

Dust Evolution in the Late Stages of Planet Forming Disks

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Abstract

We study the properties of dust in disks to constrain models of planet formation. We measure and analyze the spectral index for the dust continuum emission at millimeter wavelengths for a sample of 24 young disks in the Upper Sco star-forming region. We do this by combining data taken with the ALMA telescope at wavelengths of 2.87 mm and 0.88 mm. Since the age of this region is ~ 5 - 10 Myr, these results can constrain the properties of small solids in disks at the end of their lifetime. We examine whether dust trapping, which is key to the formation of planetesimals, happens only in much younger disks or if it is efficient all the way towards the end of the disk life cycle. Our results indicate that dust traps are present also in the relatively old disks in our sample, indicating that protoplanetary disks have the potential to form planetesimals during their entire lifetime. Our analysis also quantifies the effects of scattering by dust of the disk emission, a mechanism that has been recently proposed as potentially important to determine the fluxes of protoplanetary disks even at sub-mm/mm wavelengths. From preliminary results, based on the state-of-the-art radiative transfer code RADMC-3d, we infer that scattering is not effective for optically thin disk models, but could potentially play a significant role for optically thick models.

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1. Introduction

Exoplanets are formed in protoplanetary disks that surround young stars. Fundamentally, planet formation is the product of small sub- μm sized particles collecting into large planetesimals in these protoplanetary disks. However, one of the main obstacles of planet formation in protoplanetary disk is the radial drift problem. Fast radial drift of particles occurs in regions with gas pressure strongly decreasing with distance from the star. As a consequence of the pressure force, the gas rotates slower than solids. Because of the gas drag, dust grains with sizes 1-10mm at radius of 100 AU move inward toward the protostar in less than 1 Myr. This is much less than the usual lifetime of a protoplanetary disk which is 1-10 Myr. The dust trapping mechanism is a potential solution to this problem. Dust trapping requires the presence of local pressure maxima where dust grains can concentrate and grow into bigger solids. These pressure maxima are evident in the structures found from new observations of protoplanetary disks with younger ages of 1-3 Myr. We want to investigate whether these local pressure maxima are still present in disks at the end of their lifetime. We focus on the Upper Scorpius region which houses disks that are 5-10 Myr old. Because of their age, these disks are very faint compared to the younger disks and finding evidence for structures from direct imaging is much more difficult. We instead investigate the presence of mm-sized grains in a sample of 24 disks in Upper Sco by analyzing their spectral index values at mm-wavelengths.

3. Results

We measured alpha values between about 1.5 and 3.0. We can interpret the results and break up our 24-disks sample into two models. For $\alpha < 2$, we adopt disk models with optically thick emission, while for the cases with $\alpha > 2$ optically thin emission.

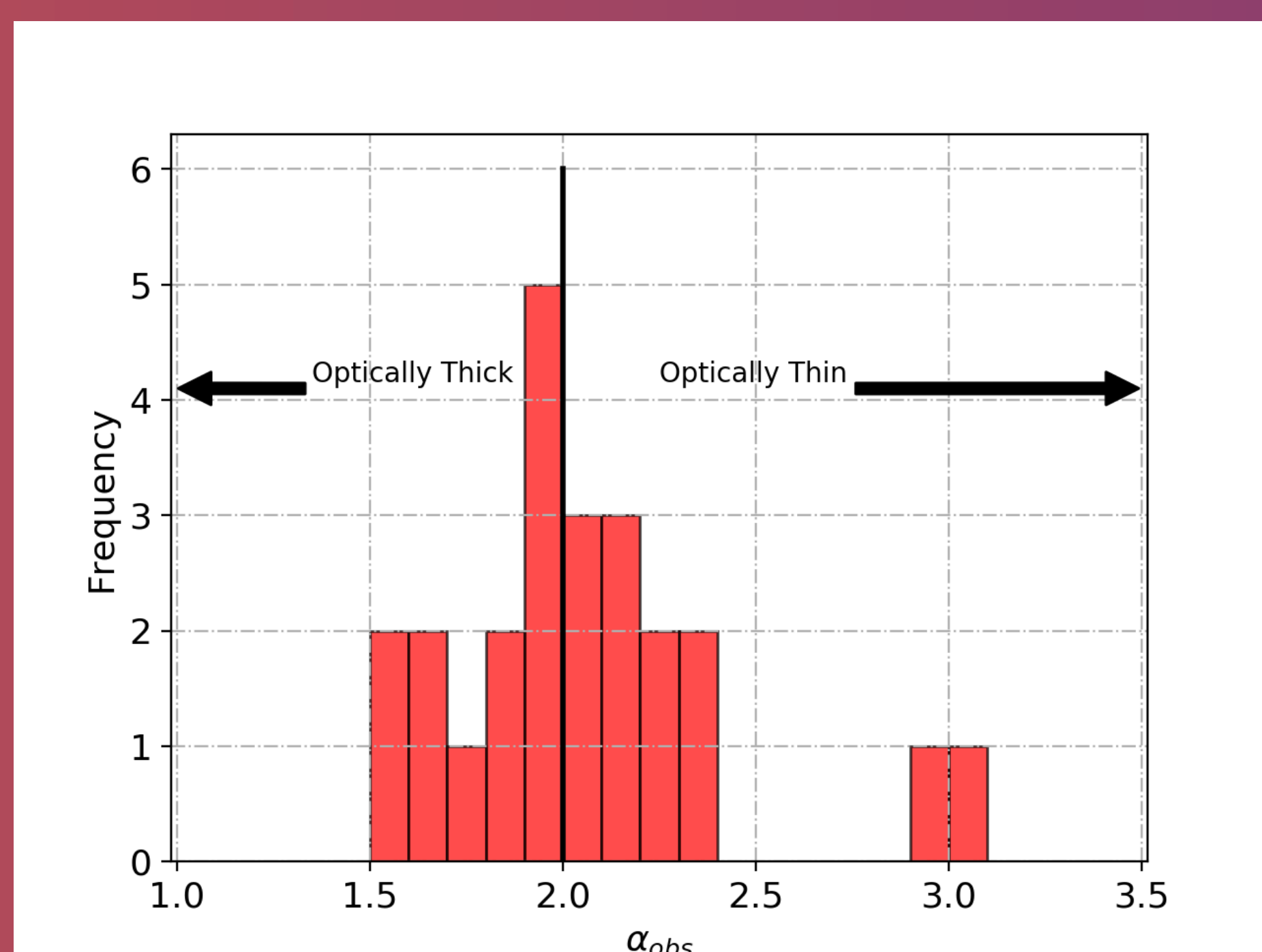


Figure 2: Histogram of measured spectral index values

5. Optically Thick

For the optically thick model, $\alpha = \alpha_{planck}$ where in the RJ-limit $\alpha_{planck} = 2$. Recent investigations which account for dust scattering of mm-wavelength dust emission can explain $\alpha < 2$ from Zhu et al³. Preliminary results from models calculated with radmc-3d suggests that models with grains as large as $a \sim 10cm$ are consistent with the data.

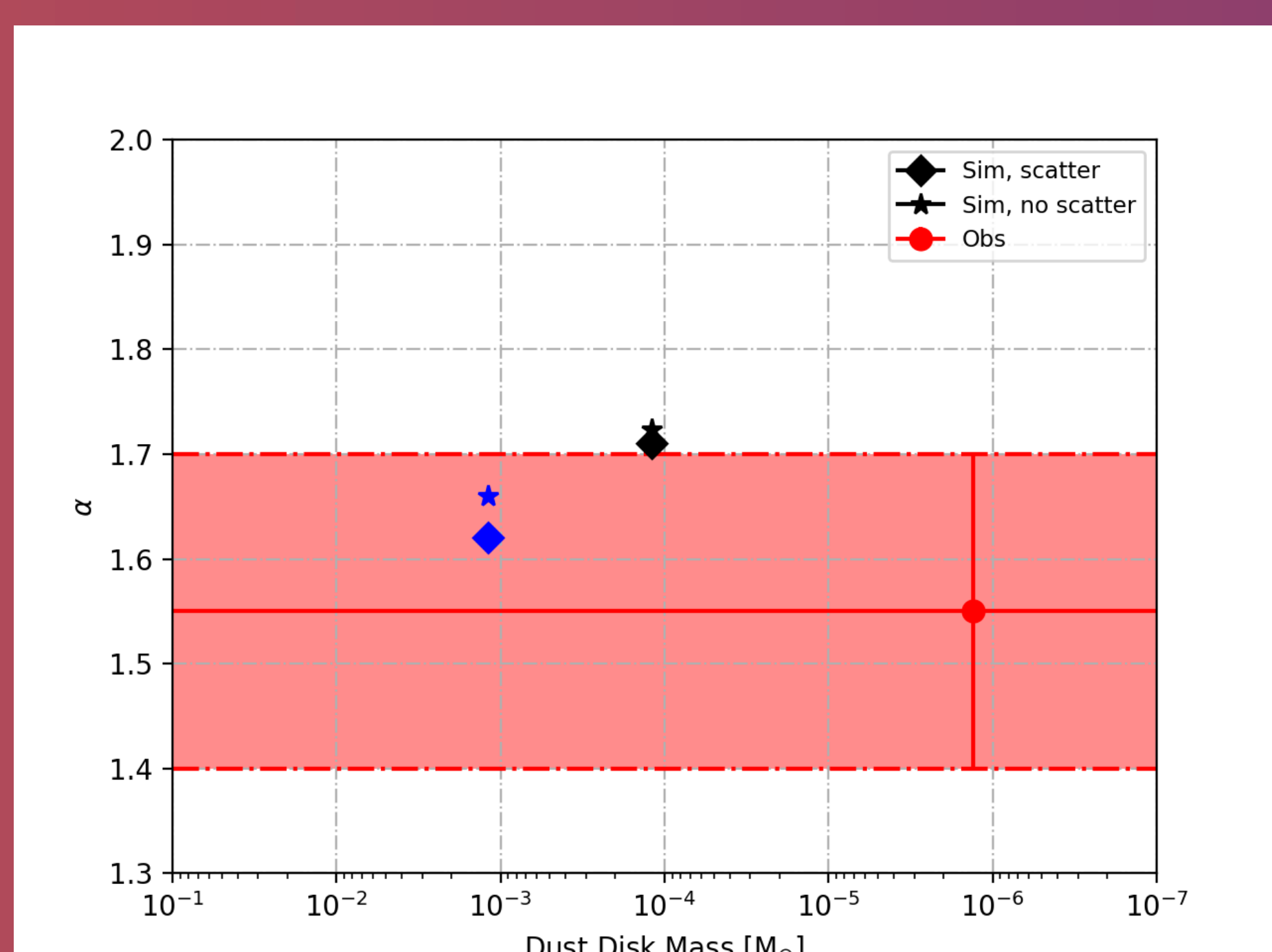


Figure 4: Disk J16062916 with a largest grain size of $a \sim 10cm$ and grain size distribution $q = 2.0$. The red value is the observed spectral index and dust mass while blue and black come from calculations done with radmc-3d.

2. Method

For each disk, we measured their spectral index by combining the flux already measured at $\lambda = 0.88mm$ by Barenfeld et al (2016)¹ with the flux at $\lambda = 2.87mm$ from new ALMA observations. We utilize the spectral index for each object to characterize the grain size for each disk.

$$\alpha = \frac{Ln(F_{\nu_1}/F_{\nu_2})}{Ln(\nu_1/\nu_2)}$$

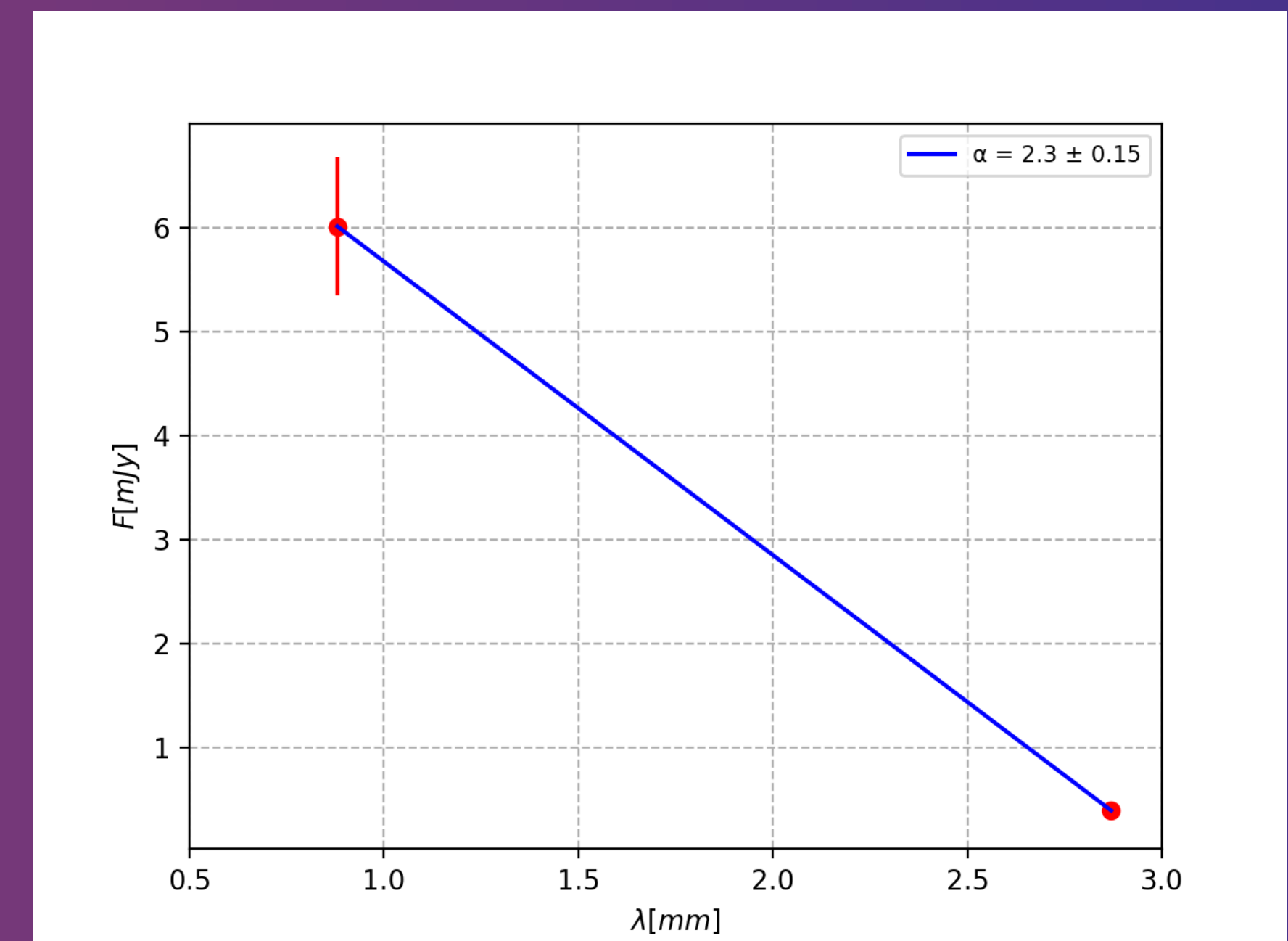


Figure 1: SED of J16123916 at mm wavelengths

4. Optically Thin

For the optically thin model, $\alpha = \alpha_{planck} + \beta$ where $\kappa_{\nu} \propto \nu^{\beta}$ and α_{planck} is the spectral index of the Planck function at the temperature of the emitting dust. We can assume the RJ-limit where $\alpha_{planck} = 2$. Hence, the disks with measured $\alpha < 2$ are explained with $0 < \beta < 1$. This implies that the grains as large as at least $a \sim 1mm$ are present in the disk.

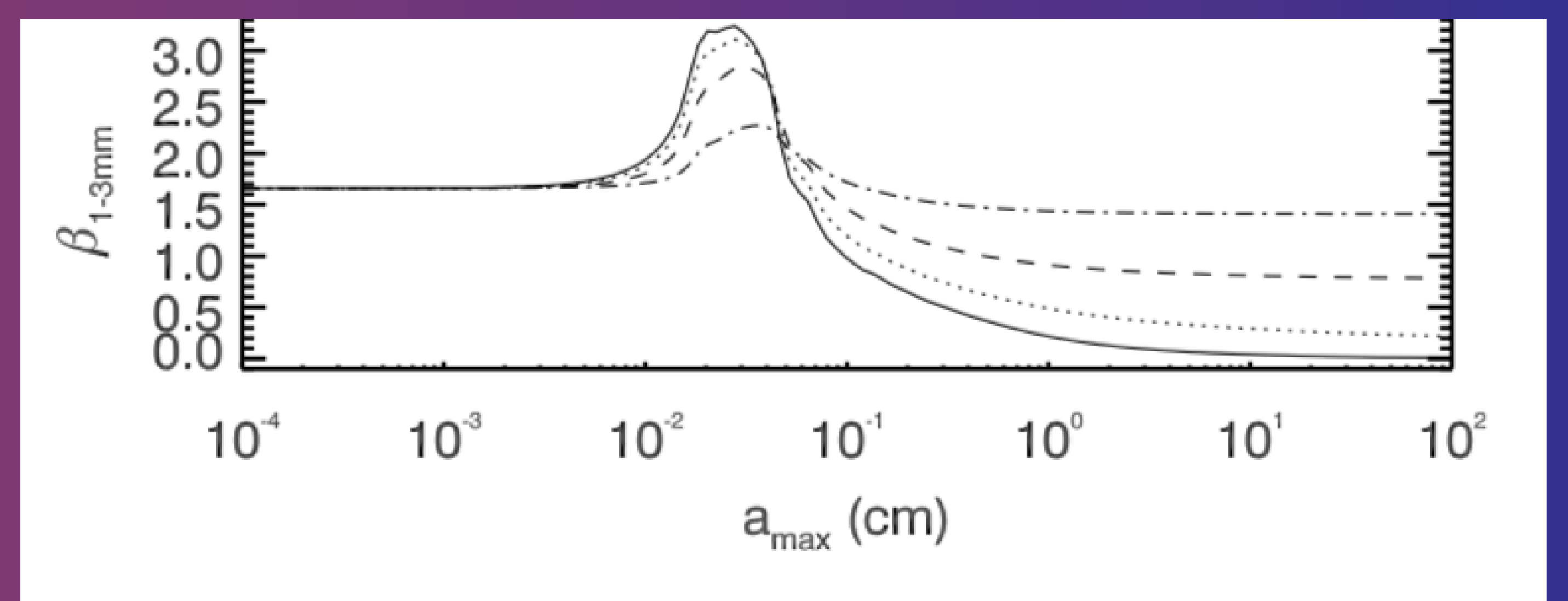


Figure 3: This plot shows the relationship of β and the largest grain size from Ricci et al 2010². For our sample, the grain size is bigger than 1mm.

6. Conclusions

We obtained information on the grain size in 24 disks in the Upper Sco region (age $\sim 5-10$ Myr). The results broke down into two models, the optically thin and thick case. From our analysis we learned that:

1. For disks with $\alpha > 2$, the optically thin disk models can explain the observed fluxes with grain sizes of $a > 1mm$
2. For disks with $\alpha < 2$, optically thick disk models can explain the observed fluxes with largest grains of size of $a \sim 10cm$
3. As the optical depth of the disk increases, the spectral index decreases and the results differentiate between scattering models and non scattering models

The presence of grains as large as $a \sim 1cm$ in these disk show that dust trapping is still efficient during the whole disk life-time. The presences of local dust traps imply that these disks have the potential to form new large solids, including possibly planets, until the end of their life.

7. References

- [1] Barenfeld, S.A et al. 2016, ApJ, 827, 142
- [2] Ricci, L. et al. 2010, A&A, 512, 15
- [3] Zhu, Z. et al. 2019, ApJ, 877, 18