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To cite this article: Fabio Iocco and Miguel Pato 2016 *J. Phys.: Conf. Ser.* **718** 042031

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On the dark matter distribution in the Milky Way

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Abstract. The distribution of dark matter in the Milky Way is a crucial input for ongoing studies in cosmology, astrophysics and particle physics. This motivates the effort over the next years to improve our mapping of dark matter, which has indeed become a top priority in the field. We report briefly on the state of the art regarding the dark matter distribution in our Galaxy, with a special emphasis in the inner part of the Galaxy where baryons start to give an important dynamical contribute to the total gravitational potential. After introducing the kinematic data used to trace the rotation curve and the photometric data used to model the different baryonic components, we combine kinematics and photometry to single out the dark matter content. The procedure is then used to assess the evidence for dark matter and to constrain the underlying dark matter distribution with two conceptually distinct approaches, which we dub profile fitting and profile reconstruction. Finally, in view of the swarm of astronomical data soon to become available, we shortly address the expected progress in pinpointing dark matter across the Galaxy.

1. Preliminaries

The formation of astrophysical structures, halos of dark matter populated by baryonic gas spanning a large range of masses, is one of the predictions of the Λ CDM in remarkable agreement with our observations of galaxies of very diverse luminous mass and spatial extension. The details of this picture and the exact degree of agreement between theory and observations constitute a vast subject of research of the last few decades, a task encompassing several fields of physics and observational challenges. One of the pieces of this many-faceted puzzle is the actual distribution of dark matter within the halos themselves. Whether the distribution is a self-similar function, insensitive to mass and size of the halo, or whether that impacts the formation of the gaseous structures, responding dynamically to the mass scaling and thus affecting the shape and details of visible structures, remains a key question in recent efforts.

Numerical simulations of structure formation in cosmological environments, as well as first principles calculations, give solid benchmarks for the dark matter profile of different types of galaxies, which can be used to fit the missing gravitational component inferred from observations. This is usually done for a host of different astrophysical objects, remarkably (also for historical



reasons) spiral galaxies, for which the dark matter component can be determined with quite a remarkable accuracy. Unfortunately, in the case of our own Galaxy, the Milky Way, our “privileged position” inside, approximately two thirds out toward the end of the luminous tail, within the plane of its stellar disc, makes it more challenging than for external galaxies to determine the dynamics of stars with respect to the centre, and therefore to infer the exact shape and extent of the gravitational potential.

Following the wake of decades of scientific activity on the subject, we have set out to determine the dark matter distribution within the Milky Way, structuring our quest along the following questions: *i*) Can the total gravitational potential of the Galaxy be explained by the component expected from the visible component only? And if not, at which distance from the Galactic centre do baryons unequivocally fail to explain the observed gravitational potential? *ii*) Can an unseen, non-interacting component of matter explain the discrepancy, and if so what is its distribution? Does this fit with predictions from numerical simulations of galaxy formation in a cosmological environment? *iii*) Can the gap between the observed gravitational potential and that expected from the luminous component only be explained by a modification of Newtonian gravity compatible with the rotation curves of external spiral galaxies?

In order to address the previous questions, we have built extensive, state-of-the-art compilations of two main categories of data, expanding upon previous work available in the literature. On the one hand, a compilation of appropriate tracers of the total gravitational potential of the Milky Way, in the form of the so-called rotation curve. On the other hand, a compilation of the morphological distribution of stars and gas across the entire Galaxy, encompassing all available shapes for the bulge, the disc(s) and the gaseous component, which we have appropriately normalised with the latest observations. We describe the datasets in Secs. 2 and 3, our methodology and results in Sec. 4 and we conclude in Sec. 5. These proceedings summarise the findings of our recent works [1, 2, 3, 4, 5]; for a synopsis of the topic, we direct the interested reader to Ref. [6].

2. Rotation curve

Spiral galaxies, the group to which our own Galaxy belongs, are known to be rotation-supported systems. This means that by tracing the circular velocity of objects in a galaxy one is in principle able to reconstruct the gravitational potential at the galactocentric distance of the tracer itself. Naturally, care must be taken in choosing tracers which follow the motion of our Galaxy and not some random impulse, and the literature offers examples of careful studies throughout the decades with different classes of objects, diverse approaches and from different groups. Whereas compilations of data do exist in the literature, they are by no means complete accounts of the entire scientific production, and often not up-to-date to the latest observations. In order to use the largest and most detailed collection of data available in the literature, in Ref. [1] we have extensively collected data between 3 kpc and 20 kpc from the Galactic centre. This database and its treatment is carefully described in that work, and will soon be released in digital form together with an out-of-the-box tool [5]. Here we simply summarise the types of objects and original references which make the state-of-the-art compilation of the Milky Way rotation curve.

Gas clouds are a prime tracer of the galactic rotation in external spiral galaxies as well as in our own, and we have included existing determinations in the compilation [7, 8, 9, 10, 11, 12, 13, 14, 15, 7, 16, 17, 18]. Moreover, our position within the Galaxy offers us with the advantage of resolving individual stars and to use them to trace the collective motion of the Galaxy too [19, 20, 21, 22, 23, 24]. Finally, strong radio emission from very small regions within star forming regions give rise to objects known as masers, which make excellent tracers of the rotation curve and which we have appropriately included in our compilation [25, 26, 27, 28, 29].

3. Baryons

We are now left with the chore of determining the actual luminous component of the Milky Way, for which we aim to construct the expected gravitational potential, in the form of equivalent generated circular velocity, to compare it with the one observed as described in Sec. 2. We make use of appropriate parametrisations of the spatial density of luminous matter, as obtained from photometric observations of the stellar bulge, the stellar disc(s) and the (subleading) component of interstellar, diffuse gas present in the Milky Way.

Bulge. Optical and infrared surveys have allowed to construct detailed models of the bulge, which however do differ in the details of its spatial allocation. We have therefore implemented different (and alternative to one another) determinations, all available from the literature, and none ruled out by recent constraints on the bulge mass [30, 31, 32, 33, 34, 35]. All morphological distributions have been normalised by matching the predicted microlensing optical depth with the MACHO observations toward the central Galactic region [36, 37].

Disc. The stellar disc is almost unanimously described as a double exponential with two components with different scale heights (thin and thick). In our work, we have implemented (separately) all determinations in the literature [38, 39, 40, 41, 42] and normalised the components to the most recent determination of the local total stellar surface density [42].

Gas. In its interstellar, diffuse form, gas is known to be a subleading component of the baryonic mass content of the Milky Way. Yet, we have carefully included its distribution as one of the three elements of the luminous component [43, 44]. Whereas affected by important uncertainties, these do not affect the final conclusions of our works.

We have constructed seventy morphologies of the Galaxy by realizing all the possible permutations of bulge, disc and gas and treated each one of these realisations separately and independently. The statistical uncertainty on each single morphology is largely overshadowed by the spread of all the possible morphologies, which we use to estimate our systematic ignorance on Milky Way modelling in this context [1, 6].

4. Dark matter

The dark matter component can now be inferred by comparing the kinematic data from Sec. 2, which sets the total gravitational potential of the Milky Way, to the photometric data from Sec. 3, which sets the contribution of baryons to the total gravitational potential. This is the essence of the analysis in Ref. [1], to which we refer the interested reader for full details. In that reference, we found that there is a very strong evidence for a dark mass component down to Galactocentric radii of 5 – 6 kpc, independently of the current uncertainty on baryonic modelling. At smaller radii, it is not possible to ascertain the presence of dark matter with a high degree of significance and baryonic modelling starts playing a major role since this is the region where baryons most contribute to the dynamics of the Galaxy. The picture just sketched is robust against kinematic data selection and treatment, photometric uncertainties and the current uncertainties on the Galactic fundamental parameters.

The evidence for dark matter in the inner Galaxy is an important result by itself. The next step is to use the same data to set constraints on the underlying dark matter distribution. There are essentially two approaches to address the problem: local methods [45, 46, 47, 48, 49], where one uses the kinematics of a given region of the Galaxy (usually through a carefully selected population of stars) to infer the dark matter dynamical contribution in that region, and global methods [50, 51, 52, 53, 54, 37, 55, 56, 57], where one makes the most of the kinematic data across the Galaxy to infer the dark matter density in a very specific region (for instance, the solar neighbourhood). For a discussion of the advantages and disadvantages of each type of methods, please see e.g. Refs. [49, 6]. Here we focus exclusively on global methods. Our aim is to constrain the dark matter radial profile and as such we set up two procedures that we now

pass to explain: profile fitting and profile reconstruction.

Profile fitting consists simply of a fit of a given parametric dark matter profile to the available data. This is a well-motivated approach that has been extensively used in the literature, see e.g. Refs. [52, 55, 56]. In Ref. [2], we applied this traditional procedure to the newly collected data described in Secs. 2 and 3. The main results of this work translate into constraints on the local dark matter density and the inner slope of the dark matter profile (cf. Fig. 3 of Ref. [2]). We show explicitly that the formal statistical uncertainties presently allowed by the available kinematic measurements are largely overshadowed by the systematics induced by baryonic modelling. This in turn induces a significant systematic uncertainty for the local dark matter density and a very large one for the inner slope. It is worth pointing out that the local dark matter density systematics are strongly (negatively) correlated with the disc mass, whereas the inner slope systematics are strongly (negatively) correlated with the bulge mass. Therefore, a more accurate description of the disc and bulge in our Galaxy will certainly help improving our constraints on the dark matter profile parameters. Let us note in passing that a profile fitting procedure can also be applied to derive constraints on modified Newtonian gravity, see Ref. [4] for a full analysis.

Profile reconstruction consists instead of a measurement of the dark matter profile radial bin by radial bin, without any assumptions about its parametric form. The point is that, in order to make the most of the available data, it is imperative to break all assumptions and extract the dark matter distribution directly from the data. In Ref. [3], we introduced this novel approach and, as a proof of concept, applied it to the simple case of a spherical dark matter profile with the latest data discussed in Secs. 2 and 3. The results show that at present it is not possible to distinguish between the different parametric forms suggested by numerical simulations (cf. Fig. 2 of Ref. [3]). However, this approach will become increasingly important as the data improves over this and the next decades and it will eventually provide an explicit test of numerical simulations of Milky Way like galaxies. Let us also mention that the case of non-spherical profiles, albeit mathematically more complicated, can also be treated with this approach, which opens an interesting avenue to constrain the shape of the dark matter halo in a model-independent fashion.

5. Future outlook

A great deal has been gleaned about the dark matter distribution in the Milky Way since the early studies by Kapteyn [58] and Oort [59]. Nevertheless, our current mapping of dark matter is not satisfactory nor sufficiently precise for ongoing research in cosmology, astrophysics and particle physics. In principle, to improve the situation we would like to carefully pinpoint the gravitational potential all across the Galaxy. This is not possible yet. In fact, there are mainly two limiting factors preventing further progress: baryonic modelling and kinematic data. Significant improvements on both fronts are expected with the next generation of astronomical surveys, including Gaia [60], APOGEE-2 (SDSS-IV) [61], WEAVE [62] and 4MOST [63]. In particular, Gaia is the perfect observatory to improve our understanding of the kinematics in the solar neighbourhood (including the local dark matter density and the measurement of the Oort constants), being complemented by the improved modelling of the disc and bulge provided by the near-infrared survey APOGEE-2 and by kinematic measurements all across the Galaxy by the optical instruments WEAVE and 4MOST. The future is thus bright and will hopefully lead to a more precise description of the dark matter distribution in the Milky Way.

Acknowledgements. M. P. acknowledges the support from Wenner-Gren Stiftelserna in Stockholm and F. I. from the Simons Foundation and FAPESP process 2014/11070-2.

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