Planetary science with wide-field CMB surveys

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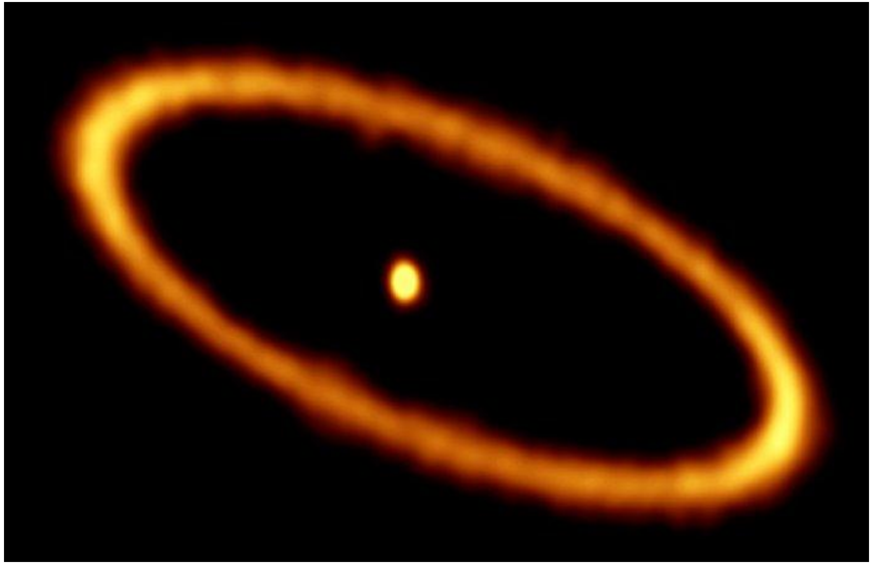
Thermal emission from dust and debris around stars

Dust and debris gravitationally bound to stars is a natural output of star and planet formation

This material absorbs optical radiation from stars and re-emits thermally

Dust that is far from parent star or around small stars can be very cold (T ~ 10 K)

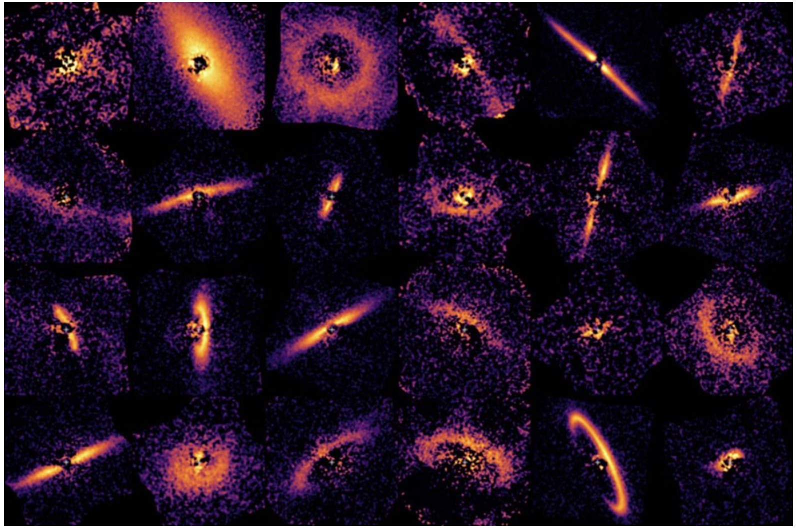
Emission from such dust is fairly well matched to passbands of CMB surveys



The debris disk of Fomalhaut as observed by ALMA

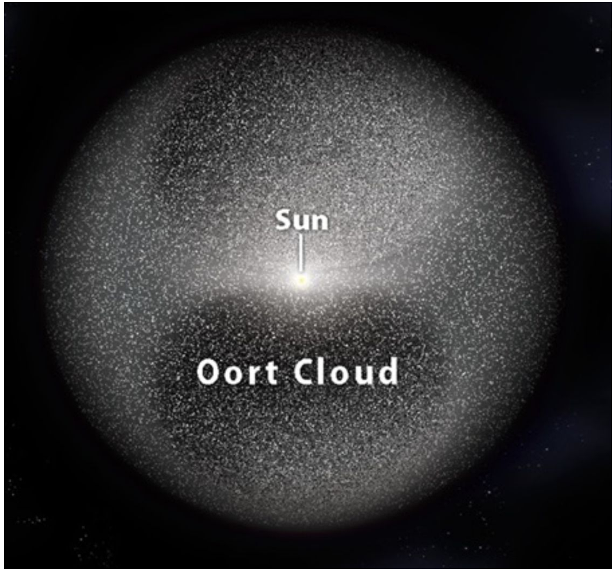
What systems are well suited to CMB observations?

1) **Debris disks**



Data from Gemini Planet Imager Exoplanet Survey

2) **(Exo-)Oort clouds**



Credit: Roen Kelly

Debris disks with CMB surveys

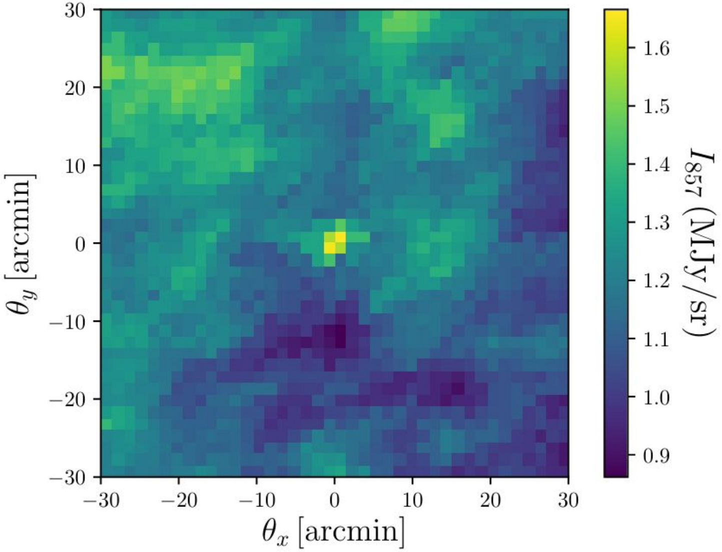
Dust in debris disks replenished by collisions of planetesimals

Low resolution of CMB surveys means we effectively measure one number per disk

Sorts of questions we might answer:

- What fraction of M Dwarfs host debris disks?
- How does presence of debris disks correlate with presence of planets?
- What is the luminosity function of debris disks?

Fomalhaut as observed by Planck



EB, Blake, Jain 2018

Extracting information about debris disks from CMB surveys

We have strong prior information about positions of debris disks because we know where (bright) stars are thanks to Gaia

Idea: combine positional information about debris disks with CMB surveys to constrain fraction of stars that host debris disks

We define a mixture model for the CMB measurement of i^{th} star:

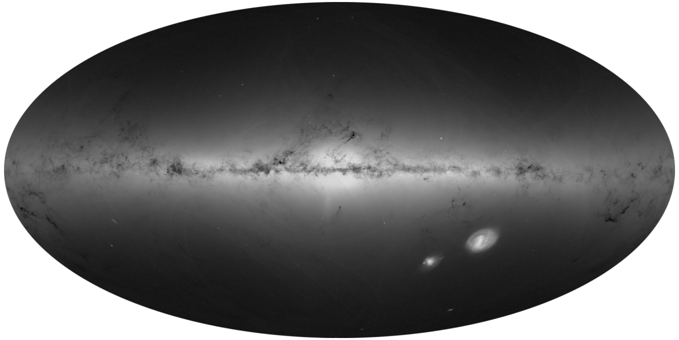
$$\boldsymbol{P}(\mathrm{data}_i \mid f, \theta) = f\, \boldsymbol{P}(\mathrm{data}_i \mid \text{has disk}, \theta) + (1-f)\, \boldsymbol{P}(\mathrm{data}_i \mid \text{no disk})$$

f = fraction of stars that have debris disks

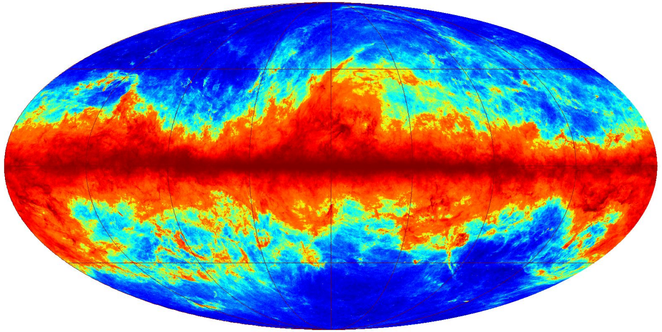
θ = parameters describing disk luminosity, etc.

Combine likelihoods from individual stars to constrain f and θ

Gaia star map



Planck 857 GHz map



Nibauer, EB, Jain 2020

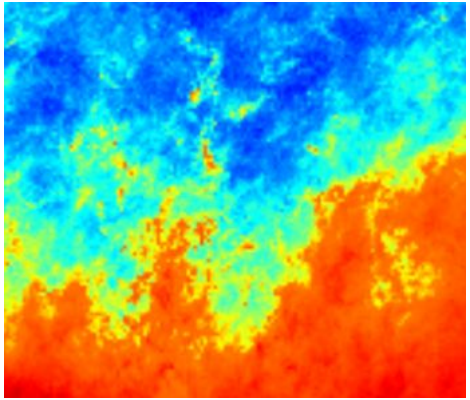
Challenge of backgrounds

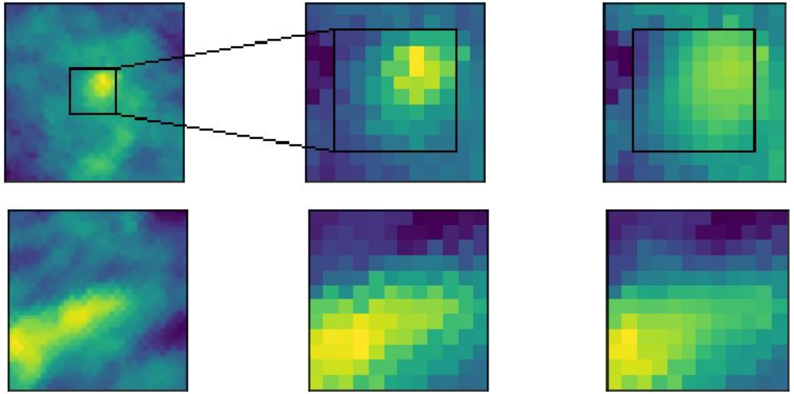
Galactic dust backgrounds are complex and highly non-Gaussian (i.e. P(data | no disk))

Simple approach: estimate background at disk location using mean flux in annulus around star

Fancy approach: train neural network on off-star measurements to build an empirical background model

Regardless of approach, higher resolution helps a lot!


Complex galactic backgrounds


Full cutout

Background truth

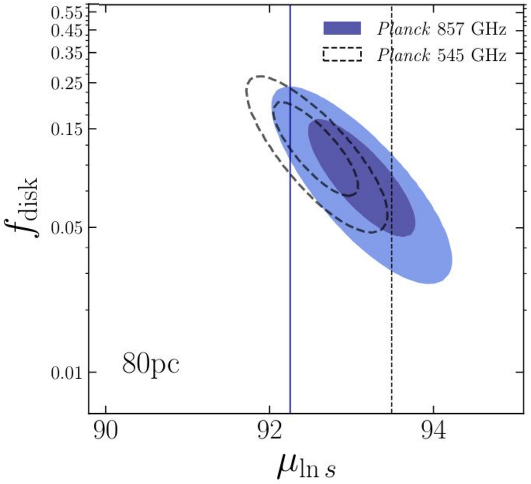
Neural network background estimate

Krejcik & EB, in prep.

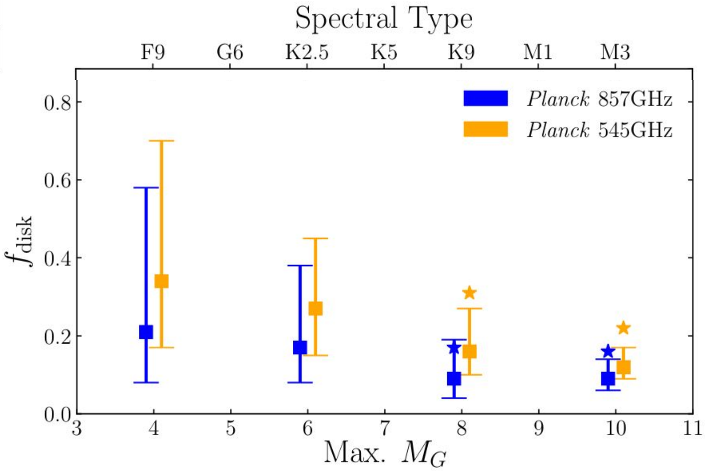
Debris disk results with Planck

Using Planck maps + Gaia star locations and simple background modeling approach, we constrain debris disk fraction and mean log-luminosity

Constraints on disk fraction and mean luminosity



Evolution of disk fraction with stellar spectral type



Nibauer, EB, Jain 2020

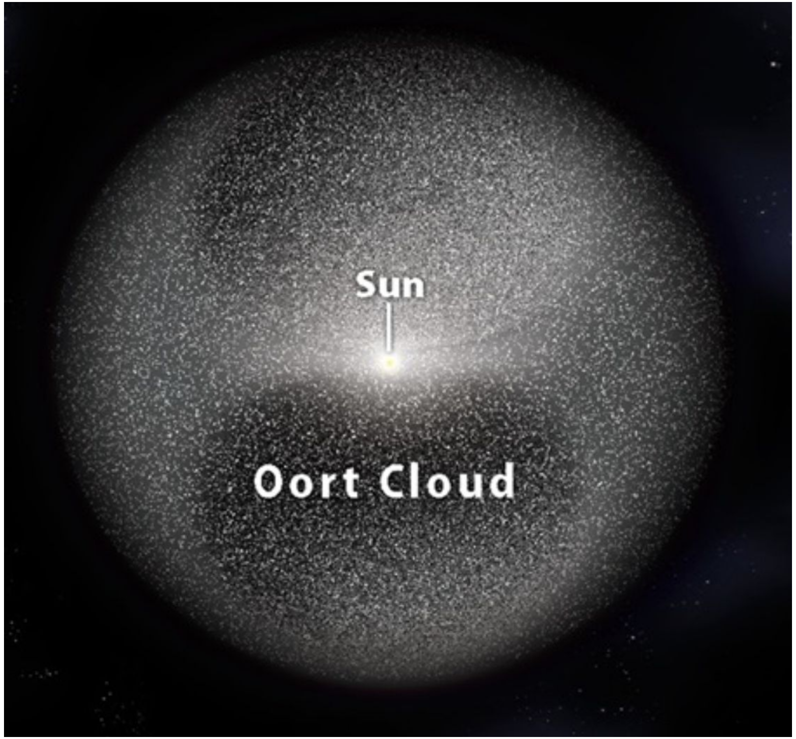
(Exo-)Oort clouds

Jan Oort hypothesized the existence of Oort cloud based on observations of long period comets

Formation of Oort cloud connected to presence of giant planets

We’ve never seen an object in the outer Oort cloud

Do other stars have their own Exo-Oort clouds?



Detecting an Oort cloud via its thermal emission

Detecting our own Oort cloud in CMB survey is difficult since signal is roughly isotropic

- Isotropic Oort cloud could induce spectral distortion (Babich, Blake, Steinhardt 2007)
- Anisotropic Oort clouds could introduce anisotropy in CMB maps (Babich & Loeb 2008)

Alternatively, could detect exo-Oort clouds based on excess flux around other stars (Stern, Stocke, Weissman 1991)

Expected flux from exo-Oort cloud in submillimeter is likely orders of magnitude larger than that from a main sequence star due to much larger size (~10^4 AU)

Large enough that an arcminute CMB survey could resolve them out to ~100 pc

EB, Blake, Jain 2018

Extracting information about Exo-Oort clouds

Simple approach: average flux in angular bins around stars

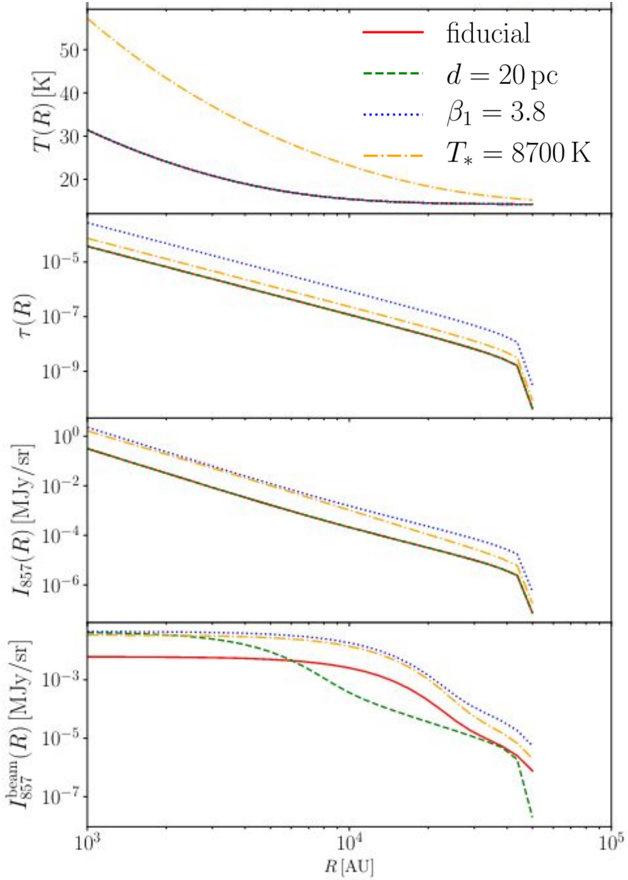
But: averaging across stars is a bad idea if only a small fraction of stars host Oort clouds

Fancy approach: use mixture model, and fit each star separately

Many uncertain parameters:

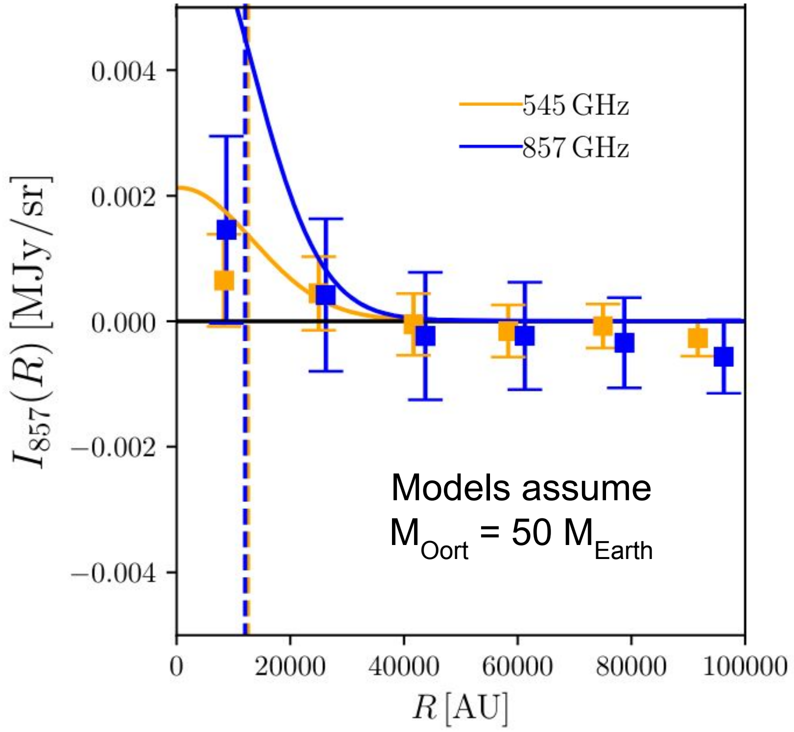
- Mass of Oort clouds (5-100s M_{Earth})
- Mass distribution within Oort cloud
- Minimum size of grains
- Power law of grain size distribution, β
- Radius of Oort cloud

Oort cloud models



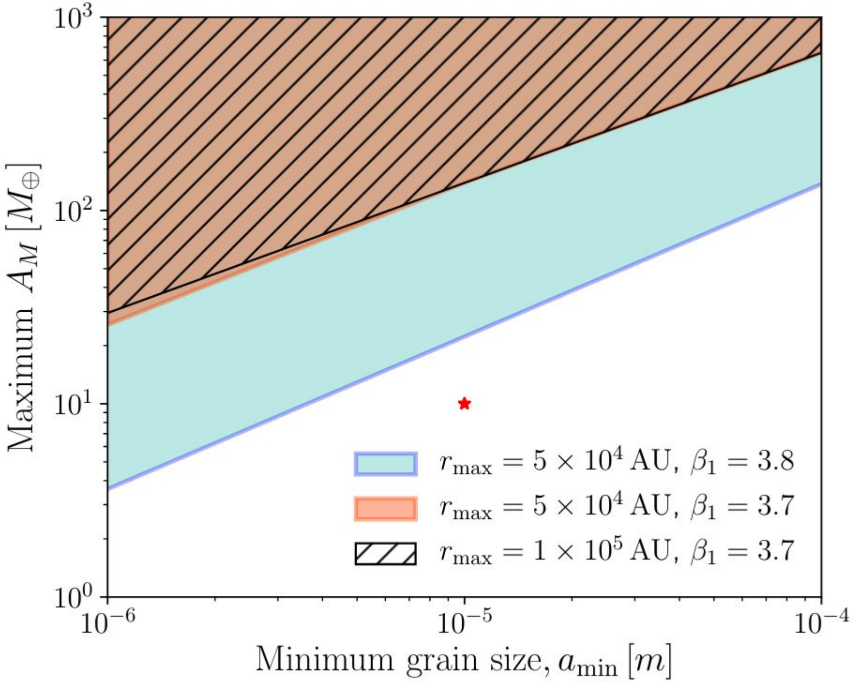
Exo-Oort search with Planck

Average profile measurements and example model



Models assume M_{Oort} = 50 M_{Earth}

Excluded regions of Exo-Oort cloud parameter space (assumes every star hosts and Oort cloud)



EB, Blake, Jain 2018

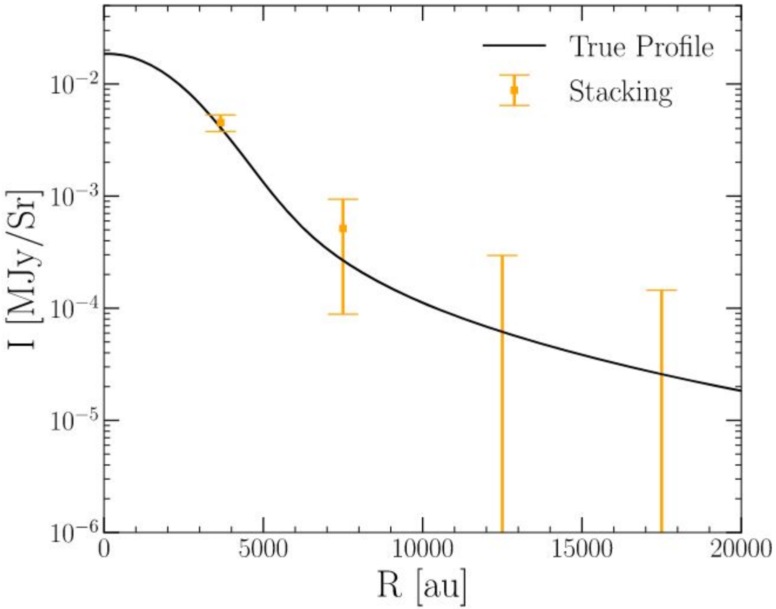
Exo-Oort forecasts for Simons Observatory

Hensley et al., EB, 2022

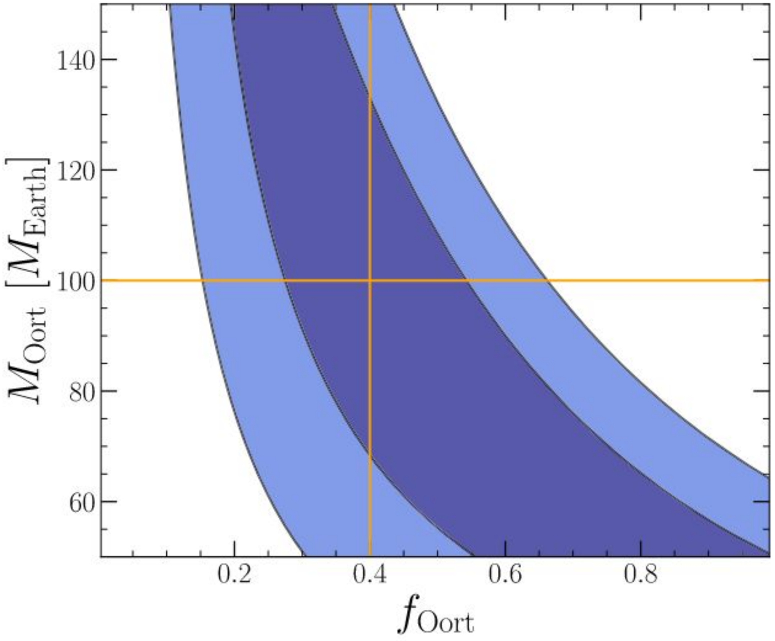
Competing effects relative to Planck analysis:

- Lower frequency means lower signal (280 GHz vs. 545 GHz)
- Higher resolution means improved background subtraction (arcmin vs. few arcmin)

Forecast stacking results



Forecast parameter constraints



Summary

- Cool dust and debris around stars is a natural output of star and planet formation.

- Wide-field CMB surveys may be able to provide interesting constraints on population statistics of cold debris disks.

- Could CMB surveys provide the first direct evidence for the existence of Oort clouds?