars. Such systems are poorly understood and have received an increasing amount of attention as strategic targets for future surveys (Debes et al. 2019). There are several current and future CMB data sets well suited to placing tighter constraints on these systems. Ongoing surveys include SPT-3G (Benson et al. 2014) and Advanced ACTPol (Henderson et al. 2016), while the planned surveys with the Simons Observatory (Ade et al. 2019) and CMB-S4 (Abazajian et al. 2016) will provide significantly higher resolution and sensitivity in the submillimeter sky compared with the Planck maps used in this analysis. These surveys are lacking in one respect relative to Planck, namely its high-frequency channels.

Like the analysis carried out by Baxter et al. (2018) on measuring thermal emission from exo-Oort clouds with Planck, one of the biggest limitations to our analysis is the modeling of backgrounds. With higher resolution data, background modeling could be significantly improved, allowing more stars to enter our sample, yielding better statistics. Additionally, higher resolution data could potentially lead to resolved observations of nearby debris disks, adding to our current understanding of finer-scale disk structure without carrying out pointed measurements.

Finally, wide-area and high-resolution CMB data, combined with a likelihood analysis such as our own, could be used to constrain other poorly understood systems such as debris disks around white dwarfs (Barber et al. 2012), transient emission events from flare stars (MacGregor et al. 2018), or extragalactic sources. Such sources of emission, while not the focus of this analysis, are well suited to detection by the methods developed in this paper.

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Appendix A

Asymptotic Behavior of Signal-to-noise Ratio with Increasing Distance Cuts

We now consider how the constraints on disk properties are expected to behave as we increase the maximum stellar distance cut. For this purpose, we can assume that every star hosts a debris disk. As above, we refer to the data for the i-th star as $d_i$, which is at a distance $r_i$. We additionally assume that the (scaled) luminosity is a constant, $\sigma_{\text{ln}}$, and that the noise variance is the same for all stars, $\sigma^2_N$. 

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The log-likelihood for the data is then

\[ L(d|s) = -\frac{1}{2} \sum_i (d_i - s/r_i^2)^2 / \sigma_N^2, \]  

(A1)

and the Fisher matrix for the single parameter \( s \) is

\[ F_{ss} = -\frac{\partial^2}{\partial s^2} \ln L \]

\[ = \sum_i \frac{1}{\sigma_N^2 r_i^4}. \]  

(A3)

Let us assume that the distribution of stars in the volume is such that the number density goes as \( n(r) \propto r^\alpha \). For uniformly distributed stars, we would have \( \alpha = 0 \). We then have that the probability of a star being in the radial bin between \( r \) and \( r + dr \) is \( P(r)dr \propto r^{\alpha+2}dr \). We can then approximate the Fisher matrix as

\[ F_{ss} \sim \int dr \ r^{2+\alpha} \frac{1}{\sigma_N^2 r^4} \]  

(A4)

\[ = \frac{[r_\text{max}^{\alpha-1} - r_\text{min}^{\alpha-1}]}{\sigma_N^2(\alpha - 1)}. \]  

(A5)

Consequently, the error on \( s \) goes like

\[ \sigma_s = \sqrt{F_{ss}^{-1}} \sim \frac{\sigma_N \sqrt{1 - \alpha}}{\sqrt{r_\text{min}^{\alpha-1} - r_\text{max}^{\alpha-1}}}. \]  

(A6)

For uniformly distributed stars with \( \alpha = 0 \), we have

\[ \sigma_s \sim \frac{\sigma_N}{\sqrt{r_\text{min}^{\alpha-1} - r_\text{max}^{\alpha-1}}}. \]  

(A7)

In the limit that \( r_\text{max} \to \infty \), the error approaches a constant value, namely,

\[ \sigma_s(r_\text{max} \to \infty) \sim \sigma_N \sqrt{r_\text{min}}. \]  

(A8)

Consequently, under the constant luminosity model, we do not expect the constraints to get arbitrarily tight as we include more and more distant stars.

Appendix B Additional Simulation Results

In this appendix we consider further results of our analysis applied to simulated data with both Gaussian white-noise backgrounds and the Planck background themselves.

B.1. Gaussian Simulation Results

In Figure B1, we present the results of our analysis applied to the Gaussian noise simulations, as a function of maximum distance cut. For each distance cut, we use five times the number of stars found in real data, after imposing the masking described in Section 3.3 and the stellar selection cuts outlined in Section 4.3. This corresponds to approximately 5000, 9800, 17,300, and \( 5 \times 10^5 \) stars for the 50, 65, 80, and 250 pc distance cuts, respectively. We find that in all cases, the input parameters are recovered without bias. As the maximum distance is increased, the constraints get tighter. The constraints do not tighten as \( 1/\sqrt{N} \), where \( N \) is the number of stars, as more distant stars have weaker signal.

B.2. Potential for Bias with the Constant Luminosity Model

The constant luminosity model is prone to potentially biased results if the true underlying debris disk population is not well

Figure B1. Parameter constraints recovered from simulations with the Gaussian backgrounds for varying maximum distance cuts. Contours depict regions of 68% and 95% confidence, where the red crosshair depicts the input parameters. Each realization uses five times the number of stars found in real data. The model recovers the input disk fraction, \( f_{\text{disk}} \), and the signal amplitude, \( s_d \), well within the 68% region for each distance cut.

Figure B2. Constraints recovered from the Planck background simulations using the constant luminosity model, where the true mock debris disk luminosity distribution is log-normal. Here, \( \sigma_{\ln s} \) refers to the width of the underlying luminosity distribution, as in Equation (10). The input \( f_{\text{disk}} \) is shown as the horizontal red line, while the underlying mean of the luminosity distribution is illustrated as the dotted vertical line. We find increasingly biased results for \( \sigma_{\ln s} \lesssim 0.5 \), where luminous outliers dominate the model likelihood. We illustrate the degeneracy of the model parameters by overplotting a curve of constant total flux, effectively the relation \( s_d f_{\text{disk}} = \text{constant} \).
approximated by a constant luminosity model. We test the extent of this bias by applying the constant luminosity model to a sample of mock debris disks with luminosities drawn from a log-normal distribution.

In Figure B2, we present results for this test with four different values of \( \ln s \). The input parameters are shown as dotted and solid red lines. We find that in the limit of small \( \ln s \), the constant luminosity model is sufficient in providing a minimally biased description of the debris disk population. For large \( \ln s \), however, luminous disks at the tail end of the log-normal distribution tend to drive \( s_d \) high and \( f_{\text{disk}} \) low, consistent with the relation for constant total flux: \( s_d f_{\text{disk}} = \text{constant} \). We overplot this degenerate relation in Figure B2 as the solid black curve.

### B.3. Log-normal Luminosity Model Simulation Results

In Figure B3, we present the full set of simulation results for the log-normal luminosity model with mock debris disk signals added to the Planck backgrounds. In this case, the signal amplitudes are drawn from a log-normal distribution. A detailed description of the simulation procedures and discussion of these results can be found in Section 5.3.

We find that our analysis recovers the input parameters to within the errors. Furthermore, for reasonable variations around our fiducial analysis choices, the constraints are minimally impacted.

### Appendix C

**Further Results From Data**

#### C.1. Spectral Types Populating Our Sample

In Figure B4, we plot the percentage of main-sequence stars in each spectral type for the three distance cuts used on data. Main-sequence stars are selected by imposing the cuts outlined in Section 3.3, and the spectral type is determined using the provided Gaia \( G \) band magnitude for each star. We find that for each distance cut, K–M stars make up the majority of our sample for \( M_G < 10 \).

#### C.2. Null Test Results

As described in Section 6.1, we perform a null test by applying our analysis to pixels in the Planck map that are not hosts to Gaia-detected stars. In this case, our analysis should recover constraints consistent with \( f_{\text{disk}} = 0 \). We use 3000 pixels for each null test, as this is approximately the number of stars included in our fiducial star sample. We assign each pixel used in the null test a distance drawn from the true distribution of Gaia stellar distances. The fiducial distance cut of 65 pc is used, with a H I mask leaving 10% of the sky uncovered.

In Figure C1, we show the results of the null tests; we find constraints consistent with no signal for both the constant...
null test, we impose the same prior on \( s_{\text{ln}} \) as we impose when centering the analysis on Gaia stars, namely, \( 0.5 < \sigma_{\text{ln}} < 2.5 \). We discuss the motivation for this prior in Appendix C.4.

### C.3. Constant Luminosity Model Results

In Figure C2, we present results on Gaia stars in the Planck 545 and 857 GHz channels using the constant luminosity model developed in Section 2. This figure adopts our fiducial analysis choices, with a 65 pc distance cut and a H\( \text{I} \) mask leaving 10% of the sky uncovered. The remaining stars are selected according to the constraints outlined in Section 4.3. Solid blue and dashed contours correspond to constraints derived from the 857 and 545 GHz maps, respectively. We remind the reader that we have reason to believe that the parameter constraints inferred when assuming the constant luminosity model are biased.

The vertical line represents the expected shift in spectral luminosity from the Rayleigh–Jeans law \( (L \propto \nu^2) \) for an unbiased model, if the disk population is well approximated by the Rayleigh–Jeans law. We overplot the same degeneracy profile shown in Figure B2.

We note that the constraints on \( s_d \) with the constant luminosity model tend to slightly larger values than known flux measurements of Fomalhaut. Meanwhile, the constraints on \( f_{\text{disk}} \) prefer significantly lower values than those commonly reported in the literature, usually in the range of 15%–25% for main-sequence stars (Matthews et al. 2014). As suggested by our tests on simulated data (and illustrated by Figure B2), the preference for low values of \( f_{\text{disk}} \) may be driven by the fact that the constant luminosity model is not a good description of the underlying debris disk population.

### C.4. Log-normal Luminosity Model Results with Varying \( s_{\text{ln}} \)

We now consider results from the Planck 545 and 857 GHz channels when applying the log-normal analysis with varying \( \sigma_{\text{ln}} \). The stellar population used in this section is the same as in Section 6.4.
As described in Section 6.4, we expect our measurements to have fairly low signal-to-noise ratio. Consequently, we impose a prior on \( s \) \( \ln \) of \( s \) \( \in [0.5, 2.5] \). Results for the log-normal model analysis are shown in Figure C3. Marginalizing over \( s \ln s \), we find constraints

\[
\begin{align*}
\mu_{\ln s} &= 94.2^{+1.29}_{-2.14} \\
f_{\text{disk}} &= 0.05^{+0.12}_{-0.03}
\end{align*}
\]

for the fiducial 65 pc distance cut.

**Figure C3.** Log-normal luminosity model results from the Planck 545 and 857 GHz channels, with a maximum distance cut of 65. Here, \( s_{\ln s} \) is varied. We use a H1 mask leaving 10% of the sky uncovered and impose the restriction \( M_\odot < 10 \). The total number of stars is \( \sim 2000 \).

### C.5. Log-normal Luminosity Model Applied to Known Debris Disks

In this section, we center the log-normal model analysis on a catalog of 75 resolved debris disks from [https://www.circumstellardisks.org](https://www.circumstellardisks.org). We expect to find measurements consistent with \( f_{\text{disk}} = 1.0 \), as each pixel in this sample of stars is known to host a disk.

In Figure C4, we present results for this subset of stars. Indeed, we find constraints consistent with \( f_{\text{disk}} = 1.0 \), \( \mu_{\ln s} = 92.9^{+2.11}_{-5.26} \), and \( s_{\ln s} = 1.32^{+2.89}_{-0.08} \) at 95% confidence.
C.6. Measurements around Individual Stars

In this section, we present the results of our analysis applied to two well-studied debris disk systems surrounding Beta Pictoris (19.4 pc) and Fomalhaut (7.7 pc). These disks have extensive observations at 857 GHz with Herschel, conveniently the same frequency channel used in this analysis.

We measure the flux from each disk using the constant luminosity model, and compare our measurements to those derived from observation with Herschel at 857 GHz by Acke et al. (2012) and Vandenbussche et al. (2010) for Fomalhaut and Beta Pictoris, respectively. Results for this test are shown in Figure C5. We note that for both stars, the best-fit $f_{\text{disk}}$ is 1.0. Marginalizing over $f_{\text{disk}}$, we find that our flux measurements are in agreement with Herschel observations of both disks to within the uncertainties.

Figure C4. Parameter constraints for the log-normal model when the analysis is applied to 75 known debris disks. Our constraint on $f_{\text{disk}}$ = 1 for this subset of stars is consistent with 1.0, as expected.
Figure C5. Flux measurements of debris disks around Beta Pictoris and Fomalhaut from the Planck 857 GHz channel with the constant luminosity model. The shaded region represents the 68% confidence interval, and the solid black lines correspond to measurements of the same stars from Herschel at 857 GHz. The dashed vertical lines represent the uncertainties on the Herschel measurements.

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