Two Evidences of Dark Matter *

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1. INTRODUCTION

Various evidences suggest the existence of dark matter. According to the Planck 2018 results [1], in the standard ΛCDM model, our Universe is made of 68.3% dark energy, 26.8% dark matter, and 4.9% ordinary matter. Thus, dark matter constitutes 85% of total mass. On the other hand, dark matter has not yet been observed directly, our knowledge of dark matter is mainly based on its gravitational effect. Detection of dark matter particles is now a hot field, but we still do not get any positive result. Because of this, some physicists still doubt the existence of dark matter and proposed some alternative theories, such as modified Newtonian dynamics (MOND). These alternative theories gained some success in explaining some phenomena but not all the observational facts.

In this paper, I will check two evidences of dark matter: the galaxy rotation curves and the cosmic microwave background (CMB). The motivation of this project is to look into the details of these evidences and re-examine the theory of dark matter.

2. MILKY WAY ROTATION CURVE

Historically, galaxy rotation curves, i.e., the circular velocity profile of visible stars and gas in a galaxy as a function of their distance from the galaxy's center, played an important role in convincing scientists that large amount of dark matter exists in the outer regions of galaxies [2]. Typically, the rotation curve of a spiral galaxy is approximately 'flat' at very large galactocentric distance, which cannot be explained by only considering visible matter in the framework of Newton's theory of gravity. The simplest theory to resolve this discrepancy is dark matter.

If dark matter exists as the dominant form of mass in the Universe, one would expect that it should also exist in the Milky Way, which is a barred spiral galaxy. There are many researches on the Milky Way rotation curve. Here, I will mainly follow Ref. [3], which demonstrated the existence of dark matter in the inner Galaxy.

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* Code and data can be found at https://github.com/wufphy/ASTR541_term_project

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2.1. Milky Way Rotation Curve Data

Data of Milky Way rotation curve are dispersed in different papers in the past several decades. In 2017, M. Pato and F. Iocco provided a python2 tool, galkin [4], a compilation of different measurements together with a tool to treat the data. Here, I will use galkin to extract the observed Milky Way rotation curve.

The galkin compilation consists of 25 data sets from different groups. According to the measurement methods, these data sets can be divided into three categories: gas kinematics, star kinematics, and masers. The total data sets contain 2780 tracers distributed between 0.6 and 24.8 kpc to the galactic center. The top panel of Fig. 1 shows the distribution of these tracers in the Galactic plane. All of the 4 quadrants are covered.

Each object has a measurement of its position (specified by its galactic longitude l, galactic latitude b, and heliocentric distance d) and heliocentric line-of-sight velocity $v_h^{\rm los}$. The uncertainties of l and b are very small and can be ignored. Therefore, the main uncertainties come from the measurements of d and $v_h^{\rm los}$. In radio observations, it is customary to report $v_h^{\rm los}$ in terms of the line-of-sight velocity in the local standard of rest, $v_{\rm lsr}^{\rm los}$. Conversion between these velocities involves the peculiar solar motion $(U,V,W)_\odot$, whose value adopted in this paper is $(U,V,W)_\odot = (11.10, 12.24, 7.25)$km s^{-1} [5]. In the literature [6–8], different values of the peculiar solar motion also exist, which would cause uncertainties related to it. With the measurement $(l, b, d \pm \Delta d, v_{\rm lsr}^{\rm los} \pm v_{\rm lsr}^{\rm los})$, one obtains the Galactocentric radius R of each object by

$$R = \left(d^2 cos^2 b + R_0^2 - 2R_0 d \; cosb \; cosl\right)^{1/2}, \tag{1}$$

in which $R_0 = 8.0 \pm 0.25$ kpc is the distance of the Sun to the Galactic center. Assuming the orbit is circular, one gets the circular angular velocity ω_c by inverting

$$v_{\rm lsr}^{\rm los} = (R_0\omega_c - v_0) cosb \; sinl, \tag{2}$$

where $v_0 = 230 \pm 20$ km/s is the local circular velocity. And the circular rotation velocity is defined by

$$v_c \equiv R\omega_c. \tag{3}$$

The assumption of circular orbits generally breaks down for objects close to the Galactic center. Due to this, the authors of Ref. [3] ignored all objects with $R \leq R_{cut} = 2.5$ kpc in their analysis. From Eq. (1)-(3), one finds that the errors on R and ω_c are uncorrelated while the errors on R and

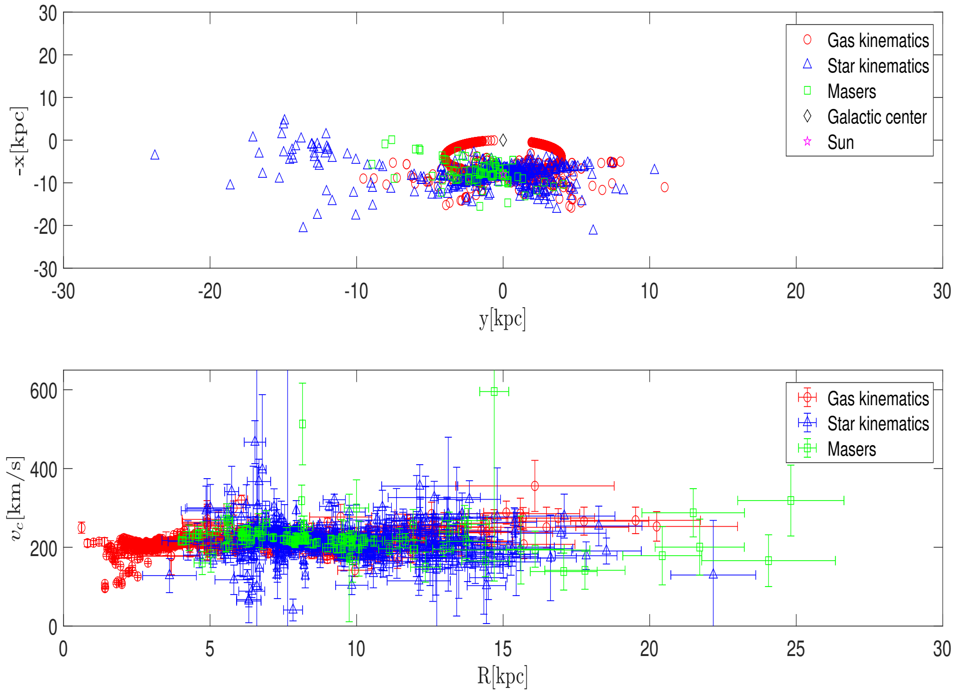

FIG. 1: Distribution of different tracers included in galkin in the Galactic plane and their derived circular rotation velocity. In the top panel, these tracers are divided into three categories: gas kinematics (denoted by red circle), star kinematics (denoted by blue triangle), and masers (denoted by green square). The black diamond point represents the galactic center while the Sun is denoted by a magenta star point. The bottom panel displays the circular rotation velocity of these tracers as a function their distance to the Galactic center. $R_0 = 8$ kpc, $v_0 = 220$ km/s, and $(U, V, W)_\odot = (11.10, 12.24, 7.25)$ km s^{-1} are used.

v_c are strongly correlated. The observed rotation curve derived from the tracers included in galkin are shown in the bottom panel of Fig. 1. At large distance to the Galactic center, the rotation curve is almost flat, as expected.

2.2. Comparison between Models and Data

To explain the observed rotation curve, one needs to know the matter distribution of the Milky Way, which consists of a bulge, stellar disk, and gas et. al. There exist many baryonic models for each of these components. For simplicity, I will only consider one model, the MWPotential2014 in Ref. [9]. The bulge in this model is described by a power-law density profile that is exponentially

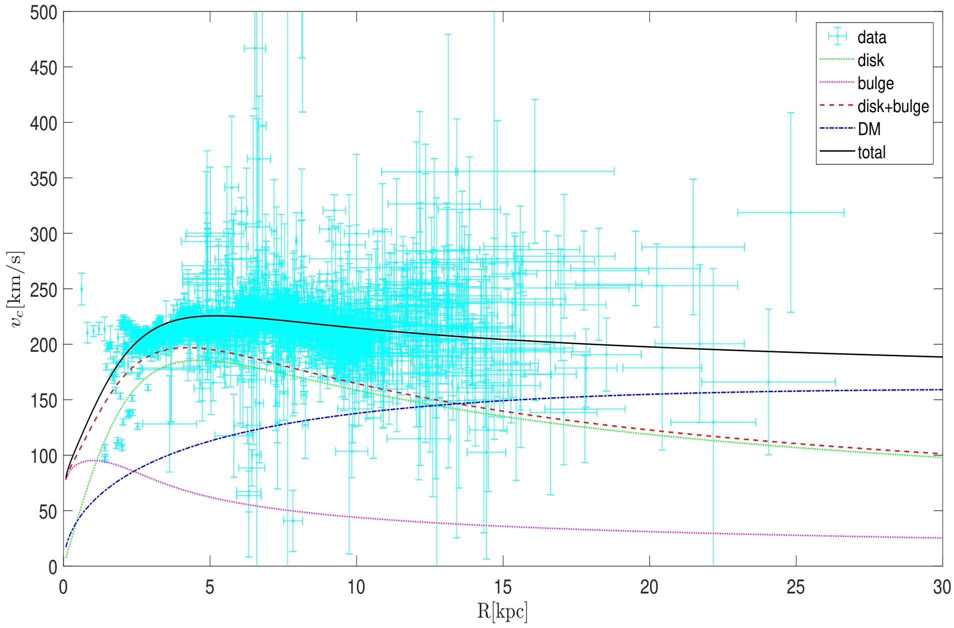

FIG. 2: Comparison between rotation curves obtained from the MWPotential2014 [9] and data. Cyan dots represent the data we got in the bottom panel of Fig. 1. The green dotted line, magenta dotted line, red dashed line, blue dash-dotted line, and black solid line represent the contribution of the disk, the bulge, disk+bulge, dark matter, and all the components, respectively. $R_0 = 8$ kpc, $v_0 = 220$ km/s, and $(U, V, W)_\odot = (11.10, 12.24, 7.25)$km s^{-1} are used.

cut-off

$$\rho(r) = amp \left(\frac{r_1}{r}\right)^\alpha exp \left[-\left(\frac{r}{r_c}\right)^2 \right], \tag{4}$$

where r_1 is the reference radius for the amplitude, $\alpha = 1.8$, and r_c=1.9 kpc. The disk is described by the Miyamoto-Nagai potential

$$\Phi(R, z) = -\frac{amp}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \tag{5}$$

in which $a = 3.0$ kpc, $b = 280$ pc. The MWPotential2014 model also has a dark matter component with a Navarro–Frenk–White (NFW) profile

$$\rho(r) = \frac{amp}{4\pi r_s^2} \frac{1}{(r/r_s)(1 + r/r_s)^2}, \tag{6}$$

in which $r_s = 16$ kpc. The calculated rotation curve with this model using galpy [9], a python package for studying galactic dynamics, and the contribution of different components are shown in Fig. 2. Comparing with the data, one finds that baryons cannot explain alone the observed rotation curve, dark matter may exist in the Milky Way. It may be too bold to draw this conclusion by only considering one model. However, in Ref. [3], the authors considered about 70 baryonic models and found that all these models underestimate the rotation curve. Besides, they also considered the effects of different choices of R_0, v_0, $(U, V, W)_\odot$, and other uncertainties, and got similar results. Therefore, the conclusion that dark matter exists in the Milky Way is robust.

2.3. Alternative Theories

In the previous sections, we have seen that dark matter can explain the observed Milky Way rotation curve with Newton's theory of gravity. There also exist theories without dark matter that can do the same job. In Ref. [10–12], it was found that MOND can also explain the data. Besides, in Ref. [13], the authors found that the observed rotation curve of the Milky Way can be explained using entire general relativity instead of Newton's theory of gravity. Therefore, more evidences of dark matter are necessary.

3. CMB

Precise measurements of the CMB spectrum play an important role in constraining cosmological models. Currently, ΛCDM model is the most successful model. It explained many observations, including the small anisotropies of the CMB spectrum, and made a number of successful predictions. Within ΛCDM, the ratio between baryons and dark matter influences the relative heights of the even and odd peaks in the CMB anisotropy spectrum [14]. Therefore, by comparing the spectrum predicted by ΛCDM with different ratios of baryons and dark matter to the observed data, one can determine the fraction of dark matter. Here, I will use CAMB [15, 16] to do the simulation, and compare the calculated results with the Planck 2018 data [17].

Fig. 3 plots the CMB temperature (TT) power spectrum. In the first five panels, Ω_Λ and h are fixed to be 0.7, and different ratios between baryonic matter and dark matter are used. We find that the parameter set with $\Omega_B = 0.0462$, $\Omega_{DM} = 0.2538$ gives the best fit, which confirms the result that dark matter is the dominant component of mass in the Universe. The best fit of the Planck collaboration is shown in the last panel for reference. Fig. 4 shows the temperature-polarization (TE) cross spectrum and the polarization (EE) spectrum with the same parameters used in the fourth panel in Fig. 3 as well as the Planck 2018 data and its best fit. Without any further adjustments, both the TE and EE spectrum are reproduced with a good precision.

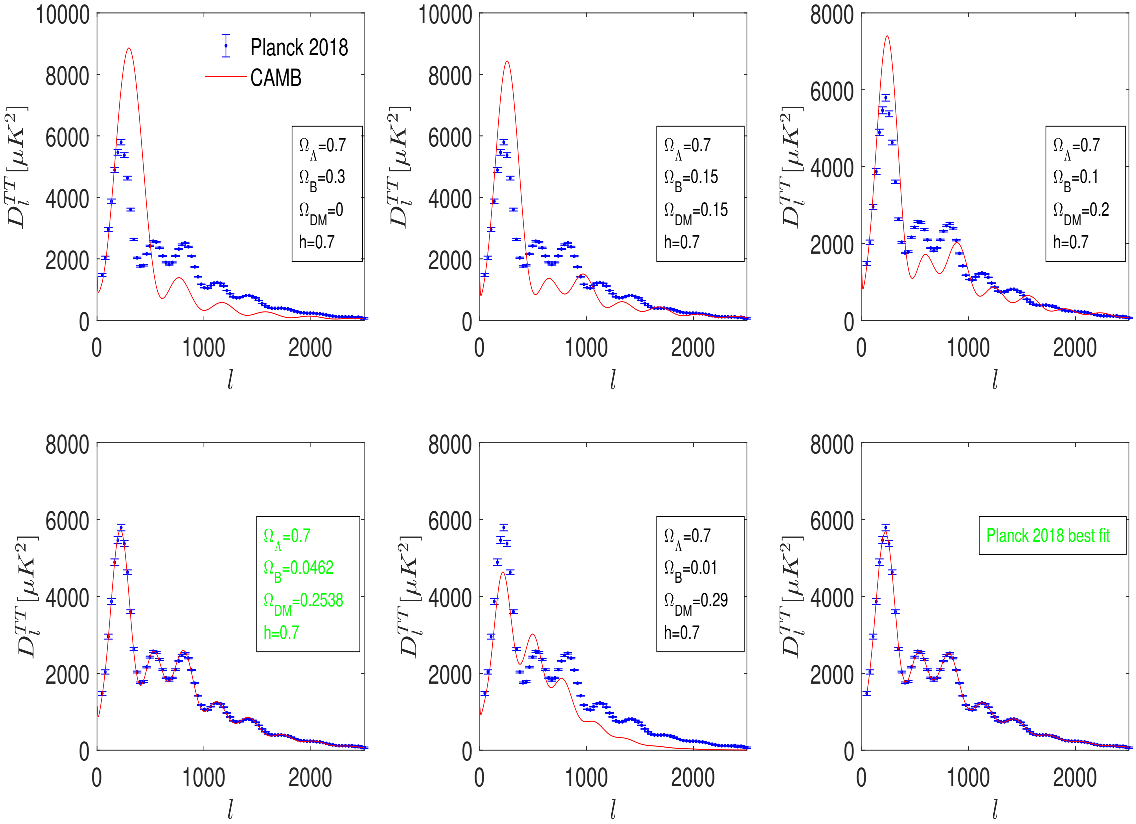

FIG. 3: The CMB temperature (TT) power spectrum. The first five panels show the simulated results using CAMB with different ratios between baryonic matter and dark matter. Ω_Λ and h are fixed to be 0.7. The Planck 2018 data is plotted in blue points with errorbars for comparison. The last panel shows the Planck 2018 best fit.

Therefore, we are more confident to draw the conclusion that dark matter exists as the dominant form of mass in the Universe.

4. SUMMARY

Two evidences of dark matter were briefly studied in this paper. By considering the Milky Way rotation curve, we have shown that dark matter may exist in our galaxy. However, alternative theories without dark matter also exist and can explain the observed rotation curve. To reproduce the CMB anisotropy spectra within ΛCDM, we have seen that dark matter is essential and is the dominant component of mass in the Universe.There are also many other evidences of dark matter,

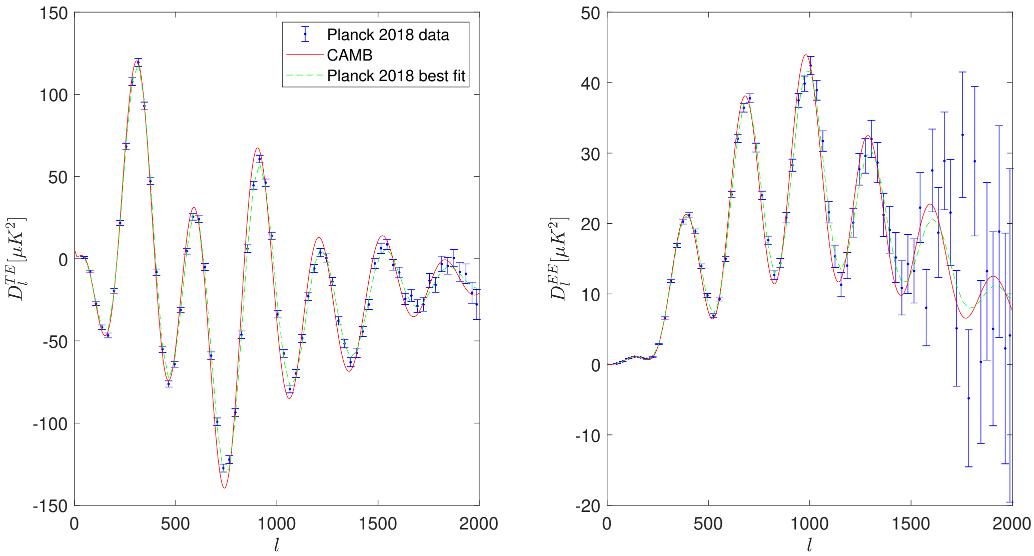

FIG. 4: The temperature-polarization (TE) cross spectrum and the polarization (EE) spectrum. Red lines represent the simulated results by CAMB. Plank 2018 data are plotted in blue points with errorbars while its best fits are shown in green dashed lines. For the simulated results, $\Omega_\Lambda = h = 0.7$, $\Omega_B = 0.0462$, $\Omega_{DM} = 0.2538$ are used.

which are not discussed in this paper. Currently, dark matter is the simplest theory to explain all these observations. Direct detection of dark matter particles becomes more and more significant to convince all scientists of the existence of dark matter.

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