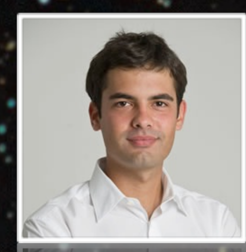
Constraining dust grain size and disc properties with ALMA and EVLA observations



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Abstract

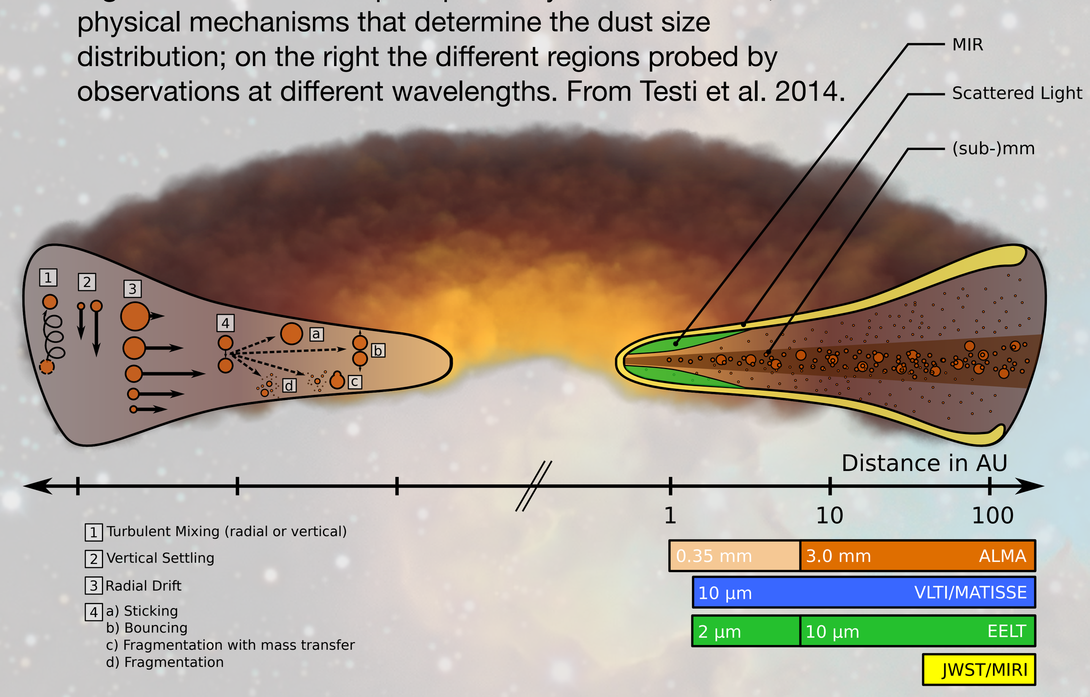
The **growth of solids** from micron-size particles to planetesimals is a critical stage in the formation of **planetary systems**. Observations at millimetre and submillimetre wavelengths allow us to probe the solids on the disk midplane where the bulk of the material is located and where planets are expected to form. The **distribution of grain sizes** in different regions of the disk is a **powerful probe** of the physical mechanisms related to grain growth and ultimately on how solids can overcome the various **growth barriers** on the way to form **planetesimals** and **planetary cores**. The upgraded VLA and, especially, the ALMA observatories provide new powerful tools to resolve grain growth in disks, but they also provide huge datasets that require **new and more efficient methods of data analysis**. I will present a novel approach to extract the dust properties in disks that I have developed and will show the preliminary results of applying this method to young protoplanetary disks.

1. Introduction

The dust size distribution in protoplanetary disks is an excellent probe to understand the effects and the relative importance of the many physical mechanisms that are involved in the formation of **planetesimals** (Testi et al. 2014).

As shown in Fig. 1, the size of dust particles is the result of several competing effects of **growth** (e.g. particle sticking, mass transfer, vertical settling) and **fragmentation** (e.g. turbulence, collisions).

Fig. 1 Sketch view of a protoplanetary disk. On the left, the physical mechanisms that determine the dust size distribution; on the right the different regions probed by observations at different wavelengths. From Testi et al. 2014.



Sub-mm and mm observations allow us to directly study the **disk interior** (that is optically thin at these wavelengths), where most of the dust mass resides. Theoretical dust evolution models predict that **large grains** settle in the disk midplane and drift radially, whereas **small grains** - more coupled to the gas - are expected to be vertically mixed by turbulence and dragged outwards following the viscous spreading of the evolving disk.

From the dust size distributions predicted by the models we can derive dust surface density distributions that we can directly compare with the observations.

2. Evidence of grain growth

The strongest evidence of grain growth is the **flattening of the spectrum at (sub-)mm wavelengths** due to the weaker dependence of dust opacity on dust grain size. For a dust size distribution

$$n(a) \propto a^{-q} \qquad a_{\min} \leq a \leq a_{\max} \qquad (1)$$

where a is the dust size, the dust opacity at mm wavelengths is well approximated by a power law:

$$\kappa_{\nu,\mathrm{mm}} \propto \nu^{\beta} \qquad (2)$$

where the value of β depends on the dust chemical composition, the porosity and to a_{max}. For ISM sub-micron particles $\beta \approx 1.7$, whereas $\beta < 1$ for dust with $a_{max} \approx 1$ mm.

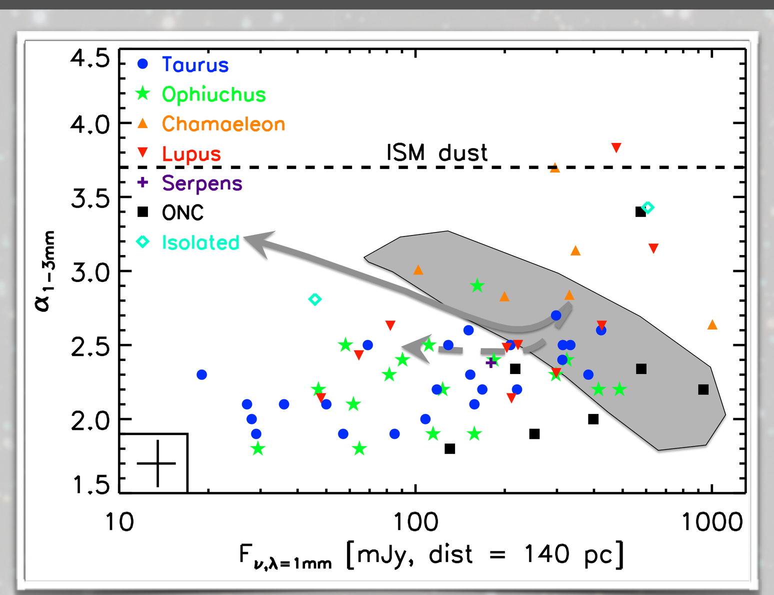


Fig. 2 Spectral index vs Flux at 1mm. From Testi et al . 2014, PPVI Review

Assuming that the disk midplane is optically thin at the mm-wavelength, and Rayleigh-Jeans regime holds, the spectrum of the disk emission results:

$$F_{\nu} \propto \nu^{\alpha} \qquad \alpha = 2 + \beta$$

In Fig. 2 we see the spectral index **α** measured between 1mm and 3mm against the flux at 1mm for several star-forming regions (Andrews and Williams, 2007, Ricci et al. 2010): almost all the disks show a small spectral index **α≈2** that might thus be a signature of the presence of dust particles larger than 1mm. Since the same spectral index can be given also by a (much smaller) optically thick disk, we need spatially resolved (sub-)mm multi-wavelength observations to disentangle this degeneracy.

3. Investigating radial variation of dust grain size: the fitting procedure

Different approaches have been used so far to study the radial variation of the dust size distribution from spatially resolved interferometric observations at (sub-)mm wavelengths.

Isella et al. 2010 assumed a dust size distribution *n(a)* **constant throughout the disk** and compared the surface brightness distribution predicted by the 2layer disk model (Chiang & Goldreich 1997, Dullemond et a 2001) with the observations, fitting each wavelength separately and finding different opacity $\tau = \kappa\Sigma$ profiles for different wavelengths. Then, provided that the disk gas surface density Σ is unique, they were able to explain the discrepancy found in the opacity **allowing a radial variation of** β, and thus inferred the radial variation of the dust grain size. With similar approach, Guilloteau et al. 2011 adopted a simple parametrization for β and found that dust models with $\beta(R)$ increasing with the disk radius better fit dual-frequency observations rather than assuming a constant β index.

More recently Perez et al. 2012, that adopted the same technique of Isella et al. 2010, took advantage of the **much wider range of wavelengths** that the renewed EVLA allows and obtained stronger **evidence for grain growth in the AS209** disk using observations from 0.8mm up to 1cm.

Our work stems from the promising results of Banzatti et al. 2011 and Trotta et al. 2013 who refined this analysis by **directly fitting the dust size distribution** (from which the dust opacity is consistently computed with the Mie Theory) and found evidence of **grain growth in the CQ Tau disk**.

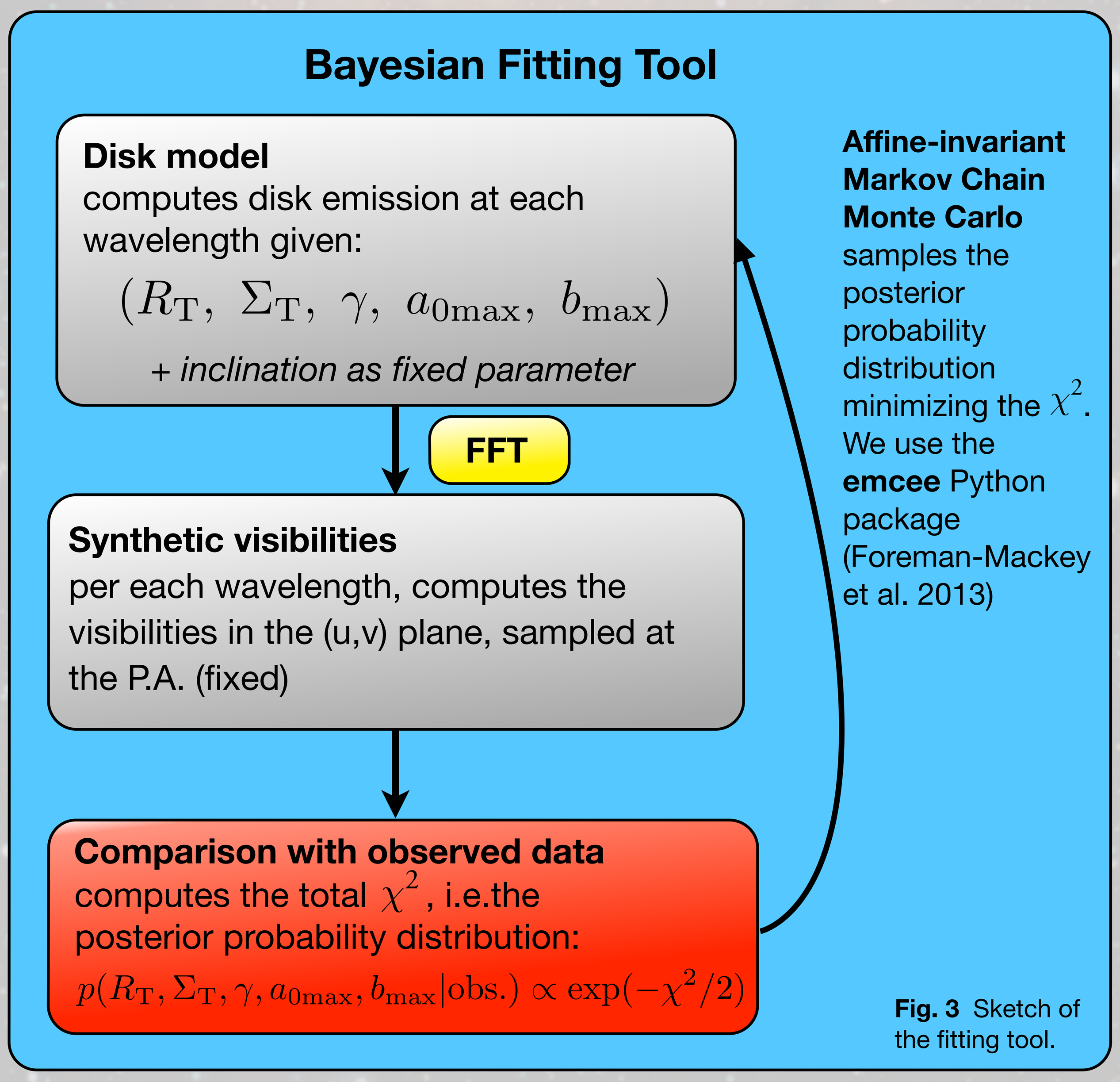


Fig. 3 Sketch of the fitting tool.

We have developed a **bayesian fitting tool** (Fig. 3) to constrain the dust size distribution by fitting **simultaneously** (sub-)mm observations at several wavelengths with a **single self-consistent disk model.**

We adopt a **2layer disk model** to compute the disk structure and for the gas surface density we assume an **exponentially tapered power-law profile**, typical of the viscous self-similar evolution of protoplanetary disks (Hartmann et al. 1998), that is defined by 3 parameters:

- R_T, the radius where the radial velocity changes sign,
- Σ_T, the surface density at RT;
- γ, the power-law index.

The dust opacity is computed with the Mie Theory given a dust size distribution, that we assume to be that in Eq. (1), with the difference that a_{max} **is not constant** but can vary as:

$$a_{\max}(R) = a_{0\max}\left(\frac{R}{40\ \mathrm{AU}}\right)^{b_{\max}} \qquad (3)$$

Thus the model has 5 parameters (R_T, Σ_T, γ, a_{0max}, b_{max}) that we constrain with a bayesian fit using **several** Markov Chain Monte Carlo (MCMC). The χ^2 is computed by comparing the observed visibilities with the synthetic visibilities (that are computed from the model image through a Fourier Transform).

4. Results

We report the results obtained for the **protoplanetary disk AS209** ($L_\star$ = 1.5$L_\odot$ $T_\star$ = 4250 K, $M_\star$ = 0.9$M_\odot$) that has already been studied by Perez et al. 2012 and we used as **benchmark** for our tool.

In Fig. 4 we report the **posterior likelihood** for the 5 parameters: we plot the marginalized distributions (1D histograms) and the bivariate distributions (2D) that show the correlations between the parameters.

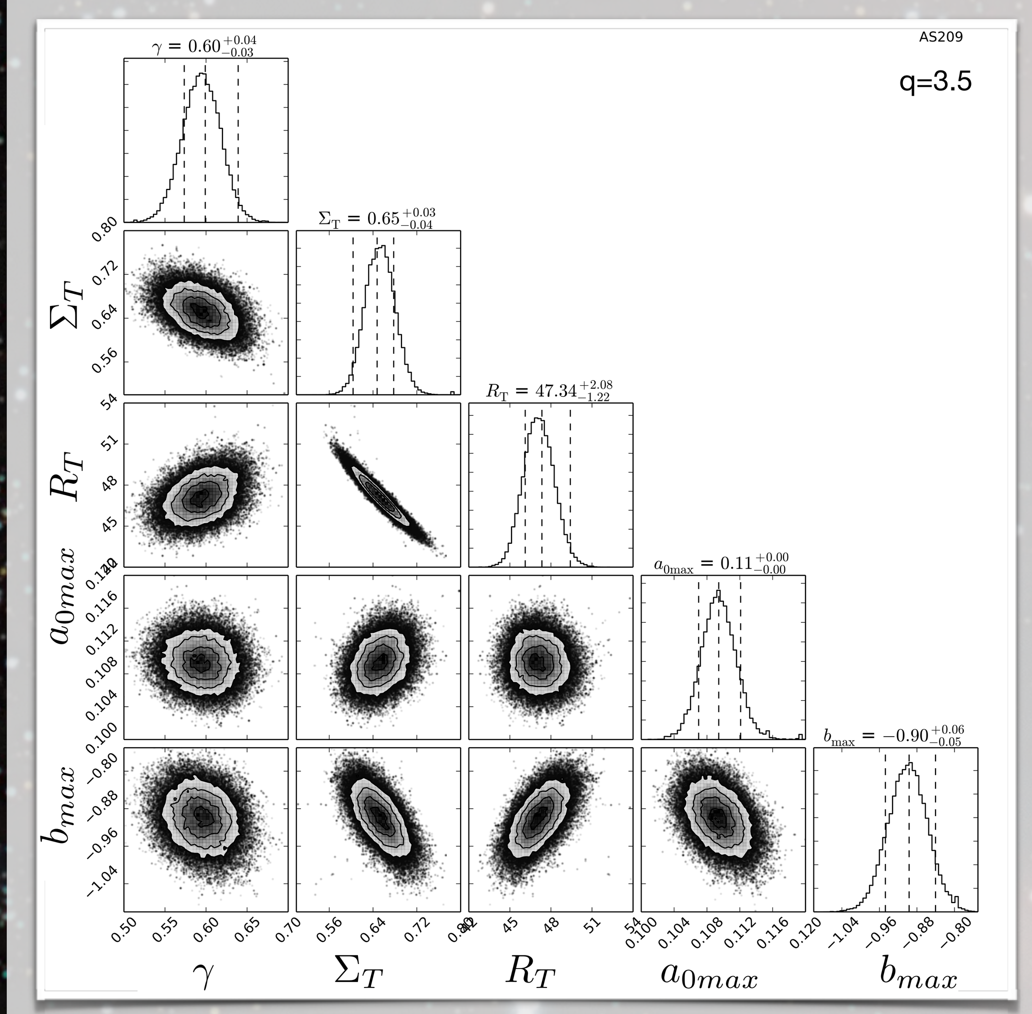


Fig. 4 Results of the MCMC after 2200 steps, with 100 walkers.

The advantage of using the **emcee** package, and thus the **affine-invariant MCMC** method proposed by Goodman & Weare, 2010, rather than a single Monte Carlo chain is that emcee samples the space of parameters with **many walkers at the same time** (here we used 100 walkers, but the number can be as large as the computing time remains reasonable). These walkers are not completely independent, but "collaborate" to find the absolute probability maximum.

In fact, these multi-walker chain is **less prone to get stuck in local maxima** and by definition do not require to be manually restarted from different initial positions to obtain an independent sampling of the posterior probability.

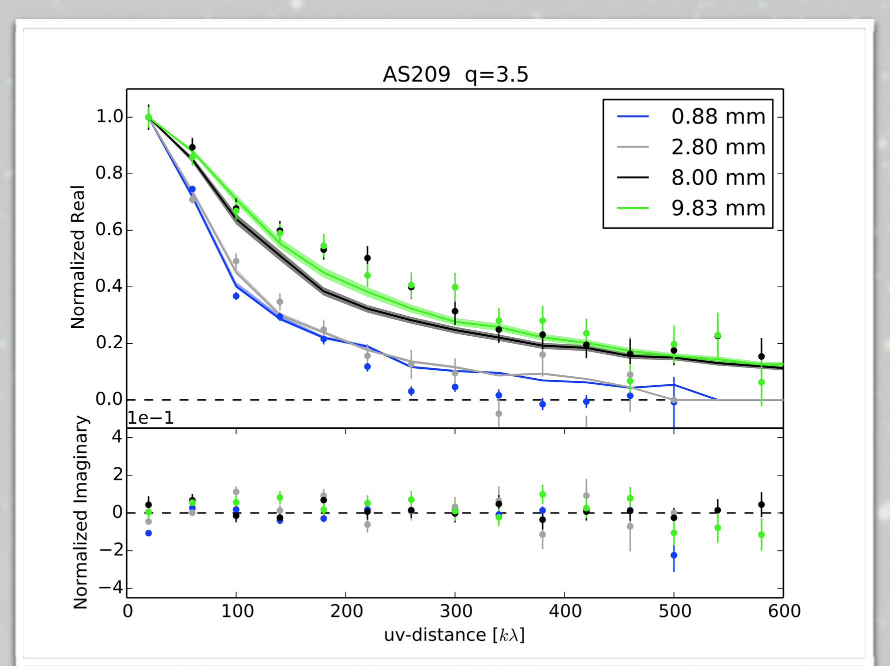


Fig. 5 Comparison between the normalized **real** and **imaginary** part of the synthetic visibilities (solid lines) and the observed visibilities (filled dots) at different wavelengths. The decline in the real part of the flux for increasing baselines ensures that **the disk has been spatially resolved.**

The imaginary part of the synthetic visibilities is by definition zero due to the fact that the 2layer disk model is axisymmetric.

The fact that the longer wavelengths (8.00 and 9.83mm, observed with the EVLA) decline more slowly than the shorter wavelengths (0.88mm and 2.80 observed respectively with SMA and CARMA), is a signature that the long-wavelength emission comes from a **more compact region.**

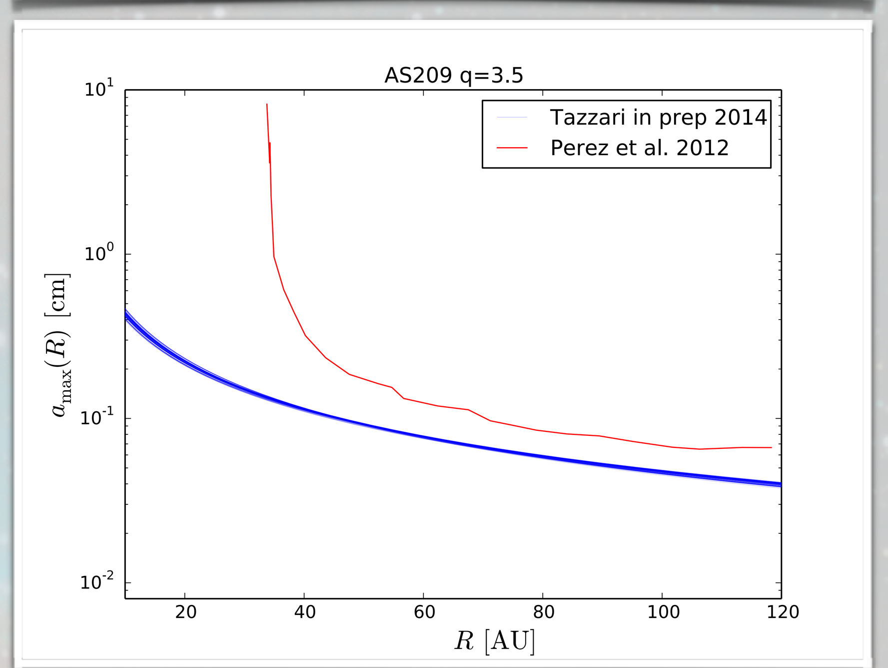


Fig. 6 Dust grain size distribution given by the fit results in Fig. 4. The solid blue curves are $a_{max}(R)$ for the 50% of the models. The red curve is the best-fit solution of Perez et al. 2012. The most evident feature is that the **dust is found to decrease with increasing radius** in both cases, as expected from dust evolution models.

In the region within the first 40 AU the agreement is not so good as in the outer parts due to the fact that **the highest spatial resolution** of the observations is around 30 AU, and therefore the uncertainties are much larger.

We are now modeling the size distribution as a simple power law (3) that has a smooth profile, but in the next future we will adopt more realistic distributions obtained by dust theoretical models.