A SCENARIO ON THE POWER-LAW TOTAL MASS-DENSITY PROFILE OF THE INNER REGIONS OF EARLY-TYPE-GALAXIES

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Abstract

We naturally obtain a power-law total mass-density profile for the inner regions (within several effective radii) of early-type galaxies (ETGs) from space-time structures, which are described by the static spherically-symmetric solutions of Einstein equations with the perfect fluid matters. We point out that, in the inner region of an early type galaxy, the average value of the equation of state $\omega$ determines the power-law index $\gamma$ of the total mass-density profile given by Koopmans et al. (2006). We then use 119 galaxy-galaxy strong gravitational lensing systems from SLACS, BELLs, BELLS GALLERY and SL2S, to constrain the equation of state $\omega$ for the inner regions of ETGs. We find that the average value of $\omega$ for totally 119 ETGs is $\omega = -0.315 \pm 0.007$ (68% CL), which is very close to $-1/3$. If $\omega = -1/3$ is the best value to describe the equation of state of the inner regions of the dark matter in galaxies, the deviation from $-1/3$ could represent the mixture of baryonic matter and dark matter in galaxies.

Subject headings: gravitational lensing: strong—mass distribution—galaxies: elliptical—equation of state

1. INTRODUCTION

According to general relativity, the light can be blended by massive celestial body. If a source galaxy is located behind a foreground galaxy, its light would be blend by the foreground galaxy. Therefore, we are able to find several images of the source galaxy, we call this phenomenon as galaxy-galaxy strong gravitational lens effect. Generally speaking, the location of the images can help us to know the Einstein radius and obtain the precise mass inside the Einstein radius (Einstein mass). However, if we want to infer the total mass from the Einstein mass, we also need to know the mass distribution. For the study of early-type-galaxies (ETGs), a power-law mass density profile is often assumed. For example, in the jointing gravitational lensing and dynamical analysis Koopmans et al. (2006, 2009), Auger et al. (2010), Bolton et al. (2012), Sonnenfeld et al. (2013), they always assume a power-law total mass density profile to study the properties of ETGs, such as the evolution of the power-law index, the ratio of the mass to light, etc. Another example is about cosmology, in order to obtain the accurate time-delay distances from strong lenses, Suyu et al. (2013) used elliptically symmetric distributions with power-law profiles to model the dimensionless surface mass density of the lens galaxies. The power-law total mass density profile seems to be reasonable, as illustrated by modeling of X-ray data (Humphrey & Buote 2010) and strong lensing and stellar kinematics Koopmans et al. (2006, Auger et al. (2010), but the origin of this profile remains unclear.

For a galaxy, the stellar fraction is embedded in a dark matter halo, and many dark matter models have been proposed. Among them, cold dark matter model (CDM) (Dubinski & Carlberg 1991) Navarro et al. (1996) is mainly used. But, at small scale (e.g., galaxy scale), several observations are not in accordance with the predictions of CDM. Therefore, warm dark matter model (WDM) (Viel et al. 2005), MOND model (Begeman et al. 1991), fuzzy dark matter model (FDM) (Press et al. 1990, Sin 1994), are proposed to explain the observations. Recently, researches also proposed a perfect fluid dark matter (PFDM) model (Guzman et al. 2003, Kiselev 2003, Rahaman et al. 2010, 2011, Xu & Wang 2017), which suggests that dark matter could be described as perfect fluid which has no stickly, shear stresses, viscosity, or heat conduction. Additionally, perfect fluid dark matter can be completely characterized by its rest frame mass density $\rho$ and isotropic pressure $p$.

It is known that the stress tensor of the dark matter fraction of a galaxy controls its gravitational influence. In this context, Rahaman et al. (2010) pointed out that many dark matter models end up with predicting anisotropic dark matter fluid stress tensor while explaining the flat rotation curves of spiral galaxies. No physical mechanism could explain why a spherical distribution should have such anisotropy and there is also no observational evidence in support of it. Therefore, it seems reasonable to consider an isotropic perfect fluid distribution for dark matter because predictions from such model at stellar and cosmic scales have been proved by observations. For example, for spiral galaxies, under the assumption of spherical symmetry mass distribution and perfect fluid matter, one can obtain the solution of Einstein equation for spherical symmetry gravitational field. When the equation of state of spiral galaxies is around $-1/3$ (Guzman et al. 2003), the PFDM model can ex-
plain the asymptotically flat rotation curves.

For ETGs, we try to know whether the PFDM model can be used to study the total mass distribution of the inner regions. In this work, we naturally obtain a power-law total mass-density profile for the inner regions of ETGs from space-time structures, which are described by the static spherically-symmetric solutions of Einstein equations with the perfect fluid matters. The perfect fluid matters include the dark matter that is postulated in the model and the baryonic matter that dominates astrophysical observables. Then we use the gravitational lensing data of ETGs to constrain the equation of state for the inner regions of ETGs. Here, we stress that we just assume the dark matter fraction of ETGs follow perfect fluid dark matter model. We do not discuss the nature of dark matter.

Throughout this paper, $R$ is the radial coordinate in two-dimensions and $r$ is the radial coordinate in three-dimensions. We adopt a fiducial cosmological model with $\Omega_m = 0.274$, $\Omega_\Lambda = 0.726$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DERIVING MASS PROFILE AND CONSTRAINING THE EQUATION OF STATE FOR ETGS

In this section we will introduce the theoretical basis of our study, including the derivation of the mass distribution from General Relativity and galaxy-galaxy strong gravitational lenses.

2.1. Mass distribution of ETGs derived from GR

PFDM model only describe the dark matter fraction. For the stellar fraction, because the interaction between stars is very weak, we can safely treat the stellar fraction as perfect fluid. The spherically symmetric space-time metric in perfect fluid matter is given by (Kiselev 2003)

$$ds^2 = -f(r)dt^2 + f^{-1}(r)dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2),$$

(1)

where

$$f(r) = 1 - \alpha r^{-(1+3\omega)},$$

(2)

$\alpha$ is the perfect fluid matter intensity in spherically symmetric space-time and $\omega$ is the equation of state which is defined by $\omega = -p/\rho$, where $p$ and $\rho$ are the pressure and energy density of perfect fluid matter, respectively. For $\omega = -1/3$, the above space-time represents the spherically symmetric space-time filled with perfect fluid dark matter.

By substituting Equ.(1) to Einstein field equation, we could calculate the energy density of perfect fluid matter as

$$\kappa \cdot (-\rho) = f(r) \frac{1}{r} \frac{df(r)}{dr} \left[ \frac{1}{r^2} - \frac{1}{r^2} \right] = -3\alpha \omega r^{-(3+3\omega)}.$$  

(3)

In this work, we will consider the cases of ETGs. Because the velocity dispersion of ETGs is much smaller than the speed of light, the energy density of perfect fluid matter approximates to the mass density. Then the mass of perfect fluid matter in a sphere of radius $r$ is

$$M(r) = 4\pi \int_0^r r^2 \rho dr = \frac{\alpha}{2} r^{-3\omega},$$

(4)

which describes how mass evolves as a function of radius $r$ on the basis of GR. Here, we use the system of natural units, if we want to use the International System of Units, the $\alpha$ should be $\alpha c^2$, where $c$ is the speed of light.

2.2. Galaxy-galaxy strong gravitational lenses

For a galaxy-galaxy strong gravitational lensing system, the light from the source galaxy could be deflected by the lens galaxy, forming arcs or multiple images around the lens galaxy. We can make use of the locations of these arcs or images to infer the Einstein radius $\theta_E$. The density inside the Einstein radius is the critical projected mass density which can be described as

$$\Sigma_{\text{crit}} = \frac{\rho_c}{4\pi G D_L D_S},$$

(5)

where $D_l$ and $D_s$ are the angular-diameter distances of the lens and the source, respectively, and $D_L$ is the angular-diameter distance between the lens and the source. The mass inside the Einstein radius is named Einstein mass which can be written as $M_{\text{ein}} = \pi R_E^2 \Sigma_{\text{crit}}$, where $R_E = D_L \theta_E$.

For ETGs, an empirically power-law total mass-density profile is usually assumed to describe the 3-dimensional mass distribution (See e.g., Koopmans et al. 2006, 2009; Auger et al. 2010; Bolton et al. 2012). This empirical total mass-density profile has a form of

$$\rho_{\text{tot}} = \rho_0 \left( \frac{r}{r_0} \right)^{-\gamma},$$

(6)

where $\gamma$ is the effective slope given by Treu & Koopmans (2004). $\rho_0$ can be determined by the Einstein mass $M_{\text{ein}}$, and $r_0$ can be chosen arbitrarily (Koopmans et al. 2006). For a lens galaxy, if the power-law total mass-density profile is assumed, the 3-dimensional total mass inside a sphere of radius $r$ can be obtained by projecting the 2-dimensional Einstein mass to the 3-dimensional space as

$$M(r) = f(\gamma) \cdot M_{\text{ein}} \cdot R_{\text{ein}}^{-\gamma} \cdot r^{3-\gamma},$$

(7)

where

$$f(\gamma) = \frac{2 \Gamma(\frac{3}{2})}{\Gamma(\frac{5}{2})},$$

(8)

2.3. Combining theoretical predictions and empirical assumption

Equ.1 theoretically predict the 3-dimensional total mass inside a sphere of radius $r$ based on (PFDM) model and GR, while Equ.2 empirically describes the 3-dimensional total mass based on the assumption of power-law mass-density profile. Letting two equations to be equal, we get

$$\omega = \frac{\gamma - 3}{3},$$

(9)

$$\alpha c^2 = 2f(\gamma) M_{\text{ein}} R_{\text{ein}}^{-\gamma}.$$

(10)

where $R_{\text{ein}}, M_{\text{ein}}$ and $\gamma$ can be inferred from observational data. Therefore, we can easily obtain the value of $\omega$ and $\alpha$ from gravitational lensing data. Now, for Equ.11 we replace $\gamma$ with $\omega$, then we get

$$\rho_{\text{tot}} = \rho_0 \left( \frac{r}{r_0} \right)^{(3+3\omega)},$$

(11)

which describes the 3-dimensional total mass-density profile using the equation of state.
2.4. Using gravitational lenses to constrain the equation of state of ETGs

Our gravitational lensing sample comes from SLACS (Auger et al. 2009, 2010), BELLs (Brownstein et al. 2012), BELLs GALLERY (Shu et al. 2016) and SL2S (Sonnenfeld et al. 2013). For SLACS and SL2S samples, the slope γ for each lens galaxy has been provided in Auger et al. (2010) and Sonnenfeld et al. (2013), but for BELLs and BELLs GALLERY samples, we have to use the joint lensing and dynamical analysis (Koopmans & Treu 2003, Treu & Koopmans 2004, Koopmans et al. 2004) to infer the best total mass density slope γ (The result is closing to be published). Our sample includes 119 gravitational lensing systems which are used to constrain ω. We use γ to obtain the value of ω for each lens galaxy using Eq. [2] and then plot the distribution of ω in Figure 1. We find that the distribution of ω is approximate Gaussian. The mean value of the Gaussian distribution is ω = −0.315 ± 0.007 (68% CL, the flowing are same), very close to −1/3, and the intrinsic scatter of ω is δ = 0.074 ± 0.007.

3. DISCUSSION

We have explained the power-law total mass-density profile for the inner regions of ETGs from GR assuming perfect fluid matter dark matter model (PFDM). The PFDM model was phenomenally constructed from the rotation curves of spiral galaxies and it use observations to constrain the characteristics of the model itself. Therefore, any other dark matter models must be accordant with this model. Now, we use PFDM model to study the mass distribution of ETGs and naturally obtain the power-law total mass-density distribution which is just an assumption before. Therefore, the PFDM model not only perfectly explain the rotation curves of spiral galaxies, but also explain the mass distribution of the inner regions of ETGs.

At beginning, the power-law mass-density profile is used in Koopmans & Treu (2003). In their work, they determined a mass-density profile that the total luminous plus dark matter mass distribution follows a single power-law ρtot ∝ r−γ, where γ is the "effective slope". Then they used this profile to fit the lensing system 0047-281 and got γ = 1.90 ± 0.05. They concluded that the total mass distribution of the foreground galaxy in system 0047-281 is well matched by a single power-law density profile. In Treu & Koopmans (2004) and Koopmans et al. (2006), they made further discussion to the rationality of the power-law mass distribution assumption. They suggested that if the mass-density profiles of lens galaxies are different from a power-law, one should expects the density slope inside Einstein radius to change with the ratio of Einstein radius to effective radius. However, they, as well as the later works (e.g., Koopmans et al. 2006, 2009; Ruff et al. 2011, Sonnenfeld et al. 2013), found that the mass-density slope has no relations with the ratio of Einstein radius to effective radius, which proved that the assumption of a single power-law shape for the total mass-density profile is valid. The power-law mass-density profile for the inner regions of ETGs seems to be reasonable, but no one have explained it theoretically. Now we point out that the average isothermal total mass-density profile is a natural result of GR and the equation of state ω determines the mass distribution of the inner regions of ETGs.

ω can be inferred from the slope γ in the empirical power-law mass-density profile described in Koopmans et al. (2006). We use 119 gravitational lenses to obtain the value of ω of each galaxy. We find that the average value of ω is ω = −0.314, which approximately equals to −1/3, and ω has a Gaussian distribution around −1/3. If ω = −1/3 is the best value to describe the equation of state of the dark matter in ETGs, the mixture of baryonic matter to the dark matter halo could cause the equation of state ω to deviate from −1/3. Additionally, For PFDM model, ω ≃ −1/3 is also the best value to describe the rotation curves in spiral galaxies (Kiselev 2003, Guzman et al. 2000, Rahaman et al. 2011). Bolton et al. (2012) pointed out that the average total mass density slope γ has a linear relation with redshift, e.g., γ = 2.11 − 0.60z. According to Eq. [2], we obtain that ω has a relation with redshift as ω = −0.90z − 0.285. Although the slope of the fitting result is small, but we should notice that a small change in ω could effectively change the mass density slope of a galaxy. One possible explanation for this relation is the ongoing contribution from dissipative processes during cosmic time, as described in Ruff et al. (2011). Another one is hierarchical dry-merging processes which can lead to an evolution in the inner mass profile (Bolton et al. 2012).

4. CONCLUSIONS

In this paper, we derive an universal power-law total mass-density profile for the inner regions of ETGs from GR under the assumption of spherical symmetry mass distribution and perfect fluid matter. The equation of state ω of perfect fluid matter determines the mass distribution of ETGs, e.g., the power-law index γ in an empirical total mass-density profile described in Koopmans et al. (2006). We then use 119 galaxy-galaxy strong gravitational lensing systems to constrain the equation of state ω for the inner regions of ETGs. We find that the average value of the equation of state is ω = −0.315 ± 0.073, which is very close to −1/3. We suggest that a small deviation of ω from −1/3 could be the mixture of baryonic matter and dark matter in ETGs.
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